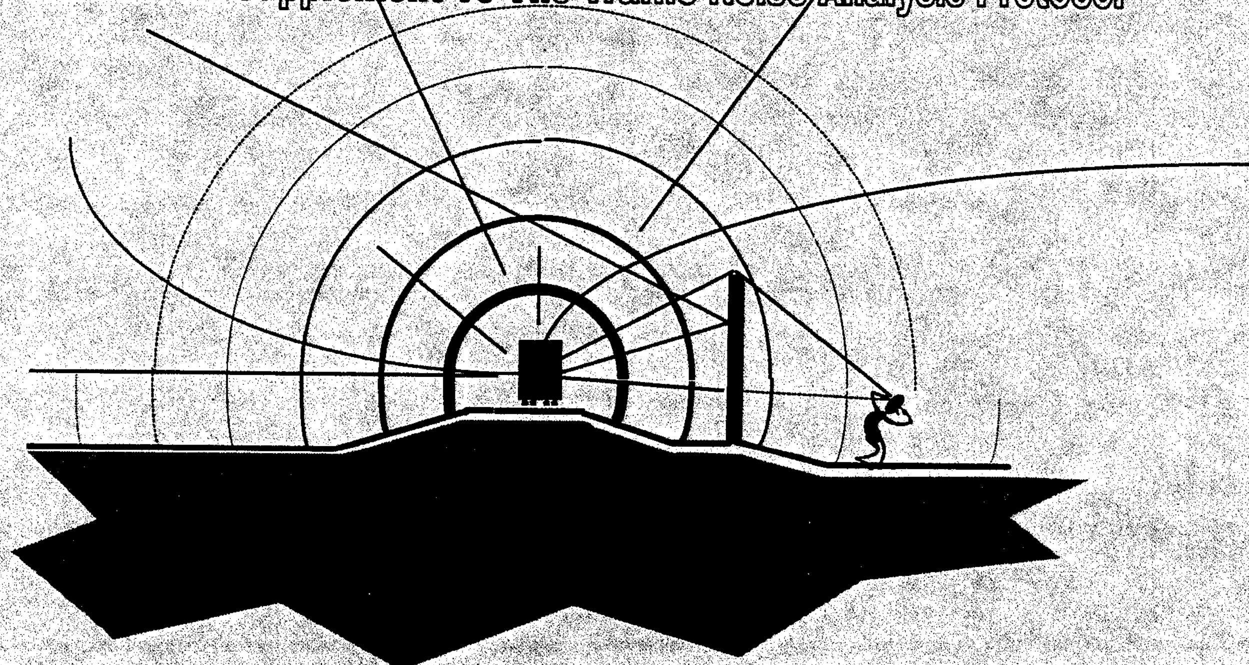
Section 4.13
Noise

Technical Noise Supplement

TeNS

A Technical Supplement To The Traffic Noise Analysis Protocol



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Environmental Engineering-
Noise, Air Quality, and Hazardous Waste Management Office

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The *Technical Noise Supplement* evolved from a 1991 draft document titled *Noise Technical Analysis Notes (NoTANs)* prepared by the former Division of New Technology and Research (TransLab). Dick Wood, a TransLab staff member, and I were the authors of the 1991 draft NoTANs. For various reasons NoTANs was never finalized. However, I edited, re-wrote, and revised original contents of the draft NoTANs and incorporated these with new information in this *Technical Noise Supplement (TeNS)*. Dick Wood's early contributions to NoTANs were extremely valuable to the development of TeNS, and I want to sincerely thank him for assisting me in the effort leading to the final completion of TeNS.

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N-1000 INTRODUCTION AND OVERVIEW

N-1100 INTRODUCTION

The purpose of this Technical Noise Supplement (TeNS) is to provide technical background information on transportation-related noise in general and highway traffic noise in particular. It is designed to elaborate on technical concepts and procedures referred to in the Caltrans Traffic Noise Analysis Protocol (the Protocol). The contents of this Supplement are for informational purposes only and unless specifically referred to as such in the Protocol they are <u>not official policy, standard or regulation</u>. The procedures recommended in TeNS are in conformance with "industry standards".

This document can also be used as a "stand alone" document for training purposes, or as a reference for technical concepts, methodology, and terminology needed to acquire a basic understanding of transportation noise with emphasis on highway traffic noise.

N-1200 OVERVIEW

TeNS consists of nine sections, numbered N-1000 through N-9000. With the exception of N-1000 (this section), each section covers a specific subject of highway noise. A brief description of the subjects follows.

- N-2000, *BASICS OF HIGHWAY NOISE* covers the physics of sound as it pertains to characteristics and propagation of highway noise, the effects of noise on humans, and ways of describing noise.
- N-3000, *MEASUREMENTS AND INSTRUMENTATION* covers the "why, where, when, and how" of noise measurements, and briefly discusses various noise measuring instruments and operating procedures.
- N-4000, *SCREENING PROCEDURE* was developed to aid in determining whether or not a highway project has the potential to cause a traffic noise impact. If the project passes the screening procedure, prudent engineering judgment should still be exercised to determine if a detailed analysis is warranted.
- N-5000, *DETAILED ANALYSIS – TRAFFIC NOISE IMPACTS* gives guidance for studying those projects failing the screening procedure, projects that are controversial, sensitive, or projects where the net effects of topography and shielding are complex and ambiguous.

- N-6000, *DETAILED ANALYSIS - NOISE BARRIER DESIGN CONSIDERATIONS* outlines the major aspects that affect the acoustical design of noise barriers. These include the dimensions, location, material, and optimization of noise barriers; the acoustical design of overlapping noise barriers (to provide maintenance access to areas behind barriers) and drainage openings in noise barriers. It also points out some pitfalls and cautions.
- N-7000, *NOISE STUDY REPORTS* discusses the contents of noise study reports.
- N-8000, *SPECIAL CONSIDERATIONS* covers some special controversial issues that frequently arise, such as reflective noise, the effects of noise barriers on distant receivers, and shielding provided by freeway landscaping.
- N-9000, *GLOSSARY* provides terminology and definitions common in transportation noise.

In addition to the above sections the *BIBLIOGRAPHY* provides a listing of literature used as a source of information in TeNS.

N-2000 BASICS OF HIGHWAY NOISE

The following sections introduce the fundamentals of sound and provide sufficient detail for the reader to understand the terminology and basic factors involved in highway traffic noise prediction and analysis. Those who are actively involved in noise analysis are encouraged to seek out more detailed textbooks and reference books in order to acquire a deeper understanding of the subject.

N-2100 PHYSICS OF SOUND

N-2110 Sound, Noise, Acoustics

Sound is a vibratory disturbance created by a moving or vibrating source, in the pressure and density of a gaseous, liquid medium or in the elastic strain of a solid which is capable of being detected by the hearing organs. Sound may be thought of as mechanical energy of a vibrating object transmitted by pressure waves through a medium to human (or animal) ears. The medium of main concern is air. In absence of any other qualifying statements, sound will be considered airborne sound, as opposed to, for example, structureborne or earthborne sound.

Noise is defined as (airborne) sound that is loud, unpleasant, unexpected or undesired, and may therefore be classified as a more specific group of sounds. Perceptions of sound and noise are highly subjective: one person's music is another's headache. The two terms are often used synonymously, although few would call the sound that emanates from a highway anything but noise.

Sound (and noise) is actually a process that consists of three components: 1) *the sound source*, 2) *the sound path*, and 3) *the sound receiver.* All three components must be present for sound to exist. Without a source to produce sound, there obviously is no sound. Likewise, without a medium to transmit sound pressure waves there is also no sound. And finally, sound must be received, i.e. a hearing organ, sensor, or object must be present to perceive, register, or be affected by sound or noise. In most situations, there are many different sound sources, paths, and receivers, instead of just one of each.

Acoustics is the field of science that deals with the production, propagation, reception, effects, and control of sound. The field is very broad, and transportation related noise and its abatement covers just a small, specialized part of acoustics.

N-2120 Speed of Sound

When the surface of an object vibrates in air, it compresses a layer of air as the surface moves outward, and produces a rarefied zone as the surface moves inward. This results in a series of high and low air pressures waves (relative to the steady ambient atmospheric pressure) alternating in sympathy with the vibrations. These pressure waves - not the air itself - move away from the source at the *speed of sound*, or approximately 343 m/s (1126 ft/sec) in air of 20^{o} C. The speed of sound can be calculated from the following formula:

$$\mathbf{c} = \sqrt{1.401\left(\frac{P}{\rho}\right)} \qquad \textbf{(eq. N-2120.1)}$$

Where:

c = Speed of Sound at a given temperature, in meters per second (m/s)

P = Air pressure in Newtons per Square Meter (N/m^2) or Pascals (Pa)

ρ = Air density in kilograms of mass per cubic meter (Kg/m^3)

1.401 = the ratio of the specific heat of air under constant pressure to that of air in a constant volume.

For a given air temperature and relative humidity, the ratio P/ρ tends to remain constant in the atmosphere, because the density of air will reduce or increase proportionally with changes in pressure. Thus the speed of sound in our atmosphere is independent of air pressure. However, when air temperature changes, only ρ changes, while P does not. The speed of sound is therefore temperature dependent, and also somewhat humidity dependent since humidity affects the density of air. The effects of the latter with regards to the speed of sound, however, can be ignored for our purposes. The fact that speed of sound changes with altitude, has nothing to do with the change in air pressure, and is only caused by the change in temperature.

For dry air of 0^{o} Celsius, $\rho = 1.2929\ Kg/m^3$. At a standard air pressure of 760 mm Hg, the pressure in Pa = 101,329 Pa. Using eq. N-2120.1, the speed of sound for standard pressure and temperature can be calculated:

$\sqrt{(1.401)(\frac{101329}{1.2929})}$ = 331.4 m/sec, or 1087.3 ft/sec. From this base value, the variation with temperature is described by the following equations:

Metric Units (m/s): $$c = 331.4\sqrt{1+\frac{Tc}{273.2}} \qquad \textbf{(eq. N-2120.2)}$$

English Units (ft/sec): $c = 1051.3\sqrt{1 + \dfrac{Tf}{459.7}}$ **(eq. N-2120.3)**

Where:

c = speed of sound in m/s (metric) or ft/sec (English)

Tc = Temperature in degrees Celcius (include minus sign for below zero)

Tf = Temperature in degrees Fahrenheit (include minus sign for below zero)

The above equations show that the speed of sound increases/decreases as the air temperature increases/decreases. This phenomenon plays an important role in the atmospheric effects on noise propagation, specifically through the process of refraction, which is discussed in section N-2143 (*Meteorological Effects and Refraction*).

N-2130 Sound Characteristics

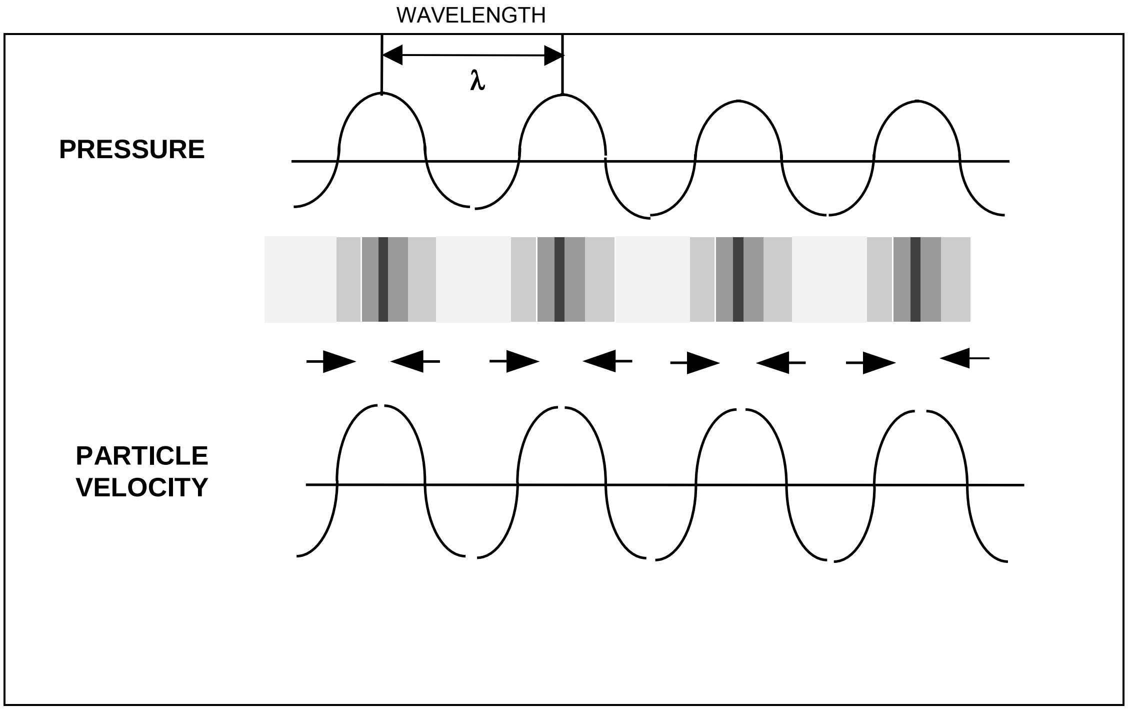
In its most basic form, a continuous sound can be described by its *frequency* or *wavelength* (pitch) and its *amplitude* (loudness).

N-2131 Frequency, Wavelength, Hertz

For a given single pitch of sound, the sound pressure waves are characterized by a sinusoidal periodic (recurring with regular intervals) wave as shown in Figure N-2131.1. The upper curve shows how sound pressure varies above and below the ambient atmospheric pressure with distance at any given time. The lower curve shows how particle velocity varies above zero (molecules moving right) and below zero (molecules moving left). Particle velocity describes the motion of the air molecules in response to the pressure waves. It does not refer to the velocity of the waves, otherwise known as the speed of sound. The distance (λ) between crests of both curves is the *wavelength* of the sound.

The number of times per second that the wave passes from a period of compression through a period of rarefaction and starts another period of compression, is referred to as the *frequency* of the wave (see Figure N-2131.2).

Figure N-2131.1. Sound Pressure

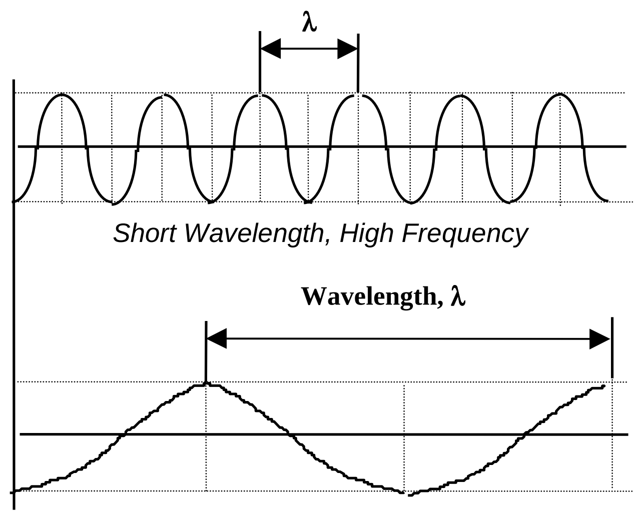


Frequency is expressed in *cycles per second*, or *Hertz* (*Hz*). One Hertz equals one cycle per second. High frequencies are sometimes more conveniently expressed in units of *Kilo Hertz* (*KHz*) or thousands of Hertz. The extreme range of frequencies that can be heard by the healthiest human ears spans from 16 to 20 Hz on the low end to about 20000 Hz (or 20 KHz) on the high end. Frequencies are heard as the pitch or tone of sound. High pitched sounds produce high frequencies, low pitched sounds produce low frequencies. Very-low-frequency airborne sound of sufficient amplitude may be felt before it can be heard, and is often confused with earthborne vibrations. Sound below 16 Hz is referred to as *infrasound*, while high frequency sound above 20000 Hz is called *ultrasound*. Both infra- and ultrasound are not audible to humans. However, many animals can hear or sense frequencies extending well into one or both of these regions. Ultrasound also has various applications in industrial and medical processes, specifically in cleaning, imaging, and drilling.

The distance traveled by a sound pressure wave through one complete cycle is referred to as the *wavelength*. The duration of one cycle is called the *period*. The period is the inverse of the frequency. For instance, the frequency of a series of waves with periods of 1/20 of a second is 20 Hertz; a period of 1/1000 of a second is 1000 Hz, or 1 KHz. Although low frequency earthborne vibrations, such as earthquakes and swaying of bridges or other structures are often referred to by period, the term is rarely used in expressing airborne sound characteristics.

Figure N-2131.2 shows that as the frequency of sound pressure waves increases, their wavelength shortens, and vice versa. The relationship between frequency and wavelength

Figure N-2131.2 - Frequency and Wavelength



is linked by the speed of sound, as shown in the following equations:

$$\boldsymbol{\lambda = \frac{c}{f}} \qquad \textbf{(eq. N-2131.1)}$$

Also: $$\mathbf{f} = \frac{c}{\lambda} \qquad \textbf{(eq. N-2131.2)}$$

and: $$\mathbf{c = f\lambda} \qquad \textbf{(eq. N-2131.3)}$$

Where:

λ = Wavelength (m or ft)

c = Speed of Sound (343.3 m/s, or 1126.5 ft/sec at 20^{o} C, or 68^{o} F)

f = Frequency (Hertz)

In the above equations, care must be taken to use the same units (distance units in either meters or feet, and time units in seconds) for wavelength and speed of sound. Although the speed of sound is usually thought of as a constant, we have already seen that it actually varies with temperature. The above mathematical relationships hold true for any value of the speed of sound. Frequency is normally generated by mechanical processes at the source (wheel rotation, or back and forth movement of pistons, to name a few), and is therefore not affected by air temperature. As a result, wavelength usually varies inversely with the speed of sound as the latter varies with temperature.

The relationships between frequency, wavelength and speed of sound can easily be visualized by using the analogy of a train traveling at a given constant speed. Individual boxcars can be thought of as the sound pressure waves. The speed of the train (and the individual boxcars) is analagous to the speed of sound, while the length of each boxcar is the wavelength. The number of boxcars passing a stationary observer each second depict the frequency (f). If the value of the latter is 2, and the speed of the train (c) is 108 km/hr (or 30 m/s), the length of each boxcar (λ) must be: c/f = 30/2 = 15m.

Using equation N-2131.1 we can develop a table showing frequency and associated wavelength. Table N-2131.1 shows the frequency/wavelength relationship at an air temperature of 20^{o} C (68^{o} F).

Table N-2131.1 Wavelength of Various Frequencies

Frequency (Hz)	Wavelength at 20^{o} C (68^{o} F) m (ft)
16	21 (70)
31.5	11 (36)
63	5.5 (18)
125	2.7 (9)
250	1.4 (4.5)
500	0.7 (2.3)
1000	0.34 (1.1)
2000	0.17 (0.56)
4000	0.09 (0.28)
8000	0.04 (0.14)
16000	0.02 (0.07)

We can check the validity of Table N-2131.1 by multiplying each frequency by its wavelength, which in each case should equal the speed of sound. Notice that, due to rounding, multiplying frequency and wavelength gives varying results for the speed of sound in air, which for 20^{o} C should be constant at 343.3 m/sec (1126.5 ft/sec).

Frequency is an important component of noise analysis. Virtually all acoustical phenomena are frequency-dependent, and knowledge of frequency content is essential. Some applications of frequency analysis will be discussed in sections N-2135 (*A-weighting, Noise Levels*) and N-2136 (*Octave and third octave Bands, Frequency Spectrums*).

N-2132 Sound Pressure Levels (SPL), Decibels (dB)

Referring back to Figure N-2131.1, we remember that the pressures of sound waves continuously changes with time or distance, and within certain ranges. The ranges of these pressure fluctuations (actually deviations from the ambient air pressure) are called the amplitude of the pressure waves. Whereas the frequency of the sound waves is reponsible for the pitch or tone of a sound, the *amplitude* determines the loudness of the sound. Loudness of sound increases and decreases with the amplitude.

Sound pressures can be measured in units of micro Newtons per square meter ($\mu N/m^2$) called micro Pascals (μPa). 1 μPa is approximately one-hundredbillionth of the normal atmospheric pressure. The pressure of a very loud sound may be 200,000,000 μPa, or 10,000,000 times the pressure of the weakest audible sound (20 μPa). Expressing sound levels in terms of μPa would be very cumbersome, however, because of this wide range. For this reason, *sound pressure levels* (*SPL*) are described in logarithmic units of ratios of actual sound pressures to a reference pressure squared. These units are called *bels*, named after Alexander G. Bell. In order to provide a finer resolution, a bel is subdivided into 10 *decibels* (deci or tenth of a bel), abbreviated dB. In its simplest form, sound pressure level in decibels is expressed by the term:

$$\textbf{Sound Pressure Level (SPL)} = \mathbf{10\ Log_{10}} \left(\frac{p_1}{p_0}\right)^{\mathbf{2}} \ \mathbf{dB} \qquad \textbf{(eq. N-2132.1)}$$

Where:

P_1 is sound pressure

P_0 is a reference pressure, standardized as 20 μPa

The standardized reference pressure, P_0, of 20 μPa, is the absolute threshold of hearing in healthy young adults. When the actual sound pressure level is equal to the reference pressure, the expression:

$$10\mathrm{Log}_{10} \left(\frac{p_1}{p_0}\right)^2 = 10\mathrm{Log}_{10}\ (1) = 0\ \mathrm{dB}$$

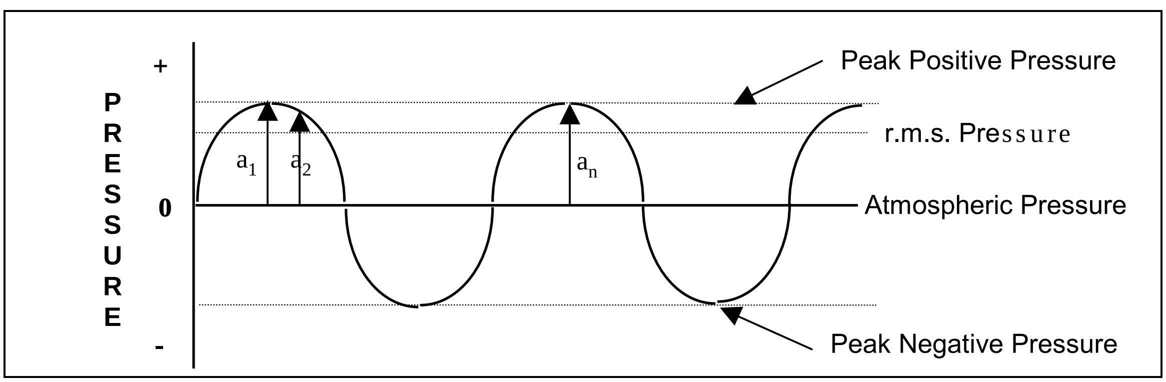
Note that 0 dB is not the absence of any sound pressure. Instead, it is an extreme value that only those with the most sensitive ears can detect. Thus, it is possible to refer to sounds as less than 0 dB (negative dB), for sound pressures that are weaker than the threshold of human hearing. For the majority of people, the threshold of hearing is higher than 0 dB, probably closer to 10 dB.

N-2133 Root Mean Square (Rms), Relative Energy

Figure N-2131.1 depicted a sinusoidal curve of pressure waves. The values of the pressure waves were constantly changing, increasing to a maximum value above normal air pressure then deceasing to a minimum value below normal air pressure, in a repetitive fashion. This sinusoidal curve is associated with a single frequency sound, also called a pure tone. Each successive sound pressure wave has the same characteristics as the previous wave. The amplitude characteristics of such a series of simple waves can then be described in various ways, all of which are simply related to each other. The two most common ways to describe the amplitude of the waves is in terms of the *peak* sound pressure level (SPL) and the *root mean square* (*r.m.s.*) SPL.

The peak SPL simply uses the maximum or peak amplitude (pressure deviation) for the value of P_1 in equation N-2132.1. The peak SPL therefore only uses one value (the absolute value of the peak pressure deviation) of the continuously changing amplitudes. The r.m.s. value of the wave amplitudes (pressure deviations) uses all the positive and negative instantaneous amplitudes, not just the peaks. It is derived by squaring the positive and negative instantaneous pressure deviations, adding these together and dividing the sum by the number of pressure deviations. The result is called the mean square of the pressure deviations, and taking the square root of this mean value is called the r.m.s. value. Figure N-2133.1 shows the peak and r.m.s. relationship for a sinusoidal wave. The r.m.s. is 0.707 times the peak value.

Figure N-2133.1 Peak Vs. r.m.s. Sound Pressures



In terms of discrete samples of the pressure deviations the mathematical expression is:

$$\textbf{r.m.s. value} = \sqrt{\left({}_1\Sigma^n(a_1^2 + a_2^2 + \ldots\ldots a_n^2)/n\right)} \qquad \textbf{(eq. N-2133.1)}$$

Sound pressures expressed in r.m.s. are proportional to the energy contents of the waves, and are therefore the most important and often used measure of amplitude. Unless otherwise mentioned, all SPL's are expressed as r.m.s. values.

N-2134 Relationship Between Sound Pressure Level, Relative Energy, Relative Pressure, and Pressure

Table N-2134.1 shows the relationship between r.m.s. SPL's, relative sound energy, relative sound pressure, and pressure.

Note that SPL's, Relative Energy, and Relative Pressure are based on a Reference Pressure of 20 μPa, and by definition all referenced to 0 dB. The Pressure values are the actual r.m.s. pressure deviations from local ambient atmospheric pressure.

The most useful relationship is that of SPL (dB) and Relative Energy. Relative Energy is unitless. Table N-2134.1 shows that for each 10 dB increase in SPL, the acoustic energy increases 10-fold. For instance an SPL increase from 60 to 70 dB increases the energy 10 times. Acoustic energy can be thought of as the energy intensity (energy per unit area) of a certain noise source, such as a heavy truck (HT), at a certain distance.

For example, if one HT passing by an observer at a given speed and distance produces an SPL of 80 dBA, then the SPL of 10 HT's identical to the single HT would be 90 dBA, if they all could simultaneously occupy the same space, and travel at the same speed and distance from the observer.

Since SPL = 10 $\text{Log}_{10}\,(P_1/P_2)^2$, the acoustic energy is related to SPL as follows:

$$\mathbf{(P_1/P_2)^2 = 10^{SPL/10}} \qquad \textbf{(eq. N-2134.1)}$$

This relationship will be useful in understanding how to add and subtract SPL's in the next section.

N-2135 Adding and Subtracting Sound Pressure Levels (SPL's)

Since decibels are logarithmic units, sound pressure levels cannot be added or subtracted by ordinary arithmetic means. For example, if one automobile produces a SPL of 70 dB when it passes an observer, two cars passing simultaneously would not produce 140 dB. In fact, they would combine to produce 73 dB. This can be shown mathematically as follows.

Figure N-2134.1 - Relationship between Sound Pressure Level, Relative Energy, Relative Pressure, and Sound Pressure

Sound Pressure Level, dB $10\ \mathrm{Log}_{10}\left(\frac{p_1}{p_0}\right)^2$	Relative Energy $\left(\frac{p_1}{p_0}\right)^2$	Relative Pressure $\left(\frac{p_1}{p_0}\right)$	Sound Pressure, μPa P_1
200 dB	10^{20}	10^{10}	
140 dB	10^{14}	10^{7}	
134 dB			10^{8} μPa
130 dB	10^{13}		
120 dB	10^{12}	10^{6}	
114 dB			10^{7} μPa
110 dB	10^{11}		
100 dB	10^{10}	10^{5}	
94 dB			10^{6} μPa
90 dB	10^{9}		
80 dB	10^{8}	10^{4}	
74 dB			10^{5} μPa
70 dB	10^{7}		
60	10^{6}	10^{3}	
54 dB			10^{4} μPa
50 dB	10^{5}		
40 dB	10^{4}	10^{2}	
34 dB			10^{3} μPa
30 dB	10^{3}		
20 dB	10^{2}	10^{1}	
14 dB			10^{2} μPa
10 dB	10^{1}		
0 dB	10^{0} = 1 = Ref.	10^{0} = 1 = Ref.	$P_1 = P_0$ = 20 μPa

Note: P_0 = 20 μPa = Reference Pressure

The sound pressure level (SPL) from any one source observed at a given distance from the source may be expressed as $10\log_{10}(P_1/P_0)^2$ (see eq. N-2132.1) The SPL from two equal sources at the the same distance would therefore be:

$$SPL = 10\log_{10}\left[(P_1/P_0)^2+(P_1/P_0)^2\right] = 10\log_{10}\left[2(P_1/P_0)^2\right].$$

This is can be simplified as $10\log_{10}(2)+10\log_{10}(P_1/P_0)^2$. Because the logarithm of 2 is 0.301, and 10 times that would be 3.01, the sound of two equal sources is 3 dB greater than the sound level of one source. The total SPL of the two automobiles would therefore be 70 + 3 = 73 dB.

***Adding and Subtracting Equal SPL's* -** The previous example of adding the noise levels of two cars, may be expanded to any number of sources. The previous section discussed the relationship between decibels and relative energy. The ratio $(P_1/P_0)^2$ is the relative (acoustic) energy portion of the expression $SPL = 10\log_{10}(P_1/P_0)^2$, in this case the relative acoustic energy of one source. This must immediately be qualified with the statement that this is not the acoustic power output of the source. Instead, the expression is the relative acoustic energy per unit area received by the observer. We may state that N identical automobiles, or other noise sources, would yield an SPL of:

$$\mathbf{SPL_{(Total)} = SPL_{(1)} + 10\log_{10}(N)} \qquad \textbf{(eq. N-2135.1)}$$

in which: $SPL_{(1)}$ = SPL of one source

N = number of identical sources to be added (must be ≥ 0)

Example: If one noise source produces 63 dB at a given distance, what would be the noise level of 13 of the same sources combined at the same distance?

Solution: $SPL_{(Total)} = 63 + 10\log_{10}(13) = 63 + 11.1 = 74.1$ dB

Equation N-2135.1 may also be rewritten as:

$$\mathbf{SPL_{(1)} = SPL_{(Total)} - 10\log_{10}(N)} \qquad \textbf{(eq. N-2135.2)}$$

This form is useful for subtracting equal SPL's.

Example: The SPL of 6 equal sources combined is 68 dB at a given distance. What is the noise level produced by one source?

Solution: $SPL_{(1)} = 68$ dB $- 10\log_{10}(6) = 68 - 7.8 = 60$ dB

In the above examples, adding equal sources actually constituted multiplying one source by the number of sources. Conversely, subtracting equal sources was performed by dividing the total. For the latter, we could have written eq. N-2135.1 as $SPL_{(1)} = SPL_{(Total)} + 10\log_{10}(1/N)$. The logarithm of a fraction yields a negative result, so the answers would have been the same.

The above excercises can be further expanded to include other useful applications in highway noise. For instance, if one were to ask what the respective SPL increases would be along a highway if existing traffic were doubled, tripled and quadrupled (assuming that traffic mix, distribution, and speeds would not change), we could make a reasonable prediction using equation N-2135.1. In this case N would be the existing traffic (N=1), N=2 would be doubling, N=3 tripling, and N=4 quadrupling the existing traffic. Since the $10\log_{10}(N)$ term in eq. N-2135.1 represents the increase in SPL, we can solve N for N=2, N=3, and N=4. The results would respectively be: +3 dB, +4.8 dB, and +6 dB.

The question might also come up what the SPL decrease would be if the traffic would be reduced by a factor of two, three, or four. In this case N = 1/2, N= 1/3, and N = 1/4, respectively. Applying the $10\log_{10}(N)$ term for these values of N would result in -3 dB, -4.8 dB, and -6 dB, respectively.

The same problem may come up in a different form. For instance, if the traffic flow on a given facility is presently 5000 vehicles per hour (vph) and the present SPL is 65 dB at a given location next to the facility, what would the expected SPL be if future traffic increased to 8000 vph? Solution: $65 + 10\log_{10}(8000/5000) = 65 + 2 = 67$ dB.

The N value may thus represent an integer, a fraction, or a ratio. However, <u>N must always be greater than 0!</u> Taking the logarithm of 0 or a negative value is not possible.

Adding and Subtracting Unequal Noise Levels. If noise sources are not equal, or if equal noise sources are at different distances, the $10\log_{10}(N)$ term cannot be used. Instead, the SPL's have to be added or subtracted individually, using the SPL and relative energy relationship in section N-2134 (eq. N-2134.1). If the number of SPL's to be added is N, and $SPL_{(1)}$, $SPL_{(2)}$, ...$SPL_{(n)}$ represent the 1^{st}, 2^{nd}, and n^{th} SPL, respectively, the addition is accomplished by:

$$\mathbf{SPL_{(Total)} = 10\log_{10}[10^{SPL(1)/10}+10^{SPL(2)/10} + \ldots\ldots\ldots\ 10^{SPL(n)/10}]} \quad \textbf{(eq. N-2135.3).}$$

The above equation is the general equation for adding SPL's. The same equation may be used for subtraction also (simply change the "+" to "-" for the term to be subtracted. However, the result between the brackets must always be greater than 0!

For example, find the sum of the following sound levels: 82, 75, 88, 68, 79. Using eq.2135.3, the total SPL is:

$$SPL = 10\ Log_{10}\ (10^{68/10} + 10^{75/10} + 10^{79/10} + 10^{82/10} + 10^{88/10}) = 89.6\ dB$$

Adding SPL's Using a Simple Table - When combining sound levels, the following table may be used as an approximation.

Table N-2135.1 Decibel Addition

When Two Decibel Values Differ By:	Add This Amount to the Higher Value:	Example:
0 or 1 dB	3 dB	70+69 = 73
2 or 3 dB	2 dB	74+71 = 76
4 to 9 dB	1 dB	66+60 = 67
10 dB or more	0 dB	65+55 = 65

This table yields results within ± 1 dB of the mathematically exact value and can easily be memorized. The table can also be used to add more than two SPL's. First, sort the list of values, from lowest to highest. Then, starting with the lowest values, combine the first two, add the result to the third value and continue until only the answer remains.

Example: find the sum of the sound levels used in the above example, using Table N-2135.1. First, rank the values from low to high:

68 dB
75 dB
79 dB
82 dB
<u>88 dB</u>
?? dB Total

Using table 2135.1 add the first two noise levels. Then add the result to the next noise level …………, etc.

a. 68 + 75 = 76,
b. 76 + 79 = 81,
c. 81 + 82 = 85,
d. 85 + 88 = **90 dB** (For comparison, using eq.2135.3, the total SPL was 89.6 dB).

Two decibel addition rules are important. First, when adding a noise level with another approximately equal noise level, the total noise level rises 3 dB. For example doubling the traffic on a highway would result in an increase of 3 dB. Conversely, reducing traffic by one half, the noise level reduces by 3 dB. Second, when two noise levels are 10 dB or more apart, the lower value does not contribute significantly (< 0.5 dB) to the total noise level.

For example, 60 + 70 dB ≈ 70 dB. The latter means that if a noise level measured from a source is at least 70 dB, the ambient noise level without the target source must not be more than 60 dB to avoid risking contamination.

N-2136 A-Weighting, Noise Levels

Sound pressure level alone is not a reliable indicator of loudness. The frequency or pitch of a sound also has a substantial effect on how humans will respond. While the intensity (energy per unit area) of the sound is a purely physical quantity, the loudness or human response depends on the characteristics of the human ear.

Human hearing is limited not only to the range of audible frequencies, but also in the way it perceives the sound pressure level in that range. In general, the healthy human ear is most sensitive to sounds between 1,000 Hz - 5000 Hz, and perceives both higher and lower frequency sounds of the same magnitude with less intensity. In order to approximate the frequency response of the human ear, a series of sound pressure level adjustments is usually applied to the sound measured by a sound level meter. The adjustments, or *weighting network*, are frequency dependent.

The A-scale approximates the frequency response of the average young ear when listening to most ordinary everyday sounds. When people make relative judgements of the loudness or annoyance of a sound, their judgements correlate well with the A-scale sound levels of those sounds. There are other weighting networks that have been devised to address high noise levels or other special problems (B-scale, C-scale, D-scale etc.) but these scales are rarely, if ever, used in conjunction with highway traffic noise. Noise levels for traffic noise reports should be reported as dBA. In environmental noise studies A-weighted sound pressure levels are commonly referred to as noise levels.

Figure N-2136.1 shows the A-scale weighting network that is normally used to approximate human response. The zero dB line represents a reference line; the curve represents frequency-dependent attenuations provided by the ear’s response. Table N-2136.1 shows the standardized values (ANSI S1.4, 1983). The use of this weighting network is signified by appending an "A" to the sound pressure level as dBA, or dB(A).

The A-weighted curve was developed from averaging the statistics of many psycho-acoustic tests involving large groups of people with normal hearing in the age group of 18-25 years. The internationally standardized curve is used world wide to address environmental noise and is incorporated in virtually all environmental noise descriptors and standards. Section N-2200 covers the most common of these, applicable to transportation noise.

Figure N-2136.1 A-Weighting Network

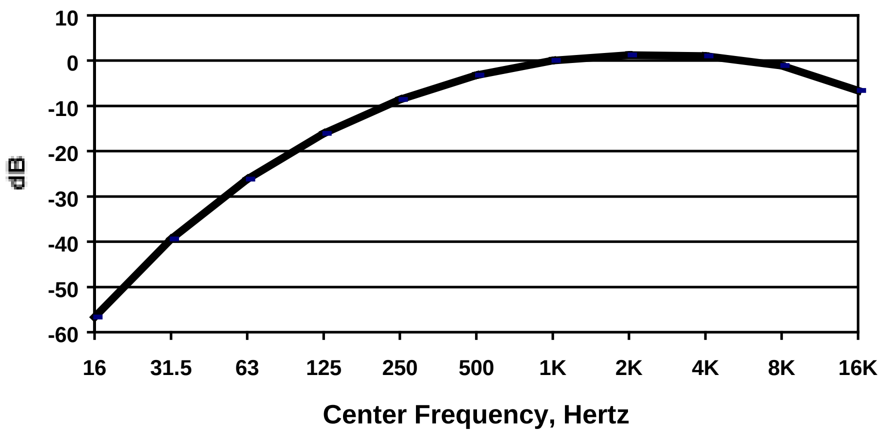


Table N-2136.1 "A"-Weighting Adjustments for 1/3 Octave Center Frequencies

Frequency, Hz	"A" - Weighting, dB	Frequency, Hz	"A" - Weighting, dB
16	-56.7	630	-1.9
20	-50.5	800	-0.8
25	-44.7	1000	0
31.5	-39.4	1250	+0.6
40	-34.6	1600	+1.0
50	-30.6	2000	+1.2
63	-26.2	2500	+1.3
80	-22.5	3150	+1.2
100	-19.1	4000	+1.0
125	-16.1	5000	+0.5
160	-13.4	6300	-0.1
200	-10.9	8000	-1.1
250	-8.6	10K	-2.5
315	-6.6	12.5K	-4.3
400	-4.8	16K	-6.6
500	-3.2	20K	-9.3

Source: American National Standards Institute (ANSI S1.4 (1983).

Sound level meters used for measuring environmental noise have an A-weighting network built in for measuring A-weighted sound levels. This is accomplished through electronic filters, also called band pass filters. As the name indicates, each filter allows the passage of a selected range (band) of frequencies only, and attenuates its sound pressure level to modify the frequency response of the sound level meter to approximately that of the A-weighted curve and the human ear.

A range of noise levels associated with common in- and outdoor activities are shown in Table N-2136.2. The decibel scale is open-ended. As was discussed previously, 0 dB or dBA should not be construed as the absence of sound. Instead, it is the generally accepted threshold of best human hearing. Sound pressure levels in negative decibel ranges are inaudible to humans. On the other extreme, the decibel scale can go much higher than shown in Table N-2136.2. For example, gun shots, explosions, and rocket engines can reach 140 dBA or higher at close range. Noise levels approaching 140 dBA are nearing the threshold of pain. Higher levels can inflict physical damage on such things as structural members of air and spacecraft and related parts. Section N-2301 discusses the human response to *changes* in noise levels.

Table N-2136.2 - Typical Noise Levels

COMMON OUTDOOR ACTIVITIES	NOISE LEVEL dBA	COMMON INDOOR ACTIVITIES
	---110---	Rock Band
Jet Fly-over at 300 m (1000 ft)		
	---100---	
Gas Lawn Mower at 1 m (3 ft)		
	---90---	
Diesel Truck at 15 m (50 ft),		Food Blender at 1 m (3 ft)
at 80 km/hr (50 mph)	**---80---**	Garbage Disposal at 1 m (3 ft)
Noisy Urban Area, Daytime		
Gas Lawn Mower, 30 m (100 ft)	**---70---**	Vacuum Cleaner at 3 m (10 ft)
Commercial Area		Normal Speech at 1 m (3 ft)
Heavy Traffic at 90 m (300 ft)	**---60---**	
		Large Business Office
Quiet Urban Daytime	**---50---**	Dishwasher Next Room
Quiet Urban Nighttime	**---40---**	Theater, Large Conference
Quiet Suburban Nighttime		Room (Background)
	---30---	Library
Quiet Rural Nighttime		Bedroom at Night, Concert
	---20---	Hall (Background)
		Broadcast/Recording Studio
	---10---	
Lowest Threshold of Human Hearing	**---0---**	Lowest Threshold of Human Hearing

N-2137 Octave and Third Octave Bands, Frequency Spectra

Very few sounds are pure tones (consisting of a single frequency). To represent the complete characteristics of a sound properly, it is necessary to break the total sound down into its frequency components; that is, determine how much sound (sound pressure level) comes from each of the multiple frequencies that make up the sound. This representation of frequency vs sound pressure level is called a frequency spectrum. Spectrums (spectra) usually consist of 8 to 10 octave bands, more or less spanning the frequency range of human hearing (20-20,000 Hz) . Just as with a piano keyboard, an octave represents the frequency interval between a given frequency and twice that frequency. Octave bands are internationally standardized and identified by their "center frequencies" (actually geometric means).

Because octave bands are rather broad, they are frequently subdivided into thirds to create 1/3-octave bands. These are also standardized. For convenience, 1/3-octave bands are sometimes numbered from band No. 1 (1.25 Hz third-octave center frequency, which cannot be heard by humans) to band No. 43 (20000 Hz third-octave center frequency). Within the extreme range of human hearing there are 30 third-octave bands ranging from No. 13 (20 Hz third-octave center frequency), to No. 42 (16,000 Hz third-octave center frequency).

Table N-2137.1 shows the ranges of the standardized octave and 1/3-octave bands, and band No's.

Frequency spectra are used in many aspects of sound analyses, from studying sound propagation to designing effective noise control measures. Sound is affected by many different frequency-dependent physical and environmental factors. Atmospheric conditions, site characteristics, and materials and their dimensions used for sound reduction are some of the more important examples.

Sound propagating through the air is affected by air temperature, humidity, wind and temperature gradients, vicinity and type of ground surface, obstacles and terrain features. These factors are all frequency dependent.

The ability of a material to transmit noise depends on the type of material (concrete, wood, glass, etc.), and its thickness. Different materials will be more or less effective at transmitting noise depending on the frequency of the noise. See section N-6110 for a discussion of Transmission Loss (TL) and Sound Transmission Class (STC).

Wavelengths serve to determine the effectiveness of noise barriers. Low frequency noise, with its long wavelengths, passes easily around and over a noise barrier with little loss in intensity. For example, a 16 Hz noise with a wavelength of 21 m (70 ft) will tend to pass right over a 5 m (16 ft) high noise barrier. Fortunately, A-weighted traffic noise tends to dominate in the 250 to 2000 Hz range with wavelengths in the order of 0.2 - 1.4 m (0.6 - 4.5 ft). As will be discussed later, noise barriers are less effective at lower frequencies, and more effective at higher ones.

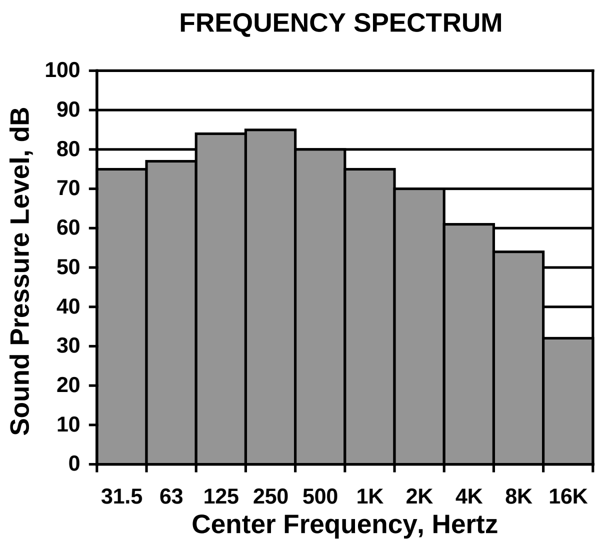
Table N-2137.1 Standardized Band No's, Center Frequencies, 1/3 Octave and Octave Bands, and Octave Band Ranges

Band No.	Center Frequency, Hz	1/3-Octave Band Range, Hz	Octave Band Range, Hz
12	**16**	14.1 - 17.8	**11.2 - 22.4**
13	20	17.8 - 22.4	
14	25	22.4 - 28.2	
15	**31.5**	28.2 - 35.5	**22.4 - 44.7**
16	40	35.5 - 44.7	
17	50	44.7 - 56.2	
18	**63**	56.2 - 70.8	**44.7 - 89.1**
19	80	70.8 - 89.1	
20	100	89.1 - 112	
21	**125**	112 - 141	**89.1 - 178**
22	160	141 - 178	
23	200	178 - 224	
24	**250**	224 - 282	**178 - 355**
25	315	282 - 355	
26	400	355 - 447	
27	**500**	447 - 562	**355 - 708**
28	630	562 - 708	
29	800	708 - 891	
30	**1000**	891 - 1120	**708 - 1410**
31	1250	1120 - 1410	
32	1600	1410 - 1780	
33	**2000**	1780 - 2240	**1410 - 2820**
34	2500	2240 - 2820	
35	3150	2820 - 3550	
36	**4000**	3550 - 4470	**2820 - 5620**
37	5000	4470 - 5620	
38	6300	5620 - 7080	
39	**8000**	7080 -8910	**5620 - 11200**
40	10K	8910 - 11200	
41	12.5K	11.2K - 14.1K	
42	**16K**	14.1K - 17.8K	**11.2K - 22.4K**
43	20K	17.8 - 22.4	

Source: Bruel & Kjaer Pocket Handbook - Noise, Vibration, Light, Thermal Comfort; September 1986

Figure N-2137.1 shows a conventional graphic representation of a typical octave-band frequency spectrum. The octave bands are depicted as having the same width, even though each successive band should increase by a factor of two when expressed linearly in terms of one Hertz increments.

Figure N-2137.1 - Typical Octave Band Frequency Spectrum



A frequency spectrum can also be presented in tabular form. For example, the data used to generate Figure N-2137.1 is illustrated in tabular form in Table N-2137.2.

Table N-2137.2 Tabular Form of Octave Band Spectrum

Octave Band Center Frequency, Hz	Sound Pressure Level, dB
31.5	75
63	77
125	84
250	85
500	80
1000 (1K)	75
2000 (2K)	70
4000 (4K)	61
8000 (8K)	54
16000 (16K)	32

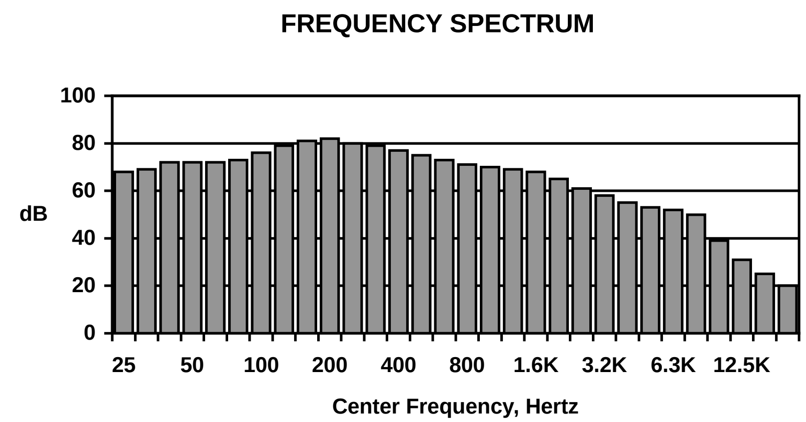
Total Sound Pressure Level = 89 dB

Often, we are interested in the total noise level, or the summation of all octave bands. Using the data shown in Table N-2137.2 we may simply add all the sound pressure levels, as was explained in section N-2135 (*Adding and Subtracting Decibels*). The total noise level for the above octave band frequency spectrum is 89 dB.

The same sort of charts and tables can be compiled from 1/3-octave band information. For instance, if we had more detailed 1/3-octave information for the above spectrum, we could construct a third octave band spectrum as shown in Figure N-2137.2 and Table 2137.2.

Note that the total noise level does not change, and that each subdivision of three 1/3-octave bands adds up to the total octave band shown in the previous example.

Figure N-2137.2 - Typical 1/3-Octave Band Frequency Spectrum



Frequency spectrums are usually expressed in linear, unweighted sound pressure levels (dB). However, they may also be A-weighted by applying the adjustments from Table N-2136.1. For example, the data in Table N-2137.2 can be "A"-weighted as follows (rounded to nearest dB) as shown in Table N-2137.3.

Table N-2137.2 Tabular Form of Octave Band Spectrum

1/3-Octave Band Center Frequency, Hz	Sound Pressure Level, dB	1/3-Octave Band Center Frequency, Hz	Sound Pressure Level, dB
25	68	800	71
31.5	69	**1000 (1K)**	70
40	72	1.25K	69
50	72	1.6K	68
63	72	**2K**	65
80	73	2.5K	61
100	76	3.2K	58
125	79	**4K**	55
160	81	5K	53
200	82	6.3K	52
250	80	**8K**	50
315	79	10K	39
400	77	12.5K	31
500	75	**16K**	25
630	73	20K	20

Total Sound Pressure Level = 89 dB

Table N-2137.3 Adjusting Linear Octave Band Spectrum to A-weighted Spectrum

Octave Band Center Frequency, Hz	Sound Pressure Level, dBA
31.5	75 - 39 = 36
63	77 - 26 = 51
125	84 - 16 = 68
250	85 - 9 = 76
500	80 - 3 = 77
1000 (1K)	75 - 0 = 75
2000 (2K)	70 + 1 = 71
4000 (4K)	61 + 1 = 62
8000 (8K)	54 - 1 = 53
16000 (16K)	32 -7 = 25

Total Sound Pressure Level = 89 dB(Lin), and 81.5 dBA

The total A-weighted noise level now becomes 81.5 dBA, compared with the linear noise level of 89 dB. In other words, the original linear frequency spectrum with a total noise level of 89 dB sounded to the human ear as having a total noise level of 81.5 dBA.

However, a linear noise level of 89 dB with a different frequency spectrum, could have produced a different A-weighted noise level, either higher or lower. The reverse may also be true. Actually, there are theoretically an infinite amount of frequency spectrums that could produce either the same total linear noise level or the same A-weighted spectrum. This is an important concept, because it can help explain a variety of phenomena dealing with noise perception. For instance, some evidence suggests that changes in frequencies are sometimes perceived as changes in noise levels, even though the total A-weighted noise levels do not change significantly. Sec. N-8000 (*Special Problems*) deals with some of these phenomena.

N-2138 White Noise, Pink Noise

White noise is noise with a special frequency spectrum that has the same amplitude (level) <u>for each frequency interval</u> over the entire audible frequency spectrum. It is often generated in laboratories for calibrating sound level measuring equipment, specifically its frequency response. One might expect that the octave or third-octave band spectrum of white noise would be a straight line. This is, however, not true. Beginning with the lowest audible octave, each subsequent octave spans twice as many frequencies than the previous ones, and therefore contains twice the energy. This corresponds with a 3 dB step increase for each octave band, and 1 dB for each third octave band.

Pink noise, in contrast, is defined as having the same amplitude for each octave band (or third-octave band), rather than for each frequency interval. Its octave or third-octave band spectrum is truly a straight, "level" line over the entire audible spectrum. Pink noise generators are therefore conveniently used to calibrate octave or third-octave band analyzers.

Both white and pink noise sound somewhat like the static heard from a radio that is not tuned to a particular station.

N-2140 Sound Propagation

From the source to the receiver noise changes both in level and frequency spectrum. The most obvious is the decrease in noise as the distance from the source increases. The manner in which noise reduces with distance depends on the following important factors:

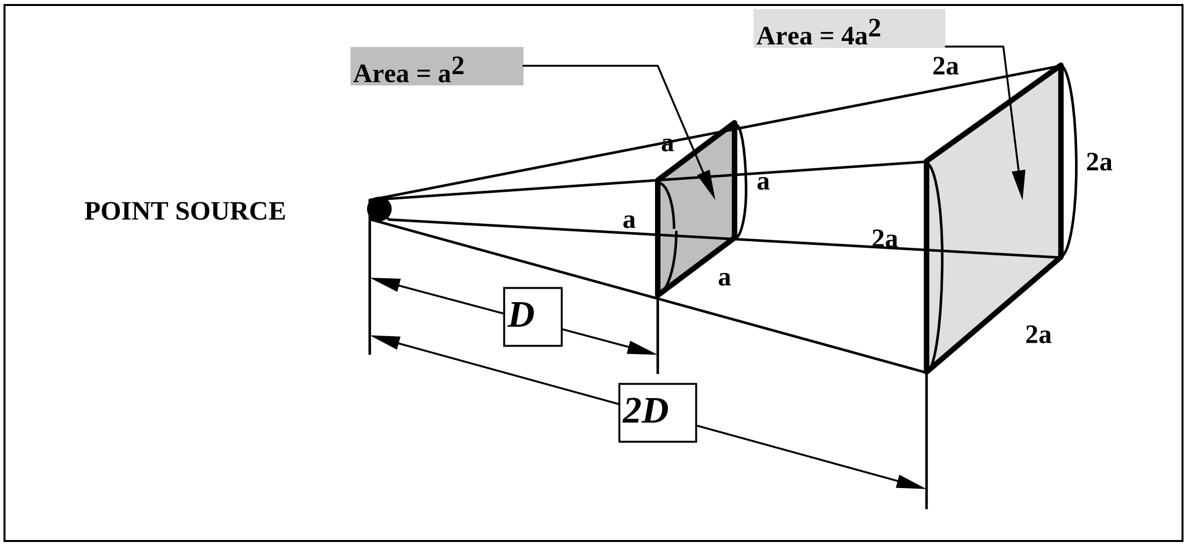
- Geometric Spreading from Point and Line Sources
- Ground Absorption
- Atmospheric Effects and Refraction
- Shielding by Natural and Manmade Features, Noise Barriers, Diffraction, and Reflection

N-2141 Geometric Spreading from Point and Line Sources

Sound from a small localized source (approximating a "point" source) radiates uniformly outward as it travels away from the source in a spherical pattern. The sound level attenuates or drops-off at a rate of 6 dBA for each doubling of the distance (6 dBA/DD). This decrease, due to the geometric spreading of the energy over an ever increasing area, is referred to as the *inverse square law*. Doubling the distance increases each unit area, represented by squares with sides "**a**" in Figure N-2141.1, from $\mathbf{a^2}$ to $\mathbf{4a^2}$.

Since the same amount of energy passes through both squares, the energy per unit area at 2D is reduced 4 times from that at distance D. Thus, for a point source the energy per unit area is inversely proportional to the square of the distance. Taking 10 $\log_{10}$ (1/4) results in a 6 dBA reduction (for each doubling of distance). This is the point source attenuation rate for geometric spreading.

Figure N-2141.1 Point Source Propagation (Spherical Spreading)



As can be seen in Figure N-2141.2, based on the inverse square law the change in noise level between any two distances due to the spherical spreading can be found from:

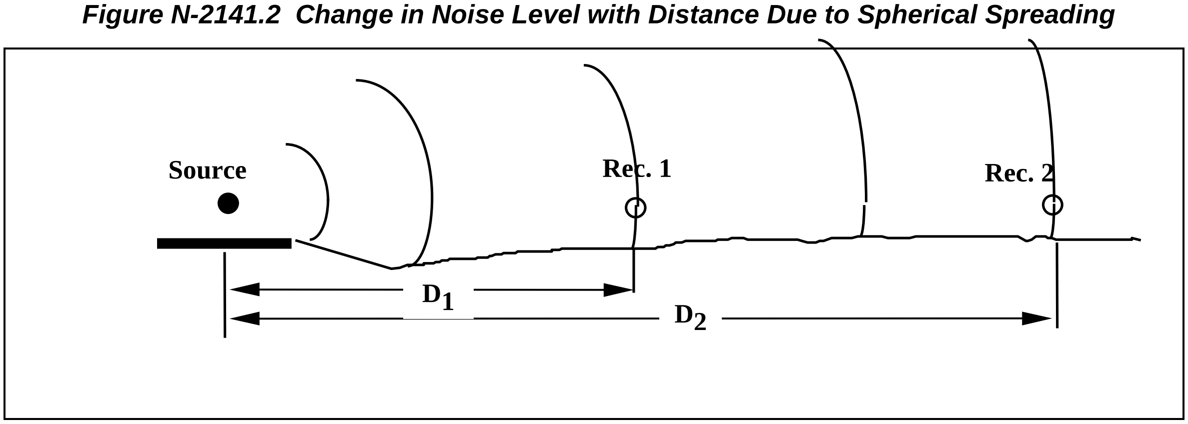
$$\mathbf{dBA_2 = dBA_1 + 10\ Log_{10}\ [(D_1/D_2)]^2 =}$$

$$\mathbf{= dBA_1 + 20\ Log_{10}\ (D_1/D_2)} \qquad \textbf{(eq. N-2141.1)}$$

Where:

dBA_1 is the noise level at distance D_1, and
dBA_2 is the noise level at distance D_2

Figure N-2141.2 Change in Noise Level with Distance Due to Spherical Spreading



However, highway traffic noise is not a single, stationary point source of sound. The movement of the vehicles makes the source of the sound appear to emanate from a line (line source) rather than a point when viewed over some time interval (see Figure N-2141.3). This results in cylindrical spreading rather than the spherical spreading of a point source.

Since the change in surface area of a cylinder only increases by two times for each doubling of the radius instead of the four times associated with spheres, the change in sound level is 3 dBA per doubling of distance. The change in noise levels for a line source at any two different distances due to the cylindrical spreading becomes:

$$\mathbf{dBA_2 = dBA_1 + 10\ Log_{10}\ (D_1/D_2)} \qquad \textbf{(eq. N-2141.2)}$$

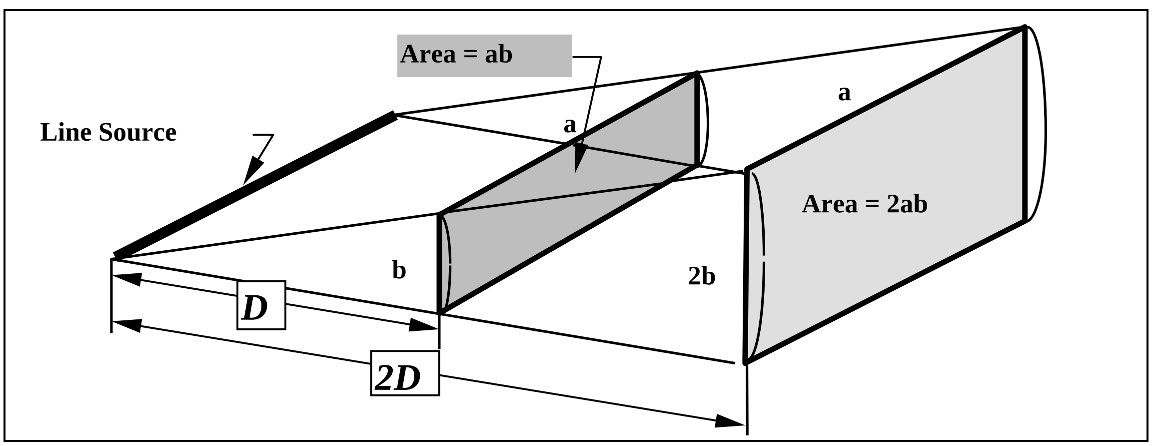
Where:

dBA_1 is the noise level at distance D_1, and conventionally the known noise level

dBA_2 is the noise level at distance D_2, and conventionally the unknown noise level

Note: the expression 10 Log_{10} (D_1/D_2) is negative when D_2 is greater than D_1, positive when D_1 is greater than D_2, and the equation therefore automatically accounts for the receiver being farther out or closer in with respect to the source (Log_{10} of a number less than 1 gives a negative result; Log_{10} of a number greater than 1 is positive, and Log_{10} (1) = 0).

Figure N-2141.3 Line Source Propagation (Cylindrical Spreading)



N-2142 Ground Absorption

Most often, the noise path between the highway and the observer is very close to the ground. Noise attenuation from ground absorption and reflective wave canceling adds to the attenuation due to geometric spreading. Traditionally, the access attenuation has also been expressed in terms of attenuation per doubling of distance. This approximation is done for simplification only, and for distances of less than 60 m (200 feet) prediction results based on this scheme are sufficiently accurate. The sum of the geometric spreading attenuation and the excess ground attenuation (if any) is referred to as the *attenuation rate*, *or drop-off rate*. For distances of 60 m (200 feet) or greater the approximation causes excessive inaccuracies in predictions. The amount of excess ground attenuation depends on the height of the noise path and the characteristics of the intervening ground or site. In practice this excess ground attenuation may vary from nothing to 8-10 dBA or more per doubling of distance. In fact, it varies as the noise path height changes from the source to the receiver and also changes with vehicle type since the source heights are different. The complexity of terrain is another factor that influences the propagation of sound by potentially increasing the number of ground reflections. Only the most sophisticated computer model(s) can properly account for the interaction of soundwaves near the ground.

In the mean time, for the sake of simplicity two site types are currently used in traffic noise models:

1. **HARD SITES** - These are sites with a reflective surface between the source and the receiver such as parking lots or smooth bodies of water. No excess ground attenuation is assumed for these sites and the changes in noise levels with distance (drop-off rate) is simply the geometric spreading of the line source or 3 dBA/DD (6dBA/DD for a point source).

2. **SOFT SITES** - These sites have an absorptive ground surface such as soft dirt, grass or scattered bushes and trees. An excess ground attenuation value of 1.5 dBA/DD is normally assumed. When added to the geometric spreading results in an overall drop-off rate of 4.5 dBA/DD for a line source (7.5 dBA/DD for a point source).

The combined distance attenuation of noise due to geometric spreading and ground absorption in the above simplistic scheme can be generalized with the following formulae:

$$\mathbf{dBA_2 = dBA_1 + 10\ Log_{10}\ (D_1/D_2)^{1+\alpha}} \qquad \textbf{(Line Source)} \qquad \textbf{(eq. N-2142.1)}$$

$$\mathbf{dBA_2 = dBA_1 + 10\ Log_{10}\ (D_1/D_2)^{2+\alpha}} \qquad \textbf{(Point Source)} \qquad \textbf{(eq. N-2141.2)}$$

where: α is a site parameter which takes on the value of **0** for a **hard site** and **0.5** for a **soft site**.

The above formulae may be used to calculate the noise level at one distance if the noise level at another distance is known. The "α scheme" is just an approximation. It is used in older versions of the FHWA Highway Traffic Noise Prediction Model. Caltrans research has shown that for average traffic and "soft site" characteristics, the α scheme is fairly accurate within 30 m (100 ft) from a typical highway. Between 30 - 60 m (100 - 200 ft) form a highway, the algorithm results in average over predictions (model predicted noise levels higher than actual) of 2 dBA. At 60 - 150 m (200 - 500 ft) over predictions average about 4 dBA.

Following are some typical examples of distance adjustment calculations using equations N-2141.1 and N-2141.2:

1. The maximum noise level of truck passing by an observer is measured to be 83 dBA at a distance of 25 m. What is the maximum noise level at 62 m if the terrain is considered a soft site?

   Solution: The truck is a point source; α for a soft site = 0.5. Hence, at 62 m the noise level is:

   83 dBA **+** 10 Log_{10} $(25/62)^{2+0.5}$= 83 + (- 9.9) = 73.1 dBA. **(eq. N-2141.2)**

2. The average noise level from a two-lane highway is 65 dBA at a receiver located 50 m from the centerline. The ground between the highway and receiver is a grassy field. What noise level can be expected for a receiver 20 m from the centerline of the same highway?

   Solution: The two-lane highway may be considered a line source (a series of moving point sources). The site parameter α is 0.5 (grassy field is a soft site). Hence, at 20 m the estimated noise level is:

   65 dBA + 10 Log_{10} $(50/20)^{1+0.5}$ **=** 65 + (+6.0) = 71 dBA **(eq. N-2141.1)**

   Notice that in the first example the known noise level was closer to the highway than the unknown one; in the second example the reverse was true.

3. The average noise level from a single truck passby, measured from the time the truck can first be heard (above the ambient noise) to the time that the truck's noise dips below ambient noise, is 62 dBA at a distance of 35 m. What is the average noise level of the truck at 50 m, if the the site is hard?

   Solution: In this case the line source formula should be used. The difference between example 1 and this example is that in 1 the maximum noise level was measured. The maximum noise level is an instantaneous noise level, occurring at one location only: presumably the closest point to the observer. In this example the noise was an average noise level, i.e. the truck noise was measured at many different locations representing the entire passby and therefore a series of point sources that may be represented by a line source. Hence, **eq. N-2141.1** should be used with $\alpha = 0$. The answer is 60.5 dBA at 50 m.

Table N-2142.1 shows a simple generalization regarding the use of point or line source distance attenuation equations for various source types, instantaneous noise and time-averaged noise levels.

Sec. N-5500 contains additional discussions on how to use the appropriate drop-off rate in the noise prediction models.

Table N-2142.1 Use of Point and Line Source Distance Attenuation Equations.

	NOISE LEVEL AT STATIONARY RECEIVERS	
SOURCE TYPE	**INSTANTANEOUS (Usually maximum)**	**TIME-AVERAGED**
Single, Stationary Point Source (e.g. idling truck, pump, machinery)	**Use Point Source Equation (eq. N-2142.2)**	**Use Point Source Equation (eq. N-2142.2)**
Single, Moving Point Source (e.g. moving truck):	**Use Point Source Equation (eq. - N 2142.2)**	**Use Line Source Equation (eq. N-2142.1)**
Series of Point Souces on a Line, Stationary or Moving: (e.g. highway traffic)	**Use Line Source Equation (eq. N-2142.1)**	**Use Line Source Equation (eq. N-2142.1)**

N-2143 Atmospheric Effects and Refraction

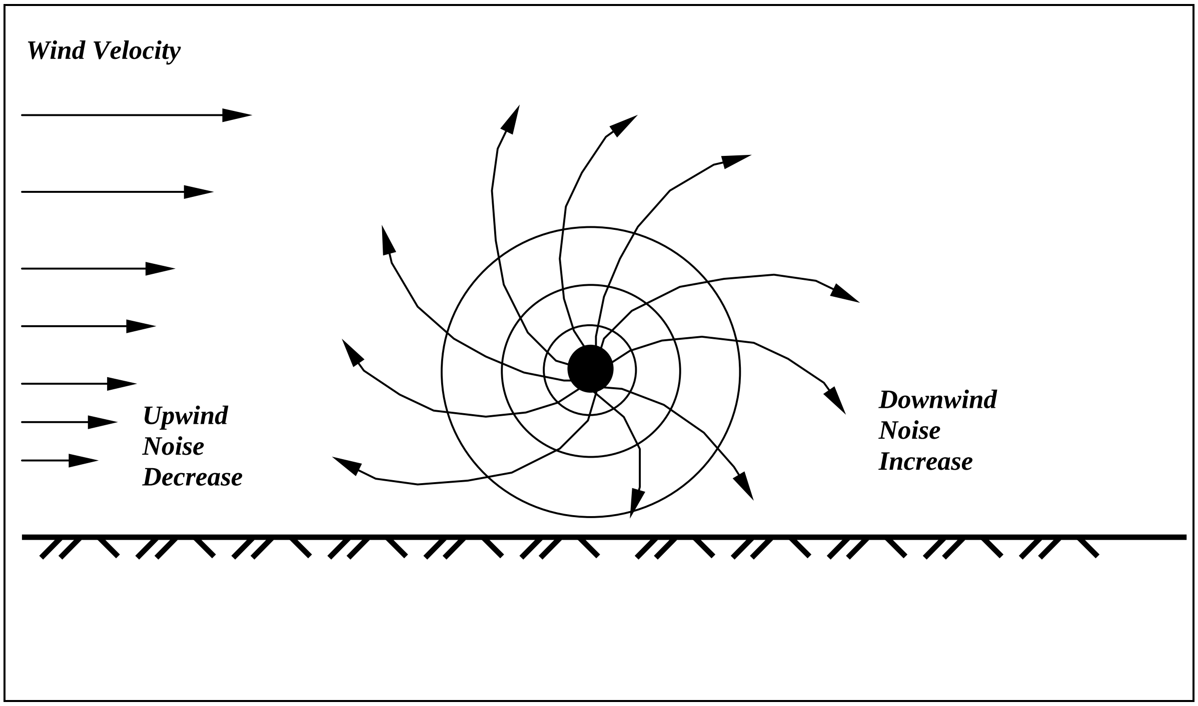
Research by Caltrans and others has shown that atmospheric conditions can have a profound effect on noise levels within 60 m (200 ft) from a highway. Wind has shown to be the single most important meteorological factor within approximately 150 m (500 ft), while vertical air temperature gradients are more important over longer distances. Other factors such as air temperature and humidity, and turbulence, also have significant effects.

Wind. The effects of wind on noise are mostly confined to noise paths close to the ground. The reason for this is the **wind shear** phenomenon. Wind shear is caused by the slowing down of wind in the vicinity of a ground plane due to friction. As the surface roughness of the ground increases, so does the friction between the ground and the air moving over it. As the wind slows down with decreasing heights it creates a sound velocity gradient (due to differential movement of the medium) with respect to the ground. This velocity gradient tends to bend sound waves downward in the same direction of the wind and upward in the opposite direction. The process, called **refraction**, creates a **noise "shadow"** (reduction) **upwind** from the source and a **noise "concentration"** (increase) downwind from the source. Figure N-2143.1 shows the effects of wind on noise. Wind effects on noise levels along a highway are very much dependent on wind angle, receiver distance and site characteristics. A 10 km/hr (6 mph) cross wind can increase noise levels at 75 m (250 ft) by about 3 dBA downwind, and reduce noise by about the same amount upwind. Present policies and standards ignore the effects of wind on noise levels. Unless winds are specifically mentioned, noise levels are always assumed to be for zero winds. Noise analyses are also always made for zero wind conditions.

Wind also has another effect on noise measurements. Wind "rumble" caused by friction between air and a microphone of a sound level meter can contaminate noise measurements even if a windscreen is placed over the microphone.

Limited measurements performed by Caltrans in 1987 showed that wind speeds of about 5 m/s produce noise levels of about 45 dBA, using a 1/2 inch microphone with a wind screen. This means that noise measurements of less than 55 dBA are contaminated by wind speeds of 5 m/s. A noise level of 55 dBA is about at the low end of the range of noise levels routinely measured near highways for noise analyses. FHWA document No. FHWA-DP-45-1R, titled “Sound Procedures for Measuring Highway Noise: Final Report”, August 1981, recommends that highway noise measurements should not be made at wind speeds above 12 mph (5.4 m/s). A 5 m/s criterion for maximum allowable wind speed for routine highway noise measurements seems reasonable and is therefore recommended. More information concerning wind/microphone contamination will be covered in the noise measurement section N-3000 of this Appendix.

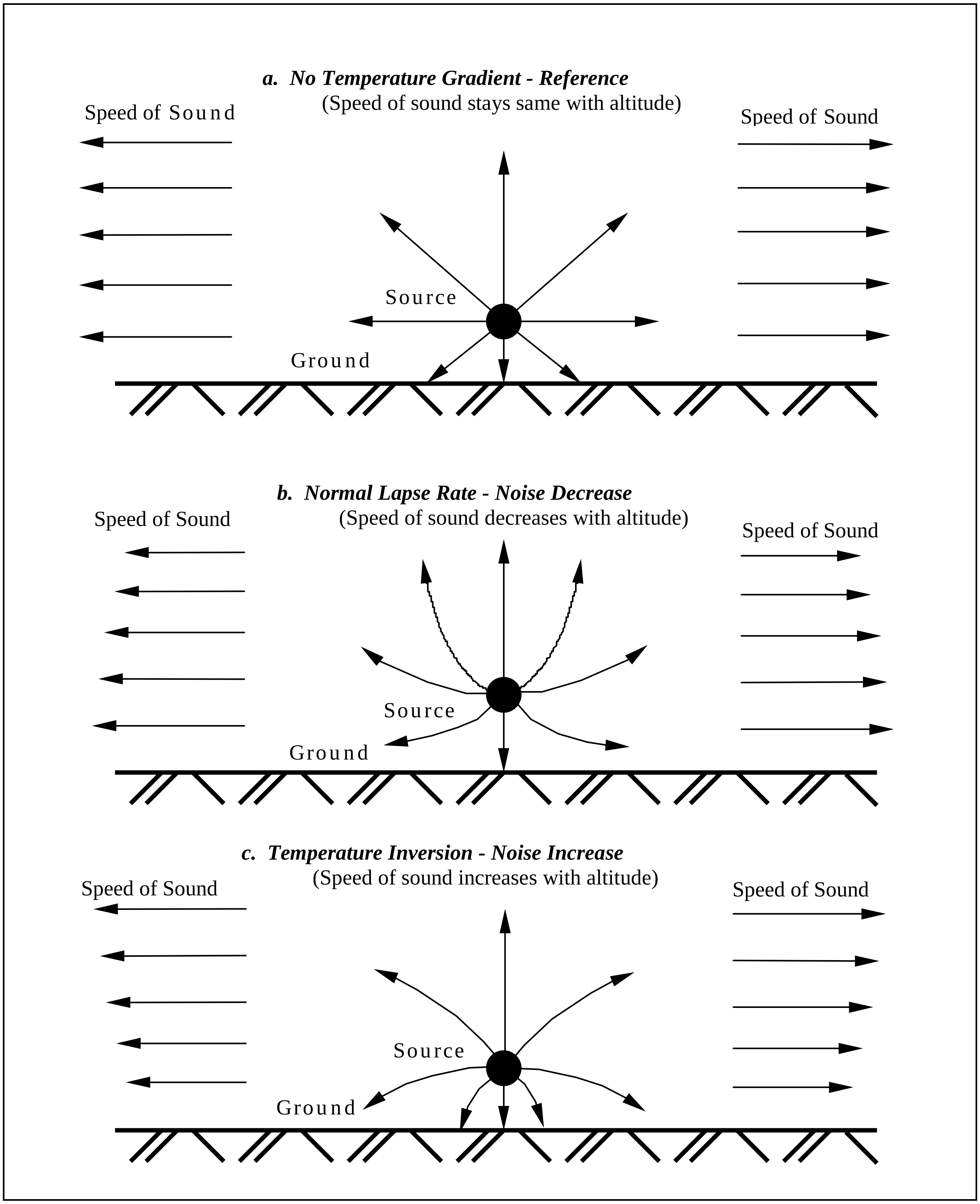
Figure N-2143.1 - Wind Effects on Noise Levels



Wind turbulence. - Turbulence also has a scattering effect on noise levels, which is difficult to predict at this time. It appears, however, that turbulence has the greatest effect on noise levels in the vicinity of the source.

Temperature gradients - Figure N-2143.2 shows the effects of temperature gradients on noise levels. Normally, air temperature **decreases with height above the ground**. This is called the normal lapse rate, which for dry air is about - 1^{o} C/100 m. Since the speed of sound decreases as air temperature decreases, the resulting temperature gradient creates a sound velocity gradient with height. Slower speeds of sound higher above the ground tend to refract sound waves upward in the same manner as wind shear does upwind from the source. The result is a **decrease in noise**. Under certain stable atmospheric conditions, however, temperature profiles are inverted, or temperatures **increase with height** either from the ground up, or at some altitude above the ground. This **inversion** results in speeds of sound that temporarily increase with altitude, causing noise refraction similar to that caused by wind shear downwind from a noise source. Or, once trapped within an elevated inversion layer, noise may be carried over long distances in a channelized fashion. Both ground and elevated temperature inversions have the effect of propagating noise with less than the usual attenuation rates, and therefore **increase noise**. The effects of vertical temperature gradients are more important over longer distances.

Figure N-2143.2 - Effects of Temperature Gradients on Noise



Temperature and humidity - Molecular absorption in air also reduces noise levels with distance. Although this process only accounts for about 1 dBA per 300 m (1000 ft) under average conditions of traffic noise in California, the process can cause significant longer range effects. Air temperature, and humidity affect molecular absorption differently depending on the frequency spectrum, and can vary significantly over long distances, in a complex manner.

Rain. **-** Wet pavement results in an increase in tire noise and a corresponding increase in frequencies of noise at the source. Since the propagation of noise is frequency dependent, rain may also affect distance attenuation rates. On the other hand, traffic generally slows down during rain, decreasing noise levels and lowering frequencies. When wet, different pavement types interact differently with tires than when they are dry. These factors make it very difficult to predict noise levels during rain. Hence, no noise measurements or predictions are made for rainy conditions. Noise abatement criteria and standards do not address rain.

N-2144 Shielding by Natural and Man-made Features, Noise Barriers, Diffraction, and Reflection

A large object in the path between a noise source and a receiver can significantly attenuate noise levels at that receiver. The amount of attenuation provided by this “shielding” depends on the size of the object, and frequencies of the noise levels. Natural terrain features, such as hills and dense woods, as well as manmade features, such as buildings and walls can significantly alter noise levels. Walls are often specifically used to reduce noise.

Trees and Vegetation **-** For a vegetative strip to have a noticeable effect on noise levels it must be dense and wide. A stand of trees with a height that extends at least 5 m (16 ft) abve the line of sight between source and receiver, must be at least 30 m (100 ft) wide and dense enough to completely obstruct a visual path to the source to attenuate traffic noise by 5 dBA. The effects appear to be cumulative, i.e. a 60 m (200 ft) wide stand of trees would reduce noise by an additional 5 dBA. However, the limit is generally a total reduction of 10 dBA. The reason for the 10 dBA limit for any type of vegetation is that sound waves passing over the tree tops (“sky waves”) are frequently refracted back to the surface, due to downward atmospheric refraction caused by wind, temperature gradients, and turbulence.

Landscaping **-** Caltrans research has shown that ordinary landscaping along a highway accounts for less than 1 dBA reduction. Claims of increases in noise due to removal of vegetation along highways are mostly spurred by the sudden visibility of the traffic source.

There is evidence of the psychological "out of sight, out of mind" effect of vegetation on noise.

Buildings - Depending on the site geometry, the first row of houses or buildings next to a highway may shield the second and successive rows. This is often the case where the facility is at-grade or depressed. The amount of noise reduction varies with house or buildig sizes, spacing of houses or buildings, and site geometry. Generally, for an at-grade facility in an average residential area where the first row houses cover at least 40% of total area (i.e. no more than 60% spacing) , the reduction provided by the first row is reasonably assumed at 3 dBA, and 1.5 dBA for each additional row. For example, behind the first row we may expect a 3 dBA noise reduction, behind the second row 4.5 dBA, third row 6 dBA, etc. For houses or buildings “packed” tightly, (covering about 65-90% of the area, with 10-35% open space), the first row provides about 5 dBA reduction. Successive rows still reduce 1.5 dBA per row. Once again, and for the reason mentioned in the above vegetation discussion, the limit is 10 dBA. For these assumptions to be true, the first row of houses or buidings must be equal to or higher than the second row, which should be equal to or higher than the third row, etc.

Noise Barriers - Although technically any natural or man-made feature between source and receiver that reduces noise is a noise barrier, the term is generally reserved for either a wall or a berm that is specifically constructed for that purpose. The acoustical design of noise barriers is covered in sections N-4000 (Traffic Noise Model) and N-6000 (Acoustical Barrier Design Considerations). However, it is appropriate at this time to introduce the acoustical concepts associated with noise barriers. These principles loosely apply to any obstacle between source and receiver.

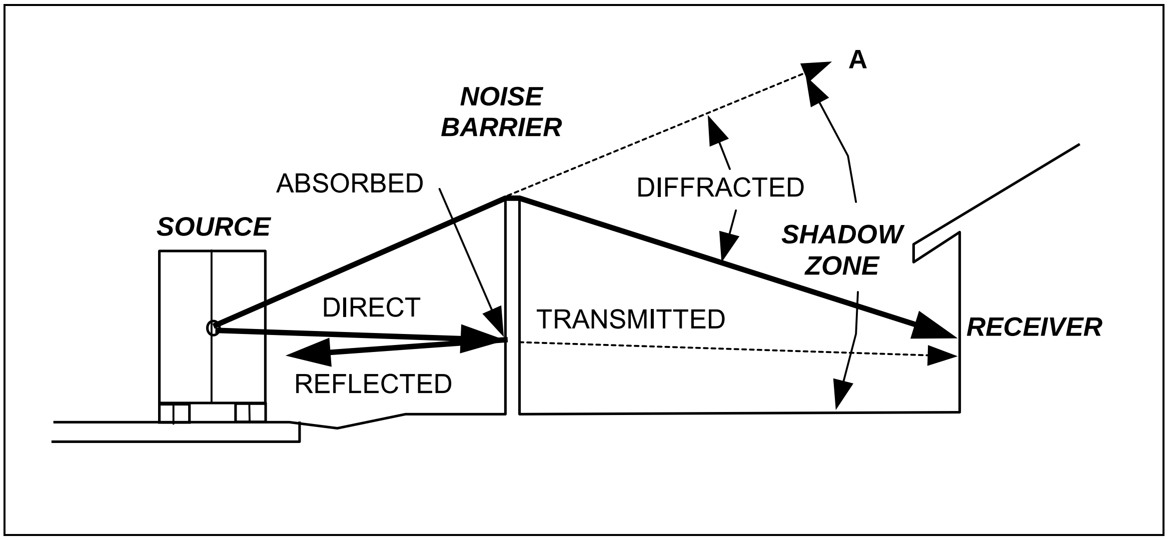
Referring to Figure N-2144.1, when a noise barrier is inserted between a noise source and receiver, the *direct* noise path along the line of sight between the two is interrupted. Some of the acoustical energy will be *transmitted* through the barrier material and continue to the source, albeit at a reduced level. The amount of this reduction depends on the material’s mass and rigidity, and is called the Transmission Loss.

The Transmission Loss (TL) is expressed in dB and its mathematical expression is:

$$\mathbf{TL = 10log_{10}(E_f/E_b)} \qquad \textbf{(eq. N-2144.1)}$$

where: E_f = the relative noise energy immediately in front (source side) of the barrier
E_b = The relative noise energy immediately behind the barrier (receiver side)

Figure N-2144.1 - Alteration of Sound Paths After Inserting a Noise Barrier Between Source and Receiver.



Note that E_f and E_b are relative energies, i.e. energies with reference to the energy of 0 dB (see section N-2134). As relative energies they may be expressed as any ratio (fractional or percentage) that represents their relationship. For instance if 1 percent of the noise energy striking the barrier is transmitted, TL = $10\log_{10}(100/1)$= 20 dBA. Most noise barriers have TL's of 30 dBA or more. This means that only 0.1 percent of the noise energy is transmitted.

The remaining direct noise (usually close to 100 percent) is either partially or entirely *absorbed* by the noise barrier material (if sound absorptive), and/or partially or entirely *reflected* (if the barrier material is sound reflective). Whether the barrier is reflective or absorptive depends on its ability to absorb sound energy. A smooth hard barrier surface such as masonry or concrete is considered to be almost perfectly reflective, i.e.almost all the sound striking the barrier is reflected back toward the source and beyond. A barrier surface material that is porous with many voids is said to be absorptive, i.e. little or no sound is reflected back. The amount of energy absorbed by a barrier surface material is expressed as an absorption coefficient α, which has a value ranging from 0 (100% reflective) to 1 (100% absorptive). A perfect reflective barrier (α=0) will reflect back virtually all the noise energy (assuming a transmission loss of 30 dBA or greater) towards the opposite side of a highway. If we ignore the difference in path length between the direct and reflected noise paths to the opposite (unprotected) side of a highway, the maximum expected increase in noise will be 3 dBA.

If we wish to calculate the noise increase due to a partially absorptive wall we may use eq. N-2144.1. E_f in this case is still the noise energy striking the barrier, but E_b now becomes the energy reflected back. For example, a barrier material with an α of 0.6 absorbs 60% of the direct noise energy and reflects back 40%. To calculate the increase in noise on the opposite side of the highway in this situation the energy loss from the transformation of the total noise striking the barrier to the reflected noise energy component is $10\log_{10}(100/40)=$ 4 dBA. In other words, the energy loss of the reflection is 4 dBA. If the direct noise level of the source at a receiver on the opposite side of the highway is 65 dBA, the reflective component (ignoring the difference in distances traveled) will be 61 dBA. The total noise level at the receiver is the sum of 65 and 61 dBA, or slightly less than 66.5 dBA. The reflected noise caused an increase of 1.5 dBA at the receiver.

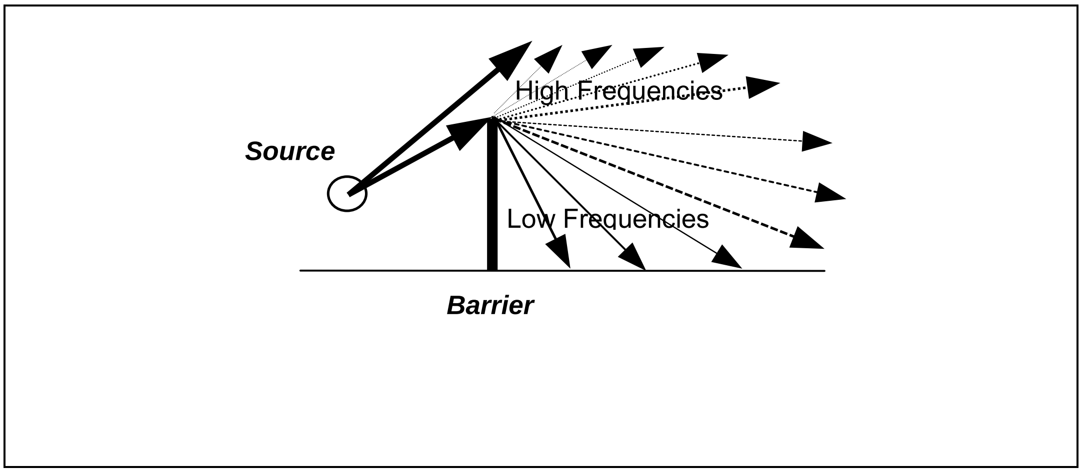
Referring back to Figure N-2144.1, we have discussed the ***direct***, ***transmitted***, ***absorbed***, and ***reflected*** noise paths. These represent all the variations of the direct noise path due to the insertion of the barrier. Of those, only the transmitted noise reaches the receiver behind the barrier. There is, however, one more path, which turns out to be the most imported one, that reaches the receiver. The noise path that before the barrier insertion was directed towards "A" is ***diffracted*** downward towards the receiver after the barrier insertion.

In general, ***diffraction*** is characteristic of all wave phenomena (including light, water, and sound waves). It can best be described as the "bending" of waves around objects . The amount of diffraction depends on the wavelength and the size of the object. Low frequency waves with long wavelengths approaching the size of the object, are easily diffracted. Higher frequencies with short wavelengths in relation to the size of the object, are not as easily diffracted. This explains why light, with its very short wavelengths casts shadows with fairly sharp, well defined edges between light and dark. Sound waves also "cast a shadow" when they strike an object. However, because of their much longer wavelengths (by at least a half dozen or so orders of magnitude) the "noise shadows" are not very well defined and amount to a noise reduction, rather than an absence of noise.

Because noise consists of many different frequencies that diffract by different amounts, it seems reasonable to expect that the greater the angle of diffraction is, the more frequencies will be attenuated. In Figure N-2144.1, beginning with the top of the shadow zone and going down to the ground surface, the higher frequencies will be attenuated first, then the middle frequencies and finally the lower ones. Notice that the top of the shadow zone is defined by the extension of a straight line from the noise source (in this case represented at the noise centroid as a point source) to the top fo the barrier. The diffraction angle is defined by the top of the shadow zone and the line from the top of the barrier to the receiver. Thus, the position of the source relative to the top of the barrier determines the extent of the shadow zone and the diffraction angle to the receiver. Similarly, the receiver location relative to the top of the barrier is also important in determinig the diffraction angle.

From the previous discussion, three conclusions are clear. First, the diffraction phenomenon depends on three critical locations, that of the source, the top of barrier, and the reciver. Second, for a given source, top of barrier and receiver configuration, a barrier is more effective in attenuating higher frequencies than lower frequencies (see Figure N-2144.2). Third, the greater the angle of diffraction, the greater the noise attenuation is.

Figure N-2144.2 - Diffraction of Sound Waves



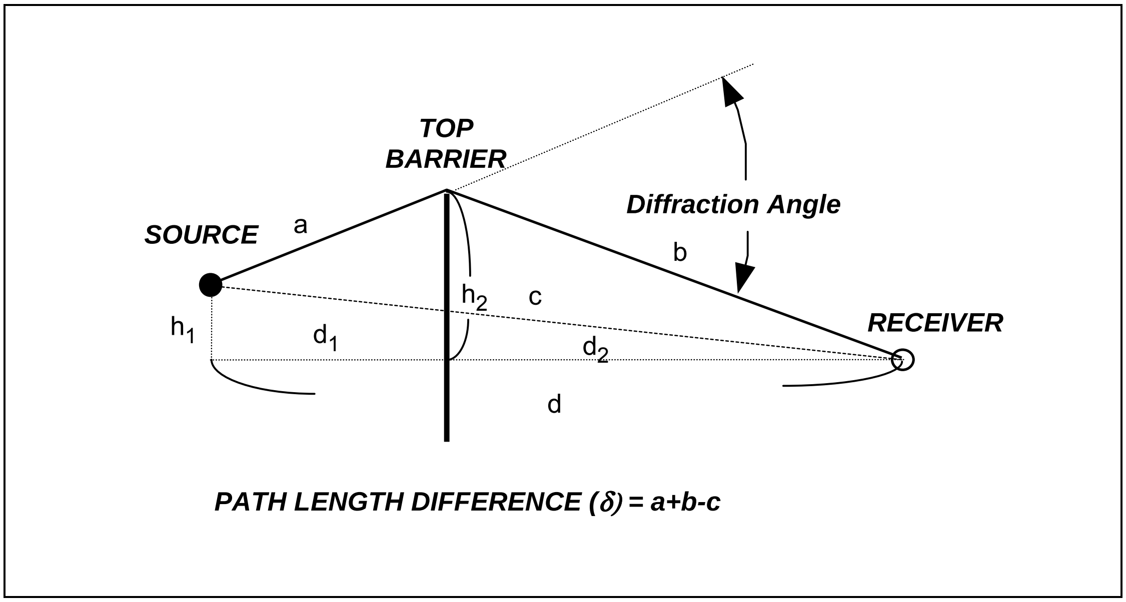
The angle of diffraction is also related to the path length difference (δ) between the direct noise and the diffracted noise. Figure N-2144.3 illustrates the concept of path length difference. A closer examination of this illustration reveals that as the diffraction angle becomes greater, so does δ. The path length difference is defined as δ = a+b-c. If the horizontal distances from source to receiver and source to barrier, and also the differences in elevation between source, top barrier and receiver are known, a,b, and c can readily be calculated. Assuming that the source in Figure N-2144.3 is a point source, a, b, and c are calculated as follows:

$$a = \sqrt{[d_1^2 + (h_2 - h_1)^2]}$$

$$b = \sqrt{(d_2^2 + h_2^2)}$$

$$c = \sqrt{(d^2 + h_1^2)}$$

Figure N-2144.3 - Path Length Difference Between Direct and Diffracted Noise Paths.



Highway noise prediction models use δ in the barrier attenuation calculations. Section N-5500 covers the subject in greater detail. However, it is appropriate to include the most basic relationship between δ and barrier attenuation by way of the so-called *Fresnel Number* (N_0). If the source is a line source (such as highway traffic) and the barrier is infinitely long, there are an infinite amount of path length differences. The path length difference (δ_0)at the perpendicular line to the barrier is then of interest.

Mathematically, N_0 is defined as:

$$\mathbf{N_0 = 2(\delta_0/\lambda)} \qquad \textbf{(eq. N-2144.2)}$$

where: N_0 = Fresnel Number determined along the perpendicular line between source and receiver (i.e. barrier must be perpendicular to the direct noise path)

δ_0 = δ measured along the perpendicular line to the barrier

λ = wavelength of the sound radiated by the source.

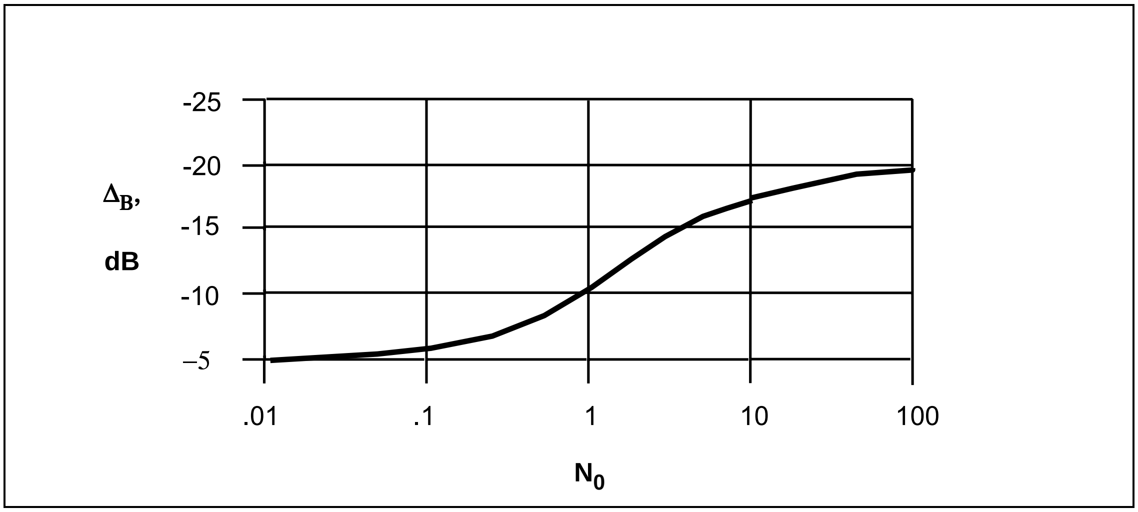
According to eq. N-2131.1, $\lambda = c/f$, and we may rewrite eq. N-2144.2:

$$\mathbf{N_0 = 2(f\delta_0/c)} \qquad \textbf{(eq. N-2144.3)}$$

where: f = the frequency of the sound radiated by the source
c = the speed of sound

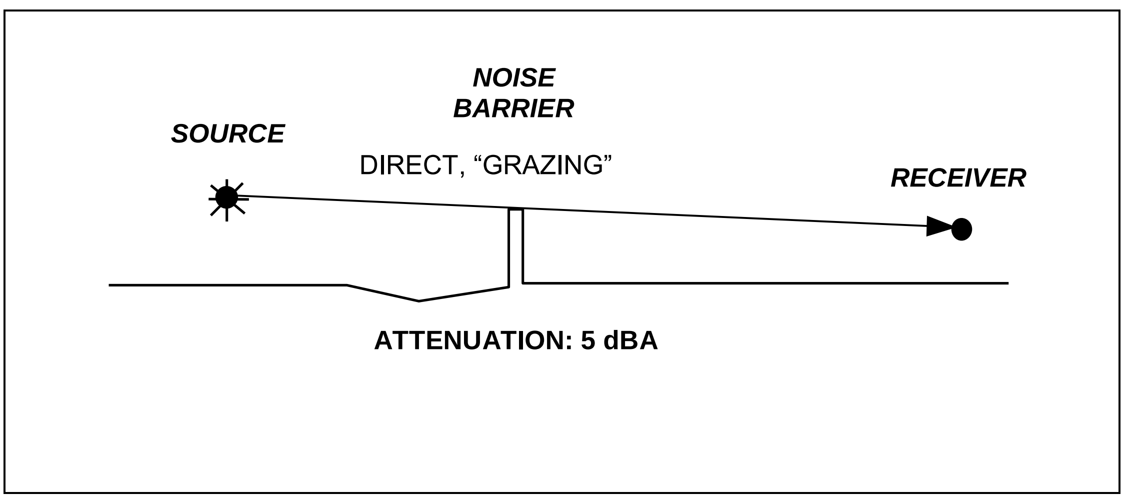
Note that the above equations relate δ_0 to N_0. If one increases, so does the other, and barrier attenuation increases as well. Similarly, if the frequency increases, so will N_0, and barrier attenuation. Figure N-2144.4 shows the barrier attenuation Δ_B for an infinitely long barrier, as a function of 550 Hz (typical "average" for traffic).

Figure N-2144.4 - Barrier Attenuation (Δ_B) vs Fresnel Number (N_0), for Infinitely Long Barriers



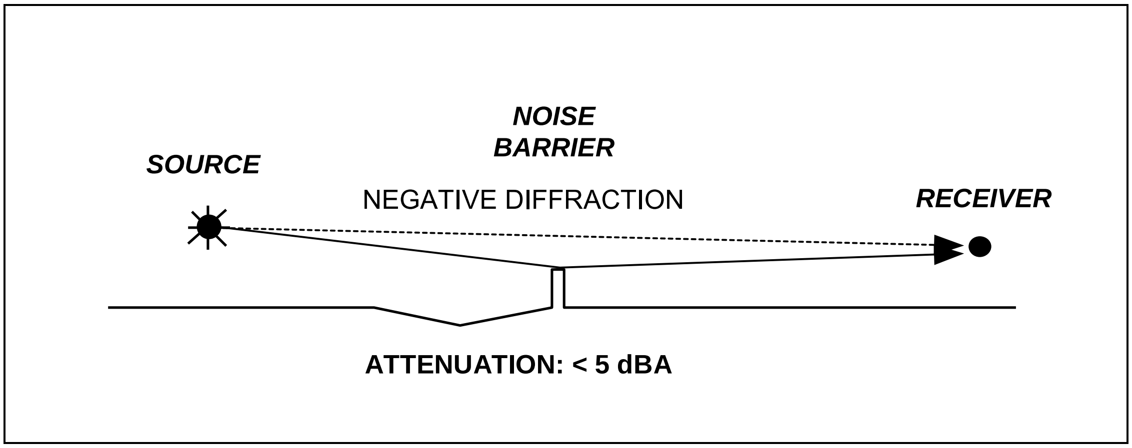
There are several "rules of thumb" for noise barriers and their capability of attenuating traffic noise. Figure N-2144.5 illustrates a special case where the top of the barrier is just high enough to "graze" the direct noise path, or line of sight between source and receiver. In such an instance the noise barrier provides 5 dBA attenuation.

Figure N-2144.5 - Direct Noise Path "Grazing" Top Barrier Results in 5 dBA Attenuation



Another situation, where the direct noise path is not interrupted but still close to the barrier, will provide some noise attenuation. Such "negative diffraction" (with an associated "negative path length difference and "negative Fresnel Number") generally occurs when the direct noise path is within 1.5 m (5 ft) above the top of barrier for the average traffic source and receiver distances encountered in near highway noise environments. The noise attenuation provided by this situation is between 0 - 5 dBA: 5 dBA when the noise path approaches the grazing point and near 0 dBA when it clears the top of barrier by approximately 1.5 m (5 ft) or more.

Figure N-2144.6 - "Negative Diffraction" Provides Some Noise Attenuation



The aforementioned principles of barriers loosely apply to terrain features (such as berms, low ridges, as well as other significant manmade features). The principles will be discussed in greater detail in sections N-5500 and N-6000.

N-2200 EFFECTS OF NOISE; NOISE DESCRIPTORS

N-2210 Human Reaction to Sound

People react to sound in a variety of ways. For example, rock music may be pleasant to some people while for others it may be annoying, constitute a health hazard and/or disrupt activities. Human tolerance to noise depends on a variety of acoustical characteristics of the source, as well as environmental characteristcs. These factors are briefly discussed below:

1. *Level, variability in level (dynamic range), duration, frequency spectrums and time patterns of noise*. Exposures to very high noise levels can damage hearing. A high level is more objectionable than a low level noise, and intermittent truck peak noise levels are more objectionable than the continuous level of fan noise. Humans have better hearing sensitivities in the high frequency region than in the low. This is reflected in the A-scale (section N-2136) which de-emphasizes the low frequency

sounds. Studies indicate that the annoyance or disturbance correlates with the A-scale.

2. *The amount of background noise present before the intruding noise*. People tend to compare an intruding noise with the existing background noise. If the new noise is readily identifiable or considerably louder than the background or ambient, it usually becomes objectionable. An aircraft flying over a residential area is an example.

3. *The nature of the work or living activity that is exposed to the noise source*. Highway traffic noise might not be disturbing to workers in a factory or office, but the same noise might be annoying or objectionable to people sleeping at home or studying in a library. An automobile horn at 2:00 a.m. is more disturbing than the same noise in traffic at 5:00 p.m.

N-2211 Human Response to Changes in Noise Levels

Under controlled conditions in an acoustics laboratory, the trained healthy human ear is able to discern changes in sound levels of 1 dBA, when exposed to steady, single frequency ("pure tone") signals in the mid-frequency range. Outside of such controlled conditions, the trained ear can detect changes of 2 dBA in normal environmental noise. It is widely accepted that the average healthy ear, however, can barely perceive noise level changes of 3 dBA.

Earlier, we discussed the concept of "A" - weighting and the reasons for describing noise in terms of dBA. The human response curve of frequencies in the audible range is simply not linear, i.e. humans do not hear all frequencies equally well.

It appears that the human perception of loudness is also not linear, neither in terms of decibels, nor in terms of acoustical energy. We have already seen that there is a mathematical relationship between decibels and relative energy. For instance, if one source produces a noise level of 70 dBA, two of the same sources produce 73 dBA, three will produce about 75 dBA, and ten will produce 80 dBA.

Human perception is complicated by the fact that it has no simple correlation with acoustical energy. Two noise sources do not "sound twice as loud" as one noise source. Based on the opinions of thousands of subjects tested by experts in the field, however, some approximate relationships between changes in acoustical energy and corresponding human reaction have been charted. The results have been summarized in Table N-2211.1, which shows the relationship between changes in acoustical energy, dBA and human perception. The table shows the relationship between changes in dBA (ΔdBA), relative energy with respect to a reference of a ΔdBA of 0 (no change), and average human perception. The factor change in relative energy relates to the change in acoustic energy.

Figure N-2211.1Relationship Between Noise Level Change, Factor Change in Relative Energy, and Perceived Change

		Perceived Change	
Noise Level Change, ΔdBA	**Change in Relative Energy, $10^{\pm \Delta dBA/10}$**	**Perceived Change in Percentage, $(2^{\pm \Delta dBA/10}-1) \times 100\%$**	**Descriptive Change in Perception**
+ 40 dBA	10,000 x		Sixteen Times as Loud
+ 30 dBA	1,000 x		Eight Times as Loud
+20 dBA	100 x	+ 300 %	Four Times as Loud
+ 15 dBA	31.6 x	+ 183 %	
+ 10 dBA	10 x	+ 100 %	Twice as Loud
+ 9 dBA	7.9 x	+ 87 %	
+ 8 dBA	6.3 x	+ 74 %	
+ 7 dBA	5.0 x	+ 62 %	
+ 6 dBA	4.0 x	+ 52 %	
+5 dBA	3.16 x	+ 41 %	Readily Perceptible Increase
+4 dBA	2.5 x	+ 32 %	
+ 3 dBA	2.0 x	+ 23 %	Barely Perceptible Increase
0 dBA	**1**	**0 %**	**REFERENCE (No change)**
- 3 dBA	0.5 x	- 19 %	Barely Perceptible Reduction
- 4 dBA	0.4 x	- 24 %	
- 5 dBA	0.316 x	- 29 %	Readily Perceptible Reduction
- 6 dBA	.25 x	- 34 %	
- 7 dBA	0.20 x	- 38 %	
- 8 dBA	0.16 x	- 43 %	
- 9 dBA	0.13 x	-46 %	
- 10 dBA	0.10 x	- 50 %	Half as Loud
- 15dBA	0.0316 x	- 65 %	
- 20 dBA	0.01 x	- 75 %	One Quarter as Loud
- 30 dBA	0.001 x		One Eighth as Loud
- 40 dBA	0.0001 x		One Sixteenth as Loud

Section N-2133 mentioned that the r.m.s. value of the sound pressure ratio squared (P_1/ P_2 is proportional to the energy content of sound waves (acoustic energy). Human perception is displayed in two columns (percentage and descriptive). The percentage of perceived change is based on the mathematical approximation that the factor change of human perception relates to ΔdBA by the following:

$$\textbf{Factor Change in Perceived Noise Levels} = 2^{\pm\Delta dBA/10} \qquad \textbf{(eq. N-2211.1)}$$

According to the above approximation, the average human ear perceives a 10 dBA decrease in noise levels as half of the original level ($2^{\pm\Delta dBA/10} = 2^{-10/10} = 0.5$). By subtracting 1 and multiplying by 100 the result will be in terms of a percentage change in perception, where a positive (+) change represents an increase, and a negative (-) change a decrease. The descriptive perception column puts into words how the percentage change is perceived.

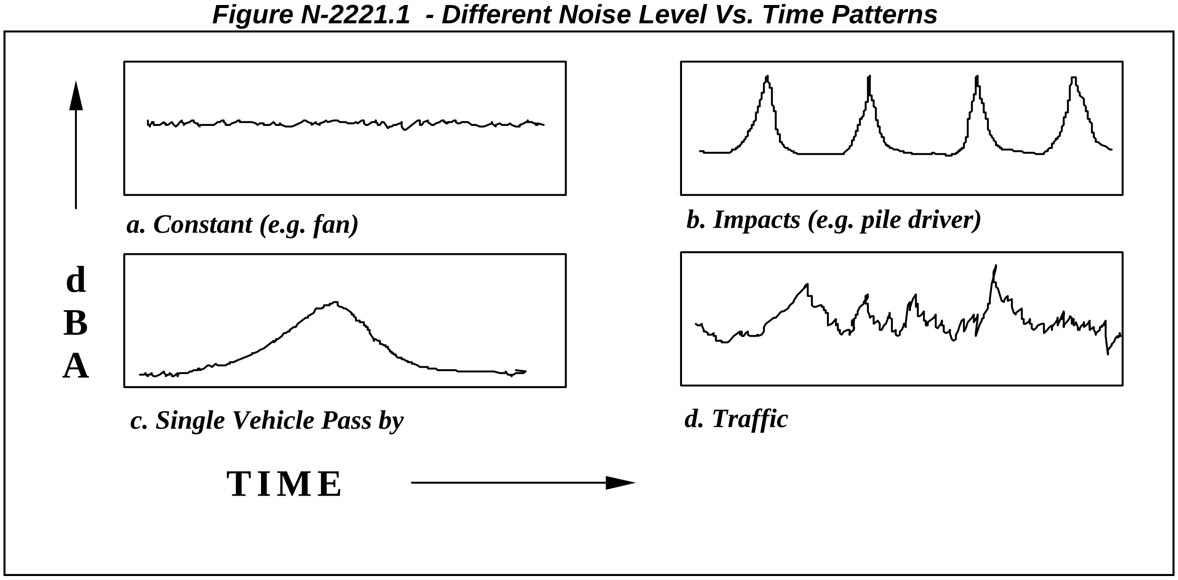
N-2220 Describing Noise

Noise in our daily environment fluctuates over time. Some of the fluctuations are minor, some are substantial; some occur in regular patterns, others are random. Some noise levels fluctuate rapidly, others slowly. Some noise levels vary widely, others are relatively constant. In order to describe noise levels, we need to choose the proper noise descriptor or statistic.

N-2221 Time Patterns

Figure N-2221.1 is a graphic representation of how noise can have different time patterns depending on the source. Shown are noise level vs. time patterns of four different sources: a fan (a), a pile driver (b), a single vehicle passby (c), and highway traffic (d).

Figure N-2221.1 - Different Noise Level Vs. Time Patterns



The simplest noise level time pattern is that of constant noise (a), which is essentially a straight and level line. Such a pattern is characteristic of stationary fans, compressors, pumps, air conditioners, etc. At each instant the noise level is about the same for a fixed observer. A single measurement taken at random, would suffice to describe the noise level at a specific distance. The minimum and maximum noise level would be nearly the same as the average noise level.

Other noise level vs. time patterns are more complicated. For instance, to describe the pile driving noise (b), noise samples need to include the instantaneous “peaks” or maximum noise levels. In our environment, there are a whole range of noises of many different patterns in addition to the ones shown in Figure 2220.1. The levels may be extremely short in duration such as a single gun shot (transient noise), or intermittent such as the pile driver, or continuous as was the case with the fan. Traffic noise along major highways tends to lie somewhere between intermittent and continuous (d). It is characterized by the somewhat random distribution of vehicles, each of which emits a pattern such as shown in (c).

N-2222 Noise Descriptors

To choose the proper noise descriptor, we have to know the nature of the noise source and also how we want to describe it. Are we interested only in the maximum levels, the average noise levels, the percentage of time above a certain level, or the levels that are exceeded 10%, 50% or 90% of the time? How can we compare the noise of a fast flying jet aircraft - loud but short in duration - with a slower but quieter propeller airplane? It is easy to see that the proper descriptor depends on the spatial distribution of noise source(s), duration, amount of fluctuation, and time patterns.

There are dozens of descriptors and scales which have been devised over the years to quantify community noise, aircraft fly-overs, traffic noise, industrial noise, speech interference, etc. The descriptors shown in Table N-2222.1 are the ones most often encountered in traffic, community, and environmental noise. There are many more descriptors, but they are not mentioned here. The word "LEVEL", abbreviated L, is frequently used whenever sound is expressed in decibels relative to the reference pressure. Thus, all of the descriptors shown in Table N-2222.1 have "L" as part of the term.

All Caltrans highway traffic noise analysis should be done in terms of worst noise hour L_{eq}(h). If a noise analysis requires other descriptors (to satisfy city or county requirements) then see section N-2230 for a discussion of descriptor conversions.

Table N- 2222.1. Common Noise Descriptors.

NOISE DESCRIPTOR	DEFINITION
L_{MAX} (Maximum Noise Level)	The highest instantaneous noise level during a specified time period. This descriptor is sometimes referred to as "peak (noise) level". The use of "peak" level should be discouraged because it may be interpreted as a non-r.m.s. noise signal (see sec. N-2133 for difference between peak and r.m.s.)
L_X (A Statistical Descriptor)	The noise level exceeded X percent of a specified time period. The value of X is commonly 10. Other values of 50 and 90 are sometimes also used. Examples: L_{10}, L_{50}, L_{90}.
L_{eq} (Equivalent Noise Level. Routinely used by Caltrans and FHWA to address the worst noise hour (**L_{eq}(h)**).	The equivalent steady state noise level in a stated period of time that would contain the same acoustic energy as the time varying noise level during the same period.
L_{dn} (Day - Night Noise Level. Used commonly for describing community noise levels).	A 24-hour L_{eq} with a "penalty"of 10 dBA added during the night hours (2200 - 0700). The penalty is added because this time is normally sleeping time.
CNEL (Community Noise Equivalent Level. A common community noise descriptor; also used for airport noise).	Same as the L_{dn} with an additional penalty of 4.77 dBA, (or 10 Log 3), for the hours 1900 to 2200, usually reserved for relaxation, TV, reading, and conversation.
SEL (Single Event Level. Used mainly for aircraft noise; it enables comparing noise created by a loud, but fast overflight, with that of a quieter, but slow overflight).	The acoustical energy during a single noise event, such as an aircraft overflight, compressed into a period of one second, expressed in decibels.

N-2223 Calculating Noise Descriptors

The following formulae and examples may be used to calculate various noise descriptors from instantaneous noise vs time data.

L_x - The L_X, a statistical descriptor, signifies the noise level that is exceeded x% of the time. This descriptor was formerly used in highway noise (before the L_{eq}). The most common value of x was 10, denoting the level that was exceeded 10% of the time. Hence, the L_{10} descriptor will be used as an example to represent the L_X family of calculations. The following instantaneous noise samples (Table 2223.1) shown as a frequency distribution (dBA vs number of occurrences), will serve to illustrate the L_{10} calculation.

The total No. of samples taken at 10 second intervals was 50. For the L_{10} we therefore need to find the 5 highest values (10% of 50). These are exceeding the L_{10}. In the above data set, we can simply count down from the top. The "boundary" of the top 10 % lies at 76 dBA. Therefore the L_{10} lies at 76 dBA. The L_{50} would be 66 dBA (25 occurrences from the top), etc.

Table N-2223.1 Noise Samples for L10 Calculation

Noise Level, dBA	Occurrences (Sampling Interval 10 seconds) (Each X is one occurrence)							Total No. of Occurrences
80								0
79								0
78	X							1
77	X							1
76	X	X	X					3
75	X	X						2
74	X	X						2
73	X	X						2
72								0
71	X	X	X					3
70	X							1
69	X	X						2
68	X	X	X	X	X			5
67	X	X						2
66	X	X	X	X				4
65	X	X	X	X	X	X	X	7
64	X	X	X	X	X			5
63	X	X	X					3
62	X	X	X					3
61	X	X						2
60	X	X						2
	Total No. of Samples							50

L

_L_{eq}_ - The L_{eq} descriptor is a special sort of average noise level. Instead of averaging decibel levels, the energy levels are averaged. The L_{eq} is also called an energy-mean noise level. The instant noise levels over a certain time period are energy-averaged by first converting all dBA values to relative energy values. Next, these values are added up and the total is divided by the number of values. The result is average (relative) energy. The final step then is to convert the average energy value back to a decibel level. Section N-2135, equation N-2135.3 showed the method of adding the energy values. This equation can be expanded to yield an L_{eq}:

$$\mathbf{L_{eq} = 10\log_{10}[(10^{SPL(1)/10}+10^{SPL(2)/10} + \ldots 10^{SPL(n)/10})/N]} \qquad \textbf{(eq. N-2223.1)}$$

Where: $SPL_{(1)}$, $SPL_{(2)}$, $SPL_{(n)}$ = the 1^{st}, 2^{nd}, and n^{th} noise level

N = number of noise level samples

Example: Calculate the L_{eq} of the following noise instantaneous samples taken at 10-second intervals:

Time	dBA
10:00:10	60
10:00:20	64
10:00:30	66
10:00:40	63
10:00:50	62
10:01:00	65

Solution (using eq. N-2223.1 with above data):

$L_{eq} = 10\log_{10}[(10^{60/10}+10^{64/10}+10^{66/10}+10^{63/10}+10^{62/10}+10^{65/10})/6] =$

$= 10\log_{10}(14235391.3/6) = 63.8$ dBA

Usually, longer time periods are preferred. Using the sampling data in the L_{10} example (Table N-2231.1) the following equation (discussed in sec. N-2135) can be used to add the dBA levels for each set of equal noise levels (occurrences):

$\mathbf{SPL_{(Total)} = SPL_{(1)} + 10\log_{10}(N)}$ **(eq. N-2135.1)**

in which: $SPL_{(1)}$ = SPL of one source

N = number of identical noise levels to be added (in this case number of occurrences of each noise level)

Next we can use eq. N-2135.3 to add the sub totals:

$\mathbf{SPL_{(Total)} = 10\log_{10}[10^{SPL_{(1)}/10}+10^{SPL_{(2)}/10} + \ldots\ldots\ldots\ 10^{SPL_{(n)}/10}]}$ **(eq. N-2135.3).**

The resulting total noise level is 87.5 dBA, which must then be energy averaged to get the L_{eq}. This may be accomplished by the following equation:

$\mathbf{L_{eq} = 10\log_{10}[10^{SPL_{(TOTAL)}/10}/N]}$ **(eq. N-2223.2)**

Where N = the total number of samples, in this case 50.

The final result is $L_{eq} = 10\log_{10}[10^{87.5/10}/N] = 70.5$ dBA. Calculation procedures are shown in Table N-2223.2.

Table N-2223.2 - Noise Samples for Leq Calculation

Noise Level, dBA	Occurrences (Sampling Interval 10 seconds) (Each X is one occurrence)							No. of Occurrences (N)	Total Noise Levels **dBA + 10log$_{10}$(N)**
80								0	
79								0	
78	X							1	78
77	X							1	77
76	X	X	X					3	80.8
75	X	X						2	78
74	X	X						2	77
73	X	X						2	76
72								0	
71	X	X	X					3	75.8
70	X							1	70
69	X	X						2	72
68	X	X	X	X	X			5	75
67	X	X						2	70
66	X	X	X	X				4	72
65	X	X	X	X	X	X	X	7	73.5
64	X	X	X	X	X			5	71
63	X	X	X					3	67.8
62	X	X	X					3	66.8
61	X	X						2	64
60	X	X						2	63
	Totals							50	87.5
	$L_{eq} = 10 \text{ Log}_{10} [(10^{8.75})/50] =$								70.5 dBA

L_{dn} - The L_{dn} descriptor is actually a 24 hour L_{eq}, or the energy-averaged result of 24 1-hour L_{eq}'s, with the exception that the night-time hours (defined as 2200 - 0600 hours) are assessed a 10 dBA "penalty". This attempts to account for the fact that nighttime noise levels are potentially more disturbing than equal daytime noise levels.

Mathematically this "day-night" descriptor is expressed as:

$$\mathbf{L_{dn} = 10 \text{ Log}_{10}} \left[\left(\frac{1}{24} \right) \sum_{i=1}^{24} 10^{\mathbf{L_{eq}(h)_i + W_i / 10}} \right] \qquad \textbf{(eq.N-2223.3)}$$

where: W_i = 0 for day hours (0700 - 2200)

W_i = 10 for night hours (2200 - 0700)

$L_{eq}(h)_i = L_{eq}$(for the i^{th} hour)

To calculate an L_{dn} accurately, we must have 24 successive hourly L_{eq}'s, representing one typical day. The hourly values between 2200-0700 (9 hourly values) must first be weighted by adding 10 dBA. An example is shown in Table N-2223.3.

The energy average calculated from the 9 weighted and 15 unweighted hourly L_{eq}'s is the L_{dn}. Once the hourly data is properly weighted, the L_{dn} can be calculated as an L_{eq} (in this case a weighted 24 hour L_{eq}). We may use eq. N-2223.1 with the weighted data. The resulting L_{dn} is 65 dBA.

Table N-2223.3 Noise Samples for Ldn Calculations

Begin Hour	*L_{eq}(h), dBA*	*Weight, dBA*	*Weighted Noise, dBA*	*Begin Hour*	*L_{eq}(h), dBA*	*Weight, dBA*	*Weighted Noise, dBA*
00:00	54	+10	64	12:00	65	0	65
01:00	52	+10	62	13:00	65	0	65
02:00	52	+10	62	14:00	63	0	63
03:00	50	+10	60	15:00	65	0	65
04:00	53	+10	63	16:00	65	0	65
05:00	57	+10	67	17:00	63	0	63
06:00	62	+10	72	18:00	64	0	64
07:00	65	0	65	19:00	62	0	62
08:00	63	0	63	20:00	60	0	60
09:00	64	0	64	21:00	58	0	58
10:00	66	0	66	22:00	57	+10	67
11:00	66	0	66	23:00	55	+10	65

CNEL - The CNEL is the same as the L_{dn} EXCEPT for an additional weighting of almost 5 dBA for the evening hours of 1900 - 2200. The equation is essentially the same as eq. N-2223.3, with an additional definition of $W_i = 10\text{Log}_{10}(3)$, which is 4.77. Calculations for CNEL are done similarly to those for L_{dn}. The result is normally about 0.5 dBA higher than that of an L_{dn} using the same 24-hour data. Following is the equation for the CNEL.:

$$\textbf{CNEL} = 10 \text{ Log}_{10}\left[\left(\frac{1}{24}\right)\sum_{i=1}^{24} 10^{\,L_{eq}(h)_i + W_i/10}\right] \qquad \textbf{(eq.N-2223.4)}$$

Where: $W_i = 0$ for day hours (0700 - 1900)

$W_i = 10\log_{10}(3) = 4.77$ for evening hours (1900 - 2200)

W_i = 10 for night hours (2200 - 0700)

$L_{eq}(h)_i = L_{eq}$(for the i^{th} hour)

The above 24-hour data used in the L_{dn} example, yields a CNEL of 65.4 dBA, as compared to 65.0 dBA for the L_{dn}.

SEL - The SEL is useful in comparing the acoustical energy of different events involving different source characteristics. For instance, the over flight of a slow propeller driven plane may not be as loud as a jet aircraft, but the former is slower and therefore lasts longer than the jet noise. The SEL makes a noise comparison of both events possible, because it combines the effects of time and level. For instance, the L_{eq} of a steady noise level will remain unchanged over time. It will be the same when calculated for a time period of 1 second or 1000 seconds. The SEL of a steady noise level, however, will keep increasing, because all the acoustical energy within a given time period is included in the reference time period of one second. Since both values are energy-weighted they are directly related to each other by time as shown in the following equations:

$$\mathbf{SEL = L_{eq}(T)+10\log_{10}(T)} \qquad \textbf{(eq. N-2223.5)}$$

$$\mathbf{L_{eq}(T) = SEL+10\log_{10}(1/T) = SEL-10\log_{10}(T)} \qquad \textbf{(eq. N-2223.6)}$$

where: T = the duration of the noise level in seconds.

Example: The L_{eq} of a 65-second aircraft over flight is 70 dBA. What is the SEL?

Solution (using eq. N-2223.2): SEL = L_{eq}(65 sec)+10$\log_{10}$(65) = 70+18.1 = 88.1 dBA.

N-2230 Conversion Between Noise Descriptors

Although Caltrans exclusively uses the L_{eq} descriptor, there are some times that comparisons need to be made with local noise standards, most of which are in terms of L_{dn} or CNEL. Twenty-four hour noise data are often not available. Following is a methodology that allows a reasonably accurate conversion of the worst hourly noise level to a Ldn or CNEL.

N-2231 L_{eq} To L_{dn}/CNEL, and Vice Versa.

The previous section showed that the L_{dn} is defined as an energy-averaged 24-hour L_{eq} with a night-time penalty of 10 dBA assessed to noise levels between the hours of 2200 and 0700 (10:00 pm and 7:00 am). If traffic volumes, speeds and mixes were to remain constant throughout the entire 24 hours, and if there were no night time penalty, there would be no peak hour and each hourly L_{eq} would equal the 24-hour L_{eq}. Hourly traffic volumes would then be 100%/24, or 4.17% of the average daily traffic volume (ADT). Peak hour corrections would not be necessary in this case. Let this be the REFERENCE CONDITION.

To convert Peak Hour L_{eq} to L_{dn}, at least two corrections must be made to the above reference condition. First, we must make a correction for peak hour traffic volumes expressed as a percentage of the ADT. Secondly, we must make a correction for the night-time penalty of 10 dBA. For this we need to know what fraction of the ADT occurs during the day and what fraction at night. Depending on the accuracy desired and information available, other corrections can be made for different day/night traffic mixes and speeds. These will not be discussed here.

The first correction for peak hour can be expressed as:

$$10 \text{ Log}_{10} \frac{4.17}{P}$$

where :

P = Peak Hour volume % of ADT

The second correction for night time penalty of 10 dBA is:

$$10 \text{ Log}_{10} (D + 10N)$$

where :

D and N are day and night fractions of ADT (D + N = 1)

To convert from PEAK HOUR L_{eq} to L_{dn} :

$$\mathbf{L_{dn} = L_{eq}(h)_{pk} + 10 \text{ Log}_{10} \frac{4.17}{P} + 10 \text{ Log}_{10} (D + 10N)} \qquad \textbf{(eq. N-2231.1)}$$

To convert L_{dn} to PEAK HOUR L_{eq}:

$$\mathbf{L_{eq}(h)_{pk} = L_{dn} - 10 \text{ Log}_{10} \frac{4.17}{P} - 10 \text{ Log}_{10} (D + 10N)} \qquad \textbf{(eq. N-2231.2)}$$

Where:

$L_{eq}(h)_{pk}$ = Peak Hour L_{eq}

P = Peak Hour volume % of ADT

D = Day-time fraction of ADT

N = Night-time fraction of ADT

Note: (D + N) must equal 1

Example: The peak hour L_{eq} at a receiver near a freeway is 65.0 dBA; the peak hour traffic is 10% of the ADT; the day-time traffic volume is .85 of the ADT; the night-time traffic volume is .15 of the ADT. Assume that the day and night-time heavy truck percentages are equal and traffic speeds do not vary significantly. What is the estimated L_{dn} at the receiver?

Solution:

$$L_{dn} = 65.0 + 10\ Log_{10} \frac{4.17}{10} + 10\ Log_{10}(0.85 + 1.50)$$

$$= 65.0 + (-3.8) + 3.70$$

$$= 64.9\ dBA$$

Note that in the above example, which is a fairly typical case, the L_{dn} is approximately equal to the $L_{eq}(h)_{pk}$. The rule of thumb is that L_{dn} is within +/- 2 dBA of the $L_{eq}(h)_{pk}$ under normal traffic conditions.

The values in the following Table N-2231.1 can also be used in equations N-2231.2 and N-2231.3. Notice that the "peak hour %" term of the equation always yields a negative value, while the weighted "day/night split" always yields a positive value. The difference between the two is the difference between the $L_{eq}(h)_{pk}$ and the L_{dn}.

Table N-2231.1 - L_{eq}/L_{dn} Conversion Factors

P, %	$10Log_{10}(4.17/P)$
5	-0.8
6	-1.6
7	-2.3
8	-2.8
9	-3.3
10	-3.8
11	-4.2
12	-4.6
13	-4.9
14	-5.3
15	-5.6
17	-6.1
20	-6.8

D	N	$10 Log_{10}(D+10N)$
0.98	0.02	+0.7
0.95	0.05	+1.6
0.93	0.07	+2.1
0.90	0.10	+2.8
0.88	0.12	+3.2
0.85	0.15	+3.7
0.83	0.17	+4.0
0.80	0.20	+4.5
0.78	0.22	+4.7
0.75	0.25	+5.1
0.73	0.27	+5.4
0.70	0.30	+5.7
0.68	0.32	+5.9
0.65	0.35	+6.2
0.63	0.37	+6.4
0.60	0.40	+6.6

Figure N-2231.1 shows the difference between $L_{eq}(h)_{pk}$ and L_{dn} graphically. For example if P is 10% and D/N = 0.85/0.15, the $L_{dn} \approx L_{eq}(h)_{pk}$.

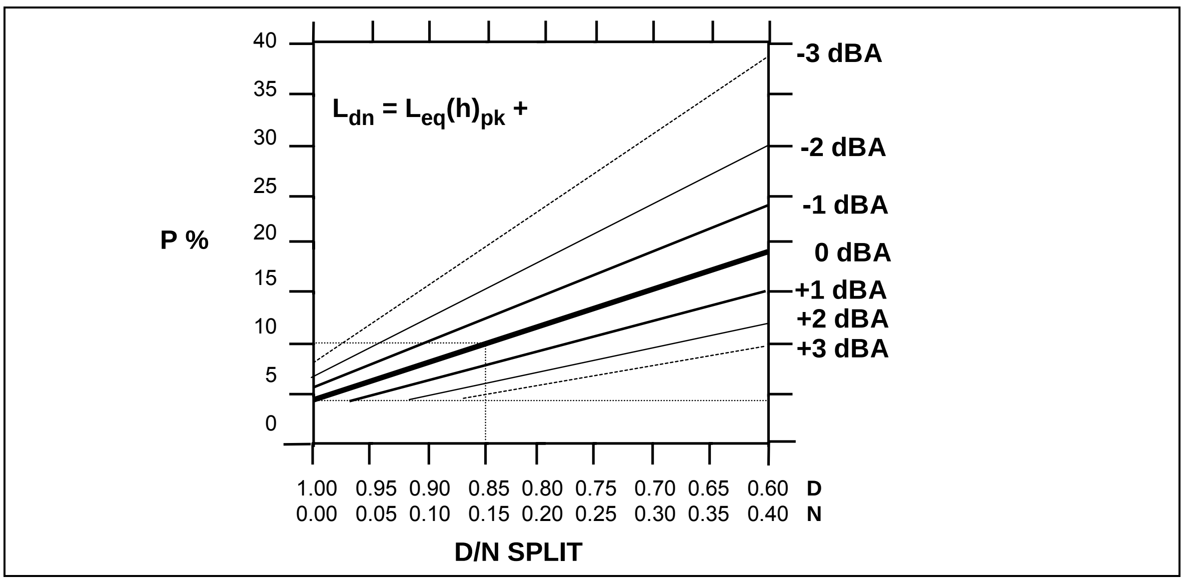


Figure N-2231.1 - Relationship Between L_{dn} and $L_{eq}(h)_{pk}$

If CNEL is desired, the L_{dn} to CNEL corrections (Δ) in Table N-2231.2 may be used.

Table N-2231.2 - Ldn/CNEL Corrections (Δ); must be added to Ldn to obtain CNEL.

d	E	(CNEL = Ldn + Δ) Δ
0.80	0.05	0.3
0.79	0.06	0.4
0.78	0.07	0.5
0.77	0.08	0.5
0.76	0.09	0.6
0.75	0.10	0.7
0.74	0.11	0.7
0.73	0.12	0.8
0.72	0.13	0.8
0.71	0.14	0.9
0.70	0.15	0.9

The values shown assume a fixed night time fractional traffic contribution of 0.15 (D/N split of .85/.15 for L_{dn}). The remaining day time traffic contribution of .85 is further subdivided into day (d) and evening (E) hours. In each instance, d+E = 0.85.

N-2240 Negative Effects on Humans

The most obvious negative effects of noise are physical damage to hearing. Other obvious effects are the interference of noise with certain activities, such as sleeping, conversation, etc. Less obvious, but nevertheless very real, are the stress effects of noise. A brief discussion of each of the topics follows.

N-2241 Hearing Damage.

A person exposed to high noise levels can suffer hearing damage. The damage may be **gradual** or **traumatic**. These are described as follows:

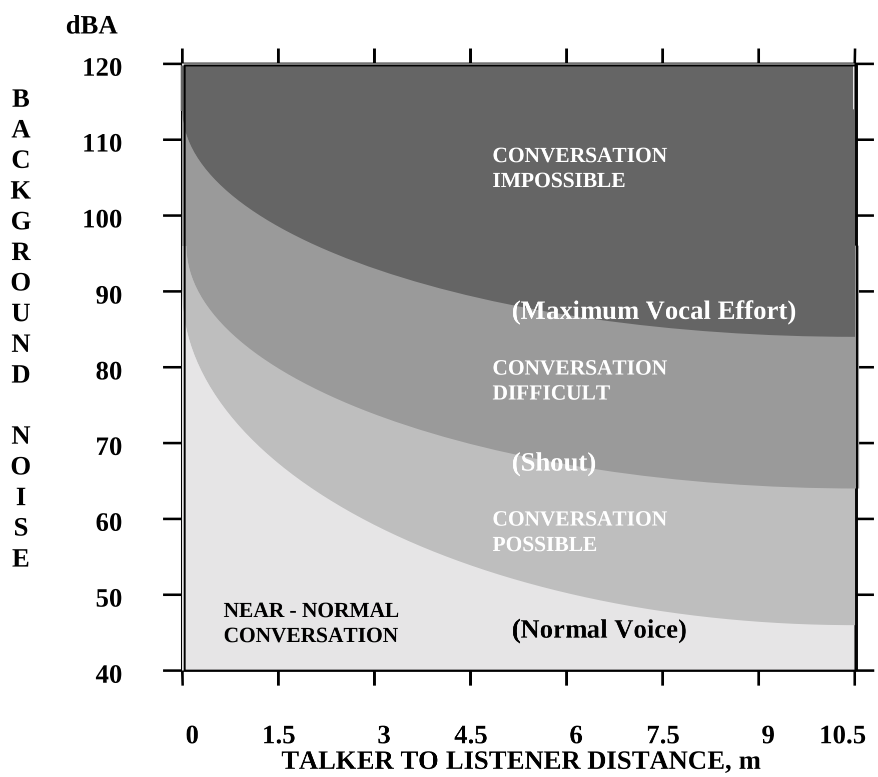
1. *Gradual.* Sustained exposure to moderately high noise levels over a period of time can cause **gradual hearing loss**. It starts out as a temporary hearing loss, such as immediately after a loud rock concert. The hearing usually restores itself within a few hours after exposure, although not quite to its pre-exposure level. This is also called a **temporary threshold shift**. Although the permanent deterioration may be negligible, it will become significant after many repetitions of the exposure. At that time, it is labeled **permanent hearing damage**. The main causes of permanent damage are daily exposure to industrial noise. Transportation noise levels experienced by communities and the general public are normally not high enough to produce hearing damage.
2. *Traumatic.* Short and sudden exposure to an extremely high noise level, such as a gun shot or explosion at very close range can cause a traumatic hearing loss. Such a loss is very sudden and can be permanent.

Hearing damage is preventable by reducing the exposure to loud noise. This can be done by quieting the source, shield the receiver by a barrier, or having the receiver wear proper ear protection. Occupational exposure to noise is controlled by the Occupational Safety and Health Agency (OSHA), and is based on a maximum allowable noise exposure level of 90 dBA for 8 hours. For each halving of the exposure time, the maximum noise level is allowed to increase 5 dBA. Thus, the maximum allowable noise exposure (100 %) is 90 dBA for 8 hours, 95 dBA for 4 hours, 100 dBA for 2 hours, 105 dBA for 1 hour, 110 dBA for 30 minutes, and 115 dBA for 15 minutes. Dosimeters, worn by workers in noisy environments, can measure noise during the workday in percentages of the maximum daily exposure.

N-2242 Interference with Activities.

Activities most affected by noise include rest, relaxation, recreation, study and communications. Although most interruptions by noise can be considered annoying, some may be considered dangerous. An example would be the inability to hear warning signals or verbal warnings in noisy industrial situations, or in situations involving workers next to a noisy freeway. Figure N-2242.1 gives an estimate of the speech communication that is possible at various noise levels and distances.

Figure N-2242.1 - Interference of Conversation due to Background Noise



For instance, if the talker to listener distance is 6 m, normal conversation can be conducted with the background level at about 50 dBA. If the background level is increased to 60 dBA, the talker must either raise his/her voice, or decrease the distance to the listener to 3 m.

N-2243 Stress Related Diseases

There is ample evidence that noise can cause stress in humans, and thus may be responsible for a host of stress-related diseases, such as hypertension, anxiety, heart disease, etc. Although noise is probably not the sole culprit in these diseases, it can be a contributor. The degree of how much noise contributes to stress related diseases, depends on noise frequencies, their band widths, noise levels, and time patterns. In general, higher frequency, pure tone, and fluctuating noise tend to be more stressful than lower frequency, broad band, and constant-level noise.

N-3000 MEASUREMENTS & INSTRUMENTATION

Noise measurements play an important role in noise analysis and acoustical design of noise attenuation for transportation projects. This section covers recommendations on why, where, when, and how noise measurements should be taken. A brief discussion on available instrumentation is also included. Because of the variety of sound instrumentation, coverage of equipment setup and operational procedures has been kept at a general level. For greater detail, manufacturers' manuals should be consulted.

The noise analyst should be aware of the importance as well as the limitations of noise measurements. As is the case with all field work, quality noise measurements are relatively expensive. They take time, personnel and equipment. The noise analyst should therefore carefully plan the locations, times, duration, and number of repetitions of noise measurements before actually taking the measurements. A conscientious effort should be made during the measurements to document site, traffic and meteorology and other pertinent factors discussed in this section.

The contents of this section are consistent with methods described in the Federal Highway Administration (FHWA) document FHWA-DP-45-1R, "*Sound Procedures for Measuring Highway Noise: Final Report*", August 1981, and FHWA-PD-96-046, *"Measurement of Highway -Related Noise"*, May 1996.

N-3100 PURPOSES OF NOISE MEASUREMENTS

There are five major purposes for measuring transportation noise. These purposes are to:

1. Determine existing ambient and background noise levels
2. Calibrate noise prediction models
3. Monitor construction noise levels for compliance with Standard Specifications, Special Provisions, and Local Ordinances
4. Evaluate the effectiveness of abatement measures such as noise barriers
5. Perform special studies and research

Ambient and background noise and model calibration measurements are routinely performed by the Districts. Construction noise monitoring is also frequently done by the Districts. Some Districts conduct before-and-after noise abatement measurements. Special studies and noise research measurements, however, are done rarely by the Districts and are often contracted out to consultants with Caltrans oversight.

Where, when, and how noise measurements are performed depends on the purpose of the measurements. The following sections discuss the reasons for the above measurements, what they include, and how the results are used.

N-3110 Ambient and Background Noise Levels

Ambient noise levels are all-encompassing noise levels at a given place and time, usually a composite of sounds from all sources near and far, including specific sources of interest. Typically, ambient noise levels include highway plus community noise levels. Ambient noise levels are measured for the following reasons:

- To assess highway traffic noise impacts for new highway construction or reconstruction projects. Existing ambient noise levels provide a baseline for comparison to predicted future noise levels. The measurements are also used to describe the current noise environment in the area of the proposed project. This information is reported in appropriate environmental documents. Generally, the noise resulting from the natural and mechanical sources and human activity, considered to be usually present, should be included in the measurements.
- To prioritize retrofit noise barrier sites along existing freeways. The measured noise levels are part of a formula used to calculate a priority index. Prioritization is required by Section 215.5 of the Streets and Highways Code. The measured noise levels are also used to design retrofit noise barriers.
- To investigate citizens' traffic or construction noise complaints. Noise measurements are usually reported in a memo to the interested party or parties, with recommendations for further actions or reasons why further actions are not justified.

Background noise is the total of all noise in a specific region without the presence of noise sources of interest. Typically, this would be the noise generated within the community, without the highway, and is usually measured at locations away from the highway where highway noise does not contribute to the total noise level. Background noise levels are typically measured to determine the feasibility of noise abatement and to insure that noise reduction goals can be achieved. Noise abatement cannot reduce noise levels below background. Section N-6160 discusses the importance of background noise levels.

Depending on the situation, the noise sources to be measured may typically include highway traffic, community noise, surface street traffic, train noise, and sometimes airplane noise (when project is near an airport).

N-3120 Model Calibration

Noise measurements near highways or other transportation corridors are routinely used to calibrate the computer models by comparing calculated noise levels with actual (measured) noise levels. The calculated levels are modeled results obtained from traffic counts and other parameters recorded during the noise measurements. The difference between calculated and measured noise levels may then be applied to calculated future noise levels assuming site conditions will not change significantly, or modeled existing noise levels (see sections N-5400 and N-5330). Obviously, model calibration can only be performed on projects involving existing highways.

N-3130 Construction Noise Levels

These measurements are frequently done by Districts to check for the contractor's compliance with the standard specifications and special provisions of a transportation construction project, and with local ordinances.

N-3140 Performance of Abatement Measures

Before-and-after abatement measurements can be used to evaluate the performance of noise barriers, building insulation, or other abatement options. The measurements provide a "systems check" on the design and construction procedures of the abatement. Although these measurements are done occasionally by some Districts, they are not part of a routine program.

N-3150 Special Studies and Research

These measurements are usually done by the NT,M&R. They may involve District assistance and generally involve noise research projects. Setups are usually complex and include a substantial amount of equipment and personnel positioned at many locations for simultaneous noise measurement. The studies generally require more sophisticated equipment than that used for routine noise studies.

N-3200 MEASUREMENT LOCATIONS

The selection of measurement locations requires a considerable amount of planning and foresight by the noise analyst. A fine balance must be achieved between a sufficient amount of quality locations on one side, and the cost in person hours on the other. Good engineering judgment must be exercised in site selection; experience makes this task easier.

There are many tools available in the search for quality noise measurement sites. Preliminary design maps (50 scale geometrics), cross sections, aerial photographs, and field survey data are all helpful sources of information; however, noise measurement sites should only be selected after a thorough field review of the project area.

N-3210 General Site Recommendations

Following are some general site requirements common to all outside noise measurement sites:

1. Sites must be clear of major obstructions between source and receiver, unless they are representative of the area of interest; reflecting surfaces should be more than 10 feet from the microphone positions.
2. Sites must be free of noise contamination by sources other than those of interest. Avoid sites located near barking dogs, lawn mowers, pool pumps, air conditioners, etc., unless it is the express intent to measure these sources.
3. Sites must be acoustically representative of areas and conditions of interest. They must either be located at, or represent locations of human use.
4. Sites must not be exposed to prevailing meteorological conditions that are beyond the constraints discussed in this chapter. For example, in areas with prevailing high wind speeds avoid selecting sites in open fields.

More detailed considerations will be discussed in the next section.

N-3220 Measurement Site Selection

For the purpose of this document, a distinction will be made between receivers (including *sensitive receivers*) and noise measurement sites. Receivers are all locations or sites of interest in the noise study area. Noise measurement sites are locations where noise levels are measured. Unless an extremely rare situation exists when a noise measurement site is used for a specialized purpose, all noise measurement sites may be considered receivers. However, not all receivers are noise measurements sites.

For the purposes of describing existing noise levels at selected receivers, measured noise levels are normally preferred. Restricted access, or adverse site conditions may force the selection of noise measurement sites at locations that are physically different from, but acoustically equivalent to the intended receivers. In some cases measurements are not feasible at all. In such cases the existing noise levels must be modeled. This can only be accomplished along an existing facility.

Generally, there are more modeled receivers than noise measurement sites. It is far less expensive to take noise measurements at selected, representative receivers and model results for the rest. Nevertheless, there needs to be an adequate overlap of measurement sites and modeled receivers for model calibration and verification.

The following factors should be considered when selecting noise measurement sites.

N-3221 Site Selection By Purpose of Measurement

Noise measurement sites should be selected according to the purpose of the measurement. For example, if the objective is to determine noise impacts of a highway project, sites should be selected in regions that will be exposed to the highest noise levels generated by the highway after completion of the project. The sites should also represent areas of human use.

Conversely, if the objective is to measure background community noise levels, the sites should be located in areas that represent the community, without influence from the highway. These measurements are often necessary for acoustical noise barrier design (see section 6150) and to document before project noise levels at distant recievers. Past controversies concerning unsubstantiated increases in noise levels at distant receivers, attributed to noise barriers could have readily been resolved if sufficient background noise receivers would have been selected (see Section N-8200) after the project has been built.

Classroom noise measurements (Street and Highways Code Section 216), or receivers lacking outside human use, require inside - as well as outside - noise measurements in rooms with worst noise exposures from the highway. Measurements should generally be made at a point in a room, hall or auditorium where people would be impacted by infiltrating noise from the sources of interest. These are typically desks, chairs, or beds near windows. Several sensitive points may have to be tested and results averaged. No measurements should be made within 3-4 feet of a wall. It is also important to take measurements in the room in its typical furnished condition. If windows are normally open, take measurements with windows open and closed. Fans, ventilation, clocks, appliances, telephones, etc. should be turned off. People should preferably vacate the room or be extremely quiet.

Model calibration measurements usually require sites to be near the highway, preferably at receivers or acoustical equivalents to the receivers. (See Model Calibration Section N-5400 for additional details).

Sites for construction noise monitoring are dictated by standard specifications, special provisions, and local ordinances, which detail maximum allowable noise levels at a reference distance: e.g. Lmax 86 dBA at 15 m (50 ft), or other requirements.

Before-and-after measurements for evaluations of noise barriers and other abatement options, and measurements for special studies or research are non-routine and require a detailed experimental design. Coordination with the NT,M&R is advisable.

N-3222 Site Selection By Acoustical Equivalence

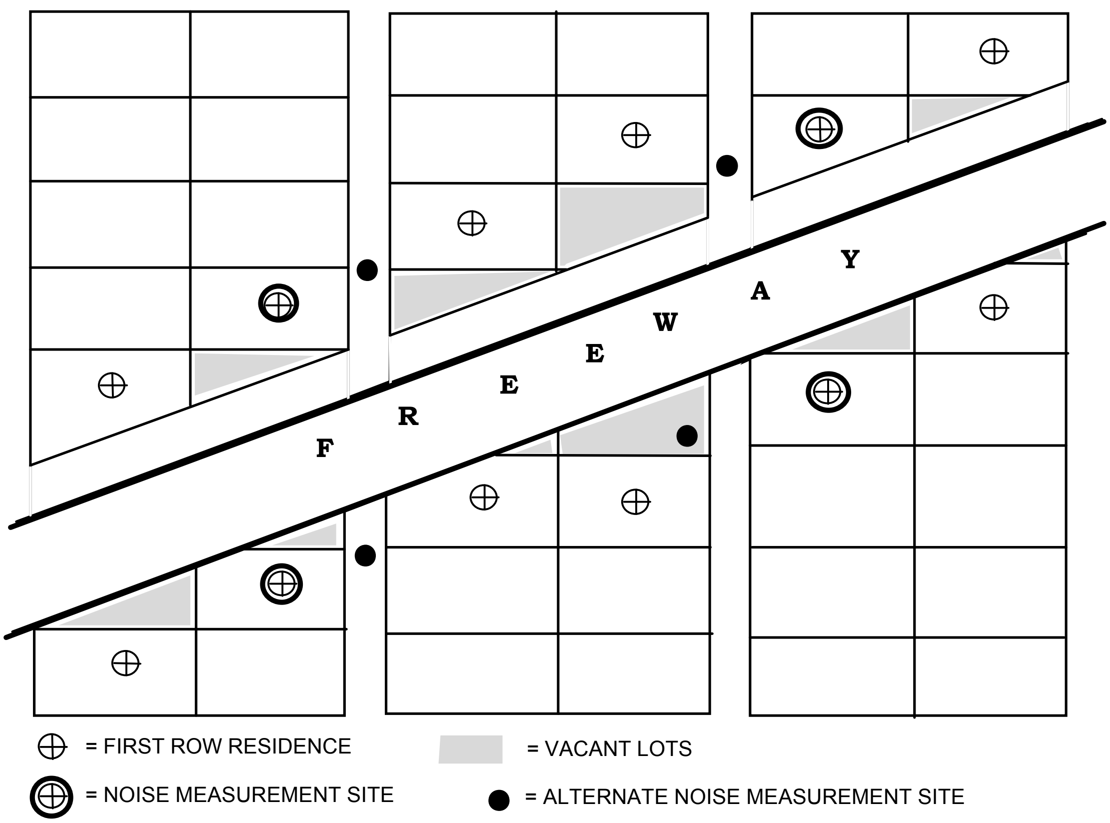
Noise measurement sites should be representative of the areas of interest. Representativeness in this case means *acoustical equivalence*. The concept of acoustical equivalence incorporates equivalences in noise sources, distances from these sources, topography, and other pertinent parameters.

The region under study may need to be subdivided into subregions in which acoustical equivalence can generally be maintained. Boundaries of each subregion must be estimated by one or more of the previously mentioned acoustical parameters. Also, in cases where measurements are being taken for more than one purpose, separate sub-regions may be defined by each purpose. The size of regions or subregions may vary from small to large. For example, noise abatement for a school may cover one small region (the school), while a noise study for a large freeway project may range from one large region to many subregions.

The number of measurement sites selected within each region or subregion under study depends on its size, number of receivers, and remaining variations in acoustical parameters. Obviously, the more conscientiously an effort is made to define acoustical subregions, the less sites are needed within each subregion. The minimum number of sites recommended for each region or subregion is two.

Figure N-3222.1 shows an example of receiver and noise measurement site selections for an at-grade freeway widening and noise barrier project. Also shown are alternate noise measurement sites to be used if the selected receivers are not accessible, or otherwise not suitable for noise measurement locations. Only sites near the freeway are shown. Background noise measurement sites would typically be off the map, further away from the freeway. Actual site selection would depend on field reviews and more information not shown on the map.

Figure N-3222.1 - Typical Measurement Sites



N-3223 Site Selection By Geometry

In addition to being an important consideration in determining acoustical equivalence, topography - or site geometry - plays an important role in determining locations of worst exposure to highway noise.

Sometimes, those receivers located farther from a highway may be exposed to higher noise levels, depending on the geometry of a site. One typical example is a highway on a high embankment, where the first tier receivers may be partially shielded by the top of the fill. Unshielded second or third tier receivers may then be exposed to higher noise levels, even though their distances from the source are greater. This concept is shown in Figure N-3223.1. Another common situation involves a close receiver shielded by the top of cut, and an unshielded receiver farther from the source.

Figure N- 3223.1 - Receiver Partially Shielded by Top of Embankment

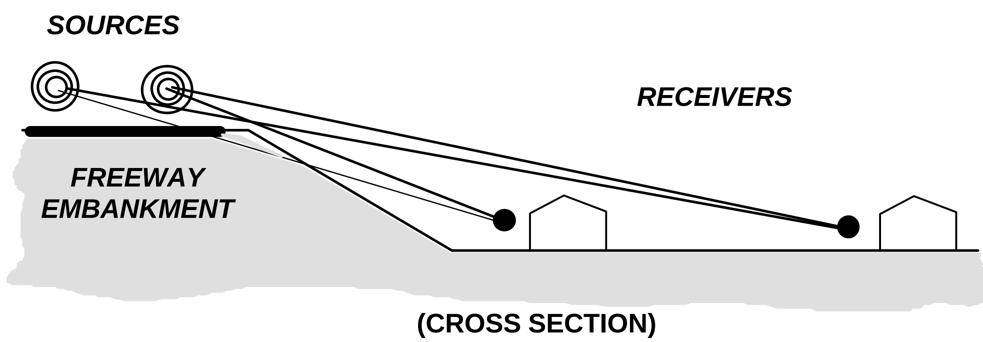
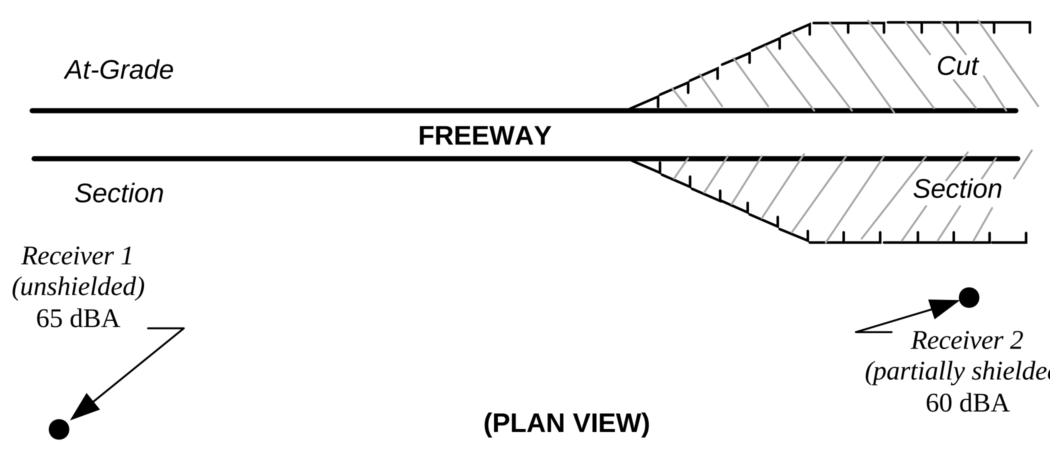


Figure N-3223.2 - illustrates the effects of site geometry on selection of highest noise exposure. The unshielded Receiver 1 shows a higher noise level than Receiver 2, although the latter is closer to the freeway.

Numerous other examples can be generated in which the nature of terrain and natural or man-made obstructions cause noise levels at receivers closer to the source to be lower than those farther away. This concept is an important consideration in impact analysis, where usually the noisiest locations are of interest.

Figure N-3223.2 - Receiver Partially Shielded by Top of Cut Vs. Unshielded Receiver



N-3300 MEASURING TIMES, DURATION, AND NUMBER OF REPETITIONS

N-3310 Measuring Times

FHWA 23 CFR Part 772 requires that traffic characteristics which yield the worst hourly traffic noise impact on a regular basis be used for predicting noise levels and assessing noise impacts. Therefore, if the purpose of the noise measurements is to determine a future noise impact by comparing predicted noise with measured, the measurements must reflect the highest existing hourly noise level that occurs regularly. In some cases, weekly and/or seasonal variations need to be taken into consideration. In recreational areas, weekend traffic may be greater than on week days and, depending on the type of recreation, may be heavily influenced by season.

Measurements made for retrofit noise barrier projects also require noise measurements during the highest traffic noise hour.

The noise impact analysis for classrooms, under the provisions of the Streets and Highways Code Section 216, requires noise measurements to be made "at appropriate times during regular school hours ...." and sets an indoor noise limit of 52 dBA, L_{eq}(h), from freeway sources. Therefore, noise measurements for schools qualifying for school noise abatement under Section 216 need to be made during the noisiest-traffic hour during school hours. Noise from school children often exceeds traffic noise levels. In order to avoid contaminated measurements it is often necessary to evacuate class rooms for the duration of the measurements, or take measurements during vacation breaks.

Noise measurements for model calibration do not have to be made during the highest noise hour, but it is desirable to have about the same estimated traffic mix (heavy truck percentages of the total volume) and traffic speeds as during the noisiest hour. Accurate traffic counts and meteorological observations (see Section N-3600) must be made during these measurements.

Noise monitoring for background community noise levels should preferably be done during the expected time of the highest noise level from the highway, even though the measurements are taken at sites that are far enough removed from an existing highway to not be contaminated by it. The reason for this is that the background levels will later be added to predicted near-highway noise levels.

Noise monitoring for investigating citizen's complaints may have to be done at a mutually-agreed-on time. Frequently, these measurements are taken before or after normal working hours, as dictated by the nature of the complaint.

Construction monitoring is performed during operation of the equipment to be monitored. This may require night work on some construction projects.

Unless other times are of specific interest, before and after noise abatement (e.g. noise barrier) measurements to verify noise barrier performance should preferably be done during the noisiest hour. There are several reasons for this. First, noise barriers are designed for noisiest hour traffic characteristics, which probably include highest truck percentages, and second, to minimize contamination by background noise. Traffic should be counted during these measurements. If before and after traffic conditions are different, measurements should be normalized or adjusted to the same conditions of traffic (see section N-3312).

The nature of special studies and research projects dictate the appropriate times for those measurements.

N-3311 Noisiest Hour For Highway Traffic

The peak *traffic* hour is generally NOT the *noisiest* hour. During rush hour traffic, vehicle speeds and heavy truck volumes are often low. Free flowing traffic conditions just before or after the rush hours often yield higher noise levels. Preliminary noise measurements at various times of the day are sometimes necessary to determine the noisiest hour.

If accurate traffic counts and speeds for various time periods are available, the noisiest hour may be determined by using the prediction model.

Experience based on previous studies may also be of value in determining the noisiest hour for a particular facility.

N-3312 Adjusting Other-Than-Noisiest Hour

For the sake of efficiency, highway traffic noise measurements are often not made when the highest hourly traffic noise levels occur. These measurements may be adjusted upward to noisiest hour levels by using the prediction model. To make the adjustments, traffic must be counted and speeds determined simultaneously with the noise measurements. The following procedure must be followed:

1. Take noise measurements and count traffic simultaneously during each measurement. Although lane-by-lane traffic counts yield the most accurate results it is usually sufficient to count traffic by direction (e.g. east bound and west bound).

Separate vehicles in the three vehicle groups used by the model (autos, medium trucks, and heavy trucks). Obtain average traffic speeds (both directions). These may be obtained by radar or by driving a test vehicle through the project area at the prevailing traffic speed.

2. Expand vehicle counts for the measurement period to hourly values: i.e., if the measurement period was 15 minutes, multiply the vehicles counted in each group by 4. (Section N-3320 discusses duration of measurement as a function of hourly vehicle volumes).
3. Input the hourly traffic volumes and speeds (from steps 1 and 2) in the Highway Traffic Noise Prediction Model. Also include the proper roadway/receiver geometry and site parameters. Run model.
4. Input the traffic volumes and speeds associated with the noisiest hour and the same roadway/receiver geometry and site parameters as used in step 3. Run model.
5. Subtract results of step 3 from those of step 4. (Step 4 results should always be larger than step 3).
6. Add the differences obtained in step 5 to the noise measurements of step 1.
7. Example:
8. Measured noise level in step 1, L_{eq} = 66 dBA
9. Calculated for step 1 conditions (step 3) = 67 dBA
10. Calculated for noisiest hour (step 4) = 69 dBA
11. Difference (step 5) = 2 dBA
12. Measured noise level adjusted to noisiest hour (step 6)
    = 66 dBA + 2 dBA = 68 dBA

If 24-hour monitoring equipment is available, a histogram of 24 hourly noise measurements may be developed for an existing freeway. This information may then be used to adjust an off-peak-hour noise level at any location along the freeway to a noisiest-hour-noise level. However, steps must be taken to reduce the chance of undetected noise contaminations, should they occur. Then, if hourly noise relationships are in agreement between the two monitors, there is reasonable assurance that neither were contaminated.

There is, however, no assurance that regional contamination such as frequent aircraft fly-overs did not take place., Hence, measurements with remote noise monitoring equipment must be approached with extreme caution and only with at least some familiarity of nearby noise sources.

N-3320 Measurement Duration

A noise measurement representing an hourly L_{eq} does not need to last the entire hour. As long as noise levels do not change significantly, a shorter time period will usually be sufficient to represent the entire hour of interest. The recommended length of measurements depends on how much the noise levels fluctuate. The greater the fluctuations, the longer the measurement needs to be. Vehicle spacing and differences in vehicle types are responsible for fluctuating noise levels. These fluctuations become less as traffic densities increase. Highway noise also becomes more constant as the distance from the highway increases because the rate of distance change between a moving vehicle and a receiver diminishes.

The following durations are recommended for highway traffic noise measurements as a function of number of vehicles per hour (vph) per lane (Table N-3320.1):

Table N-3320.1 - Suggested Measurement Durations

Traffic Volume	Veh./Hour/Lane	Duration
High	> 1000	10 Minutes
Medium	500 - 1000	15-20 “
Low	< 500	20-30 “

Most sound level meters automatically integrate and digitally display cumulative L_{eq}'s. Near the beginning of each measurement period, the displays fluctuate considerably. However, after more data is collected they tend to stabilize. The time it takes to stabilize depends on the amount of noise fluctuations. A measurement may be terminated when the range of the fluctuations in displayed L_{eq} is less than 0.5 dBA. When in doubt, measure a little longer.

N-3330 Number of Measurement Repetitions

Noise measurements taken at a specific site tend to vary from measurement to measurement. The most common causes of these variations are:

1. Changes in traffic volumes, speeds, and/or mixes.
2. Contamination from other noise sources, such as barking dogs, aircraft, nearby construction, etc.
3. Change in meteorology (wind speed, wind direction, temperature, humidity, etc.)

4. Changes in site conditions
5. Instrument error
6. Operator error
7. Calibration error
8. Malfunctioning instruments

Because of these potential variables and errors that may occur during a measurement, it is strongly recommended that a time averaged measurement (such as the L_{eq} descriptor) be repeated AT LEAST once at each site. This procedure will reduce the chances of undetected errors. There are exceptions to this recommendation. Whenever three or more noise measurements are made in the same general area, either simultaneously or in relatively rapid succession, one measurement at each site may be sufficient, <u>if the sites are acoustically equivalent (see Section N-3222</u>). However, to determine if a measurement at any particular site is acceptable, the measurement should be compared with those at the other sites and subjected to the same criteria for repeat measurements discussed later in this section.

The recommended minimum of two measurements should be taken independently (using two different setups and separate calibrations). That, of course, does not preclude the operator from taking more than one measurement per setup and calibration. As a matter of fact, if time permits, multiple measurements during each setup are encouraged in order to improve accuracy. The two setups may be made consecutively, at different times of day, or on different days.

If done consecutively, the setup should be broken: power must be turned off and on and instruments must be calibrated again. If a recording device - such as a graphic level recorder (GLR) - is connected to a sound level meter (SLM), the device should also be turned off and on and recalibrated. It is further recommended that equipment be disassembled and reassembled to avoid undetected errors through bad connections in the cables or microphone.

<u>Repeat measurements should be compared with the original(s) under the same conditions of traffic, meteorology and site.</u> Noise contamination, instrument malfunction, operator error, or any other anomalies in the measurements can then readily be detected. To insure that conditions are the same for all measurements, traffic counts and some basic meteorological measurements should be made during the noise measurements (see sections N-3340 and N-3600).

If the repeat measurements do not agree with the original(s), further repetitions will be necessary. How close the measurements should agree depends on the purpose of the measurements.

For routine measurements, such as determining ambient noise levels or calibrating noise prediction models, the above recommended minimum of two measurements normalized for differences in traffic mix and volumes should agree within 2 dBA. If more than one measurement is taken per setup, the mean noise levels for the two setups should agree within 2 dB. Repetitive measurements for each setup should then be within +/- 1 dBA of the mean noise level of the setup.

The above criteria have been set empirically from many years of field experience with a variety of sound level meters approved for transportation noise measurements (ANSI S1.4 1983, Types 1 and 2).

Following are some examples illustrating these criteria. They were purposely selected to show the extreme allowable limits. Usually, better agreement between setups and within setups can be expected. The examples assume that all meteorological conditions, traffic conditions and site conditions are the same throughout all measurements.

Example 1 data:

Meas'ment No.	Leq (dBA) Setup 1	Setup 2
1	74.5	76.5
Mean	75.5	

(Example 1 measurements are acceptable because they agree by 2 dBA.)

Use the mean of 2 measurements = 75.5 dBA

Example 2 data:

Meas'ment No.	Leq (dBA) Setup 1	Setup 2
1	69	71
2	67	69
Mean of Setups	68	70
Mean of All	69	

(Example 2 measurements are acceptable because the means of setups 1 and 2 agree by 2 dBA, AND measurements within each setup are within ± 1 dBA of the setup's mean.

Use mean of all measurements = 69 dBA

Example 3 data:

Meas'ment No.	Leq (dBA) Setup 1	Setup 2
1	61.6	58.6
2	59.6	-
Mean of Setups	60.6	58.6
Mean of All	59.9 (round off to 60)	

(Example 3 measurements are acceptable)

Use mean of all measurements = 60 dBA

The above examples indicate that as long as the agreement criteria between the two setups and within each setup are met, all measurements can be averaged together.

Following are examples of what to do if the setups do not agree by 2 dBA:

Example 4 data:

Measurement No.	L_{eq}(dBA) Setup 1	Setup 2
1	65.3	68.0

(Example 4 measurements are NOT acceptable:)

After the second measurement, a decision should be made to either take another measurement during setup 2, or break the setup and take a measurement for a new setup 3. Either method will be acceptable. If the choice is to take another measurement during setup 2, however, and the agreement criteria can still not be met, it is then recommended to break setup 2 and perform additional measurement(s) with setup 3. If agreement is reached between setups 2 and 3, then eliminate setup 1, as illustrated in example 5:

Example 5 data:

Measurement No.	L_{eq}(dBA) Setup 1	Setup 2	Setup 3
1	65.3	68.0	69.0
2	-	68.5	-

(Setup 2 & 3 measurements are acceptable.)

Mean of setup 2 and 3 = 68.5 dBA

If setup 3 measurement would have agreed with both setup 1 and 2 (say with 67.0, instead of 69.0) then another decision would have to be made: a) use setups 1 and 3, b) use setups 2 and 3, or c) use the average of all three setups (all measurements). The safest approach would then be to use the average of all measurements, unless there would be a good reason to eliminate one setup.

The above examples illustrate some extreme cases. Obviously, many other combinations are possible. Most measurements will show better agreement. The examples are intended to show how the recommended criteria may be applied in general. Individual judgment and experience may have to be relied on in more complicated situations.

In some cases greater accuracy is required than the criteria allow. These cases mostly apply to special studies or research. However, they may also be applied to a few key noise measurement sites on a large project for the purpose of accurate model calibration. In these cases 95% confidence interval for the mean of several measurements (using a minimum of two setups) can be calculated. The 95% confidence interval should be specified to be no more than ± 1 dBA. Table N-3330.1 shows the maximum allowable standard deviations as a function of number of samples (measurements). Although the table is calculated for up to 10 measurements, the criterion can be met after five or less measurements in most cases. A scientific calculator with statistical functions is essential when making calculations in the field.

Table N-3330.1 -Maximum Allowable Standard Deviations (S_{MAX}). For 95% Confidence Interval for Mean Measurement of ± 1 dBA

Number of Measurements	S_{MAX}
2	0.11
3	0.40
4	0.63
5	0.81
6	0.95
7	1.08
8	1.20
9	1.30
10	1.40

Example:

Measurement No.	L_{eq}(dBA) Setup 1	Setup 2	
1	67.8	68.7	
2	66.9	67.9	S = 0.73 S_{MAX} = 0.63 (for 4 meas.) (Need more data)
3	-	67.8	S = 0.64 S_{MAX} = 0.81 (for 5 meas.) (Accept the 5 measurements)

(Use mean of 5 measurements = 67.8 dBA, or 68 dBA)

All the above examples presume that the previously mentioned site, traffic, and meteorological conditions remain the same during all measurements.

Site conditions and contamination from other noise sources can be controlled by careful site selection. Noise contamination from intermittent sources can further be controlled by pausing the instruments during the contamination, or by marking and editing recorded data.

Operator error and instrument malfunction usually cause larger errors that are easily detected. Instrument error is a function of equipment brand, type, and calibration. Instrument records of calibration, repair, and performance, manufacturers' manuals, and accuracy standards (discussed later), will give a good estimate of instrument error.

Meteorological limits for comparisons of noise measurements will be discussed in section N-3600, "Environmental Constraints".

The remaining factor to be discussed is traffic. The next topic covers a method of normalizing noise measurements made under different traffic conditions.

N-3340 Normalizing Measurements for Differences in Traffic Mixes and Volumes

Before applying the criteria discussed in section N-3330, repeated measurements must be adjusted for differences in traffic mix and volume. The effects of traffic differences can be calculated by the noise prediction models and compared with the actual differences in the measurements. However, a simple method to normalize measurements for differences in traffic mixes and volumes has been developed for <u>optional</u> use in the field.

The method involves field calculations that, with practice, can be carried out in a few minutes with a log function calculator. The repeated measurements are field adjusted for the same traffic conditions as the first measurement. The adjusted (normalized) measurements may then be compared directly according to the criteria in section N-3330.

The obvious advantage of using the field method is that it may eliminate the need for coming back to the same site at a later date, if repetition criteria are not met.

As is the case with most simplified methods, there are certain limitations to the use of this field normalization procedure. The method should NOT be used when:

1. Average traffic speeds are not the same for each measurement. (This is difficult to verify, but under free flow conditions at a specific location speeds will generally be constant within a few mph).
2. Truck speeds are significantly different (more than 5 mph) from auto speeds.
3. Speeds cannot be determined within 5 mph.
4. Ratio of distances from receiver to the center line of far (directional) lane group, and receiver to center line of near (directional) lane group is greater than 2:1. For most 8-lane urban freeways, this means that the receiver should not be closer than 45 feet from the edge of the traveled way.
5. Directional split of traffic is different by more than 20% for each vehicle group between measurements. For example, if during the first measurement the directional split between heavy trucks is 60/40 and during the next measurement 80/20 or 40/60, the method would still be valid. However, if the second split would be 85/15 or 35/65 the method would be inaccurate. This criterion is usually met.

The method uses the concept of Equivalent Vehicles (V_E), which equates medium and heavy trucks to an acoustically equivalent number of autos. Based on California Vehicle Noise Reference Energy Mean Emission Levels (Calveno REMELs, see Section N-5510) one heavy truck traveling at 55 mph makes as much noise as approximately 13 autos cruising at the same speed. A medium truck at 55 mph is acoustically equivalent to approximately 5 autos passing at the same speed. These heavy truck, medium truck and auto relationships are speed dependent and are the same for the maximum noise level (L_{MAX}) and time averaged noise levels (L_{eq}).

The relationships do not take into consideration source heights and may not be used if the source to measurement site is intercepted by a barrier or natural terrain feature. Table N-3340.1 shows Equivalent Vehicles for speeds from 56 km/h (35mph) to 105 km/h (65 mph) in 5 mph increments, based on Calveno REMELS. Table N-3340.2 shows the same table based on the new TNM REMELs for baseline conditions. The latter should be used when the TNM noise prediction model (Section N-5520) is officially implemented.

Table N-3340.1 - Equivalent Vehicles Based on Calveno REMELs*

	NUMBER OF EQUIVALENT VEHICLES		
Speed, km/h (Mph)	1 Heavy Truck =	1 Medium Truck =	1 Automobile =
56 (35)	30.9	9.4	1
64 (40)	24.1	7.8	1
72 (45)	19.0	6.7	1
80 (50)	15.3	5.8	1
88.5 (55)	12.8	5.1	1
97 (60)	10.9	4.7	1
105 (65)	9.5	4.3	1
*Based on California Vehicle Noise Reference Energy Mean Emission Levels and vehicle definitions in FHWA-RD-77-108 (Also see sections N-4400 and N-5510)			

Table N-3340.2 - Equivalent Vehicles Based on TNM REMELs**

	NUMBER OF EQUIVALENT VEHICLES		
Speed, km/h (mph)	1 Heavy Truck =	1 Medium Truck	1 Automobile =
56 (35)	19.1	7.1	1
64 (40)	15.1	5.8	1
72 (45)	12.9	5.0	1
80 (50)	11.5	4.5	1
88.5 (55)	10.4	4.1	1
97 (60)	9.6	3.7	1
105 (65)	8.9	3.5	1
113 (70)	8.3	3.2	1
**Based on FHWA Traffic Noise Model (TNM) Reference Energy Mean Emission Levels and vehicle definitions in FHWA-PD-96-008, DOT-VNTSC-FHWA-96-2 (Also see sections N-4400 and N-5520)			

Example of calculating equivalent vehicles using Table N-3340.1:

Given: In 15 minutes the following traffic was counted: 76 heavy trucks, 34 medium trucks, and 789 autos Average traffic speed was 55 mph.

Assignment: Convert traffic counts to Equivalent Vehicles.

Solution: (using Table N-3340.1)

76	*heavy trucks*	*= 76 x 12.8*	=	*973* V_E
34	*medium trucks*	*= 34 x 5.1*	=	*173* V_E
789	*autos*		=	*789* V_E
		Total	=	*1935* V_E

To normalize one noise measurement for one traffic count to another noise measurement for a different traffic count, the following procedures should be followed:

1. Use the first noise measurement as a reference measurement. Let this measurement be $L_{eq}(1)$.
2. Convert the traffic count for $L_{eq}(1)$ to equivalent vehicles. Let this number be $V_E(1)$.
3. Let the measurement to be normalized be $L_{eq}(2)$.
4. Convert the traffic count for the measurement to be normalized to equivalent vehicles. Let this number be $V_E(2)$.
5. Let c be the correction to be applied to $L_{eq}(2)$ for normalization to the traffic of $L_{eq}(1)$.
6. Calculate $c = 10\ LOG_{10}[V_E(1)/V_E(2)]$ (Note that c may be negative or positive).
7. Let $L_{eq}(2N)$ be the normalized $L_{eq}(2)$.
8. Calculate $L_{eq}(2N) = L_{eq}(2) + c$.
9. $L_{eq}(2N)$ may be directly compared with $L_{eq}(1)$ in the field for the purposes of determining whether agreement criteria discussed in section N-3330 are met. If more than two measurements are made, the same procedure can be used for subsequent measurements. The same reference measurement must be used throughout the procedure.

Following is an example for determining in the field whether three 15 min. measurements for different traffic conditions meet the agreement criteria in section N-3330 (for convenience the measurements have been numbered consecutively regardless of setup):

Meas. No.	Setup No.	15 min L_{eq} (dBA)	Heavy Trucks	Medium Trucks	Autos	Speed (mph)	Equivalent Vehicles (V_E)
1	1	74.4	100	50	1275	55	2810
2	1	75.5	150	100	850	55	3280
3	2	74.0	60	30	1700	55	2621

Correction c for $L_{eq}2 = 10\ \mathrm{LOG}_{10}\left(\frac{V_E 1}{V_E 2}\right) = 10\ \mathrm{LOG}_{10}\left(\frac{2810}{3280}\right) = -0.7$

$L_{eq}2N = L_{eq}2 + c = 75.5 - 0.7 = 74.8$ dBA

Correction c for $L_{eq}3 = 10\ \mathrm{LOG}_{10}\left(\frac{2810}{2621}\right) = +0.3$

$L_{eq}3N = 74.0 + 0.3 = 74.3$

Normalized Data, L_{eq}, dBA:

Meas. No.:	Setup No.:	Norm. L_{eq} (dBA)
1	1	74.4
2	1	74.8
3	2	74.3

Further examination indicates that the agreement criteria of section N-3330 were met, and no further measurements are necessary.

The actual measurements and traffic counts may now be used back at the office as follows:

Average the energy of the measurements = 74.5 dBA (Report as 75 dBA)

Average the 15-minute traffic counts:

Mean HT's (15 min.) = $\left(\frac{100 + 150 + 60}{3}\right) = 103.3$

Mean MT's (15 min.) = $\left(\frac{50 + 100 + 30}{3}\right) = 60.0$

Mean Autos (15 min.) = $\left(\frac{1275 + 850 + 1700}{3}\right) = 1275.0$

Expand the average 15 minute traffic counts to 1-hour:

Mean HT's (1-hour) =103.3x 4 = 413

Mean MT's (1-hour) =60.0x 4 = 240

Mean Autos (1-hour) =1275.0x 4 = 5100

The expanded average traffic count may be used in the prediction model to calculate the noise level. The result may be compared to the energy-averaged measurement. Section N-5400 explains how this comparison may be used for "calibrating" the prediction model.

Although Tables N-3340.1 and N-3340.2 are based on different REMELS, the results of the normalization process will not be significantly different using either table. For example, using the data in the previous example with Table N-3340.2, instead of Table N-3340.1 would yield only slight differences (0.2 dBA) in normalized measurements No.2 and 3, and the same energy-averaged noise level.

Normalized Data, L_{eq}, dBA:

Meas. No.:	Setup No.:	Norm. L_{eq} (dBA)
1	1	74.4
2	1	75.0
3	2	74.1

Average the energy of the measurements = 74.5 dBA (Report as 75 dBA).

N-3350 Classroom Noise Measurements

Determining a project's traffic noise impacts on school classroom interiors (see Section 4.3) requires taking simultaneous noise measurements inside and outside the classroom to measure the attenuation provided by the building. While outside noise levels can be predicted, there are no reliable modeling techniques available for interior noise levels. To predict an interior noise level, the measured building attenuation may be applied to the predicted outside level.

If the project involves a reconstruction of an existing freeway, simultaneous traffic noise measurements may be taken inside and outside the classroom. Microphones should be placed as shown in Figure N-3350.1 (a) and (b).

Figure N-3350.1(a) shows the preferred setup. Microphone 1 (Mic.1) should be placed outside the classroom at approximately the same distance from the freeway as the center of the classroom. Care must be taken to place the microphone far enough away from the building to a avoid significant shielding by the corner of the building. This can be accomplished by maintaining at least a 70^{o} angle between a perpendicular line to the freeway and a line to the corner of the building (see Figure N-3350.1(a)). Mic. 2 should be placed in the center of the classroom.

Figure N-3350.1(b) shows an alternate setup, to be used if (a) is not possible. Mic. 1 should be positioned at least 3 m from the building to avoid noise reflections from the building. The disadvantage of this setup is that Mic.1 and Mic.2 are not equal in distance from the freeway. If Mic. 1 is 60 m or more from the freeway, the effects of unequal distances can usually be ignored. Assuming a 10 m x 10 m classroom the error would be 0.5 dBA or less. Between 20 and 60 m a distance adjustment of -1 dBA would have to be applied to Mic.1 in order to normalize Mic. 1 to Mic. 2. If the distance from Mic.1 to the freeway is less than 20 m, a greater adjustment will be necessary. The model (Section 2.4) may be used to calculate the adjustments.

If the classrooms are not air-conditioned and rely on open windows/doors for ventilation, the simultaneous measurements should be made both with doors and windows open and closed conditions. The noise attenuation provided by the building under these conditions is useful for predicting inside classroom noise levels as well as choosing noise abatement options if needed. For instance, if a classroom interior is not expected to meet the inside classroom noise criterion with the windows/doors open, but will meet the criterion with windows/doors closed, noise abatement considered may include sealing windows, and adding air-conditioning.

If the project is on a new alignment, there is no existing traffic source that can be used to measure building attenuation. In that case it is appropriate to use an artificial noise source (Figure N-3350.2). Acceptable choices would be traffic noise tape recordings or an electronically generated noise spectrum that approximates typical traffic noise. This spectrum should be linear, from 31.5 Hz to 500 Hz, and decrease at six decibels per octave from 500 Hz to 4000 Hz. Amplification should be sufficient to produce A-weighted sound levels at least 10 dBA above background noise levels at exterior as well as interior locations. A commercial quality loudspeaker should be used with directional characteristics such that a 2000 Hz signal measured at 45 degrees from a perpendicular to the face of the speaker is no more than six decibels below the level measured at the same distance on the perpendicular axis. The sound level output must be kept constant for inside and outside measurements.

Figure N-3350.1 - Classroom Noise Measurements (Reconstruction of Existing Freeway)

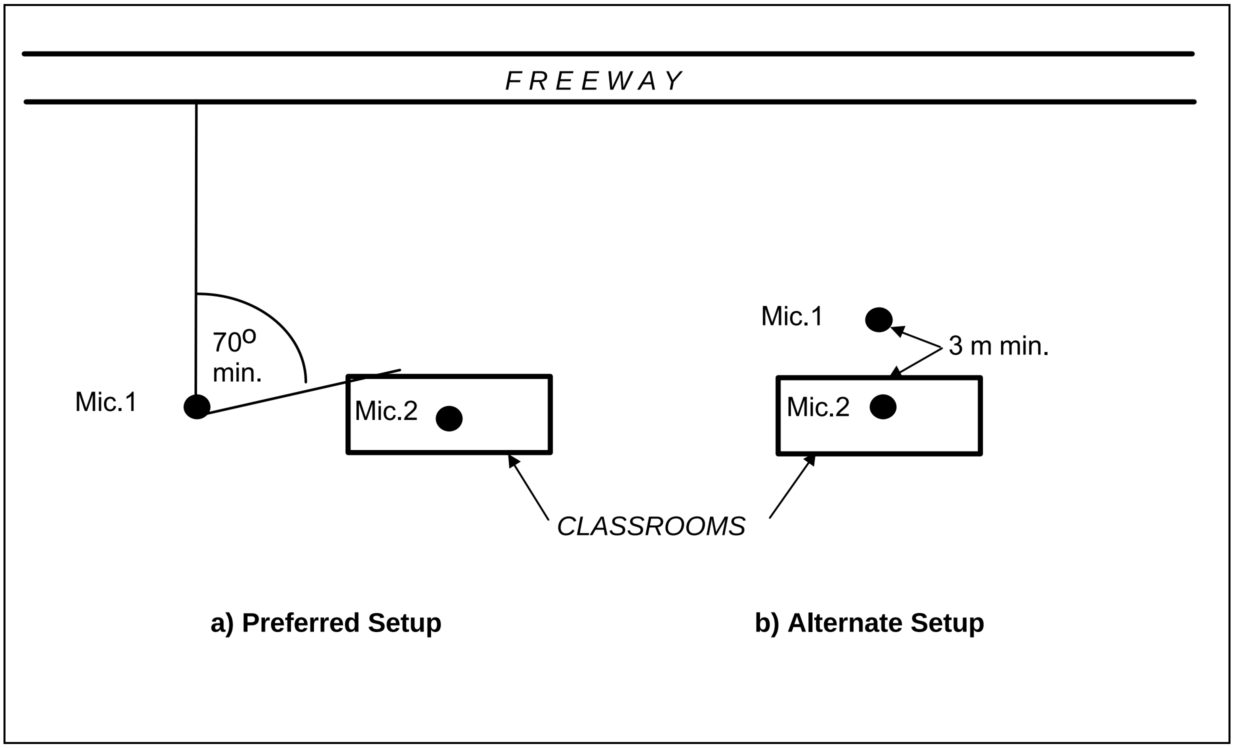
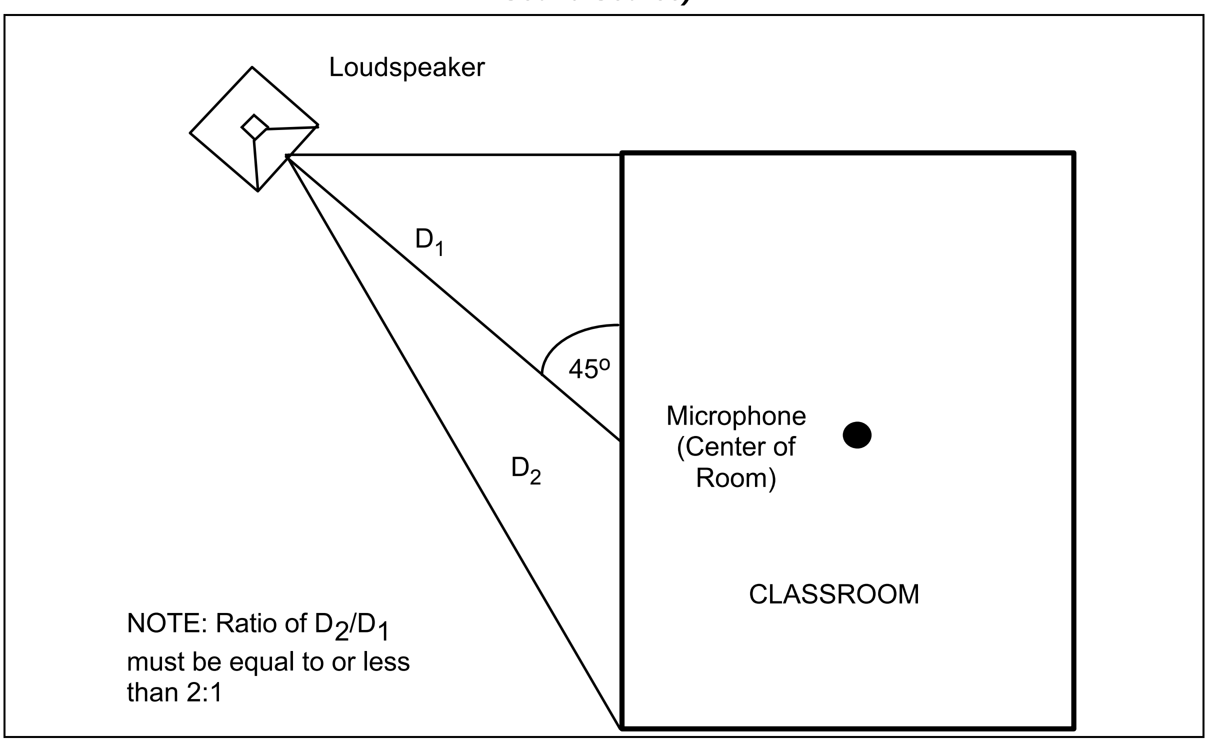


Figure N-3350.2 - Classroom Noise Measurements (Project on New Alignment, Using Artificial Sound Source)



The loudspeaker is a point source. To account for all the possible angles of incidence provided by a line source and to avoid reflections from the building face, the speaker should be positioned as shown in Figure N-3350.2 for the indoor noise measurements.

Avoid placing the speaker and the microphone so that there is a direct line of sight between the two through an open door or window. If possible, take additional measurements at 15, 30, and 60 degrees and average the results. If only one angle is used, it should be 45 degrees.

For the outdoor noise measurements, the distance from speaker to the outdoor microphone should be equal to the distance from the speaker to the indoor microphone. Since indoor and outdoor measurements can not be taken simultaneously, the sound level output of the artificial source must be the same for inside and outside measurements.

N-3400 INSTRUMENTATION

The instruments used for measuring or recording noise are available from a wide variety of manufacturers, models, types, accessories, degrees of accuracy, prices, and levels of sophistication. It is not the intent of these Technical Analysis Notes to delve into all the details of noise instruments, nor to endorse certain manufacturers. There are informative catalogs available from all major manufacturers to help decide which equipment to purchase, and sales representatives are usually very helpful in demonstrating the equipment. Once purchased, user's manuals will be useful, ready references for specific operating procedures.

It is, however, strongly recommended that the NT,M&R be consulted before purchasing noise instrumentation. NT,M&R calibrates all district noise equipment; compatibility with its calibration system is essential.

This section will cover general features common to most instruments. The following categories will be discussed:

1. Sound Level Meters
2. Recording Devices
3. Frequency Analyzers
4. Acoustical Calibrators
5. Meteorological and Other Non-Noise-Related Equipment.

N-3410 Sound Level Meters (SLM)

The American National Institute of Standards (ANSI) has established requirements for SLM accuracy in standard ANSI S1.4-1983 (Revision of S1.4-1973) and ANSI S1.4N-1985 Amendment To ANSI S1.4-1983. The standard defines three basic types of SLM:

1. Type 0 - Laboratory Standard (primarily designed for laboratory use)
2. Type 1 - Precision (field use)
3. Type 2 - General Purpose (field use)

The expected total allowable error for a type 1 SLM in the field is +/-1.5 dB; for a type 2 SLM in the field the allowable error is +/- 2.3 dB. These expected values of total allowable errors apply to an instrument selected at random. These errors may be reduced for a specific instrument through careful calibration and adjustment.

For each type, the standard requires three frequency weightings, A, B, and C, and two response settings: slow and fast. In addition, the standard permits other optional features in an SLM, such as impulse and peak measuring capabilities, wide ranges for the display of sound level on an analog indicator, digital displays, etc.

Because an SLM may be needed for special purposes that require only part of the basic type requirements, a meter may be designated type S, followed by the type, and the available frequency weighting, and/or response setting. Example: type "S2A, fast" is a type 2 SLM with only an "A" weighting network and a "fast" response setting.

The standard also requires the manufacturer to mark the SLM with the type number and the special purpose (if any).

All SLM used by Caltrans or its contractors shall be of any type described above (types 0, 1, 2 or S with A weighting). The type must be marked on the SLM by the manufacturer.

An older type 3 SLM defined in ANSI S1.4-1971 and S1.4-1971 (R1976) or SLM not marked with the type shall not be used. Type 3 was discontinued with S1.4-1983.

Although SLM come in many levels of sophistication they all have the following general components:

1. *Microphone System (Microphone and Preamplifier)* - The microphone converts air pressure fluctuations into an electrical signal that is in turn measured by instrumentation such as the SLM, or a third -octave band spectrum analyzer. Most microphones can be detached from the SLM body and connected to an extension

cable. (In order to satisfy a type 0 or 1 requirement the microphone may need to be separated from the SLM body.)

Microphones come in various diameters. The 1/2 inch diameter microphone is most commonly used. The air condenser microphone (most common) consists of a membrane and a back plate, separated by an air gap. The width of the air gap fluctuates as the membrane vibrates in a sound field, thereby changing the capacitance. Microphones of SLM complying with the type standards are omni-directional, have a flat frequency response and are sensitive over a wide range of frequencies.

A compatible preamplifier, usually manufactured as part of the microphone system should always be used. A preamplifier provides high-input impedance and constant low-noise amplification over a wide frequency range. Depending on the type of microphone, a preamplifier may also provide a polarization voltage to the microphone.

2. *Wind screen* - a spherically or cylindrically shaped screen, generally made of open-celled polyurethane. When placed over the microphone it reduces wind noise (see section 3600, "Meteorological Constraints"). The wind screen should always be used - even in absence of wind - as it helps protect the microphone against dust and/or mishaps.
3. *RMS Detector* - converts peak-to-peak signals to an RMS (root mean square) signal. The RMS measure is derived by first squaring the signal at each instant, obtaining the average (mean) of the squared values, and taking the square root of this average.
4. *Amplifier* - amplifies the electrical signal.
5. *Frequency weighting filters (A, B, C)*, as required by ANSI S1.4-1983 and S1.4-1985. The "A-weighting" is used internationally for environmental noise measurements (including transportation noise).
6. *Slow and/or Fast Response Switch* - refers to time averaging characteristics of the SLM. On the slow setting, the averaging of sound levels takes place over 1 second increments; on the fast setting the averaging time is 0.125 second. On a real time display (digital or analog) the sound level fluctuations are easier to read on the slow setting than in the fast position. The latter, however, gives a better resolution of instantaneous sound levels.
7. *Range Setting* - allows setting of the correct range of sound levels to be measured.

8. *Analog or Digital Display* - displays instantaneous noise levels and/or integrated averages. Digital displays often have multi-function switches that allow the user to view various noise descriptors such as L_{eq}, L_{MAX} etc.

9. *Battery Check Switch* - allows user to check battery voltage.

10. *Output* for various recording devices.

11. *Power On/Off Switch*

Many SLM also have pause switches to interrupt data sampling; preset time switches allowing sampling over a predesignated time period; reset switches for starting a new sampling period and other features.

More sophisticated SLM can be mated to external filter sets to allow 1 or 1/3 octave frequency analysis in the field.

N-3420 Recording Devices

Three main types of recording devices can be connected to most SLM outputs: Graphic Level Recorders, Audio Tape Recorders, and Microprocessors.

N-3421 Graphic Level Recorder (GLR)

The GLR records sound levels graphically by instantaneous dB vs. time. GLR's provide a permanent record of fluctuating noise levels over time. Such a record is useful in several ways:

- The GLR trace provides additional information for time averaged noise levels with respect to constancy or fluctuation of sound levels. Noise intrusion is a function of the number and dynamic range of these fluctuations.
- The traces can be effectively used in litigation involving noise. A third, independent party can analyze the trace and derive various noise descriptors from it.
- The traces can also be used as a backup for noise levels obtained from a visual display. This guards against errors.

The GLR traces can either be manually or electronically (with a digitizer) reduced to various noise descriptors at a later date.

N-3422 Audio Tape Recorders

Audio recording of sound levels for lab analysis at a later time are especially suited for special studies and research. Tape recordings give the noise analyst a great amount of freedom to do different types of analysis, using any noise descriptor desired, and various frequency analyses.

Tape recorders need to be high quality scientific recorders, with flat frequency response and high signal-to-noise ratios.

N-3423 Microprocessors

Microprocessors can analyze the signals from one or more SLM's simultaneously. The signals are converted into various noise descriptors, designated by the noise analyst. Depending on the available software, frequency analysis can also be performed. The microprocessor is an invaluable tool in research as it enables the researcher to take many noise measurements simultaneously at different locations.

Microprocessors are usually connected to a printer or plotter for a hard copy of the data results.

N-3430 Frequency Analyzers

Frequency analyzers are used to study frequency spectrums of sound levels. They are used more for research than for routine noise analysis. There are two basic types of frequency analyzers: Real Time Analyzers and Fast Fourier Transform (FFT) Analyzers.

N-3431 Real Time Analyzers

The output of an SLM or tape recorder is fed through a set of filters and decomposed into frequency ranges of 1 or 1/3 octaves. The term *real time* refers to the processing and display of ever changing instantaneous sound spectra. When a tape recorder is used to feed in the audio signal, frequency spectra at various instants can easily be analyzed by freezing the spectrum at the exact moments of interest. A typical example might be the frequency spectra of vehicles passing by an observer, coinciding with the maximum noise levels.

N-3432 Fast Fourier Transform (FFT) Analyzers

The sound signal is processed by using mathematical equations to construct a continuous frequency power spectrum. The FFT does not produce a 1 or 1/3 octave band analysis. The

FFT analyzer is a useful tool in sound intensity measurements, requiring specialized equipment. This is not a tool for routine environmental noise measurements.

N-3440 Acoustical Calibrators

Acoustical calibrators are used to calibrate the SLM/Recorder system in the field. They are manufactured to fit specific SLM only. The calibrator fits over the top of the microphone (wind screen removed). Care must be taken that the microphone is properly seated in the calibrator cavity. When activated the calibrator emits an audio signal at a reference frequency and decibel level. Most calibrators have a reference level of 94 dB at 1000 Hertz. The SLM/Recorder system can than be adjusted to this level.

N-3450 Meteorological and Other Non-Noise-Related Equipment

Basic meteorological instruments are necessary to perform measurements for section N-3600, "Meteorological Constraints".

It is recommended that, at the minimum, the following meteorological equipment be used simultaneously with noise measurements:

1. Hand-held anemometer which measures wind speed to the nearest mile per hour or knot up to at least 15 mph, and direction to the nearest 22 1/2 degrees (16 point compass). Hand held anemometers may be adapted to fit on a tripod for easier use.
2. The anemometer must be oriented to true north with an accurate pocket compass, adjusted for magnetic declination.
3. Thermometer.
4. Relative Humidity Meter.

Non-essential, but helpful equipment includes a radar gun to measure traffic speeds.

Other recommended items include tape measures, survey levels (or hand levels), and rods to survey the site and document microphone positions with reference to landmarks, and watches or stopwatches to time the measurements. Portable radios may be helpful to maintain contact with traffic counting personnel. Traffic counters are also very useful.

N-3500 NOISE MEASUREMENT PROCEDURES

This section covers general procedures for routine noise measurements. Manufacturers' user's manuals should be consulted for operating each specific instrument. The following procedures are common to all routine Caltrans noise measurements.

N-3510 Instrumentation Setup

The SLM microphone should be placed 5 feet above the ground, and at least 10 feet from reflecting surfaces, such as buildings, walls, parked vehicles, bill boards, etc. Operators should be careful not to shield the microphone with their bodies during the measurements. Other obstructions between microphone and noise source should be avoided, unless they are representative of the region of interest.

If the microphone is not separated from the SLM body, the SLM should be used with a tripod. If the microphone is separated from the SLM body, the microphone should be placed on a tripod or other stand. Test tube clamps are useful for this purpose.

Set up meteorological equipment. Thermometers should be in the shade. Anemometer should have good exposure to representative winds.

N-3520 Field Calibration

Acoustical calibrators are used to calibrate the SLM/Recorder system in the field. They are manufactured to fit specific SLM only. The calibrator fits over the top of the microphone (wind screen removed). Care should be taken that the microphone is properly seated in the calibrator cavity. When activated the calibrator emits an audio signal at a reference frequency and decibel level. Most calibrators have a reference level of 94 dB at 1000 Hertz. Some have a choice of several frequency settings. If the calibrator offers these choices, 1000 Hertz should be used for calibration. The SLM/Recorder system can then be adjusted to this level. Follow procedures in manufacturers' user's manuals.

SLMs/Recorder system should be calibrated before and after each setup. If several measurements are made during the same setup, calibration may also be checked between measurements. For routine measurements, if the SLM reading differs by less than 0.5 dB from the reference level indicated on the calibrator, the SLM/Recorder system need not be adjusted. If the SLM reading deviates by 0.5 dB or greater, or if measurements are part of a special study where extreme accuracy is required, the SLM/Recorder system should be adjusted within 0.1 dB of the reference level.

For all measurements, if the final calibration of the acoustic instrumentation differs from the initial calibration by 1 dB or more, all the data measured with the system between the calibrations should be discarded and repeated. The instrumentation and connections should be thoroughly checked before repeating the measurements.

If the final calibration is less than 1 dB from the initial calibration, all data measured with that system between the initial and final calibration should be adjusted as follows:

Data Adjustment = Calibrator Reference Level - [($CAL_{INITIAL}$ + CAL_{FINAL}) / 2].

An example for routine measurements follows:

- Calibrator Reference Level = 94.2 dB
- $CAL_{INITIAL}$ = 94.4 dB
- CAL_{FINAL} = 94.6 dB

Then: Data Adjustment = 94.2 - [(94.4 + 94.6) / 2] = -0.3 dB.

All data measured in between the two calibrations should be adjusted by -0.3 dB; i.e. a measurement of 66.7 dBA would become 66.4 dBA. NOTE: For routine measurements it is customary to round off and report the final adjusted value to the nearest dB. 66.4 dBA would be reported as 66 dBA, 66.5 dBA as 67 dBA.

The field calibration procedure follows:

1. Allow adequate warm-up of instruments before calibration (at least 1 minute or as specified in manufacturer's manual). Be sure that all proper connections have been made, and batteries are fresh or adequately charged.

2. Calibrator should be carefully placed over the microphone and properly seated. Avoid touching calibrator during calibration.

3. Use proper screwdriver to make calibration adjustments to the SLM. If a GLR, or other device is used as part of a system the calibration should include the GLR also. The SLM should be calibrated first, then the GLR.

4. See manufacturer’s user’s manual for particular instructions.

N-3530 Measurements

Following calibration of equipment a wind screen should be placed over the microphone. Frequency weighting should be set on "A". Set proper response setting at fast or slow. Whenever possible use fast.

On more sophisticated SLMs, preset the sampling time, sampling interval, and proper noise descriptor (L_{eq}, or in some cases L_{MAX}).

Set the proper range of noise levels. If unsure, take a short preliminary measurement.

During the noise measurements, note any noise contaminations, such as barking dogs, local traffic, lawn mowers, aircraft overflights, etc. If SLM is equipped with a Pause or Standby switch or button, the measurement should be temporarily interrupted until contamination ceases. Mark contaminated section of GLR trace with pre-assigned codes, such as "D" for barking dog, "AC" for aircraft, etc.

Avoid talking during measurements. Curious bystanders will often ask the operator what is going on. A good way to avoid talking near the microphone is to stand 25 to 50 feet from the microphone, far enough not to contaminate measurement, but close enough to watch the set up.

If highway noise measurements are taken, traffic should be counted simultaneously with the noise measurements. As a minimum, directional traffic should be counted separately. Lane-by-lane traffic counts are best, but often not practical as they are too labor-intensive. Traffic should be segregated into three vehicle groups: heavy trucks, medium trucks, and autos. Definitions of these are covered in FHWA-RD-77-108 and in Chapter 4000 Noise Analysis Procedures. Average speeds for each vehicle group and each direction should be estimated from either a radar gun (if available) or test runs with a vehicle in the flow of traffic during the noise measurements.

Wind speed, wind direction, temperature, humidity, and sky conditions (clear, partly cloudy, overcast, fog, or haze) should be observed and documented.

After the last measurement of the setup, equipment should be recalibrated before turning power off. Also, any time the power is accidentally or otherwise interrupted during or in between measurements, instruments need to be recalibrated before taking additional measurements.

After the last measurement of the setup, equipment should be recalibrated before turning power off. The procedure for calibration and necessary data adjustment was discussed in the preceding section N-3520 *Field Calibration*.

N-3540 Documentation

Measurement data should be carefully recorded. If the data is read from a display and hand copied on a form, double-check the readings and, if possible, have another confirm your record.

It is recommended that blank forms be printed in advance for noise data, meteorological data, traffic counts, and site data. With the advent of personal computers, the forms can easily be designed for various types of measurements or specific studies.

The following items should be documented:

1. *Noise measurement sites.* A sketch showing microphone location in relationship to natural or artificial land marks. Show distances to the nearest foot to building corners, trees, street signs, curbs, fences, etc. Include enough detail on the sketch to enable anyone to reoccupy, at a later date, the three dimensional (including height above ground) position of the microphone within one foot horizontally and 0.5 foot vertically. Show accurate three dimensional relationships between source and site. Cross sections should be obtained, either from accurate maps or field surveys. Sites should also be located on maps showing all receivers used in the noise analysis. Also include District, County, Route No. And Kilometer Post of site.

2. *Noise Measurements.* Record all instruments used for the noise measurements, manufacturers, model numbers, serial numbers. Also important are the calibrator make, model, serial number, reference level, frequency, and last calibration date. Show names of instrument operators and persons recording the data. Show before and after calibration data. Record site number, date, time, length of measurement, noise descriptor, pertinent settings on SLM/Recorder system, and noise data. Include remarks, notes of contamination, or anything that might have a possible effect on the measurement results.

3. *Meteorological Conditions.* Include prevailing wind direction and speed during the noise measurements, as well as temperature, relative humidity, and sky conditions. Indicate approximate height, and location of measurements. Show date, time, site no., name of observer.

4. *Traffic Counts.* Show the number of vehicles broken down by classification. It is important to indicate the location of the traffic counts, no. of lanes or lane groups counted, direction, length of time, time, District, County, Route, Post Mile, names of personnel, along with the counts and speeds.

Usually, four different forms need to be used to accommodate all of the above documentation. Care must be taken that each form contains enough information to make necessary cross references between noise measurements, traffic counts, meteorology and site information.

N-3600 METEOROLOGICAL CONSTRAINTS ON NOISE MEASUREMENTS

There are several ways meteorological conditions can affect noise measurements. Wind speeds over 5 m/s (11 mph) may at an ambient noise level of 40-45 dBA begin to contaminate noise measurements with a rumbling noise due to frictional forces on a microphone covered with a wind screen. Without the screen, the effect would be present at a much lower wind speed.

Extremes in temperature and relative humidity will affect critical components of sound level meters. For instance, during conditions of high humidity water condensation can form on the vibrating microphone membrane causing a “popping” sound which can contaminate noise measurements.

Rain or snow on highway pavement alter the levels and the frequencies of tire/pavement noise, causing it to vary in unpredictable ways from noise levels on dry pavements, on which vehicle noise source characteristics are based.

Refraction caused by wind shear and/or temperature gradients near the ground surface, will also alter noise levels. The effects of refraction were discussed in section N-2143. When noise levels are compared to determine the effect(s) of a transportation project on the noise environment, or to evaluate the effectiveness of a noise abatement measure, the “before” and “after” noise levels must be for equivalent meteorological conditions.

The following sections include listings of meteorological constraints on noise measurements and equivalent meteorological conditions.

N-3610 Meteorological Criteria

Noise measurements should NOT be made when one or more of the following meteorological conditions exist(s):

1. Wind speeds of more than 5 m/s (11 mph) for routine highway noise measurements.
2. Manufacturers' recommendations for acceptable temperature and humidity ranges for instrument operation are exceeded. Typically, these ranges are from -10^{o}C to

50°C (14°F to 122°F) for temperature, and 5% to 90% for relative humidity. Heavy fog conditions usually exceed the 90% relative humidity range.

3. During rain, snow, or wet pavement conditions.

N-3620 Equivalent Meteorological Conditions

Wind effects on noise levels are caused by refraction (or bending) of the noise rays due to wind shear near the ground. Noise rays are bent upward upwind, and downward downwind from the source. The result is the decrease of noise upwind and increase of noise downwind from a source.

Recent studies by Caltrans N.T.M.&R. and others have shown that this wind effect can affect noise measurements significantly even at relatively close distances to noise sources. Section N-3330 indicates that, in order to compare noise measurements for agreement, all site, traffic, and meteorological conditions must be the same.

Noise measurement comparisons can therefore only be made for similar meteorological conditions. ANSI S12.8 - 1987 "Methods for Determination of Insertion Loss of Outdoor Noise Barriers" recommends that meteorological equivalence be based on wind, temperature and cloud cover. The latest revison of the 1987 standard will (as of this writing in 1998) be published in the near future. The revision recommends the following criteria for atmospheric equivalence average wind velocities from the source position to the receiver position. In the case of highway noise, the wind component of interest is perpendicular to the highway. The standards recommended by the ANSI may be used to define meteorological equivalency for the purposes of section N-3330, or any time BEFORE and AFTER noise measurements are performed on noise barriers.

Equivalent Wind Conditions - Wind conditions are equivalent for noise measurements if the wind class (defined in Table N-3600.1) remains unchanged AND the vector components of the average wind velocity from the source to receiver (perpendicular to the highway) do not differ by more than a certain limit. This limit depends on the accuracy desired and the distance from sound source to receiver. To keep the measurement accuracy due to atmospheric wind conditions to within ± 1dB, for distances less than 70 m (230 ft), this limit should be 1 m/s (2.2 mph). If it is desired to keep this accuracy within ± 0.5 dB for the same distance, the measurements to be compared should each be repeated at least four times. The 1 m/s limit does not apply to the Calm condition. By convention, the perpendicular wind component blowing from highway to receiver (microphone position) is positive (+) while the same component blowing from receiver to the highway is negative (-).

Table N-3600.1 - Classes of Wind Conditions

WIND CLASS	VECTOR COMPONENT OF WIND VELOCITY, m/s (mph)
Upwind	-1 to -5 (-2.2 to -11)
Calm	-1 to +1 (-2.2 to +2.2)
Downwind	+1 to +5 (+2.2 to +11)

For example, two measurements may be compared when their respective wind components are 0 m/s and -1 m/s, -1 m/s and -2 m/s, -2.5 m/s and -3.5 m/s, etc, but not when their respective components are 0.5 m/s and 1.5 m/s (due to the change in wind class).

For purposes of comparison with the Traffic Noise Model, which has no provisions for wind inputs and therefore predicts noise levels for calm (zero wind) conditions, the perpendicular wind component needs to be between -1 m/s and +1 m/s (-2.2 mph and +2.2 mph.

Note that the actual wind velocity (direction and speed) needs to be resolved into two components with directions parallel and perpendicular to the highway. Then, only the perpendicular component is considered (as long as the actual wind speed does not exceed 5 m/s (11 mph), any wind velocity may be resolved in this manner).

The component of wind velocity for a given set of acoustical measurements should be determined by:

1. monitoring wind velocity (speed and direction) throughout any period of acoustical measurements;
2. noting the average speed and direction; and
3. computing from these averages the vector component of wind velocity from the source to receiver (perpendicular to the highway)

Equivalent Temperature and Cloud Cover - Measurements to be compared (such as before and after noise barrier measurements, or repeat measurements) should be made for the same class of cloud cover, as determined from Table N-3600.2, and with the average air temperatures within 14^{o} C (25^{o} F) of each other.

Equivalent Humidity - Although there are no strict guidelines for equivalence of humidity, an attempt should be made to pair measurements for similar conditions of humidity, i.e. avoid comparisons of measurements made under extremely dry conditions (e.g. < 25%) with those made during humid conditions (e.g. >75%).

Table N-3600.2 - Cloud Cover Classes

CLASS	DESCRIPTION
1	Heavily overcast
2	Lightly overcast (either with continuous sun or the sun obscured intermittently by clouds 20% to 80% of the time)
3	Sunny (sun essentially unobscured by clouds at least 80% of the time)
4	Clear night (less than 50% cloud cover)
5	Overcast night (50% or more cloud) cover)

N-3700 QUALITY ASSURANCE

All SLM should be calibrated by, and at the interval recommended by the manufacture, or by a laboratory accredited to perform calibrations on specified instruments. All calibrations should be traceable to the National Institute of Standards and Technology (NIST) in Washington, DC.

N-4000 TRAFFIC NOISE IMPACT SCREENING PROCEDURE

This procedure has been developed to aid in determining whether or not a potential for a traffic noise impact will exist with a proposed Type I highway project defined in the Traffic Noise Analysis Protocol Section 2.1. If the project passes the screening procedure, prudent engineering judgment should still be exercised to determine whether a detailed noise analysis is warranted. If the project is controversial, sensitive, or when net results of the effects of topography and shielding are complex and ambiguous, a detailed analysis is recommended (See Sections N-5000 and N-6000). If the project fails the screening procedure, a detailed noise analysis should be performed.

A "Noise Analysis Screening Procedure Checklist", shown in section N-4500 (Figure N-4500-1), is included for the user's convenience.

N-4100 SCREENING PROCEDURE STEPS

Following are the steps of the procedure (refer to definitions of *italicized* words and phrases in section N-4200 "Definitions for Screening Procedure").

1) If there <u>are no</u> *potentially impacted receivers* in the vicinity of the project, this screening procedure will be considered passed. If there <u>are</u> *potentially impacted receivers* in the vicinity of the project, the conditions in the following steps should be satisfied. Failure of one condition constitutes failure of this screening procedure, and the detailed analyses in Sections N-5000 and N-6000 are recommended.
2) The proposed project should be along an alignment or a realignment of an existing facility. Potential noise impacts along new alignments are best investigated by a detailed analysis.
3) *Shielding* conditions, if any, should be equal or improved for the after project *critical receiver(s)* in comparison with those for the same receiver(s) before the project.
4) Measure existing worst hour noise level(s) at the *critical receiver(s).*
5) If the existing worst hourly noise is above a level that is 5 dBA below the NAC (e.g. L_{eq}(h) above 62 dBA for land use category B), stop this screening procedure; a noise analysis should be performed according to the procedures covered in Appendix B. If the existing noise level(s) at the most *critical receiver(s)* is (are) 5 dBA or more below the NAC, continue with step (6).
6) The following equation in terms of existing and future hourly *equivalent vehicles* and *equivalent lane distances* should yield a value of less than 3.0 dBA:

$$10 \mathrm{Log}_{10}\left[\frac{V_{E(FUTURE)}}{V_{E(EXISTING)}}\right] + 15 \mathrm{Log}_{10}\left[\frac{D_{E(EXISTING)}}{D_{E(FUTURE)}}\right] < \mathbf{3.0\ dBA}$$

Where: $V_{E(FUTURE)}$ = Number of Equivalent Vehicles per hour after the project.

$V_{E(EXISTING)}$ = Number of Equivalent Vehicles per hour before the project.

$D_{E(EXISTING)}$ = Equivalent Lane Distance before project.

$D_{E(FUTURE)}$ = Equivalent Lane Distance after project.

7) If the above value is less than 3.0 dBA the project passes the screening procedure.
8) If the above value is equal to or greater than 3.0 dBA the project does not pass the screening procedure.

(See section N-4300 “ Method of Calculating Equivalent Lane Distance” to determine D_E, and section N-4400 “ Method of Calculating Equivalent Vehicles” to determine V_E).

Note: Due to the approximation of the coefficient “15” in the above equation, the ratio $D_{E(EXISTING)}/D_{E(FUTURE)}$ should not exceed 4. If it does, it is recommended that a detailed technical noise analysis be performed.

N-4200 DEFINITIONS FOR SCREENING PROCEDURE

For the purpose of the screening procedure, the following definitions (in alphabetical order) apply:

Critical Receiver(s) - Potentially impacted receiver(s) where the worst noise impacts (if any) would occur. Critical receivers are potentially impacted receivers where the after project noise level or increase is expected to be the greatest.

Equivalent Lane - (See “Method of Calculating Equivalent Lane Distances”, Sec. N-4300) - An imaginary single lane that acoustically represents a multi-lane highway. An *Equivalent Lane* contains the total traffic volumes present on the highway.

Equivalent Lane Distance - (“See “Method of Calculating Equivalent Lane Distances”, Sec. N-4300) - Distance from the receiver to an Equivalent Lane.

Equivalent Vehicle - (See Method of Calculating Equivalent Vehicles, Sec. N-4400) - A basic noise source unit that expresses the noise level emitted by heavy trucks and medium trucks in terms of the equivalent noise level emitted by a certain number of automobiles. This number is speed-dependent. For example, at 88.5 km/h 1 heavy truck produces the same noise level as 13 automobiles; at 56 km/h the noise level is that of 31 automobiles. The term *equivalent vehicle* (V_E) is synonymous with automobile, but should be used when a vehicle mix normalized to automobiles is implied. Definitions of heavy trucks, medium trucks and automobiles are the same as those used in the FHWA Highway Traffic Noise Prediction Model (Report No. FHWA-RD-77-108).

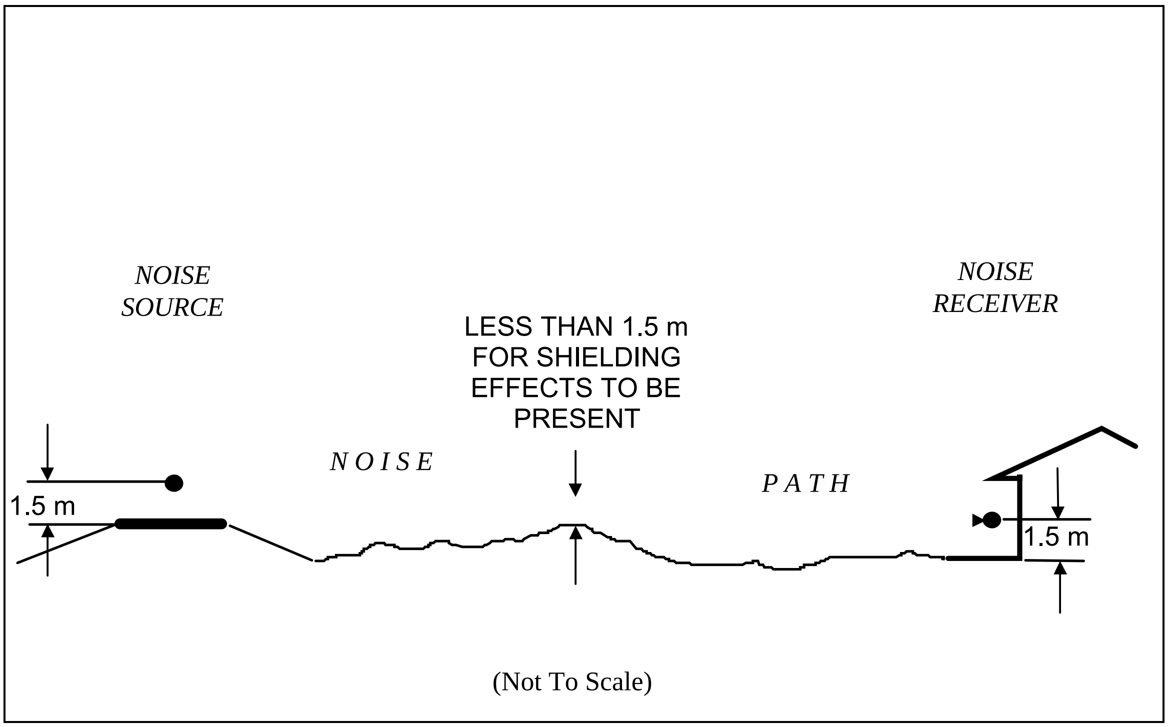
Noise Sources - The existing or future traffic along the before or after project alignment.

Potentially Impacted Receiver - Receiver that may be impacted by the predicted traffic noise level. Determining whether a receiver has a reasonable chance to be impacted can easily be determined by steps 1-8 of section N-4100. However, in many cases the determination will be obvious without going through the steps.

Shielding - Generally, when the noise path between noise source and critical receiver is less than 1.5 m above the highest point(s) of the terrain and/or major obstacle(s) between the source(s) and receiver(s), shielding effects may reduce noise levels at the receivers. As an approximation, and for the purpose of the screening procedure, a receiver is shielded when:

- The straight line noise path from source (vehicles on highway) to receiver is partially or completely interrupted, or when the noise path is less than 1.5 m above the highest point of the intervening terrain or major obstacle(s). For the purposes of estimating noise paths, the source is assumed to be 1.5 m above the roadway, and the receiver 1.5 m above the ground (Figure N-4200-1).
- Judgment of whether or not shielding (if any) is the same or improved after project compared to before project conditions may range from obvious to ambiguous, depending on the project. For example, a proposed highway realignment that will reroute the existing facility from the receiver side of a hill to a route behind the hill would obviously cause an improvement. Less obvious would be the case where the existing noise path grazes gently rolling terrain while the after project noise path will be one meter above the high points in the terrain due to raising the highway profile. The latter case would degrade the shielding, and invalidate the screening procedures.

Figure N-4200-1 Shielding Criterion

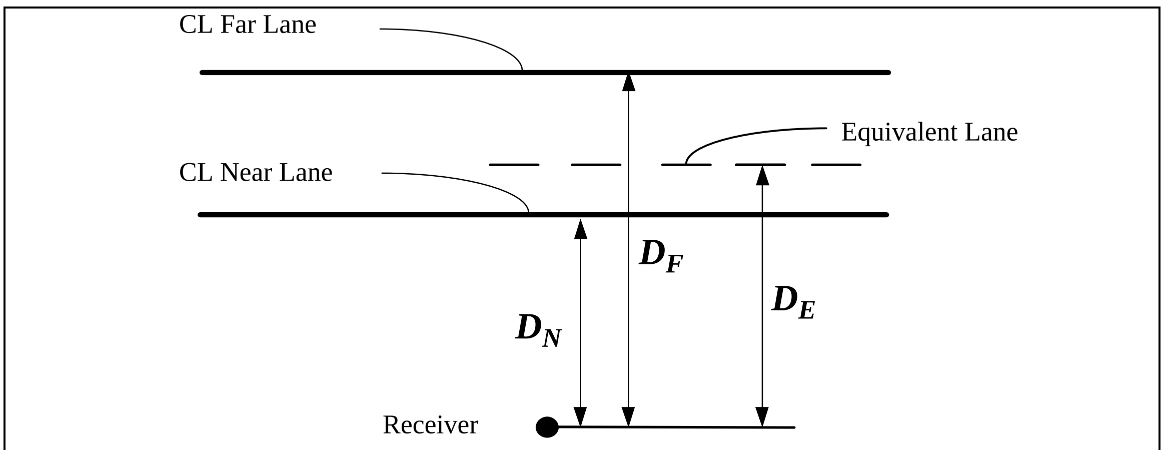


N-4300 METHOD OF CALCULATING EQUIVALENT LANE DISTANCE

The concept of equivalent lane distance is discussed in detail in FHWA-RD-77-108, “FHWA Highway Traffic Noise Prediction Model”. The FHWA Model allows traffic to be segregated lane-by-lane, the center line of each lane being associated with a different source-to-receiver distance. Normally, traffic data is not available lane-by-lane, but rather by direction, e.g. eastbound (E/B) and westbound (W/B). The normal procedure is to use the centerline of the directional lanes grouped together, approximating an acoustical representation of two source locations (e.g. centerline E/B and centerline W/B). Instead of using the centerline distances however, it is more accurate to use the equivalent lane distance (D_E) as determined by the formula shown in Figure N-4300-1.

This screening procedure recommends a further simplification by grouping all lanes (both directions) together and using a single D_E , calculated from the source-to-centerline distances of the nearest and farthest lanes. This method assumes more or less balanced directional traffic flows and normal medians. If such is not the case, the method may still be used if traffic flows will have roughly the same (unbalanced) directional flow ratio with or without the project, and changes in source-to-receiver distances are not excessive.

Figure N-4300.1 - Equivalent Lane Distance.



$$D_E = \sqrt{(D_N \times D_F)}$$

Equivalent Lane Distance, D_E

Example of Equivalent Lane Distance Calculation:

<u>Given</u>: an eight-lane freeway with a 6.6 m median. The distance from the receiver to the center line of the near lane (D_N) is 35 m. The distance to the center line of the far lane (D_F) is 66.8 m. What is the Equivalent lane distance (D_E)?

<u>Solution</u>: $D_E = (D_N \times D_E)^{0.5} = (35 \times 66.8)^{0.5} = 48.4$ m

Notes:

- When using one Equivalent Lane Distance for an entire freeway, the <u>total</u> hourly traffic volumes (in terms of Equivalent Vehicles) of that freeway should be used with the Equivalent Lane Distance.
- Equivalent Lane Distances may be derived from the two centerlines of directional lanes, or from the single nearest lane and farthest lane on the opposite side.

N-4400 METHOD OF CALCULATING NUMBER OF EQUIVALENT VEHICLES

The following method, using either Table N-4400.1 or both Tables N-4400.1 and N-4400.2 is used to calculate equivalent vehicles (V_E). The method essentially normalizes heavy trucks, medium trucks and autos, to one vehicle group (V_E), on the basis of their acoustical energy. The auto is used as a reference (1 Auto = 1 V_E).

Table N-4400.1 may be used by itself if traffic speeds of all vehicles are assumed to have the same speed, and there is no difference between with and without project speeds.

Table N-4400.1 - No. of Equivalent Vehicles as a Function of Vehicle Type and Speed Based on California Vehicle Noise Reference Energy Mean Emission Levels (Calveno REMELs)*
(see Sec. N-5510).

Speed, km/h (mph)	1 Heavy Truck = No. of V_E	1 Medium Truck = No. of V_E	1 Auto = No. of V_E
56 (35)	30.9	9.4	1
64 (40)	24.1	7.8	1
72 (45)	19.0	6.7	1
80 (50)	15.3	5.8	1
88.5 (55)	12.8	5.1	1
97 (60)	10.9	4.7	1
105 (65)	9.5	4.3	1

Note:

*** This table must only be used while the FHWA-RD-77-108 prediction method is still in force (see Section N-5510). It must not be used after the prediction method is replaced by the new FHWA TNMâ . (see Table N-4400.3)**

Example of Equivalent Vehicle calculation using Table N-4400.1:

Given: an hourly vehicle volume of 5000 autos, 175 medium trucks (MT), and 325 heavy trucks (HT). The traffic speed is 88.5 km/h (55 mph). Convert this volume to number of V_E.

Solution:	*5000 autos*	*= 5000 x 1*	*=5000 V_E*
	175 MT	*= 175 x 5.1*	*= 893 V_E*
	325 HT	*= 325 x 12.8*	*=4160 V_E*
		Total V_E =	*10053 V_E*

If speeds of autos, medium trucks and heavy trucks are different, or when with and without project noise comparisons are made for different speeds, an additional speed correction factor must be applied. The correction for speeds involves multiplying the V_E of each of the three vehicle types at the indicated speeds, with a sound energy ratio relative to the noise level, L_{eq}(h), dBA of a pass by of 1 auto at 15 m (50 ft), traveling at 88.5 km/h (55 mph). The number of the V_E is thus normalized to a reference speed of 88.5 km/h (55 mph), and since the V_E is in terms of autos, the energy ratio values were derived from Calveno curves for autos. In the following Table N-4400.2 the conversion of instantaneous noise levels to L_{eq}(h) was accounted for in the energy ratios by including the traffic flow adjustments per FHWA-RD-77-108.

Table 4400.2 - Speed Corrections For Equivalent Vehicles Based on California Vehicle Noise Reference Energy Mean Emission Levels (Calveno REMELs)* (see Sec. N-5510).

Speed, km/h (mph)	Noise Level of 1 Auto at 15 m (50 ft), Leq(h), dBA *	Energy ratio **
56 (35)	34.4	0.27
64 (40)	36.1	0.40
72 (45)	37.5	0.55
80 (50)	38.9	0.76
88.5 (55)	40.1	1.00
97 (60)	41.1	1.26
105 (65)	42.1	1.58

Notes:

*** This table must only be used while the FHWA-RD-77-108 prediction method is still in force (see Section N-5510). It must not be used after the prediction method is replaced by the new FHWA TNMâ (see Table N-4400.4).**

**** Energy Ratio values were derived from the Calveno Emission Levels for autos with reference to 88.5 km/h (55 mph) speed and traffic flow adjustment per FHWA-RD-77-108.**

Example of using number of equivalent vehicles in Table N-4400.1 and speed corrections in Table N-4400.2:

<u>Given</u>: an hourly vehicle volume of 3000 autos at 105 km/h (65 mph), 150 medium trucks (MT) at 97 km/h (60 mph), and 325 heavy trucks (HT) at 80 km/h (50 mph). Convert this volume to number of V_E.:

<u>Solution</u>:	*3000 autos*	*= 3000 x 1 x 1.58*	*= 4740 V_E*
	150 MT	*= 150 x 4.7 x 1.26*	*= 888 V_E*
	325 HT	*= 325 x 15.3 x 0.76*	*= <u>3779</u> V_E*
		Total V_E	*= 9407 V_E*

When the new FHWA Traffic Noise Model (TNM) is officially mandated for use in California, Tables N-4400.3 and N-4400.4 will need to be used. These are based on FHWA-PD-96-010; DOT-VNTSC-FHWA 98-2 and FHWA-PD-96-008; DOT-VNTSC-FHWA-96-2.

Table N-4400.3 - No. of Equivalent Vehicles as a Function of Vehicle Type and Speed Based on TNM Reference Energy Mean Emission Levels (TNM REMELs)* (see Section N-5520).

Speed, km/h (mph)	1 Heavy Truck = No. of V_E	1 Medium Truck = No. of V_E	1 Auto = No. of V_E
56 (35)	19.1	7.1	1
64 (40)	15.1	5.8	1
72 (45)	12.9	5.0	1
80 (50)	11.5	4.5	1
88.5 (55)	10.4	4.1	1
97 (60)	9.6	3.7	1
105 (65)	8.9	3.5	1
113 (70)	8.3	3.2	1

Note:

*** This table must only be used when the new FHWA TNM® noise prediction model is in force.**

Example of Equivalent Vehicle calculation using Table N-4400.3:

<u>Given</u>: an hourly vehicle volume of 5000 autos, 175 medium trucks (MT), and 325 heavy trucks (HT). The traffic speed is 88.5 km/h (55 mph). Convert this volume to number of V_E.

<u>Solution</u>:	*5000 autos*	*= 5000 x 1*	*=5000 V_E*
	175 MT	*= 175 x 4.1*	*= 718 V_E*
	325 HT	*= 325 x 10.4*	*=<u>3380 V_E</u>*
		Total V_E =	*9098 V_E*

Table N-4400.4 - Speed Corrections For Equivalent Vehicles Speed Corrections For Equivalent Vehicles Based on (TNM REMELs) (see Section N-5520).

Speed, km/h (mph)	Noise Level of 1 Auto at 15 m (50 ft), Leq(h), dBA *	Energy Ratio**
56 (35)	35.0	0.25
64 (40)	36.8	0.37

72 (45)	**38.4**	**0.54**
80 (50)	**39.8**	**0.74**
88.5 (55)	**41.1**	**1.00**
97 (60)	**42.3**	**1.32**
105 (65)	**43.4**	**1.70**
113 (70)	**44.5**	**2.19**

Notes:

*** This table must only be used when the new FHWA TNM® noise prediction model is in force.**

**** Energy Ratio values were derived from the TNM Emission Levels for autos with reference to 88.5 km/h (55 mph) speed and traffic flow adjustment per FHWA-PD-96-010; DOT-VNTSC-FHWA 98-2 and FHWA-PD-96-008; DOT-VNTSC-FHWA-96-2.**

Example of using speed corrections:

<u>Given</u>: an hourly vehicle volume of 3000 autos at 105 km/h (65 mph), 150 medium trucks (MT) at 97 km/h (60 mph), and 325 heavy trucks (HT) at 80 km/h (50 mph). Convert this volume to number of V_E.

<u>Solution</u>:	*3000 autos*	*= 3000 x 1 x 1.70*	*= 5100 V_E*
	150 MT	*= 150 x 3.7 x 1.32*	*= 733 V_E*
	325 HT	*= 325 x 11.5 x 0.74*	*= <u>2766</u> V_E*
		Total V_E	*= 8599 V_E*

N-4500 NOISE ANALYSIS SCREENING PROCEDURE CHECKLIST

The following check list format shown on the next two pages may be used for convenience of the user of the screening procedure.

NOISE ANALYSIS SCREENING PROCEDURE CHECKLIST

Dist______Co______Rte_______P.KM.___________________E.A ______________________

1. Are there potentially impacted receivers in the vicinity of project?

   Yes___*(continue)*

   No ___*(Stop. Passed screening procedure. Check step 7).*

2. Is the proposed project along an existing alignment or realignment?

   Yes___*(continue)*

   No ___*(Stop. Did not pass screening procedure. Check step 8).*

3. Will shielding of critical receivers be the same or improved after the project?

   Yes___*(continue)*

   No ___*(Stop. Did not pass screening procedure. Check step 8).*

4. Measure existing worst hourly noise levels at critical receivers. Measured existing worst hourly noise level (L_{eq}(h)) is _______ dBA.

5. Is the above noise level more than 5 dBA below the NAC?

   Yes___*(continue)*

   No ___*(Stop. Did not pass screening procedure. Check step 8).*

6. Is the result of the following expression less than 3 dBA?

$$10\mathrm{Log}_{10}\left[\frac{V_{E(FUTURE)}}{V_{E(EXISTING)}}\right]+15\mathrm{Log}_{10}\left[\frac{D_{E(EXISTING)}}{D_{E(FUTURE)}}\right]< 3 \text{ dBA}$$

Where: $V_{E(FUTURE)}$ = Number of Equivalent Vehicles per hour for project design year.
$V_{E(EXISTING)}$ = Number of Equivalent Vehicles per hour before the project.
$D_{E(EXISTING)}$ = Equivalent Lane Distance before the project.
$D_{E(FUTURE)}$ = Equivalent Lane Distance after the project.

(See Sec. N-4300 " Method of Calculating Equivalent Lane Distance" to determine D_E, and Sec. N-4400 " Method of Calculating Equivalent Vehicles" to determine V_E.)

   Yes___*(Passed the screening procedure. Check step 7.)*

   No ___*(Did not pass screening procedure. Check step 8.)*

Note: The ratio $D_{E(EXISTING)}/D_{E(FUTURE)}$ should not exceed 4:1 (*See Note in Section. N-4100)*). The ratio for this project is:___ : 1.

THE PROPOSED PROJECT: *(Check one)*

7. ____ **PASSED** the screening procedure. No further analysis is necessary.

8. ____ **DID NOT PASS** the screening procedure. Detailed analyses discussed in Sections N-5000 and N-6000 are recommended.

Prepared By:_________________________________ Date:_________________

N-5000 DETAILED ANALYSIS - TRAFFIC NOISE IMPACTS

If the project fails the screening procedure discussed in Section 2.2 of the Protocol and Section N-4000, or if the other conditions discussed in Section 2.2 apply, a detailed traffic noise impact analysis must be performed. The procedures in this section comply with analysis requirements of 23 CFR 772, and are consistent with standard acoustical practices and reasonable engineering judgment.

N-5100 GATHERING INFORMATION

The first step in a technical noise analysis is to determine how detailed the study needs to be. This understandably depends on the size and nature of the project. Generally, as the size of the project, complexity of terrain, and the population density increases, so does the amount of information and level of effort needed for an adequate noise analysis.

For the analysis, it is necessary to obtain adequate information and mapping showing project alternates and their spatial relationships to potentially noise sensitive areas. The "No-Build" alternate should be included. Early in the project, final design details usually are not yet available and additional analyses may have to be performed as more details are introduced. Topographical information may also be sketchy in early stages. Field reviews and recent aerial photographs may be necessary to augment information shown on maps. Design year traffic information for all project alternates is also necessary.

N-5200 IDENTIFYING EXISTING AND FUTURE LAND-USE AND APPLICABLE NOISE ABATEMENT CRITERIA

Existing and reasonably expected future activities on all lands that may be affected by noise from the highway must be identified (see Section 2.3(a) of the Traffic Noise Analysis Protocol). Identify existing activities, developed lands, and undeveloped lands for which development is *planned, designed and programmed*, which may be affected by noise from the highway. Development is considered *planned, designed and programmed,* if a noise sensitive land-use (subdivisions, residences, schools, churches, hospitals, libraries, etc.) has received final development approval (generally the issuance of a building permit) from the local agency with jurisdiction. This information is essential to assess which Noise Abatement Criteria (NAC) apply for determining traffic noise impacts (see Section 2.4.2 and Table 2-1 in the Traffic Noise Analysis Protocol). For convenience, the NAC are shown again in Table N-5200-1.

Table N-5200-1. Activity Categories and Noise Abatement Criteria (NAC)

Activity Category	NAC, Hourly A-Weighted Noise Level, dBA L_{eq}(h)	Description of Activities
A	57 Exterior	Lands on which serenity and quiet are of extraordinary significance and serve an important public need and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose.
B	67 Exterior	Picnic areas, recreation areas, playgrounds, active sport areas, parks, residences, motels, hotels, schools, churches, libraries, and hospitals.
C	72 Exterior	Developed lands, properties, or activities not included in Categories A or B above.
D	--	Undeveloped lands.
E	52 Interior	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals, and auditoriums.

N-5300 DETERMINING EXISTING NOISE LEVELS

Existing noise levels may be determined at discrete locations in the project area, by either actual noise measurement (see TeNS N-3000), using the traffic noise prediction model (TeNS N-5510 and N-5520), or a combination of both. The latter is usually the case. This section discusses how to select these locations, the methods used to determine existing noise levels, and, where appropriate, to “calibrate” the noise prediction model with measurements.

N-5310 Selecting Noise Receivers and Noise Measurement Sites

For the purposes of noise analysis a *noise receiver* is any location included in the noise analysis. A *noise measurement site* is a location where noise measurements are taken to determine existing noise levels, and verify or calibrate the noise prediction model. Receivers and noise measurement sites may or may not coincide. Normally, there are more receivers than noise measurement sites, especially when the project involves reconstruction of existing facilities. In such situations, existing noise levels at receivers are first determined using the noise prediction model, then verified or calibrated with field measurements at a fewer number of representative sites. It is far less expensive to model (calculate) noise levels for receivers, than to take noise measurements in the field.

N-5311 Receivers

Within the identified land-use activity categories adjacent to the project typically lie numerous noise receivers that need to be examined for future noise impacts. It is not reasonable, or possible, to examine the impacts at all these receivers. Receivers should therefore be carefully selected for the noise analysis on the basis of their acoustical representativeness.

Following are some general recommendations for selecting receivers:

a) Select receivers generally in locations that are now receiving, or are expected to receive the highest noise levels over the period covered by the analysis. Since, in most cases, impacts will be at receivers closest to the highway, the vast majority of receivers should be in the first row of residences relative to the project alternative. Some common exceptions include:

    1) Projects where realignment would move the noise sources toward receivers other than those adjacent to the existing alignment;

    2) Projects involving geometry where the first row of homes is partially shielded and the second row homes may actually receive higher noise levels, for example roadways on high embankments;

    3) Areas near the ends of proposed barriers where second or third row receptor sites may be needed to better define the barrier limits;

    4) Projects that involve widening where additional R/W requirements may clear the first row of residences and turn the second row into the first.

b) Coincide a noise measurement site with a receiver, whenever possible. However, this may often not be the case. The selected receiver may not be a good or accessible location for setting up a sound level meter. In that case, a noise measurement site acoustically representative of the receiver should be selected in a more accessible location.

c) Include other noise-sensitive locations, such as libraries, churches, hospitals, schools, etc.

d) Choose receivers that are *acoustically equivalent* of the area of concern. The concept of *acoustical equivalence* incorporates equivalencies in noise sources (traffic), highway cross sections, distance from the highway, topography of intervening terrain, shielding, and other pertinent factors. The region under study may need to be subdivided into subregions in which acoustical equivalence can generally be maintained. One or more of the previously mentioned acoustical factors should dictate boundaries of each subregion. The size of subregions may vary depending on the scope of the project.

e) Select a minimum of two receivers for each acoustically equivalent region or subregion. The actual number necessary to define noise impacts depends not only on the type of project but also on such influences as the complexity of highway profile and the variability of the surrounding terrain. A highway with a straight grade or very shallow vertical curves in a relatively flat area with tract-type residential development that parallels the highway may need only a couple of receivers to adequately define the noise impacts. On the other hand, a project involving a major freeway that includes interchanges, cuts and fills in an area of rolling terrain and non-tract mixed residential and commercial development will likely need more receivers.

f) Receivers are 1.5 m above the ground elevation, unless dictated by unusual circumstances, special studies, or other requirements. Exceptions would include placing a receiver 1.5 m above a wooden deck of a house situated on a steep slope, instead of 1.5 m above the ground. Similar situations might be encountered with houses built on top of garages, where second story levels would be more logical receiver locations. Generally, second story levels are not used as receivers, because exterior uses are negligible and the additional cost of attenuation is high.

g) Select receivers in areas of frequent human use. There is little need to address the noise impacts of areas where people do not spend much time (for example, parking lots).

h) To determine the amount of benefited receivers (defined as those predicted to receive at least 5 dBA noise reduction from noise abatement under consideration), it is often necessary to include receivers at the first, second, and third tiers of residences or beyond in the noise analysis.

N-5312 Noise Measurement Sites

The selection of noise measurement locations requires planning and foresight by the noise analyst. A fine balance should be achieved between a sufficient number of quality locations on one side, and the cost and availability of resources on the other.

Preliminary design maps, cross sections, aerial photographs, and field survey data are all helpful sources of information for selecting noise measurement sites; however, the sites should be selected only after a thorough field review of the project area.

Following are some recommended site characteristics common to all outside noise measurement sites:

a) Sites should be clear of major obstructions; reflecting surfaces such as walls of residences should be more than 3 m from the microphone positions.

b) Sites should be free of noise contamination by sources other than those of interest. Avoid sites located near barking dogs, lawn mowers, pool pumps, air conditioners, etc., unless it is the express intent to measure noise from these sources.

c) Sites should be acoustically representative of areas and conditions of interest. They should either be located at, or represent locations of frequent human use.

In addition to the above general site requirements the selection of noise measurement sites is governed by the same general guidelines as those for selection of receivers in Section N-5311. Of particular importance is the concept of acoustical equivalence for representativeness of the area of concern.

More detailed considerations are discussed in the Technical Noise Supplement Section N-3200.

N-5320 Measuring Existing Noise Levels

When possible, existing noise levels should be determined by field measurements. As is the case with all fieldwork, quality noise measurements are relatively expensive. They take time, personnel and equipment. The noise analyst should therefore carefully plan the locations, times, duration and number of repetitions of the measurements before taking the measurements. Meteorological (atmospheric) and other environmental conditions can significantly affect noise measurements. Particular attention should be given to the meteorological and environmental constraints described in the Technical Noise Supplement Section N-3600.

In the noise analysis for a project, the noise measurements are used both to determine existing ambient and background noise levels, and to calibrate the noise prediction model when appropriate. Section N-3000 contains details of noise measurements and should be referred to.

N-5330 Modeling Existing Noise Levels

Noise levels near existing facilities can also be determined by modeling. Although measurements are preferred, adverse environmental conditions, construction, unavailability of good measurement sites, or lack of time may make it necessary to calculate existing noise levels, using the appropriate traffic noise prediction model (s) described in Section N-5500. However, this can only be done in areas where a defined highway source exists with minimal surface grid traffic or other contaminating noise sources.

Often, a combination of measurements and modeling at various receivers is used to determine existing noise levels. In addition to the measurement sites, additional receivers are modeled to establish better resolution of existing noise levels. Measurements are used in a process called "model calibration", which is discussed in the following section. This process can be applied to the additional modeled receivers for determining existing noise levels at a greater resolution. Model calibration insures that existing noise levels at the measured and modeled receivers are based on the same datum.

N-5400 CALIBRATING THE PREDICTION MODEL

The purpose of model calibration is to "fine-tune" the prediction model to actual site conditions which are not adequately accounted for by the model. In general, model calibrations are recommended if site conditions, highway alignment, and profile are not expected to change significantly before and after construction of a project, and until its design year.

N-5410 Definitions

In this section, model calibration is defined as the process of adjusting calculated future noise levels by algebraically adding a calibration constant derived from the difference between measured and calculated noise levels at representative sites. The difference, called “calibration constant”, "K-constant", or simply "K", is defined as measured noise level(s) (M) minus calculated noise level(s) (C), or: K = M - C. Note that the sign of K is positive when M is greater than C, and the sign of K is negative when M is less than C. In this section, a distinction will be made between calculated and predicted noise levels as follows:

- Calculated noise levels (existing or future) are the results of the model.
- Predicted noise levels are adjusted or *calibrated* calculated values.

N-5420 Limitations

Highways constructed along new alignments and profiles do not lend themselves to model calibration. The site before project construction does not include the new highway. Ambient noise levels are generated by typical community noises, such as surface street traffic, lawn mowers, air conditioners, barking dogs, etc. These are impossible to model. Also, the site and source characteristics change substantially after the project, making model calibration meaningless, even if it were possible.

Similarly, highway reconstruction projects which significantly alter alignments and profiles of an existing highway are also poor candidates for model calibration.

However, predictions of future noise levels for simple highway widening projects, design of retrofit noise barriers, or other improvements that do not significantly change highway alignment or profile, are excellent candidates for model calibration, as long as other site conditions do not change.

N-5430 Pertinent Site Conditions

To determine whether the model can be calibrated successfully or not, the site conditions which are allowed to change between the present and the expected life of the project should be examined first. For this purpose, site conditions should be divided into two groups:

Group 1 - Site conditions that CAN be accounted for by the model. These include but are not necessarily limited to:

- Traffic mix, speeds, volumes.
- Noise drop-off rates and distances.
- Opaque barriers (noise transmission through barrier material may be ignored; i.e. high transmission loss).
- Roadway and barrier segment adjustments.

- Receptor locations.
- Grade Corrections.

Group 2 - Site conditions that CANNOT be accounted for by the model, and are therefore ignored, even though they affect the local noise environment. They include but are not necessarily limited to:

- Pavement types and conditions. The model has no provisions to deal with these.
- A typical (or nontypical) vehicle noise populations. The California Vehicle Noise Emission Levels (Calveno) are statewide averages. Individual sites may have vehicle noise sources that deviate significantly from Calveno.
- Transparent shielding (noise transmission through material is significant: i.e. low transmission loss). Examples of this type of shielding are wood fences with shrinkage gaps (noise leaks), areas of heavy brush or trees.
- Reflections off nearby buildings and structures.
- Meteorological conditions.

For the purposes of model calibration of future noise levels, Group 1 site conditions are allowed to change somewhat. How much becomes a judgment call and is further discussed in section N-5450.

Group 2 site conditions are NOT allowed to change. These conditions affect noise levels to some unknown extent, but they are ignored by the model. However, as long as they remain constant during the entire analysis period, they may be corrected for with the K - constant. But if they change at some point in the future, K must also change by an unknown amount and model calibration becomes invalid.

There are some cautions and pitfalls associated with site conditions of both Groups 1 and 2 that will be discussed in section N-5450. First, however, the calibration procedures will be explained.

N-5440 Procedures

The actual mechanics of model calibration are fairly straight-forward:

1. Select locations along the existing highway that are representative of the area of interest.
2. Take noise measurements at these locations and count traffic, preferably during the peak noise hour. If this is not possible, select any other time during which traffic mix and speeds (not necessarily volumes) are roughly similar to those of the noisiest time. This may be estimated. Typically, this condition occurs during day time whenever traffic is free flowing.
3. Calculate the noise levels with the prediction model after having input the traffic counts (expanded to one hour), site geometry, and any other pertinent existing features.

4. Compare measured with calculated noise levels. The difference is called the "K-constant" or calibration constant. K is determined as follows:

   K = Measured - Calculated

   or for short:

   $$K = M - C \qquad \textbf{(eq. N-5450.1)}$$

   Add K to the future calculated noise levels to obtain predicted noise levels (P):

   $$P = C + K \qquad \textbf{(eq. N-5450.2)}$$

Following are some simple examples to illustrate the mechanics of the above calibration procedures with some typical values. Example A is a straight forward noise prediction problem. Example B includes a barrier design problem. In order to distinguish between the various C's and P's in the two examples, a sequential number was added.

Example A.

1. Existing Noise Levels	2. Future Noise Levels
$L_{eq}(h)$, dBA	$L_{eq}(h)$, dBA
73 (C1)	75 (C2)
70 (M)	? (P1)

K = M - C1 = 70 - 73 = -3 dBA
P1 = C2 + K = 75 + (-3) = 72 dBA

The predicted future noise level is 72 dBA. In essence we are saying that, although the model calculated the future noise level to be 75 dBA, we are expecting the actual future noise level to be 72 dBA. This may be due to the inability of the model to account for existing obstacles or other site features that attenuate noise.

Now suppose it is necessary to construct a noise barrier that will attenuate the noise level to 65 dBA. The problem has to be turned around. In Example A, the predicted (or expected actual) noise level was sought. In example B, however, the predicted noise level is known; thus, the calculated with-barrier-noise level should be:

Example B.

1. Without Barrier:	2. With Barrier:
$L_{eq}(h)$, dBA	$L_{eq}(h)$, dBA
72 (from Example A)	65 (P2)
75 (from Example A)	? (C3)

C3 = P2 - K = 65 - (-3) = 68 dBA (Alternate form of eq. N-5440.2)

In order to reduce the noise level to 65 dBA with the barrier, the calculated noise level should be 68 dBA.

The Caltrans computer model SOUND32 allows input of K - constants, eliminating the need for manual conversion of calculated to predicted values.

N-5450 Cautions And Pitfalls of Model Calibration

Section N-5430 indicated that Group 1 conditions are allowed to vary somewhat. How much is somewhat? Experience has shown that significant changes in traffic volumes, speeds and mix can be adequately accounted for by the model, as can shielding by barriers over 1.8 m (6 ft) and segment adjustments within the range normally encountered.

The main problem areas in Group 1 site conditions pertaining to model calibrations are differences in source-to-receiver distances and low barriers.

Consider the distances first. The accuracy of the prediction model appears to decrease as the distance from the highway increases. This is attributed to the inaccuracies in the drop-off rates used by the model: either 3 dBA/DD for hard sites or 4.5 dBA/DD for soft sites. In reality, the drop-off rates may be somewhere between 3 and 4.5, or exceed 4.5 dBA/DD, depending on ground cover and average height of noise path above the ground.

The K - constant therefore tends to be distance dependent. This has two major implications for the calibration process:

1. Source-to-receiver distances, their relative heights and the ground cover in between should not change significantly during the analysis period. Slight changes in distances, such as due to widening projects, or even slight changes in profile or receiver height are permissible. Also, the differences between drop-off rates before and after construction of a noise barrier appear to be approximately correct in the model.
2. Receivers need to be selected for several representative distances to include the effects of drop-off inaccuracies in the K - constants. Each receiver may have a different K. It is up to the user to decide on their radius of influence, and whether or not to group some K - constants together (if they are close enough).

The second Group 1 problem area is that of low barriers. Although it is Caltrans' policy to build barriers that are at least 1.8 m (6 ft) high, it is possible that the before barrier condition includes a low rise in terrain, a hinge point, etc. Due to noise centroid (vehicle source height) assumptions in the model, low barrier calculations are usually less accurate. Model calibrations should be avoided at these sites if the future condition includes a noise barrier.

Meteorology is one of the major problems in Group 2 site conditions. The effects of wind speed and direction on noise levels at a receiver can be substantial, even at relatively short distances from a highway. Since the prediction model does not take meteorology into consideration, noise measurements have to be taken under calm wind conditions. Section N-3600 discussed the criteria for calm winds. Any attempt to calibrate the model for a prevailing wind condition is only valid for that wind condition. Noise standards, however, are not linked to meteorology.

Finally, noise contamination from other sources not considered by the model, CANNOT be corrected by model calibration. The following hypothetical case illustrates this.

Assume that at a calibration site, the existing noise level is measured to be 68 dBA. This noise level is contaminated by surface streets and other neighborhood noises, but the freeway contribution and background noise cannot be separated from the measurement. It is not known that the freeway traffic and the background noise contribute 65 dBA each (for a total of 68 dBA). The existing noise level from the freeway was calculated to be 65 dBA. This happens to agree with the actual freeway contribution. There is no reason to believe that the background noise will change in the future, thus the model is (incorrectly) calibrated. The calculated future noise level is 70 dBA. What is the predicted future level?

Following is an outline of the problem:

Existing Noise Levels			Future Noise Levels		
Freeway	65	dBA (unknown)	Freeway	70	dBA (unknown)
Background	65	dBA (unknown)	Background	65	dBA (unknown)
Total	68	dBA (measured)	Total	71	dBA (actual)
Freeway	65	dBA (calculated)	Freeway	70	dBA (calc'd)
$K = M - C = 68 - 65 = +3$			Freeway	?	dBA (predicted)

Predicted Freeway:
$P = C + K = 70 + 3 = 73$ dBA
(Compared to 71 dBA actual).

In the above situation the calibration process caused an over-prediction of 2 dBA, even though the background remained the same during the analysis period.

Background noise high enough to contaminate the noise measurements can therefore not be considered a Group 1 or Group 2 site condition. In short, it represents a site condition that cannot be tolerated in the calibration process in any situation.

Noise measurement sites should be carefully selected to eliminate as many Group 2 site conditions as possible, and to avoid any contamination. Contamination occurs when an undesired noise source is less than 10 dBA lower than the noise of interest. A quick check for contamination can be performed with a simple analog meter, by watching the indicator.

If it responds at all to fluctuations of the undesired source the noise level will most likely be contaminated.

N-5460 Tolerances

Given the inherent uncertainties in the measurements and calibration procedures, model calibration should definitely not be attempted when calculated and measured noise levels agree within 1 dBA. If there is great confidence in the accuracy and representativeness of the measurements, calibration may be attempted when calculated noise levels are within 2 dBA of the measured values. Differences of 3 - 4 dBA may routinely be calibrated unless the validity of the measurements is in serious doubt. Differences of 5 dBA or greater should be approached with caution: retake measurements, look for obvious causes for the differences such as meteorology, pavement conditions, obstructions, reflections, etc. Check traffic and other model input parameters (remember to expand traffic counted during the noise measurement to one hour), and confirm that the traffic speeds are accurate.

If differences of 5 dBA or greater still exist after confirming the measurements and input parameters, the decision to calibrate or not calibrate the model should be made after determining if any of the responsible Group 2 site conditions will change during the project life.

N-5470 Common Dilemmas

The following hypothetical cases present some common dilemmas the noise analyst may have to resolve when selecting model calibration sites.

Suppose that a receiver was selected in a back yard abutting a freeway R/W. The only obstacle between the receiver and the freeway is a 1.8 m (6 ft) high wood tract line fence running parallel to the freeway. The fence boards are standard 1” x 6” with shrinkage gaps in between. Should this receiver be used for model calibration measurements?

There is no clear-cut answer. IF the fence is new and expected to remain in good condition for the next twenty years or so, AND IF no noise barrier is planned, this would probably be a good representative location to measure existing noise levels and predict model-calibrated future noise levels for all the backyards bordering the R/W.

Now suppose that the predicted (calibrated) noise level at this receiver is high enough to qualify for a noise wall. Before the wall is constructed, the existing fence provides *transparent shielding* (a Group 2 site condition). After the wall is constructed, however, any effect from the fence will be eliminated, regardless of whether or not the fence remains (i.e., the effects of a Group 2 site condition change). In that case the location would be a bad choice for model calibration.

In many cases it is uncertain whether noise levels are high enough to justify noise barriers until the noise is measured. Neither are there any assurances of the longevity of wooden back yard fences. In the above case (and for wooden privacy fences in general) it is good policy to pick for calibration purposes, locations on the freeway side of the fence, or on a side street dead-ending at the freeway R/W. Similar situations may exist in areas of heavy shrubs or dense woods.

Remember, however, that *opaque* shielding, such as by a block wall of at least six feet in height, can be adequately handled by the model and therefore does not represent a problem in calibration.

N-5500 PREDICTING FUTURE NOISE LEVELS

After determining the existing noise levels future noise levels are predicted for all project alternatives under study for the analysis period. This information is needed to determine if any of the alternatives cause traffic noise impacts.

The traffic noise prediction procedures are specified in Title 23, United States Code of Federal Regulations, Part 772. At the time of this writing, these are as detailed in Section N-5510. Recently, the FHWA and Volpe National Transportation Systems Center in Cambridge, MA, contracted the development of a new noise prediction model, named FHWA Traffic Noise Model® (TNM). This model was released on March 30, 1998, and is outlined and referenced in Section N-5520. Until FHWA mandates the use of TNM, the procedures described in Section N-5510 are to be used.

N-5510 FHWA-RD-77-108 METHODOLOGY

23 CFR 772 is specific about the procedures that should be used in predicting highway traffic noise and specifies the following two conditions:

1. The methodology used must be consistent with the methodology in the FHWA Highway Traffic Noise Prediction Model (FHWA-RD-77-108).

2a. The noise emission levels used must be the National Reference Energy Mean Emission Levels (Remels).

OR

2b. The emission levels must be determined as spelled out in "Sound Procedures for Measuring Highway Noise: Final Report" (DP-45-1R).

Caltrans versions of the FHWA model (approved by FHWA) are LEQV2 and SOUND32. Both are available in personal computer (PC) versions only, and either model should be used for all Caltrans noise analyses and acoustical barrier design. Either computer program will hereafter be referred to as the model.

LEQV2 is a simple model that follows the FHWA RD-77-108 report procedures. It can handle only one receiver at a time, and can take care of only simple site geometries. Noise barriers are presumed parallel (horizontally as well as vertically) to the roadways. LEQV2 can be run with either California specific (Calveno) REMELS or National REMELS. Three-dimensional roadway and barrier segments and receiver geometries are expressed as distances and angles from the observer (receiver), and elevations relative to the roadway.

SOUND32 is the Caltrans version of the two federal programs STAMINA2.0 (also based on FHWA-RD-77-108 and OPTIMA. The two FHWA programs were modified and combined in the Caltrans version. Modifications and improvements incorporated into SOUND32 include:

a) the ability to use either Calveno or National REMELS;
b) addition of berm calculations (berms are more effective than walls in attenuating noise);
c) correction of inaccuracies that may occur in STAMINA/OPTIMA when more than one barrier lie between receiver and roadway;
d) correction of a problem that occurs in STAMINA with low barriers, which causes the program to skip the calculation of medium truck barrier attenuation when there is no heavy truck barrier attenuation;
e) addition of emission levels for heavy trucks on positive grades from California specific data (Calgrade); and
f) the ability to easily modify the Calgrade levels by editing of a data file rather than changing the program code.

As is the case with STAMINA2.0, SOUND32 uses a x-y-z coordinate system for the roadway and barrier segments and receivers, instead of distances, angles and elevations used in LEQV2.

For simple highway-barrier-receiver geometries both LEQV2 and SOUND32 may be used. For more complex geometries SOUND32 should be used.

For the same conditions under which LEQV2 can be used, SOUND32 yields approximately the same results. Some negligible differences of generally less than 0.5 dBA could result, due to rounding.

The accuracy LEQV2 and SOUND32 is distance dependent. Typically, less than 30 m from the source, accuracies are ± 1 dBA. Farther away from the source the results are less accurate. At 100 m accuracies are ± 3 dBA or more. Therefore Model results should be rounded by conventional method, and reported to the nearest dBA.

The following sections are a brief overview of the FHWA Highway Traffic Noise Model. The sections are aimed at providing an introduction to the procedures and to point out some of the shortcomings. The FHWA-RD-77-108 report forms the basis for the computer programs and users are encouraged to read it in order to understand what is happening inside the computer models.

The FHWA-RD-77-108 procedures start with the Remels and apply a series of adjustments to these emission levels to arrive at the predicted noise levels (Figure N-5510-1):

Figure N-5510.1 Flow Chart of FHWA Highway Traffic Noise Prediction Model

Reference Energy Mean Emission Level

Traffic Flow Adjustment

Distance Adjustment

Roadway Segment Adjustment

Shielding Adjustment

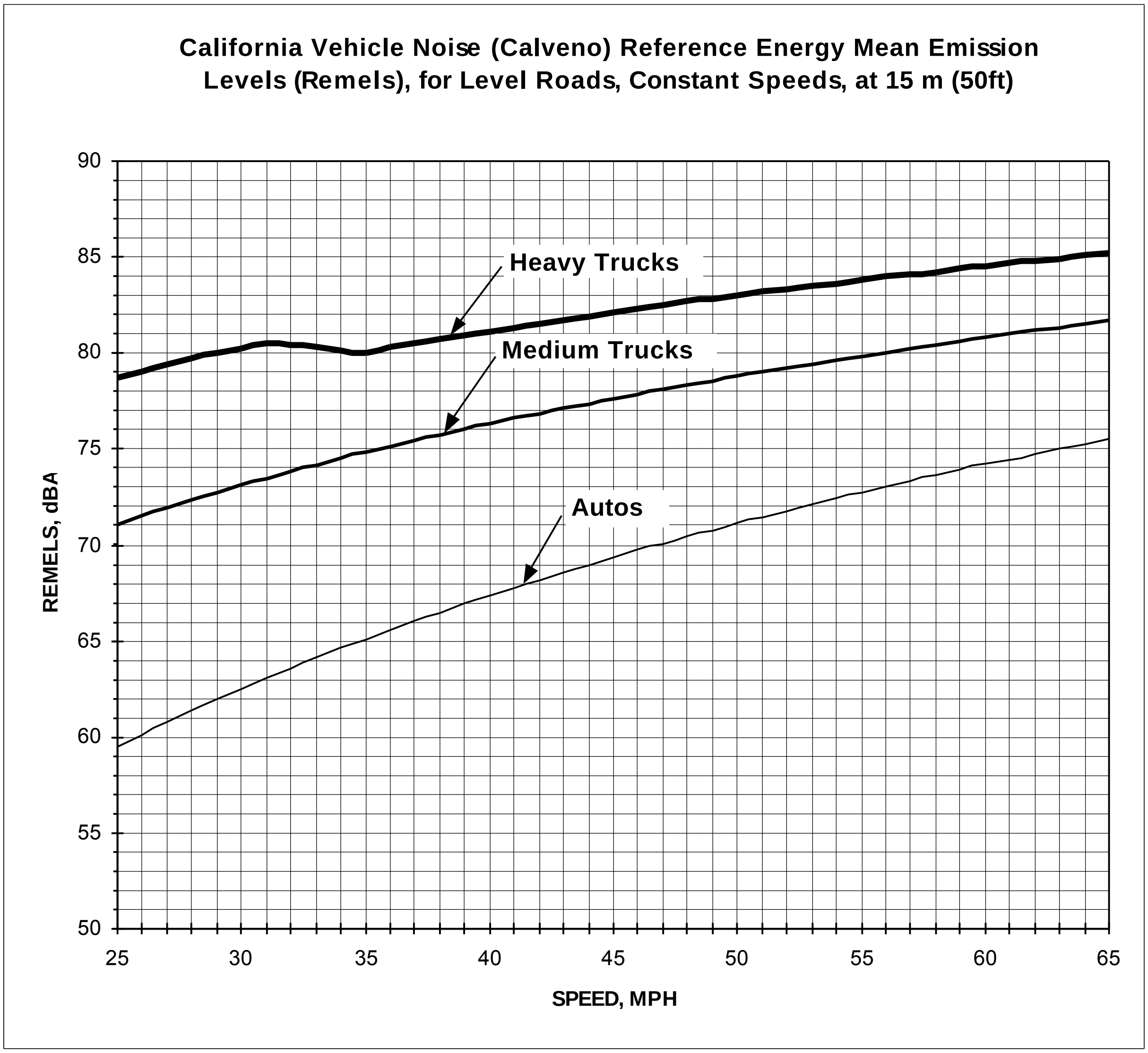
Predicted Noise Level (L_{eq}, dBA)

N-5511 Reference Energy Mean Emission Levels (REMELS)

The first step in the prediction procedure is to determine the reference energy mean emission levels. The emission level, L_0, is defined as the speed-dependent energy-averaged A-weighted maximum pass-by noise level generated by a defined vehicle type, as measured by a microphone at 15 m (50 ft) from the centerline of travel (traffic lane) at a height of 1.5 m (5 ft). The California Vehicle Noise (Calveno) Reference Energy Mean Emission Levels (REMELS) are shown in Figure N-5511-1. The Calveno Remels were developed as part of research performed by the former Office of Transportation Laboratory, and meet the previously-mentioned 23 CFR 772 requirement 2b.

Vehicles on the highway do not have identical Remels. Emission levels are dependent on a whole range of characteristics related to vehicles and the highways on which they travel. Among these are vehicle type, engine size, speed, number of wheels and axles, type of tires, as well as pavement type, age, texture, and condition.

Figure N-5511.1 - California Vehicle Noise Reference Energy Mean Emission Levels



Heavy Trucks:	
25-31 mph (40-50 km/h):	**51.9+19.2Log$_{10}$(Speed, mph) or 47.9+19.2Log$_{10}$(Speed, km/h)**
35-65 mph: (56-105 km/h):	**50.4+19.2Log$_{10}$(Speed, mph) or 46.4+19.2Log$_{10}$(Speed, km/h)**
31-35 mph: (50-56 km/h):	**Straight line**
Medium Trucks::	**35.3+25.6Log$_{10}$(Speed, mph) or 30.0+25.6Log$_{10}$(Speed, km/h)**
Autos:	**5.2+38.8Log$_{10}$(Speed, mph) or -2.8+38.8Log$_{10}$(Speed, km/h)**

The FHWA model groups vehicles into three classifications and defines emission levels for each as a function of speed. In California, these have been replaced with the Calveno curves. The three vehicle type classifications are:

1. Automobiles (A) - all vehicles with two axles and four wheels designed primarily for transportation of nine or fewer passengers (automobiles), or transportation of cargo (light trucks). Generally the gross vehicle weight is less than 4,500 kg (10,000 lbs).
2. Medium Trucks (MT) - all vehicles with two axles and six wheels designed for transportation of cargo. Generally the gross vehicle weight is greater than 4,500 kg (10,000 lbs) and less than 12,000 kg (26,500 lbs).
3. Heavy Trucks (HT)- all vehicles with three or more axles designed for the transportation of cargo. Generally, the gross weight is greater than 12,000 kg (26,500 lbs).

Calveno curves are only valid for vehicles traveling at a constant speed between 25 and 65 mph (40 - 105 km/h) on level roadways.

N-5512 Traffic Flow Adjustment

The traffic flow adjustment is really just an expansion of the reference levels to account for the traffic volumes and to adjust for the vehicle speeds (given the reference level an observer will *hear* a car going 60 mph only half as long as one going 30 mph).

$$\text{Traffic Flow Adjustment} = 10\ \mathrm{Log}_{10}\left(\frac{N_i \pi D_o}{T S_i}\right) \qquad \textbf{(eq. N-5512.1)}$$

Where :

N_i is the number of vehicles in the ith class

D_0 is 15 metres

T is the time (normally 1-hour)

S_i is the speed in kph

The equation can be simplified to:

$$\text{Traffic Flow Adjustment} = 10\ \mathrm{Log}_{10}\left(\frac{N_i D_0}{S_i}\right) - 25 \qquad \textbf{(eq. N-5512.2)}$$

Where the - 25 is derived from $10\ \mathrm{Log}_{10}\left(\frac{\pi}{1000}\right) = -25$, where 1000 is the conversion from meters to kilometers.

N-5513 Distance Adjustment

The distance adjustment is generally referred to as either the drop-off rate or the *alpha* soil parameter (see Section N-2140 for a discussion of propagation of sound) and is expressed in the FHWA-RD-77-108 methodology it is expressed in terms of decreasing decibels per doubling of distance from the line source as:

$$\text{Distance Adjustment} = 10\ \mathrm{Log}_{10}\left(\frac{D_0}{D}\right)^{1+\alpha} \qquad \textbf{(eq. N-5513.1)}$$

Where: D is the perpendicular distance from receiver to centerline of the lane

D_0 is the reference distance of 15 metres

α is the excess attenuation due to ground effects

When the ground between the roadway and the receiver is *hard* the site is considered reflective and a becomes 0, the distance adjustment reduces to:

$$\text{Distance Adjustment} = 10\ \text{Log}_{10}\left(\frac{D_0}{D}\right) \qquad \textbf{(eq. N-5513.2)}$$

and the drop-off rate becomes 3 dB per doubling of distance (3 dB/DD) (see sec.N-2141).

With the FHWA model the user must decide on the appropriate drop-off rate to use. Table N-5513-1 may be used for guidance.

Table N-5513.1 - FHWA-RD-77-108 Criteria for Selection of Drop-Off Rates.

SITUATION	DROP-OFF RATE	**a**
1. All situations in which the source or receiver are located 10 ft (3m) above the ground whenever the line-of-sight averages more than 10 ft (3m) above the ground.	3 dBA /DD	0
2. All situations involving propagation over the top of a barrier 3 m or more in height.	3 dBA /DD	0
3. Where the height of the line-of-sight is less than 10 ft (3m) and:		
(a) There is a clear (unobstructed) view of the highway, the ground is hard and there are no intervening structures.	3 dBA /DD	0
(b) The view of the roadway is interrupted by isolated buildings, clumps of bushes scattered trees, or the Intervening ground is soft or covered with vegetation.	4.5 dBA /DD	0.5

Distance adjustments to distances less than 50 ft (15 meters) should always be made using 3 dBA/DD ($\alpha = 0$).

N-5513.1 Lane-by- Lane

Ideally, distance adjustments are made from each individual lane (line source) of a multi-lane highway. However, this is often a cumbersome process and often not possible without making certain assumptions about distribution of traffic volumes over the various lanes.

The next two sections show simplifications of the process that can be made in many instances without compromising too much accuracy.

N-5513.2 Equivalent Lane Distances

The distance adjustments previously shown assumed one lane of traffic only and involved the distance from the center of a lane to the receiver. As the number of traffic lanes increases, computation of the noise levels on a lane-by-lane basis becomes very tedious, even for a computer. It has become common practice to lump the directional traffic into an imaginary single lane which will provide approximately the same acoustical results as an analysis done on a lane-by-lane basis. This imaginary single lane is located at a distance from the receiver called the equivalent lane distance, D_E.

For a free field (no barriers present) the equivalent distance is computed as:

$$D_E = \sqrt{(D_N)(D_F)} \qquad \textbf{(eq. N-5513.3)}$$

Where:

D_N = perpendicular distance from the receiver to the center of the near lane
D_F = perpendicular distance from the receiver to the center of the far lane

These distances are shown in Figure 5513-1(a).

When a barrier is present the equivalent distance is computed as:

$$D_E = \sqrt{(D_N)(D_F)} + X \qquad \textbf{(eq. N-5513.4)}$$

Where:

D_N = perpendicular distance from the receiver to the center of the near lane
D_F = perpendicular distance from the receiver to the center of the far lane
X = perpendicular distance from receiver to the barrier

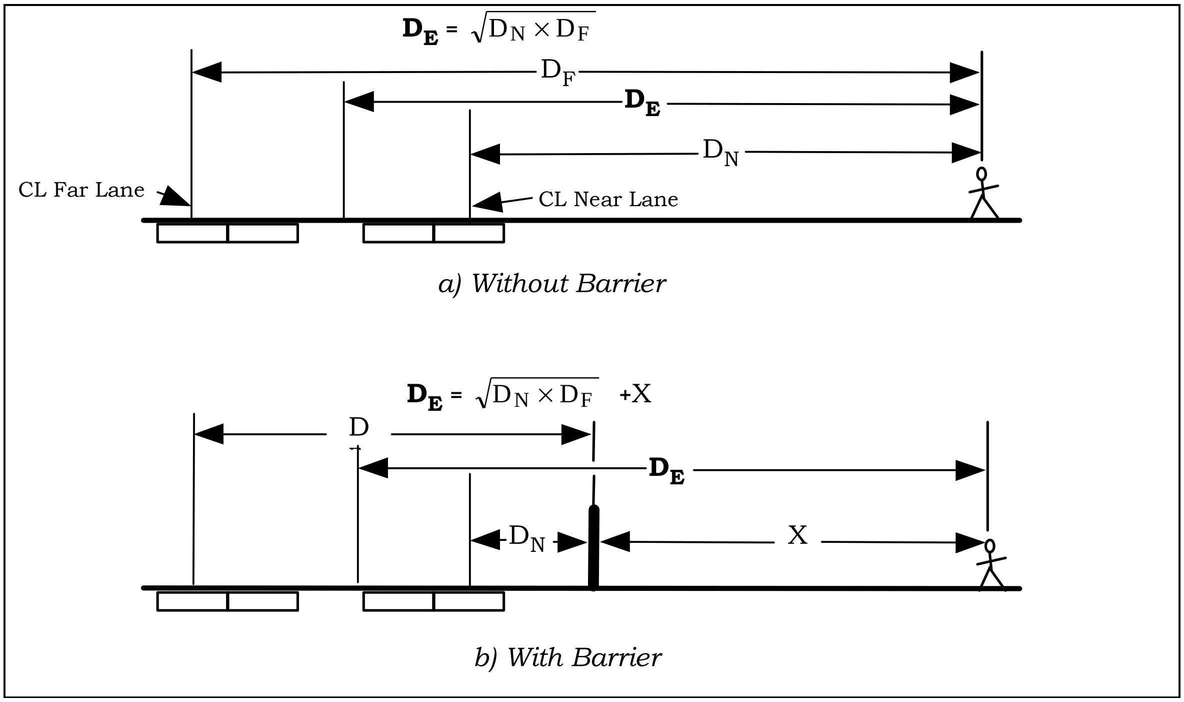
These distances are shown in of Figure N-5513.1(b)

Care should be used when using equivalent lane distances when deep cuts or high fill sections are involved or when the directional traffic varies significantly from 50-50.

Figure N-5513.1 illustrates the use of one equivalent lane distance for both directions of traffic. A compromise may be made between the accurate (but cumbersome) lane-by-lane and the simplistic (but less accurate) single equivalent distance may made by using directional equivalent lane distances, i.e. using the near and far lane for each direction. This method, yielding two equivalent lane distances (one for each direction) is less cumbersome than using individual lane distances, and more accurate than the single equivalent lane distance for all lanes. It can also be effectively used if the directional traffic is unbalanced, or if the center median is very wide.

LeqV2, the simple Caltrans computer program based on FHWA-RD-77-108, automatically calculates the equivalent lane distance for each lane group (element) identified. It accomplishes this task from user input distance(s) to the center line of near lane of each lane group, and the user input number of lanes in each lane group (it assumes 3.66 m (12 ft) lane widths).

Figure N-5513.1 - Equivalent Lane Distances, D_E



N-5513.3 Centerlines of Directional Traffic

The simplest compromise between the lane-by-lane and equivalent lane distance methods is to use the center line of each (directional) lane group. This method also yields two distances, one for each directional lane group. Unlike the equivalent lane distances, however, this method does not change the source to receiver distances when a barrier is inserted, making it slightly less accurate, but simple to use.

In most cases, using the center lines of the directional traffic as opposed to using directional equivalent lane distances does not change the final results by more than a few tenths of a dB. Because of it's simplicity, this is the most common method used with Sound32 (complex Caltrans computer program based on Stamina 2 and Optima, which are also both based on FHWA-RD-77-108).

N-5514 Finite Roadway Adjustment

When the roadway is not infinitely long in both directions in relationship to the observer, it becomes necessary to adjust the reference levels to account for only that energy coming from a portion of the roadway. It is often necessary to separate a roadway into sections to account for changes in topography, traffic flows, shielding etc.

For hard sites where the drop-off rate is 3 dBA/DD ($\alpha = 0$) the adjustment is simply:

$$\text{Finite Roadway Adjustment - Hard Site} = 10\ \text{Log}_{10}\left(\frac{\Delta\phi}{180}\right) \qquad \textbf{(eq. N-5514-1)}$$

Where:

$\Delta\phi = \phi_1 - \phi_2$

ϕ_1 and ϕ_2 are angles in degrees as shown in Figure N-5514-1.

Note that in all cases $\Delta\phi$ will be positive and will be numerically equal to the included angle subtended by the roadway relative to the receiver.

For soft sites, where the drop-off rate is 4.5 dBA/DD ($\alpha = 0.5$), the adjustment is more complex since the excess distance attenuation must also be accounted for:

$$\text{Finite Roadway Adjustment - Soft Site} = 10\ \text{Log}_{10}\ \frac{1}{\pi}\int_{\phi 1}^{\phi 2}\sqrt{\cos\phi}\ d\phi \qquad \textbf{(eq. N-5514-2)}$$

N-5515 Shielding Adjustments

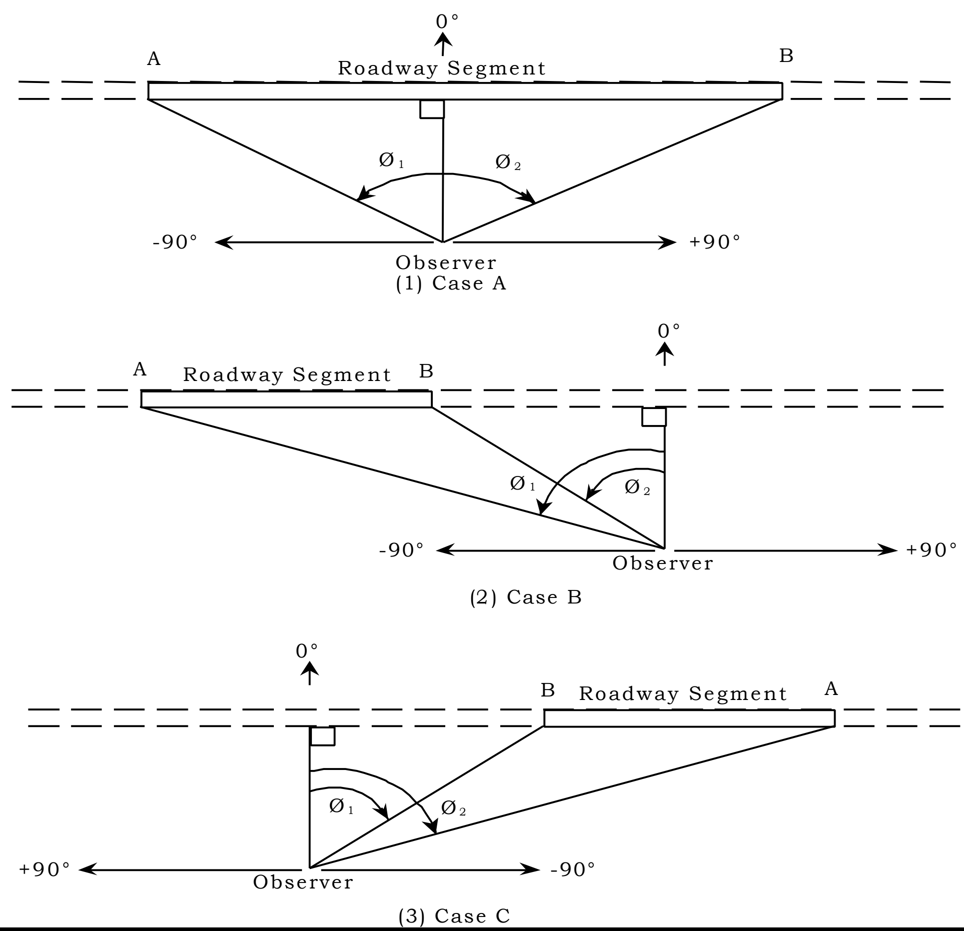
Shielding is one of the most effective ways of reducing traffic noise. Shielding occurs when the observer's view of the highway is obstructed or partially obstructed by natural or man-made features interfering with the propagation of the sound waves. Figure N-5515.1 illustrates the general rules of thumb for various shielding adjustments.

Figure N-5515.1 shows the attenuation credit given by the FHWA model to plantings, woods and vegetation: 5 dBA for the first 30 m (100 ft), with an additional 5 dBA for the second 30 m. The height of the trees should extend at least 5 m (16 ft) above the line of sight, and the woods must be dense enough to completely block the view of the traffic from the receiver. Obviously, to be effective throughout the year the trees must be mostly evergreens. Ordinary landscaping along the highway is not effective in actually reducing traffic noise, although it may provide a psychological “out of sight, out of mind” effect that tends to reduce the awareness of traffic noise.

Figure N-5514.1 - Identification of Angles

Based on this procedure, only three cases are possible:

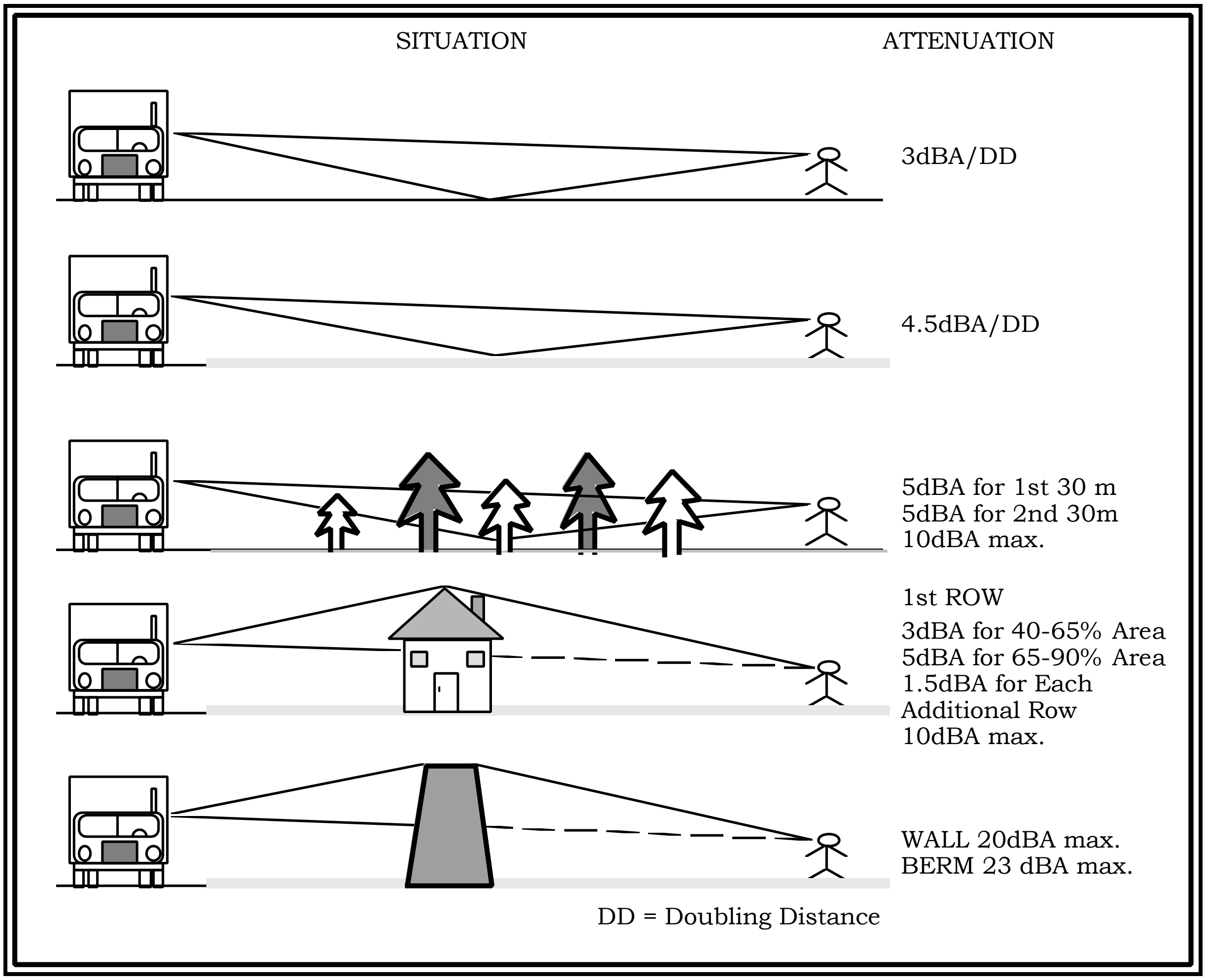
Case A – $Ø_1$ is negative, $Ø_2$ is positive.
Case B – $Ø_1$ is negative, $Ø_2$ is negative.
Case C – $Ø_1$ is positive, $Ø_2$ is positive.



The amount of attenuation provided by rows of buildings (d) depends on the size of the gaps between the buildings. 3 dBA attenuation is allowed for the first row of buildings when they occupy 40 to 65% of the row (35 to 60% gaps). 5 dBA is allowed when the buildings occupy 65 to 90% of the row (10 to 35% gaps). Rows of buildings behind the first row are given 1.5 dBA attenuation each.

While attenuation due to temperature gradients, winds and atmospheric absorption also occur, they are not accounted for in the FHWA model. Since they may vary by time and location, their effects are not considered permanent, although these factors become very important when making measurements. Also, the noise abatement criteria to which the modeled results are compared are set for normal conditions.

Figure N-5515.1 - Shielding Adjustments

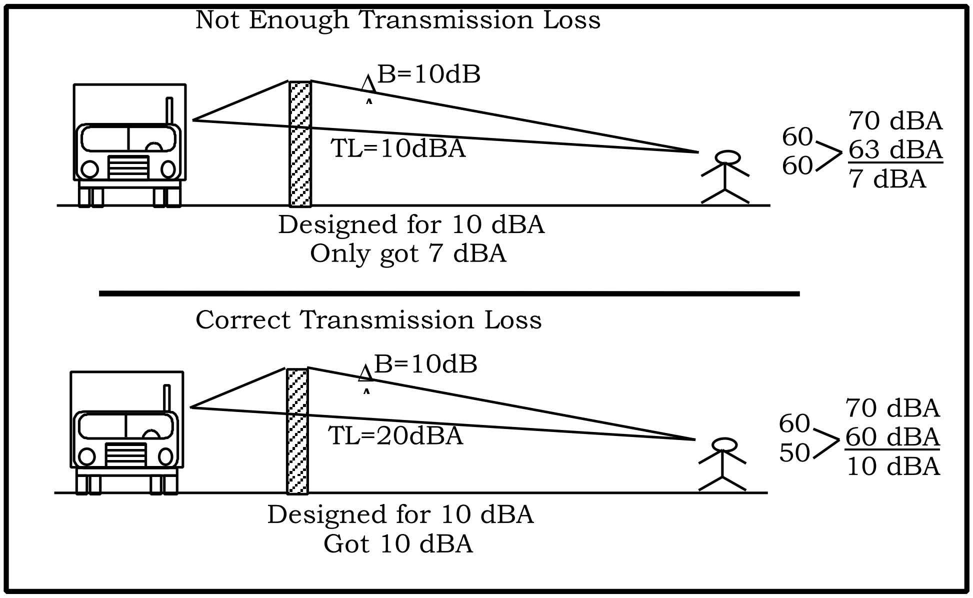


N-5515.1 Noise Barriers

Section N-2144 discussed the general characteristics of noise barriers and principles of diffraction, transmission loss and barrier atttenuation. Noise barriers can be constructed of any number of materials. The FHWA model works with the assumptions that:

1. The noise transmitted through the barrier will not contribute to the diffracted noise, i.e. is at least 10 dBA less than the noise diffracted over the top of the barrier. For this to be true the barriers transmission loss must be at least 10 dBA greater than the noise attenuation due to diffraction. For example, if the desired barrier attenuation is 10 dBA, the transmission loss of the barrier material must be at least 20 dBA. See Figure N-5515.2 for the effects of insufficient transmission loss)
2. The barrier cannot have cracks that would allow noise leakage. The FHWA model does not consider any noise that passes through a barrier or that may be diffracted around the ends of a barrier. (See Section N-6230 for a discussion of the effects of barrier openings for maintenance purposes on barrier performance.)

Figure N-5515.2 - Barrier Transmission Loss



The FHWA model calculates barrier attenuation as a function of the Fresnel number, the barrier shape and the barrier length. The Fresnel number (N_o), is defined as:

$$N_o = 2\left(\frac{\delta_o}{\lambda}\right) = 2\left(\frac{f\,\delta_o}{c}\right) \qquad \textbf{(eq. N-5515.1)}$$

Where: δ_o = pathlength difference
λ = wavelength of the sound
f = frequency of the sound
c = speed of sound = 343 m/s (1125 ft/s)

Highway traffic noise is broadband, (contains energy in the frequency bands throughout the audible range) and the Fresnel number will vary according to the frequency chosen. However, it has been found that the attenuation of the A-weighted sound pressure level of a typical auto is almost identical to the sound attenuation of the 550 Hz band. Based on this, equation N-5515.1 reduces to:

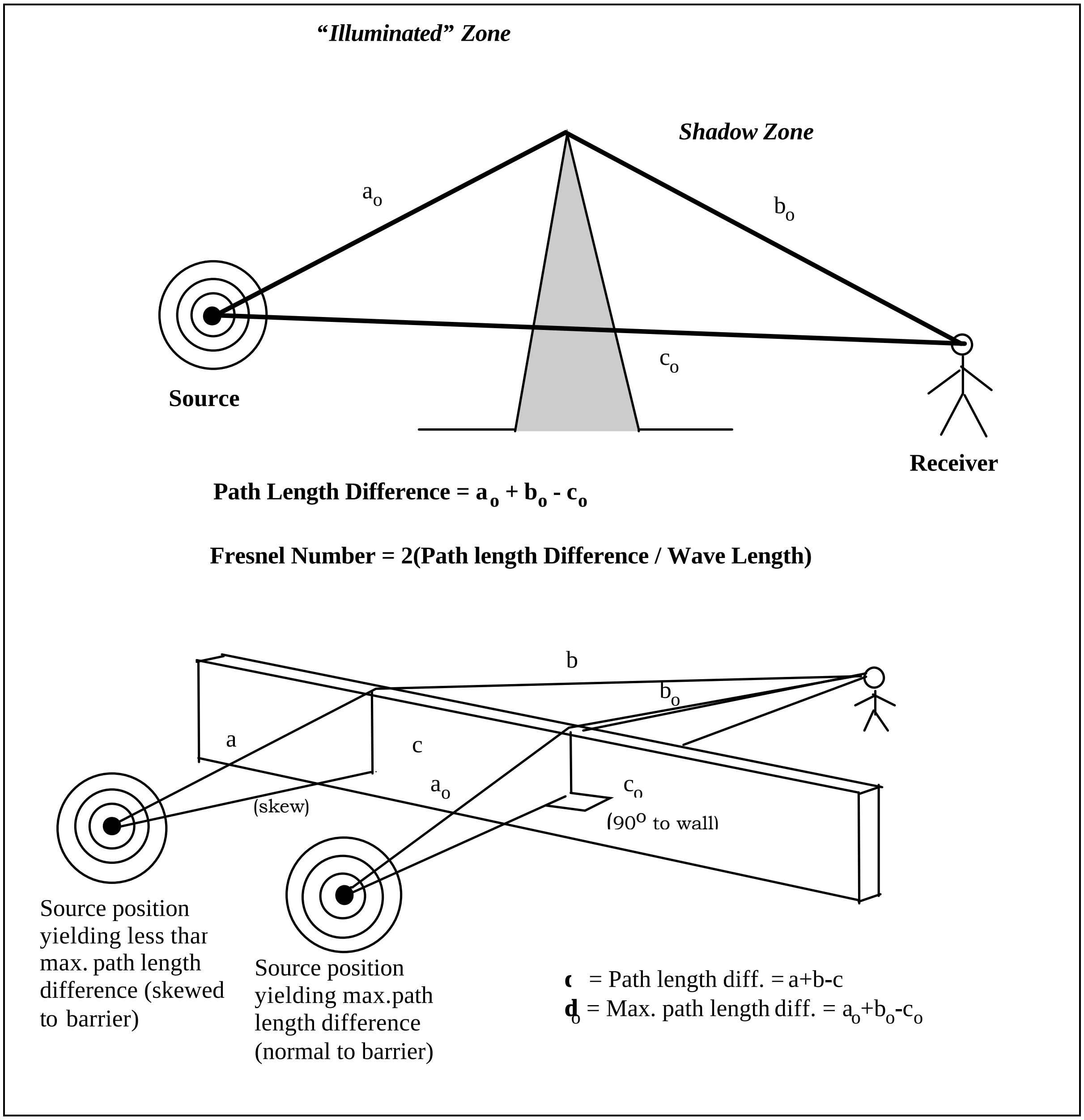
$$N_o = \frac{f\,\delta_o}{550} \qquad \textbf{(eq. N-5515.2)}$$

The path length difference, δ_o, is the difference between a perpendicular ray traveling directly to the observer and a ray diffracted over the top of the barrier.

$$\delta_o = a_o + b_o - c_o \qquad \textbf{(eq. N-5515.3)}$$

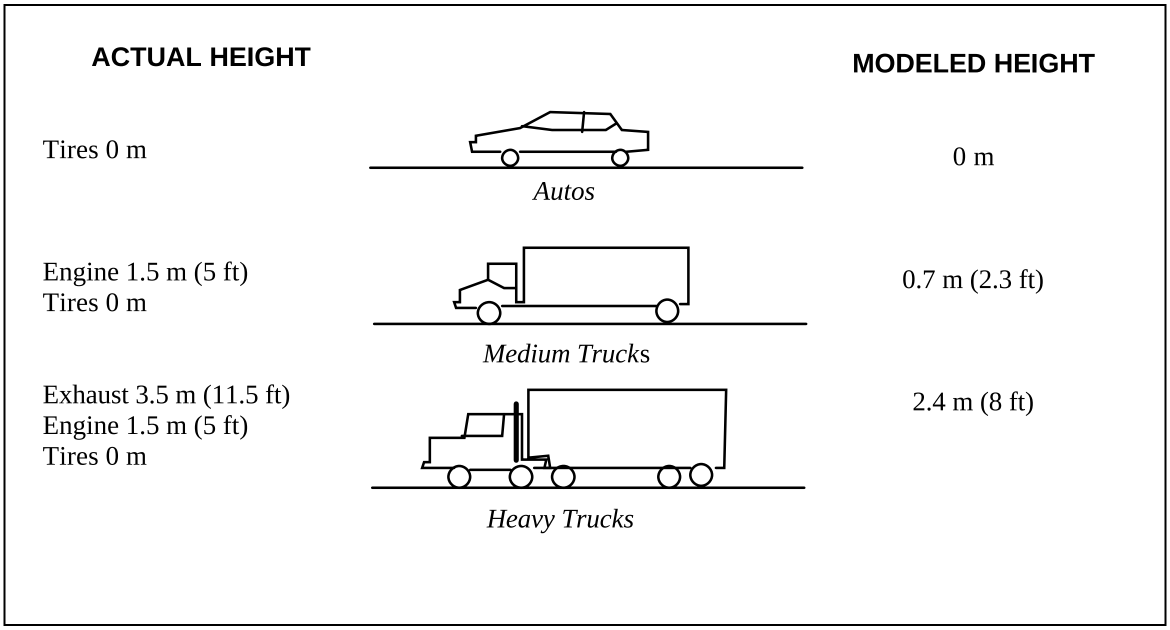
where the distances a_o , b_o and c_o are the distances normal to the barrier, as shown in Figure N-5515.3.

Figure N-5515.3 - Path Length Difference and Fresnel Number



For barrier calculation purposes, the vehicle noise sources are also simplified to those shown in Figure N-5515.4. These heights attempt to take into account and centralize the locations of the many individual sources of noise radiated from the vehicle types.

Figure N-5515.4 - Vehicle Source Heights Above Pavement



For barriers of finite length, the attenuation provided by a barrier depends on how much of the roadway is shielded from the observer. As with the finite roadway adjustment for soft sites, the finite barrier attenuation, Δ_{B_i}, calculations involves the solution of an integral:

$$\Delta_{B_i} = 10\log_{10} \frac{1}{f_R - f_L}\int_{f_L}^{f_R}(x)\,d f$$, where: **(eq. N-5515.4)**

X = 1 for Ni ≤ -0.1916 - 0.0635 **(eq. N-5515.5)**

$$X = \frac{10^{-0.3\varepsilon}\tan^2\sqrt{2\pi|N_0|_i}\cos\phi}{\sqrt{10}\cdot 2\pi|N_0|\cos\phi}$$ for $(-0.916-0.0635\varepsilon)\le N_i\le 0$ **(eq. N-5515.6)**

$$x = \frac{10^{-0.3\varepsilon}\tanh^2\sqrt{2\pi(N_0)_i\cos\phi}}{\sqrt{10}\cdot 2\pi(N_0)_i\cos\phi}$$ for $0\le N_i\le 5.03$ ***Note:*** $\tanh(x) = (e^x-e^{-x})/(e^x+e^{-x})$

(eq. N-5515.7)

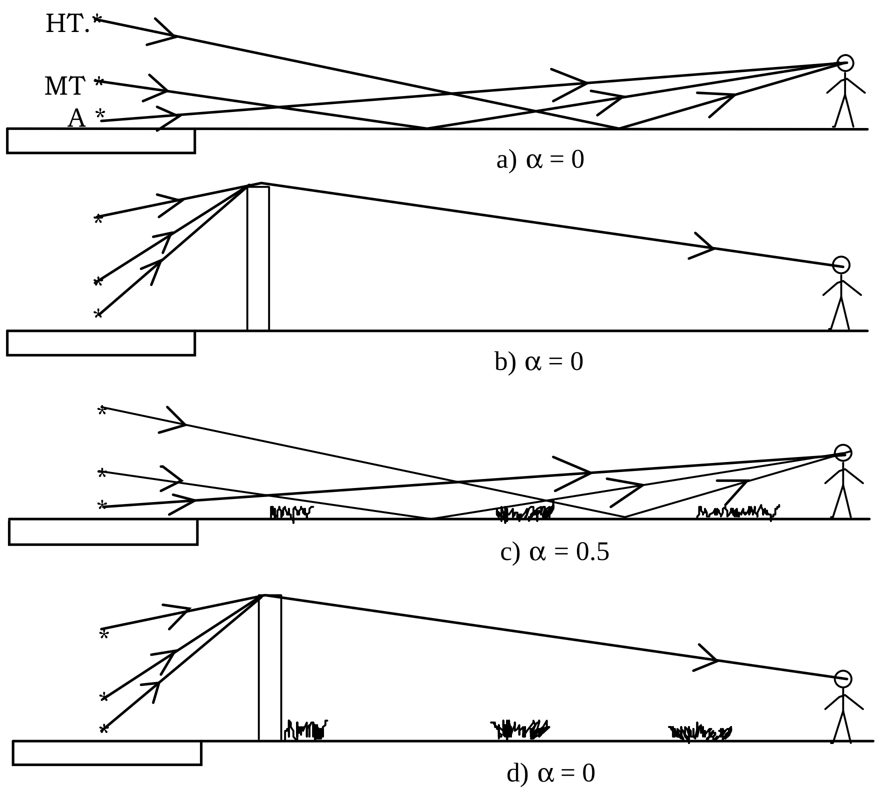
$$x = \frac{10^{-0.3\varepsilon}}{10^0}$$ for $Ni\ge 5.03$ **(eq. N-5515.8)**

Note the ε (epsilon) term in the equations: ε = 0 for a wall, and ε = 3 for a berm. The FHWA model assumes that earth berms perform about 3 dB better than free standing walls due to the top of barrier shape. ε accounts for this difference.

N-5515.2 Ground Effects

Consider the situation where the ground between the roadway and the observer is reflective (the drop-off rate is 3, or $\alpha = 0$). This situation is illustrated in Figure N-5515.5(a). As was indicated in Table N-5513.1, under these circumstances the drop-off rate is 3 dBA/DD [from 3(a)]. When a barrier is constructed between the roadway and the observer, the top of the barrier appears to be the noise source to the observer and again, the drop-off rate should be 3 dBA/DD (Figure N-5515.5(b)).

Figure N-5515.5 - Ground Effects



Effects of Noise Barrier on α = 0 (a and b) and α = 0.5 (c and d).

However, when the ground between the roadway and the observer is soft (4.5 dBA/DD, α = 0.5) the ground effects can provide an additional 1.5 dBA/DD when both the source and the receiver are close to the ground (Figure N-5515.5(c)). In this case, when a barrier is constructed between the observer and the roadway, the top of the barrier again appears to be the noise source to the observer and the appropriate drop-off rate is 3 dBA/DD (Figure 5515.5(d)). Thus, the 1.5 dBA/DD excess attenuation from the ground effects has been lost. Constructing a barrier effectively raises the source height and the ground effect is lost. Consequently, if the barrier attenuation was 9 dBA, an observer at 200 ft would get a field insertion loss of only 6 dBA (9 dBA barrier attenuation minus the 3 dBA lost excess ground effects).

N-5520 FHWA-TRAFFIC NOISE MODEL® (FHWA-PD-96-009 & -010; DOT-VNTSC-FHWA-98-1 & -2) OVERVIEW

The FHWA Traffic Noise Model® (TNM) was released on March 30, 1998. TNM will replace the FHWA-RD-77-108 methodology and the computer versions LEQV2 and SOUND32. The phase in period will be two years from the above date. The model is described in the "FHWA Traffic Noise Model® - Technical Manual ", Report Number: FHWA-PD-96-010; DOT-VNTSC-FHWA-98-2. The instructions for using the TNM version 1.0 software are contained in "FHWA Traffic Noise Model® - User's Guide", Report Number: FHWA-PD-96-009; DOT-VNTSC-FHWA-98-1.

FHWA TNM is a registered Copyright. The Copyright encompasses the User's Guide, Technical Manual, and software source and executable codes. FHWA TNM is also a registered Trademark. The Trademark encompasses the copyrighted User's Guide, Technical Manual, and software source and executable codes. It provides the FHWA with the exclusive right to use the names "Federal Highway Administration Traffic Noise Model" and "FHWA TNM". A TNM package, including the model software, the User's Guide, the Technical Manual and a TNM tutorial CD-ROM has been distributed to each Caltrans District, and Caltrans may make sufficient copies for internal use. All other users must purchase the TNM package through:

> The McTrans Center at the University of Florida, Telephone (904) 392-3225,
> Fax: (904) 392-3224, World Wide Web: http://www-mctrans.ce.ufl.edu

Following sections provide a brief overview of TNM. For detailed information the above referenced TNM Technical Manual and User's Guide should be consulted.

Limited TNM test runs results have generally agreed within two decibels with Sound 32 results.

N-5521 TNM Reference Energy Mean Emission Levels (REMELs)

TNM computes highway traffic noise at nearby receivers and aids in the design of noise barriers. The noise sources include an entirely new data base of 1994-1995 noise reference energy mean emission levels (REMELs) that is detailed in "Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model (FHWA TNM®), Version 1.0", Report Number: FHWA-PD-008; DOT-VNTSC-FHWA-96-2. The database includes speed-dependent emission levels for constant speeds on level roadways from idle to 80 mph (129 km/h), for the following vehicle types:

- Automobiles: same definition as in FHWA-RD-77-108
- Medium Trucks: same definition as in FHWA-RD-77-108
- Heavy Trucks: same definition as in FHWA-RD-77-108
- Buses: all vehicles designed more than nine passengers; and
- Motorcycles: all vehicles with two or three tires and an open-air driver/passenger compartment

In addition, the database includes data for:

- vehicles on grades
- three different pavements (dense-graded asphaltic concrete, open-graded asphaltic concrete, and Portland cement concrete)
- accelerating vehicles
- acoustic energy apportioned to two sub-source heights above the pavement: 0 m and 1.5 m (5 ft) for all vehicles, except for heavy trucks where the sub-source heights are 0 m and 3.66 m (12 ft)
- data stored in 1/3 octave bands

Figure N-5520.1 compares the new TNM Baseline REMELs with the Calveno REMELs. The latter were used in SOUND32 and LEQV2 programs (see Section N-5510) and must not be used with TNM. The TNM Baseline REMEL curves in Figure N-5520.1 were plotted from the TNM Baseline equations:

Speed 0 km/h (IDLE): $L_{(s_i)} = 10 \log_{10} (10^{C/10}) =$ **(eq.N-5520.1)**

$L_{(s_i)} = C$ **(eq.N-5520.1a)**

Speed > 0 km/h: $L_{(s_i)} = 10 \log_{10} [(0.6214\ s_i)^{A/10}\ 10^{B/10} + 10^{C/10}]$ **(eq.N-5520.2)**

Where: $L_{(s_i)}$ = REMEL for vehicle type i, at speed s (km/h)

s_i = Speed of vehicle type i in km/h

A, B, C are constants for each vehicle type, shown below (Table N-5521.1)

Note: For speeds in mph omit 0.6214 in above eq. 2.

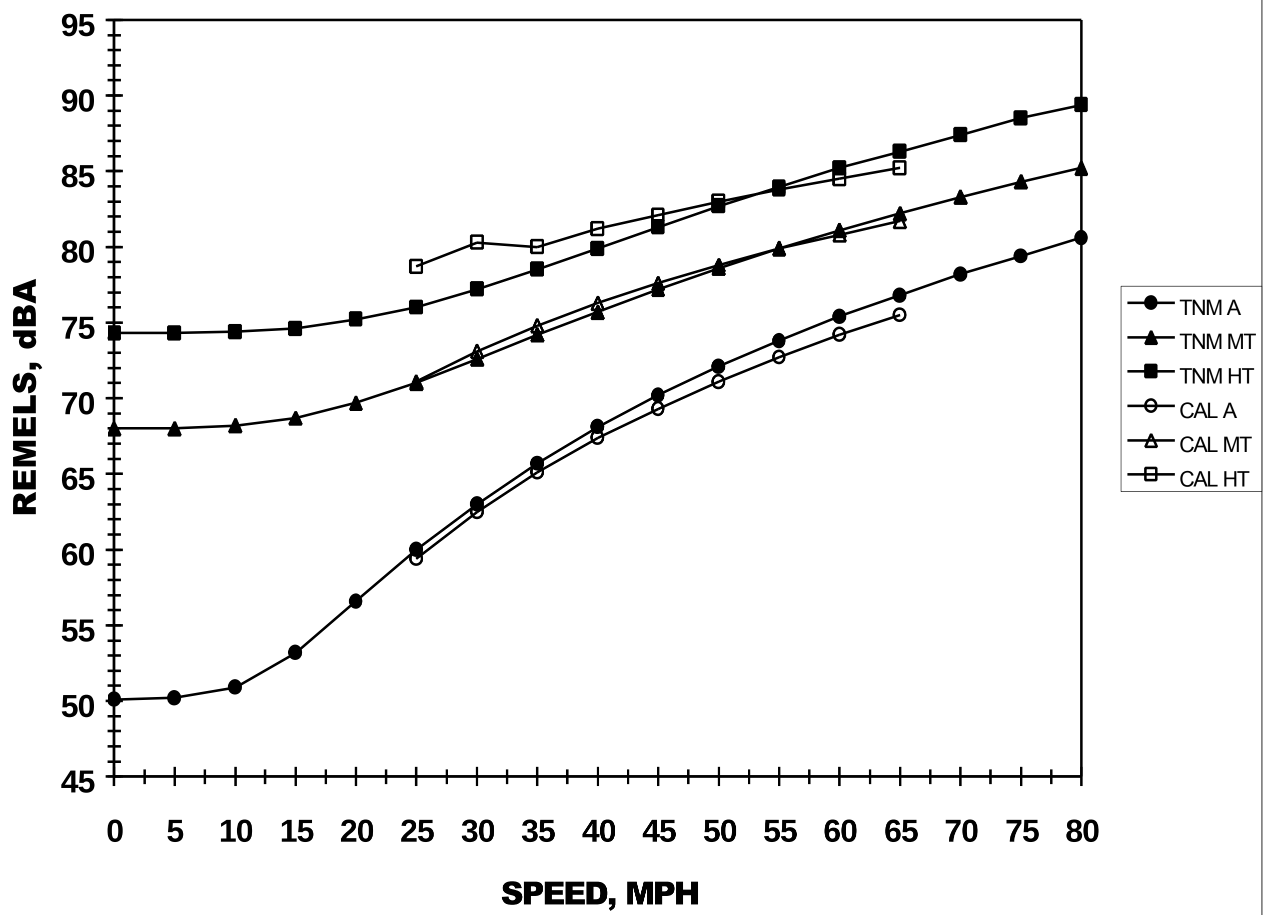
Table N-5521.1

	Constants		
Vehicle Type	**A**	**B**	**C**
Autos (A)	41.740807	1.148546	50.128316
Medium Trucks (MT) (2-axles, dual wheels)	33.918713	20.591046	68.002978
Heavy Trucks (HT) (3-axles)	35.879850	21.019665	74.298135

***Baseline REMELs =** *Reference Energy Mean Emission Levels for the following conditions:*

- **Average Pavement -** *Average for all pavements in the study, including Concrete (PCC), Dense-graded Asphalt (DGAC), and Open-graded Asphalt (OGAC)*
- **Level Roadways** - *Grades of 1.5 % or less*
- **Constant-Flow Traffic**
- **A-weighted, Total Noise Level at 15 m (50 feet)**

Figure N-5520.1 - Comparison Of A-Weighted Baseline FHWA TNM Vs Calveno REMELs



The exact TNM REMEL and Calveno REMEL values at 55 mph (88.5 km/h) are shown in Table N-5521.2:

Table N-5521.2 – Comparison of A-Weighted TNM and Calveno REMELs at 55 mph (88.5 km/h)

	Auto	**Medium Truck**	**Heavy Truck**
Calveno REMEL	72.8 dBA	79.9 dBA	83.8 dBA
TNM REMEL	73.8 dBA	79.9 dBA	84.0 dBA

N-5522 Noise Level Computations

TNM calculations of noise levels include:

- Three noise descriptors: Leq(h), Ldn, and CNEL (see Section N-2222).
- Capability of inserting traffic control devices. Such devices include traffic signals, stop signs, tollbooths, and on-ramp start points. TNM calculates vehicle speeds and emission levels, and noise levels accordingly.

- Computations performed in 1/3 octave bands for greater accuracy (not visible to users).
- Noise contours if specified.

Roadways and roadway segments define noise source locations (x-y-z-coordinates). Hourly traffic volumes determine the noise characteristics of the source.

N-5523 Propagation, Shielding, and Ground Effects

TNM incorporates state-of-the art sound propagation and shielding (e.g. noise barriers) algorithms, which are based on recent research of sound propagation over different ground types, atmospheric absorption, and shielding effects of noise barriers (including earth berms), ground, buildings and trees. However, TNM does not include the effects of atmospheric refraction, such as varying wind speed and direction or temperature gradients. TNM propagation algorithms assume neutral atmospheric conditions (zero wind speed, isothermal atmosphere).

The propagation algorithms can use the following user input information:

- Terrain lines (x-y-z coordinates) define ground location. Height above the ground is important in noise propagation.
- Ground zones (x-y-z coordinates) define perimeters of selected ground types. The latter may be selected from either a ground types menu (e.g., lawn, field grass, pavement, etc.), specified default, or user input flow resistivity (if known).
- Berms may be defined with user-selectable heights, top widths, and side slopes; they are computed as if they are terrain lines.
- Rows of buildings (x-y-z coordinates) with percentage of area shielded relative to the roadway(s) may be input to calculate additional attenuation.
- Tree zones (x-y-z coordinates) may be included for additional attenuation calculations if appropriate.

The propagation algorithms also include double diffraction. The net effect from the most effective pair of barriers, berms, or ground points that intercept the source-receiver line of sight is computed.

N-5524 Parallel Barrier Analysis

TNM includes a multiple reflection module that computes a degradation of the performance of one reflective barrier in the presence of another reflective barrier on the opposite side of the roadway. Unlike other TNM acoustics, which are computed in three dimensions, the multiple reflection module computes the results from a two dimensional cross-section. The results of this module are used to modify the TNM noise levels.

N-5600 COMPARING RESULTS WITH APPROPRIATE CRITERIA

After the predicted noise levels (including model calibration, if appropriate) have been determined they should be compared with the appropriate impact criteria in the Traffic

Noise Analysis Protocol, Section 2.4. Examination of traffic noise impacts includes comparing for each project alternative the following:

a) Predicted noise levels with existing noise levels (Section 2.4.1)
b) Predicted noise levels with the appropriate Noise Abatement Criterion (Section 2.4.2)
c) Predicted noise level of classroom interior with 52 dBA L_{eq}(h) (Section 2.5)

N-5700 EVALUATING NOISE ABATEMENT OPTIONS

If traffic noise impacts have been identified, noise abatement must be considered as discussed in the Traffic Noise Analysis Protocol, Sections 2.7 (Noise Abatement Feasibility) and 2.8 (Noise Abatement Reasonableness). Noise abatement measures may include, but are not necessarily limited to the measures listed in Traffic Noise Analysis Protocol Section 5.3. These potential measures are based on avoiding impacts, interrupting the noise paths, or protecting selected receivers. If the project alternative locations are flexible, alignments and profiles can be selected to avoid sensitive receivers or lessen the noise impacts. Most often highway alignments and profiles are selected on the basis of other overriding factors. The construction of noise barriers is then usually the most common noise abatement option available.

The consideration of noise abatement described in the Traffic Noise Analysis Protocol Sections 2.7 and 2.8 requires at a minimum a preliminary design of the abatement. The following Section N-6000 gives guidance on the design considerations of noise barriers.

N-6000 DETAILED ANALYSIS - NOISE BARRIERS DESIGN CONSIDERATIONS

The primary function of highway noise barriers is to shield receivers from excessive noise generated by highway traffic. While there are other ways to attenuate transportation-related noise, noise barriers are the most reasonable noise attenuation option available to Caltrans.

Many factors need to be considered in the proper design of noise barriers. First of all, barriers must be acoustically adequate. They must reduce the noise as described by policies or standards. Acoustical design considerations include barrier material, barrier locations, dimensions, shapes, and background noise levels. Acoustical considerations, however, are not the only factors leading to proper design of noise barriers.

A second set of design considerations, collectively labeled as non-acoustical design considerations, are equally important. As is often the case, the solution of one problem (in this case noise), may cause other problems such as unsafe conditions, visual blight and lack of maintenance access due to improper barrier design. With proper attention to structural integrity, safety, aesthetics, and other non-acoustical factors, these potential negative effects of noise barriers can be reduced, avoided, or even reversed.

Caltrans Highway Design Manual, Chapter 1100, "Highway Traffic Noise Abatement" should be consulted for specific noise barrier design criteria. As these may change in the future, the discussion in this section of this manual will focus on general applications and consequences of the design criteria, rather than on the criteria themselves.

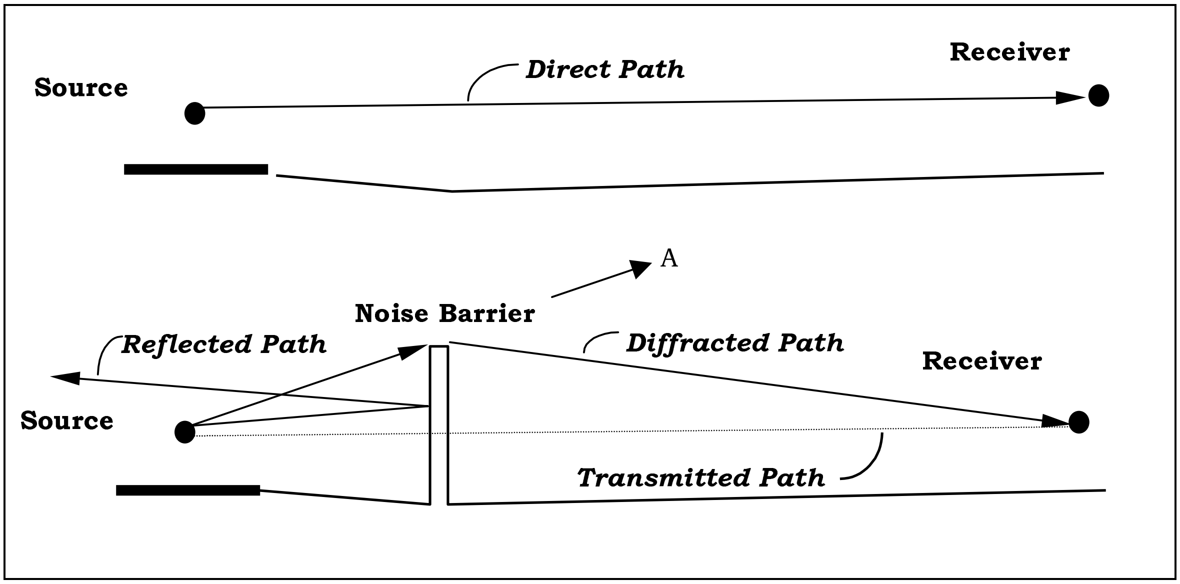
N-6100 ACOUSTICAL DESIGN CONSIDERATIONS

The FHWA models described in Section N-4000 are used for determining proper heights and lengths of noise barriers. The models assume that the noise barriers do not transmit any sound through the barrier. Only the noise diffracted by the barrier, as well as any unshielded segments are considered. The material of the barrier must therefore be sufficiently dense or thick to insure that the sound transmission through the barrier will not contribute to the total noise level calculated by the model at the receiver.

The material, location, dimensions, and shape of a noise barrier all affect its acoustical performance. In order to gain a better understanding of the interaction of these acoustical factors, it is essential to review the concepts of shielding of noise barriers in sections N-2144 and N-5515.1, as well as to introduce some new concepts.

Figure N-6100.1 is a simplified sketch showing what happens to vehicle noise when a noise barrier (sound wall) is placed between the source (vehicle) and receiver. The original straight line path from the source to the receiver is now interrupted by the barrier. Depending on the barrier material and surface treatment, a portion of the original noise energy is reflected or scattered back towards the source. Another portion is absorbed by the material of the barrier, while still another portion is transmitted through the barrier. Notice that the reflected (scattered) and absorbed noise paths never reach the receiver.

Figure N-6100.1 Alteration of Noise Paths by a Noise Barrier

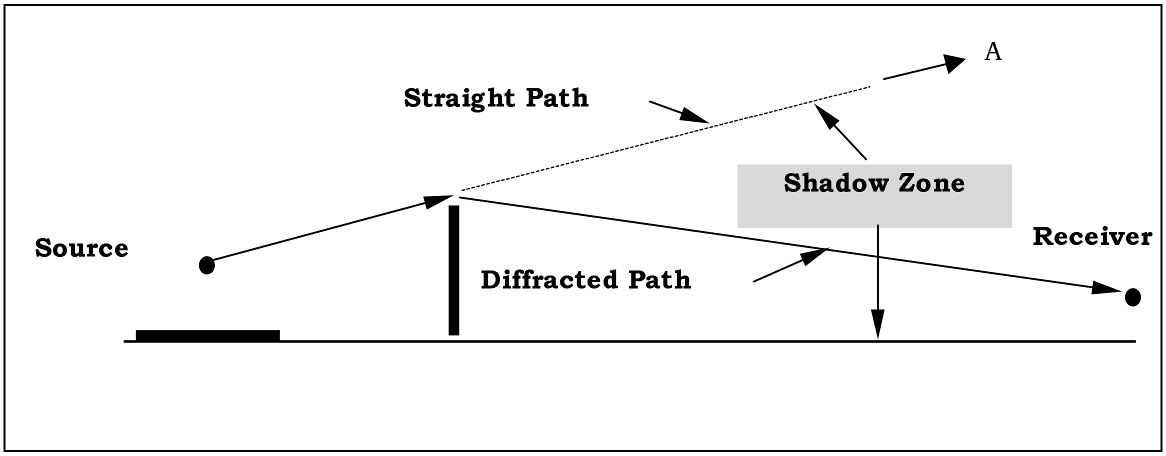


The transmitted noise, however, continues on to the receiver with a “loss” of acoustical energy (acoustical energy redirected and some converted into heat). The common logarithm of energy ratios of the noise in front of the barrier and behind the barrier, expressed in decibels, is called the transmission loss (TL). The TL of a barrier depends on the barrier material (mainly its weight), and the frequency spectrum of the noise source.

The transmitted noise is not the only noise from the source reaching the receiver. The straight line noise path from the source to the top of the barrier, originally destined in the direction of A without the barrier, now is diffracted downward towards the receiver (Figure N-6100.2). This process also results in a “loss” of acoustical energy.

The receiver is thus exposed to the transmitted and diffracted noise. Whereas the transmitted noise only depends on barrier material properties, the diffracted noise depends on the location, shape, and dimensions of the barrier. These factors will be discussed in the following sections.

Figure N-6100.2 Barrier Diffraction



N-6110 Barrier Material, Transmission Loss

For acoustical purposes, any material may be used for a barrier between a noise source and a noise receiver as long as it has a transmission loss (TL) of at least 10 dBA greater than the desired noise reduction. This insures that the only noise path to be considered in the acoustical design of a noise barrier is the diffracted noise path.

For example, if a noise barrier is designed to reduce the noise level at a receiver by 8 dBA, the TL of the barrier must be at least 18 dBA. The transmitted noise may then be ignored, because the diffracted noise is at least 10 dBA greater.

As a rule of thumb, any material weighing 4 lbs/sq ft or more has a transmission loss of at least 20 dBA. Such material would be adequate for a noise reduction of at least 10 dBA due to diffraction; this is the average noise reduction of Caltrans noise barriers. Note that a weight of 4 lbs/sq.ft can be attained by lighter and thicker, or heavier and thinner materials. The greater the density of the material, the thinner the material may be. TL also depends on the stiffness of the barrier material and frequency of the source.

Barrier theory used in the FHWA Model states that the maximum noise reduction that can be achieved is 20 dBA for thin screens (walls) and 23 dBA for berms. A material that has a TL of 33 dBA or greater would therefore always be adequate for a noise barrier in any situation.

Table N-6110.1 gives approximate TL values for some common materials, tested for typical A-weighted traffic frequency spectra. They may be used as a rough guide in acoustical design of noise barriers. For accurate values, consult material test reports by accredited laboratories. These usually accompany literature provided by the manufacturer of the materials.

Table N-6110.1 - Approximate Transmission Loss Values For Common Materials

Material	Thickness	Weight lbs/Sq. ft	Transmission Loss (dBA)
Concrete Block, 8"x8"x16" light weight	8"	31	34
Dense Concrete	4"	50	40
Light Concrete	6"	50	39
Light Concrete	4"	33	36
Steel, 18 ga	0.050"	2.00	25
Steel, 20 ga	0.0375"	1.50	22
Steel, 22 ga	0.0312"	1.25	20
Steel, 24 ga	0.025"	1.00	18
Aluminum, Sheet	1/16"	0.9	23
Aluminum, Sheet	1/8"	1.8	25
Aluminum, Sheet	1/4"	3.5	27
Wood, Fir	1/2"	1.7	18
Wood, Fir	1"	3.3	21
Wood, Fir	2"	6.7	24
Plywood	1/2"	1.7	20
Plywood	1"	3.3	23
Glass, Safety	1/8"	1.6	22
Plexiglass	1/4"	1.5	22

Table N-6110.1 assumes no openings or gaps in the barrier material. Some materials, such as wood, however, are prone to develop openings or gaps due to shrinkage, warping, splitting, or weathering. These openings decrease the TL values. The TL of a barrier material with openings can be calculated if the ratio of area of openings to total barrier area and the TL of the material is known. The following formula can be used to calculate the transmission loss with the openings (TLo):

$$TLo = TL - 10\log_{10}(Ao \times 10^{TL/10} + Ac)$$

where:

TLo= transmission loss of material with openings.

TL = transmission loss of material without openings.

Ao = area of openings as a fraction of the total area of the barrier.

Ac = area of closed portion as a fraction of the total area of the barrier = 1 - Ao

The above method of calculation assumes that the openings or gaps are equally distributed over the surface of a barrier.

For example, a barrier made of 2" thick fir planks has openings that make up about 5% of the total area, and are more or less equally distributed. What is the transmission loss of the material with these gaps?

From Table N-6110.1 it is found that the TL for 2" fir is 24 dBA. The Ao is 5%, or 0.05; Ac is 1-0.05 = 0.95.

$$TLo = 24 - 10Log_{10}(0.05 \times 10^{2.4} + 0.95) = 12.7, \text{ or about } 13 \text{ dBA}$$

The reduced TL could have an effect on the barrier's performance. For example, assume that the before barrier noise level was 75 dBA and the intention was to reduce noise levels by 10 dBA (i.e., the diffracted noise was to be 65 dBA and the transmitted noise 75 - 24 = 51 dBA). The total noise level would have been 65 dBA + 51 dBA = 65 dBA. With the gaps, however, the transmitted noise is now 75 - 13 = 62 dBA, and the total noise level is 65 dBA + 62 dBA = 66.8 dBA. The effectiveness of the barrier is reduced by almost 2 dBA. Instead of a designed noise reduction of 10 dBA, an actual noise reduction of only 8 dBA will be realized in this case.

Properly treated materials will reduce or eliminate noise leakage. For example, lumber should be treated with preservatives that provide proper penetration and do not interfere with any protective coatings (such as paint) to be applied later. The wood should also have a low moisture content, requiring kiln drying after waterborne preservatives have been used. Wood planks should have tongue and grooves deep enough to allow for shrinkage without gaps to maintain a high TL. Such tongue and grooving is usually non-standard.

There are several other ratings used to express the ability of materials in specific construction configurations to resist sound transmission. Two of these are worth mentioning. They are the Sound Transmission Class (STC), and the Exterior Wall Noise Rating (EWNR). Both are most often used in conjunction with indoor acoustics.

STC is universally accepted by architects and engineers. The STC rating uses a standard contour against which the TL values in one-third octave bands are compared in the frequency range between 125 Hz and 4000 Hz. The standard contour is moved up or down relative to the test curve until the sum of the differences between them is 32 dB or less, and the maximum difference at each 1/3 octave center frequency is no greater than 8 dB. The STC is then the TL value of the standard contour at the 500 Hz center frequency.

The disadvantage of the STC rating scheme is that it is designed to rate noise reductions in frequencies of normal office and speech noises, and not for the lower frequencies of highway traffic noise. The STC, however, can still be used as a rough guide, but it should be pointed out that for frequencies of average traffic conditions, the STC is 5 to 10 dBA greater than the TL. For example, material with an STC rating of 35 has a TL of about 25 - 30 dBA for traffic noise.

The EWNR rating scheme is different from the STC, in that it uses a standard contour developed from transportation noise frequencies. It therefore agrees closely with the A-weighted TL for traffic noise.

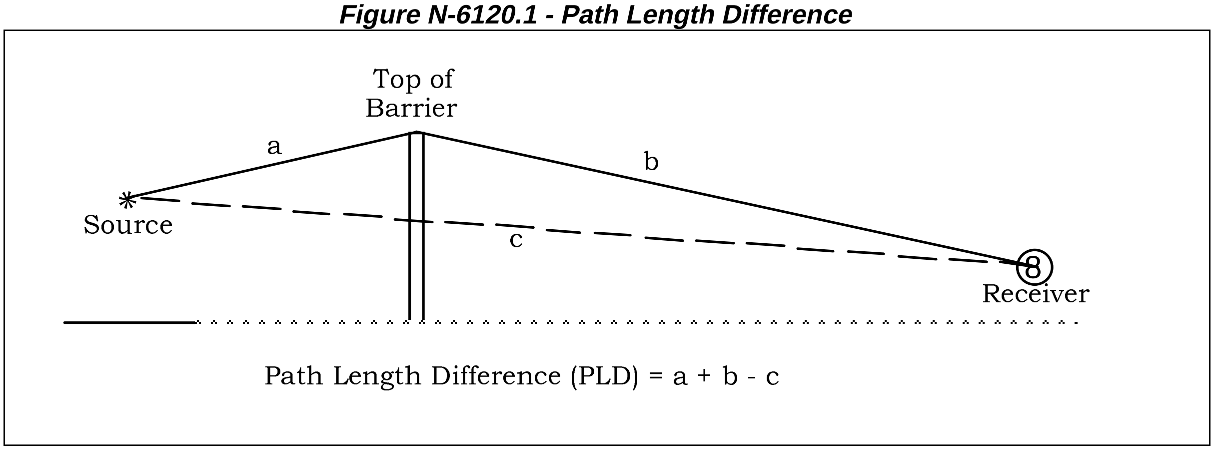
The Federal Highway Administration report, *Insulation of Buildings Against Highway Noise*, FHWA-TS-77-202 provides further useful information for calculating outdoor to indoor traffic noise reductions.

N-6120 Barrier Location

The previous section indicated that by selecting materials with sufficient TL, noise transmitted through a barrier may be ignored since its contribution to the total noise level is negligible (less than 0.5 dBA).

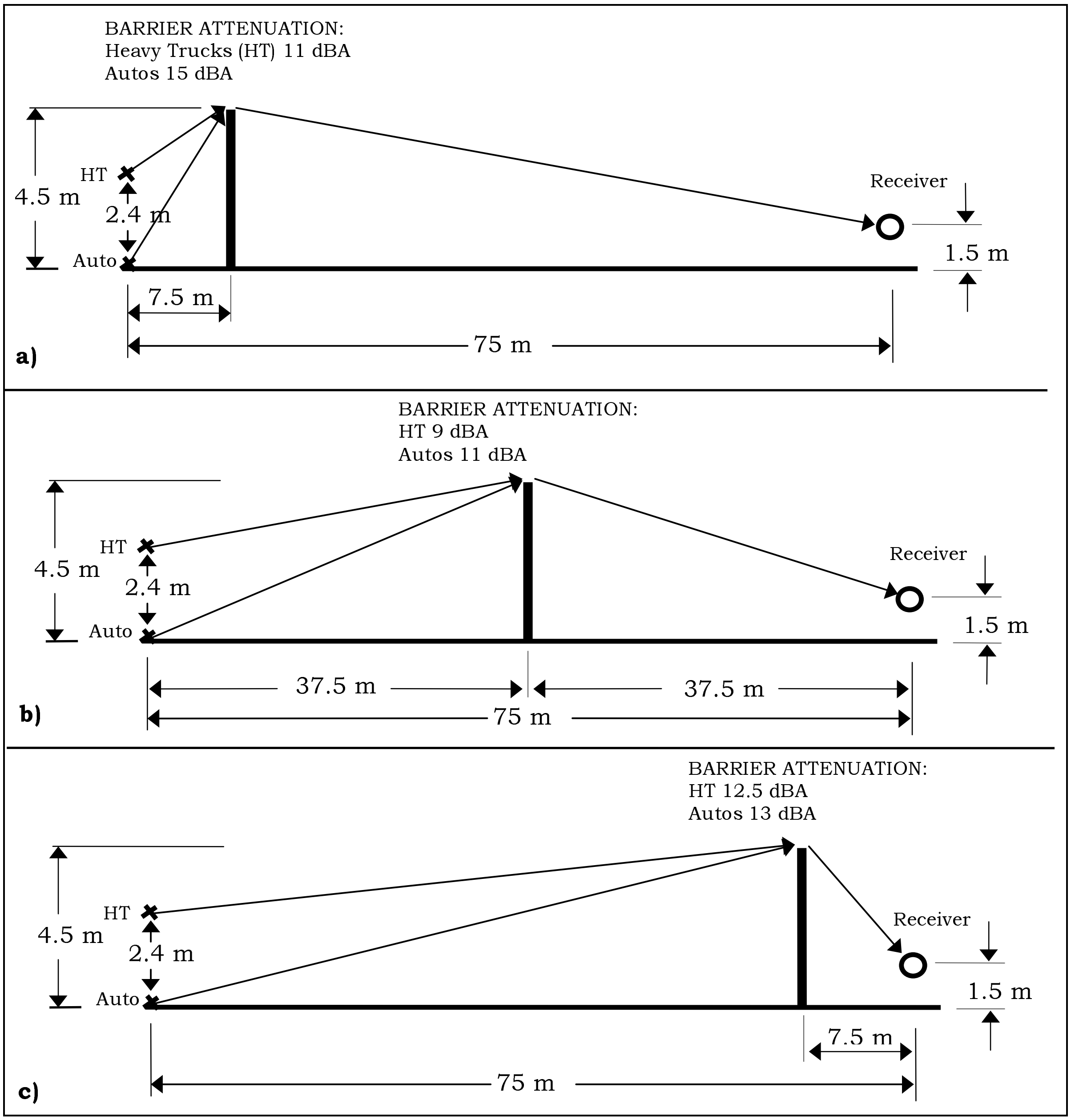
The only remaining noise of concern then, is the diffracted noise. Sections N-2144 and N-5515.1 discussed the basics of diffraction and barrier attenuation. The principal factor determining barrier attenuation is the Fresnel Number, which is related to the path length difference (PLD) between the original, straight line path between source and receiver, and the diffracted path, described by source-top of barrier-receiver. The greater this difference, the greater the barrier attenuation (up to a limit of 20 dB for walls, and 23 dB for berms). Figure N-6120.1 shows the PLD concept.

Figure N-6120.1 - Path Length Difference



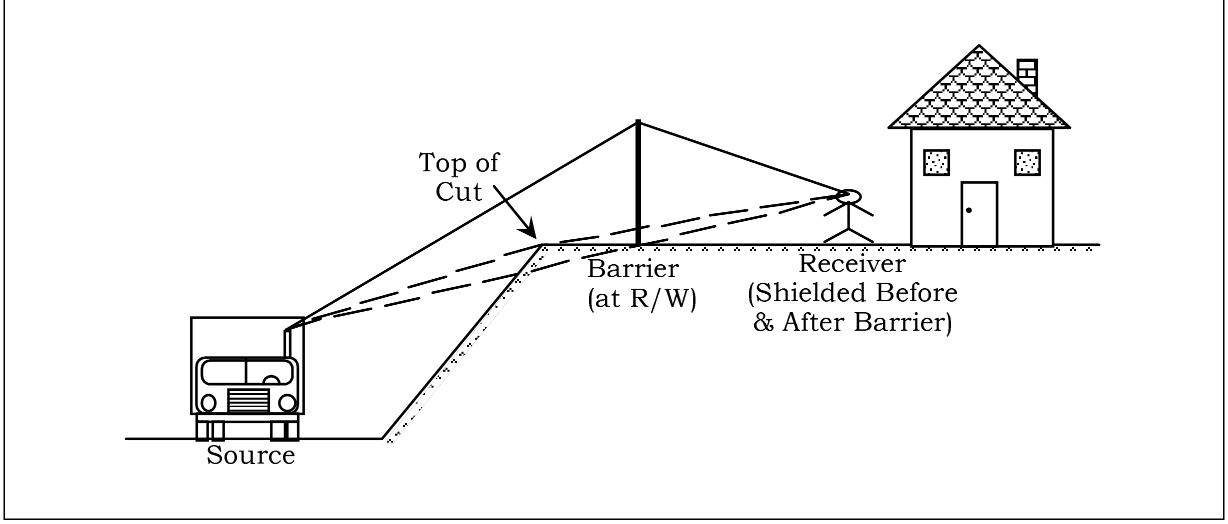
In level, at-grade roadway-receiver cross sections, a noise barrier of a given height provides greater barrier attenuation when it is placed either close to the source, or close to the receiver. The least effective location would be about halfway in between the source and receiver. Figure N-6120.2a), b), and c) shows these situations for two source heights (autos and heavy trucks). Location b) gives the lowest barrier attenuations for a given barrier height.

Figure N-6120.2 - Barrier Attenuation as a Function of Location (at-grade highway). Barrier attenuation is least when barrier is located half way between source and receiver (b). Best locations are near the source (a), or receiver (c).



In depressed highway sections, the barrier is obviously most effective near the receiver on top of the cut (Figure N-6120.3). Note that the without barrier path is generally not a straight path between source and receiver. The top of cut is already a fairly effective noise barrier. The PLD in this case is the difference between the paths described by source-top of barrier- receiver, and source-top of cut-receiver. The barrier attenuation is then calculated from the difference in barrier attenuation provided by the top of cut and the top of the noise barrier.

Figure N-6120.3 - Typical Barrier Location Depressed Highways



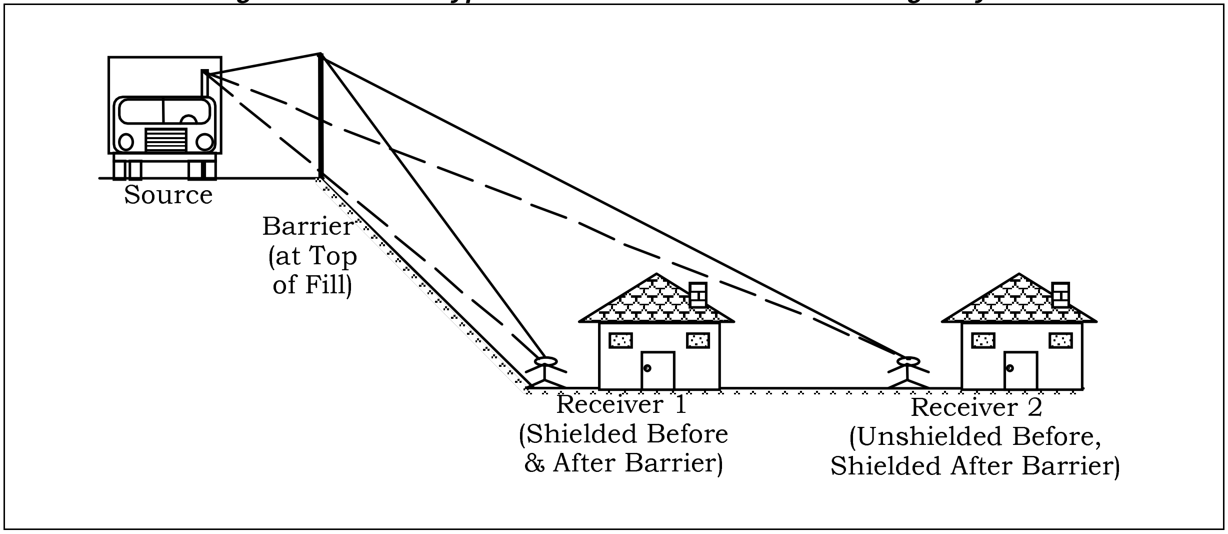
Since the attenuation per incremental increase in barrier height diminishes with the effective height of a barrier (see Sec. N-6130), this difference may be small; noise barriers in depressed highway sections are generally not very effective in reducing noise. This is mostly because the cut section by itself may already be an effective barrier (earth berm).

The most effective location of noise barriers along highways on fills is on top of the embankment, as shown in Figure N-6120.4. Any attempt to place the barrier closer to the receivers will result in a higher barrier for the same or less attenuation. The same holds true for elevated highways on structures. The most effective barrier location from an acoustical standpoint is on top of the structure.

The foregoing discussions point out that the most acoustically effective location for a noise barrier depends on the source to receiver geometry. In most cases, the choices are fairly obvious. To recap the simplest situations:

1. Highway at-grade: barrier location near the edge of shoulder, or at the right-of-way (R/W).
2. Highway in depressed section: barrier at the R/W.
3. Elevated highway on embankment or structure: barrier near edge of shoulder.

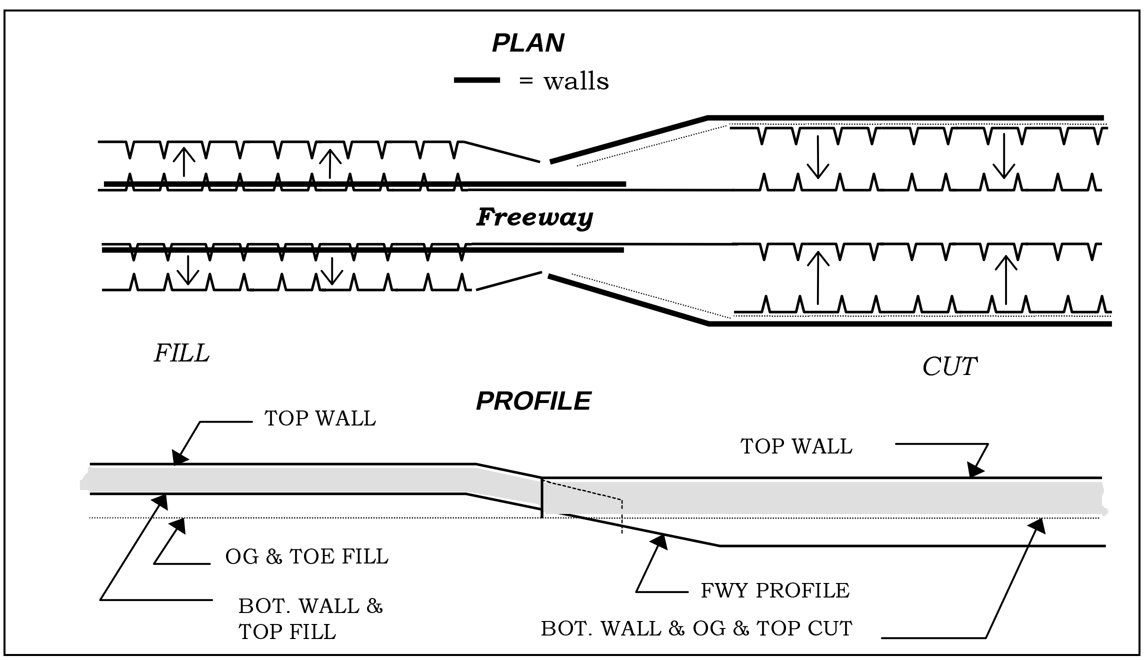
Figure N-6120.4 - Typical Barrier Location - Elevated Highways



In some cases, however, the choices are not so simple. In more complex highway/receiver geometries, the best locations from an acoustical standpoint may not be obvious. They may have to be determined by using the FHWA Highway Traffic Noise Prediction Model, for several barrier location alternatives.

Transitions between cuts and fills, ramps, and interchanges are some examples of cases needing careful consideration. Figures N-6120.5 through N-6120.7 show typical noise barrier locations in some of these transitional areas. Barrier overlaps are often necessary in these cases, as shown in Figures N-6120.5, and N-6120.6.

Figure N-6120.5 Barriers for Cut and Fill Transitions



One of the more common reasons for barrier overlaps are to provide maintenance access to those areas within the R/W that are on the receiver side of noise barriers (Figure N-6120.5). This will be discussed in greater detail in the maintenance consideration portion of this section.

Figure N-6120.6 - Barriers for Highway on Fill With Off-Ramp

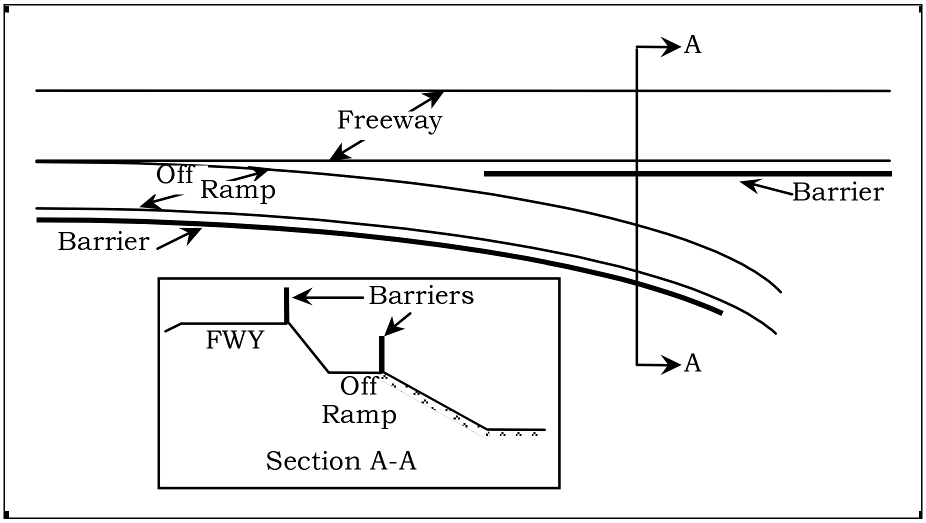
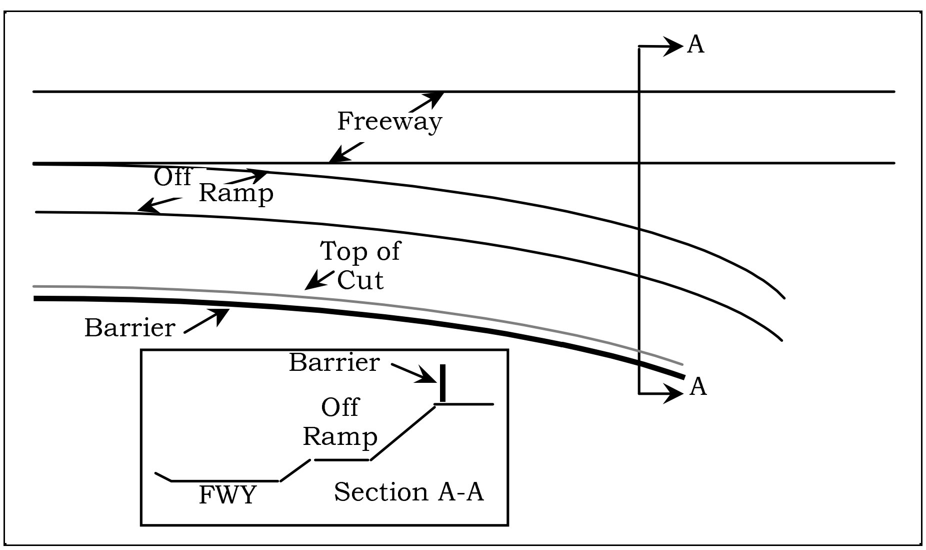


Figure 6120.7   Barriers for Highway in Cut with Off-Ramp



Restrictions on lateral clearances, sight distances and other safety considerations may also dictate final noise barrier locations. The Caltrans Highway Design Manual should always be consulted before finalizing alternate noise barrier alignments.

N-6130 Barrier Dimensions (Height and Length)

Noise barrier dimensions depend largely on freeway geometry, topography of the surrounding terrain, the location of the noise barrier, and the size of the area to be shielded by the barrier. According to sections N-2144 and N-5515, barrier attenuation depends on the path length difference between the direct (before barrier) and diffracted (after barrier) noise paths. Figure N-6120.1 reviewed the concept. Regardless of its orientation, the triangle formed by the source, top of noise barrier and the receiver, will always yield the same barrier attenuation. Since the location of the bottom of the barrier is not part of the triangle, the highway geometry and terrain topography determine how high the barrier should be for a given barrier attenuation. Figure N-6130.1 shows this concept.

Similarly, the length of the barrier is governed by the extent of the area to be shielded and also the site geometry/topography as shown in Figure N-6130.2.

Figure N-6130.1 - Actual Noise Barrier Height Depends on Site Geometry and Terrain Topography (same barrier attenuation for a), b), c), and d)).

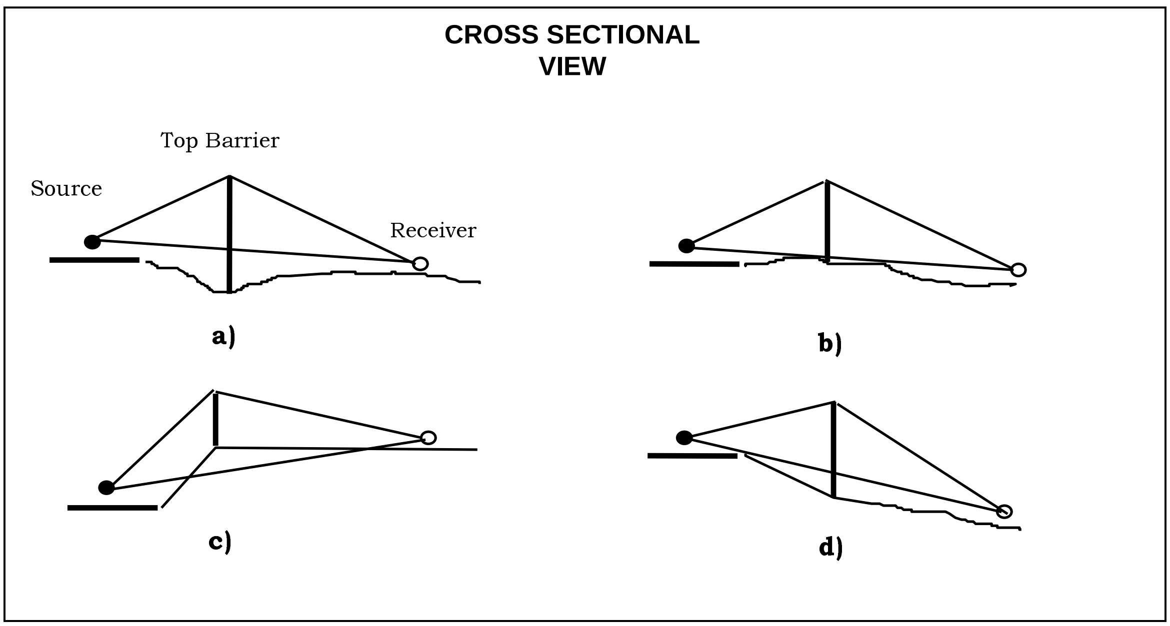
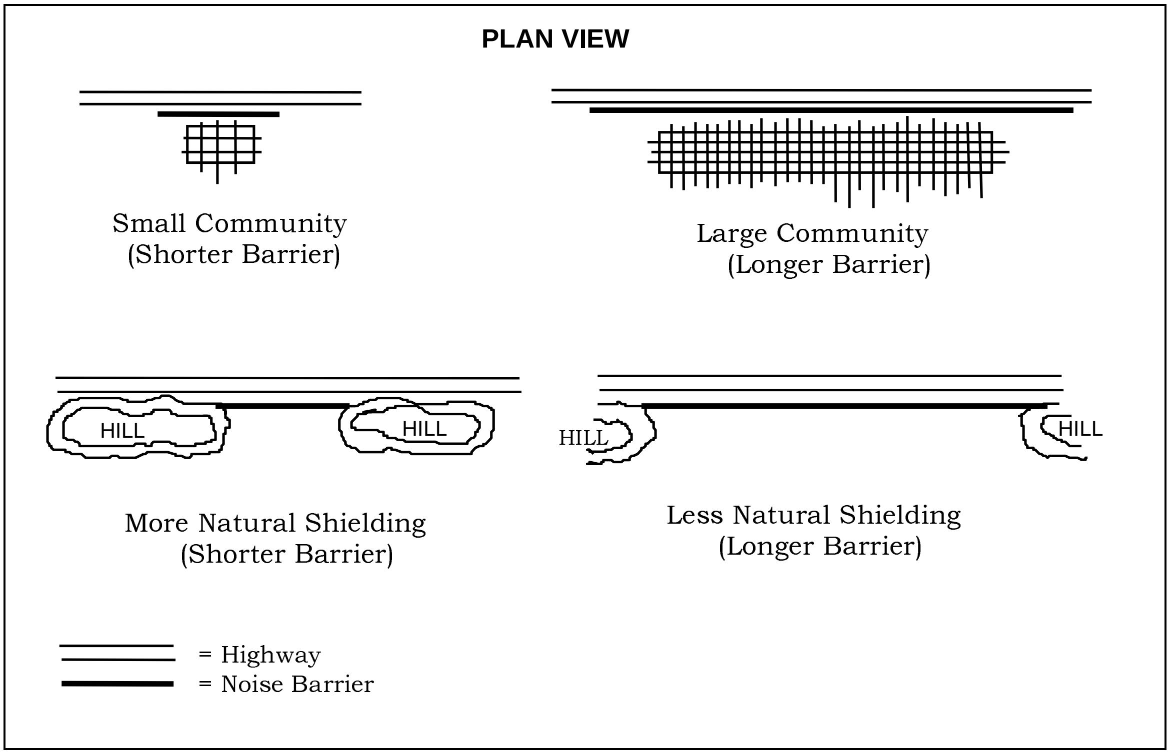


Figure N-6130.2 - Noise Barrier Length Depends on Size of the Area to be Shielded and Site Geometry/Topography

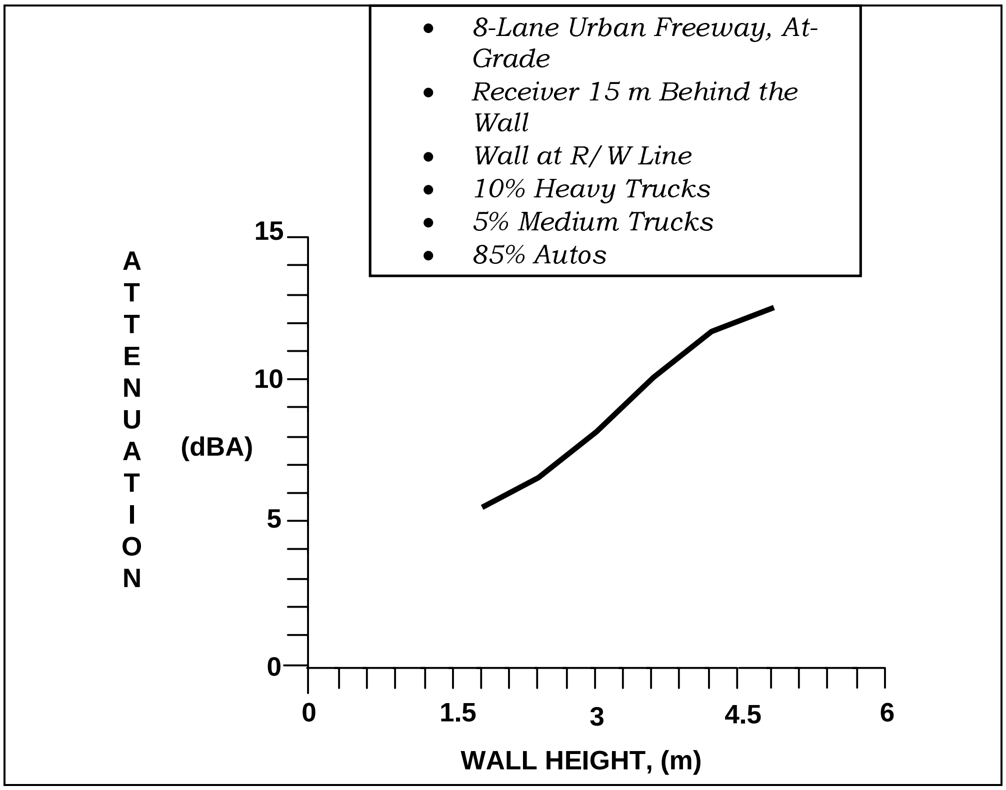


N-6131 Noise Barrier Height

Barrier height generally has the greatest direct influence on the the effectiveness of a noise barrier. Figure N-6120.1 reviewed the PLD concept. An increase in height of a noise barrier will result in a greater PLD and therefore a greater noise attenuation. This increase in height is not linear, however.

Figure N-6131.1 shows the barrier attenuation as a function of wall height at a 1.5 m (5 ft) high receiver, 15 m (50 ft) behind a sound wall located along the R/W of a typical urban at-grade 8-lane freeway. The traffic consists of 10% heavy trucks, 5% medium trucks, and 85% autos. Attenuations are plotted for wall heights from 2 to 5m (6 to 16 ft), representing minimum and maximum heights allowed by Chapter 1100 of the Caltrans Highway <u>Design Manual</u>. Also shown is the height at which the line-of-sight between a 3.5 m (11.5 ft) truck stack and a 1.5 m (5-ft) high receiver is intercepted by the wall. For this particular highway/barrier/receiver geometry this height is 2.75 m (9 ft).

Figure N-6131.1 Sound Wall Attenuation Vs. Height - At-Grade Freeway



Note that in this case, the change in attenuation per incremental change in wall height is highest between wall heights of 2.7 and 3.4 m (9 - 11 ft), at 0.9 dBA per 0.3 m (1 ft). Above and below this range the values are lower. Once the optimum height has been reached, any further increases in noise barrier height result in diminishing returns in effectiveness. However, higher barriers are often necessary to meet design goals.

Noise barriers along depressed freeways are less effective than those along at-grade freeways. In deep cuts, the receiver often is already effectively shielded by tops of cuts. In some cases this shielding may not reduce noise levels enough to satisfy noise abatement criteria, and an additional barrier behind the top of cut may be necessary to achieve further noise reductions.

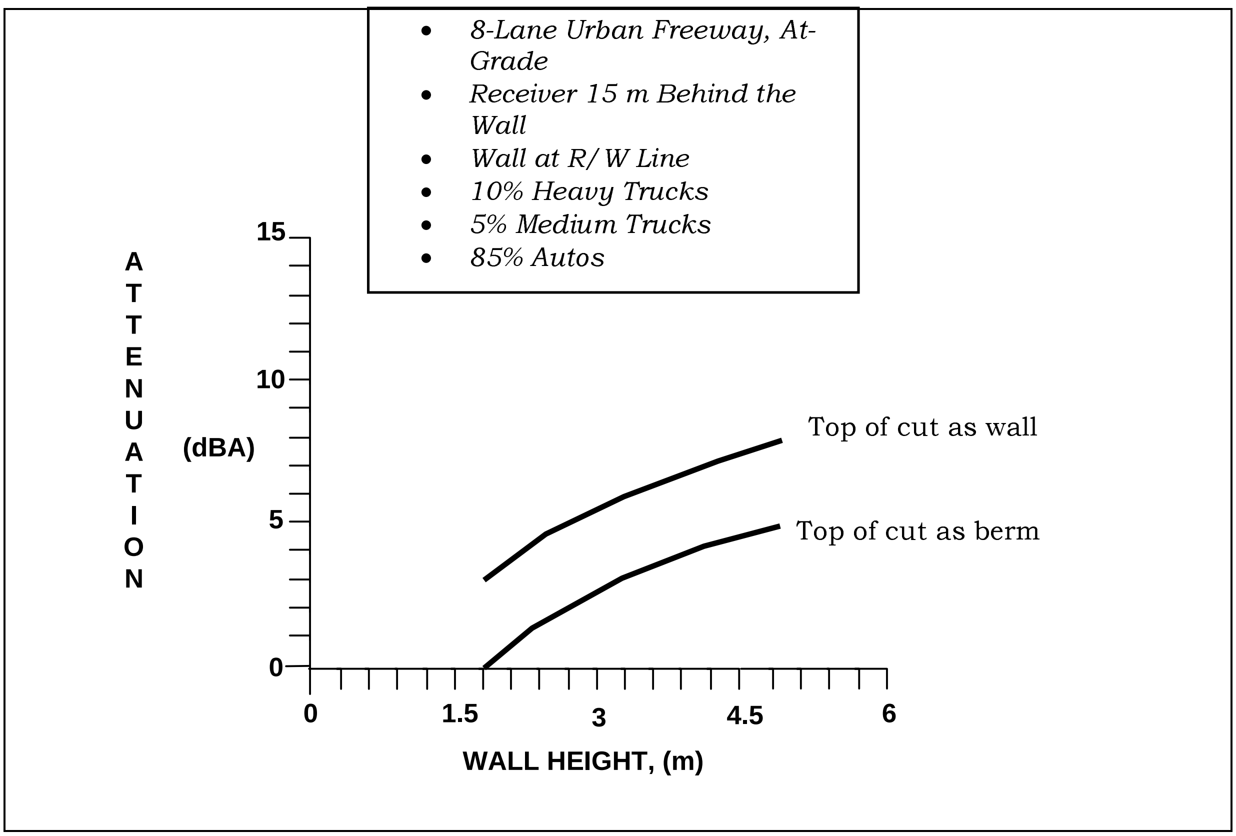
When designing such a barrier, the designer should recognize that the without barrier or *before* condition includes the shielding of the existing top of cut. Because of the before-mentioned diminishing returns effect, a barrier of a given height along a depressed freeway will generally be less effective than a barrier of the same height at-grade. The diminishing return effect, however, is not the only thing to take into consideration.

It has been mentioned that a berm is more effective than a wall. Computer noise prediction models generally give berms 3 dBA more attenuation than a wall of the same height. A wall built at or near the top of cut essentially eliminates the 3 dBA extra attenuation afforded by the original top of cut, thereby further reducing the effectiveness of the wall.

Figure N-6131.2 shows the barrier attenuation vs. height plots for a receiver 15 m (50 ft) behind a barrier located on the R/W of a typical urban 8-lane freeway, in a 7.5 m (25 ft) deep depressed section. The traffic mix is the same as that for Figure N-6131.1, described above. Two attenuation curves are shown.

The upper curve represents attenuation differences between a wall (after construction condition), and the top of cut (before construction condition), in which the latter is treated as an existing wall. Such a condition would exist if a sound wall were built on top of an existing retaining wall: i.e., the top of cut would be the top of retaining wall.

Figure N-6131.2 - Sound Wall Attenuation vs Height, 7.5m (25 ft) Depressed Freeway



Both the before and after conditions would then involve a wall. Likewise, if the before and after conditions consist of berms (built at or near a top of cut), the upper curve would also be a correct representation.

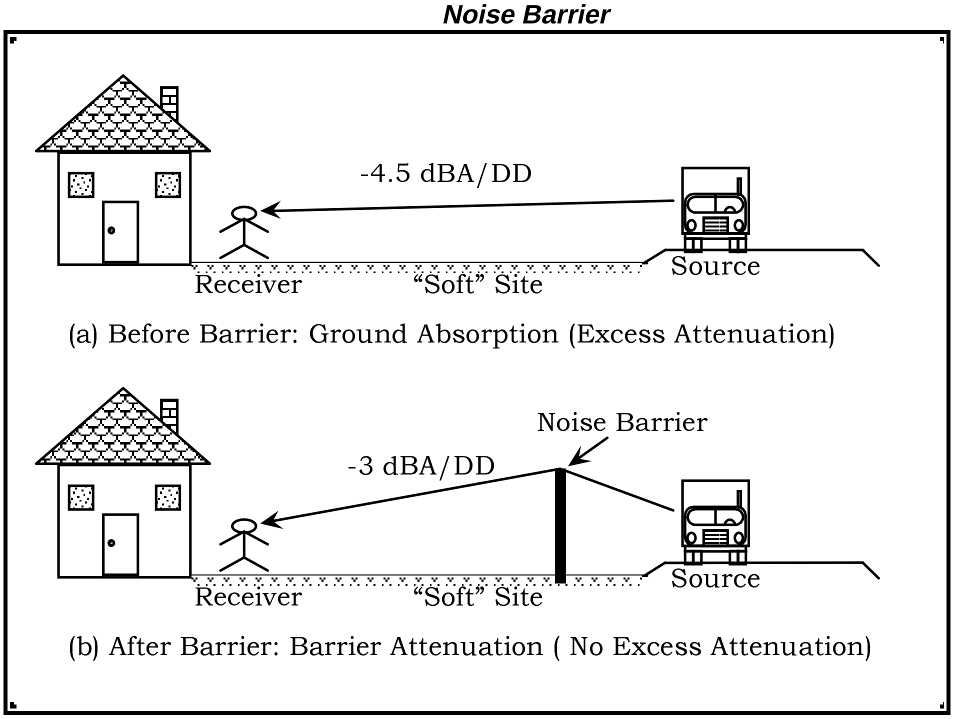
The lower curve consists of attenuation differences between a sound wall and the existing top of cut, with the latter treated as a berm. The additional 3 dBA attenuation provided by the before condition is eliminated by the wall, making it less effective.

A similar phenomenon may also be encountered when freeways are built on embankments. Receivers located near the toe of the fill may be fully or partially shielded from the traffic by the top of the fill or hinge point. For these receivers a wall built on top of the embankment may be less effective than for receivers located farther from the freeway.

The above discussions illustrate the importance of noise source, barrier, and receiver relationships in designing effective noise barriers. These geometries not only affect the barrier attenuation, but also noise propagation in many cases.

Sections N-2140 and N-5513 discussed hard site and soft site characteristics. The excess noise attenuation provided by a soft site is caused by the noise path's proximity to a noise absorbing ground surface. If a noise barrier is constructed between a source and a receiver, the diffracted noise path is lifted higher off the ground. This causes less noise absorption by the ground, and a lesser rate of noise attenuation with distance. Figure N-6131.3 illustrates this concept.

Figure N-6131.3 - Loss of "Soft" Site Characteristics Due to Constructing a Noise Barrier



In (a), the before barrier situation shows a noise attenuation rate of 4.5 dBA per doubling of distance (/DD), in (b), the after barrier attenuation is 3 dBA/DD. The lesser attenuation rate reduces the barrier's effectiveness.

The potential of a barrier to be less effective than indicated by barrier attenuation alone, gave rise to the term *insertion loss*. The insertion loss of a barrier is the net noise reduction provided by a barrier at a receiver. It includes barrier attenuation and before and after barrier differences in noise propagation characteristics: i.e., it is the actual noise reduction caused by inserting a noise barrier between source and receiver. A measured insertion loss is usually referred to as *field insertion loss*.

Finally, another very important height consideration in the acoustical design of noise barriers is a Caltrans requirement to break the line of sight (L.O.S.) between a 3.5 m (11.5 ft) high truck exhaust stack and a 1.5 m (5 ft) high receiver in the first tier of houses. This requirement, detailed in Chapter 1100 of the Highway Design Manual, was intended to lessen the visual and noise intrusiveness of truck exhaust stacks at the first line receiver(s). Barrier heights determined by the noise prediction model often satisfy the acoustical requirements without shielding high truck exhaust stacks. Even though such barriers may reduce noise levels sufficiently in terms of noise abatement criteria, they will still generate complaints from the public The L.O.S. break criterion frequently governs the height of a noise barrier.

The 3.5 m (11.5 ft) height used for truck stacks was determined to be the average height of truck stacks in a 1979 District 7 study, including 1000 heavy trucks measured at a truck inspection station along I-5. This means that the L.O.S. break will shield first line receivers from the exhaust stacks of about half of the the trucks on the highways.

The 3.5 m (11.5 ft) dimension is in no way related to the 2.44 m (8 ft) high noise centroid used for heavy trucks in the traffic noise prediction model, and should therefore not be used for noise predictions. The noise centroids indicated in FHWA-RD-77-108 are the resultant location of the noise sources coming from a truck, not just the noise from the exhaust outlet.

Determining the L.O.S. break is a separate process from predicting noise. Generally, it is desirable to calculate and plot the L.O.S. break profile along the barrier alignment before the acoustical design of the noise barrier. A Caltrans computer program named *LOS* is available for this purpose. If more than one barrier alignment is under consideration, the L.O.S. break must be calculated for each alignment alternative.

The L.O.S. break height depends on the three dimensional location of the 3.5 m (11.5 ft) truck stack, the three dimensional location of the receiver, and the three dimensional location of bottom of the barrier (interface between barrier and ground).

To calculate the L.O.S. break height for a certain source, barrier, and receiver combination the designer needs to determine the critical truck stack lane. This is the lane in which the

3.5 m (11.5 ft) truck stack creates the highest L.O.S. break. Figure N-6131.4 shows a quick method of determining which lane is critical. If the receiver is located above a base line drawn through far and near lane truck stacks, the far lane is critical. If the receiver is located below this line, the near lane is critical, and when the receiver is on the line, either lane is critical. Note that the line need not be horizontal or level.

Chapter 1100 of the Highway Design Manual does not give guidance on whether the entire barrier or just a portion of the barrier should break the L.O.S. for a certain receiver. On one extreme, a series of L.O.S. intercepts can be calculated from one receiver, covering the entire barrier; on the other extreme only one intercept can be calculated using a perpendicular line from the receiver to the barrier or highway. In absence of official policy, it is recommended that a distance of 2D left and right along the centerline of the critical lane, measured from a perpendicular line from the receiver to the lane, be used; where D is the distance from receiver to the lane. Also, it is recommended that the above be further constrained by a maximum distance from receiver to truck stack (Dt) of 500 feet. Figure N-6131.5 shows the recommended constraints.

Figure N-6131.4 - Determination of Critical Lane for L.O.S. Height

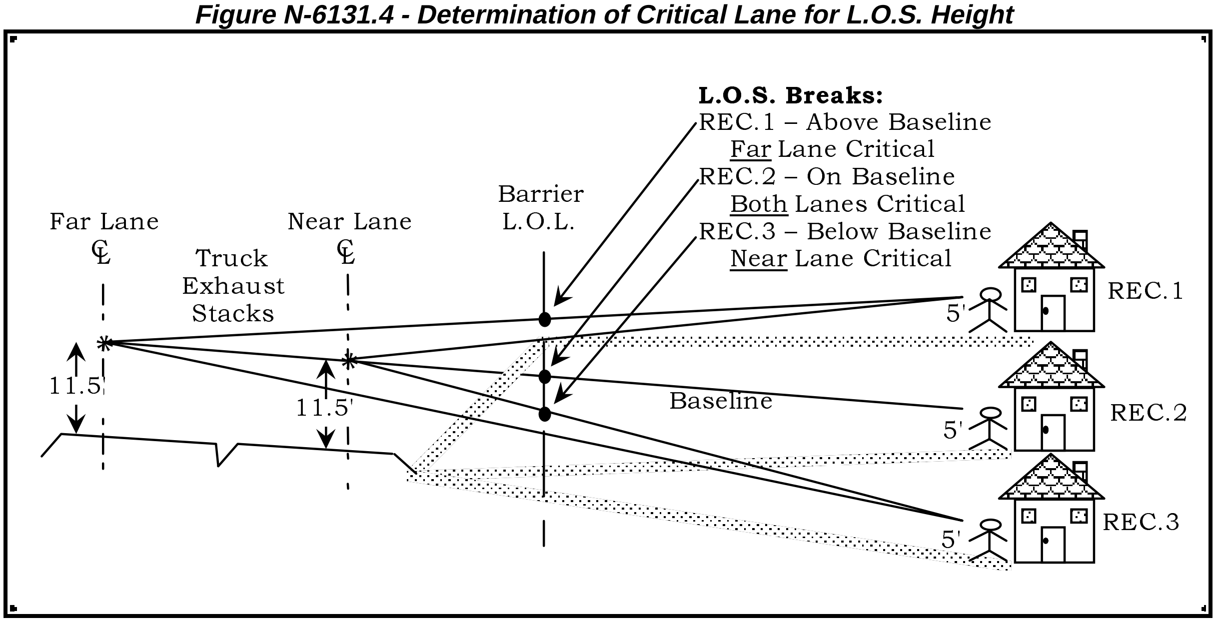
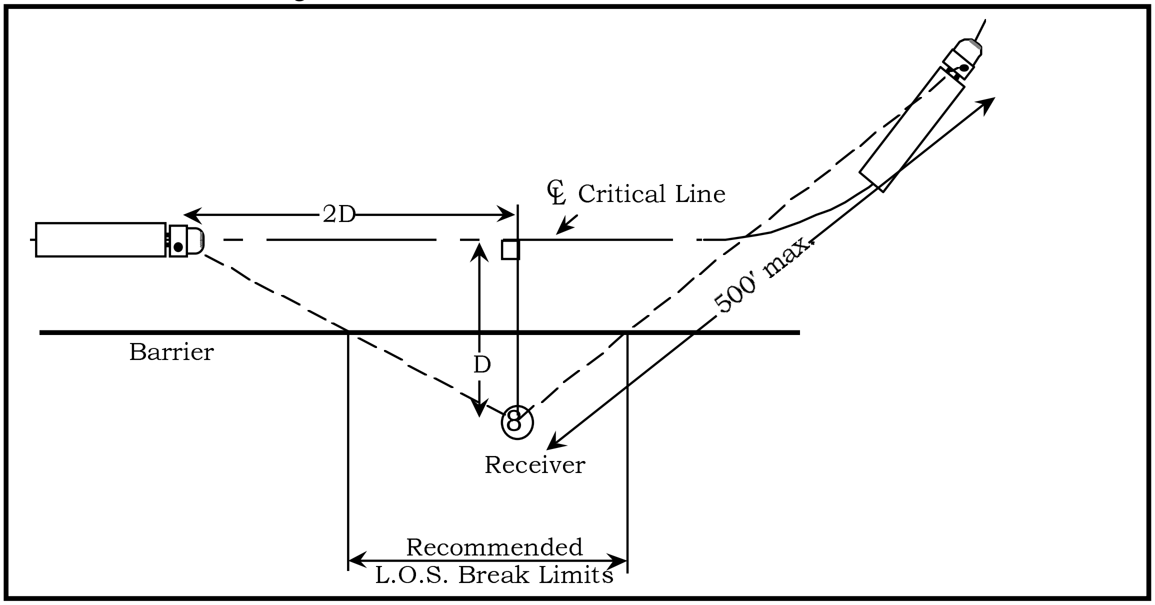


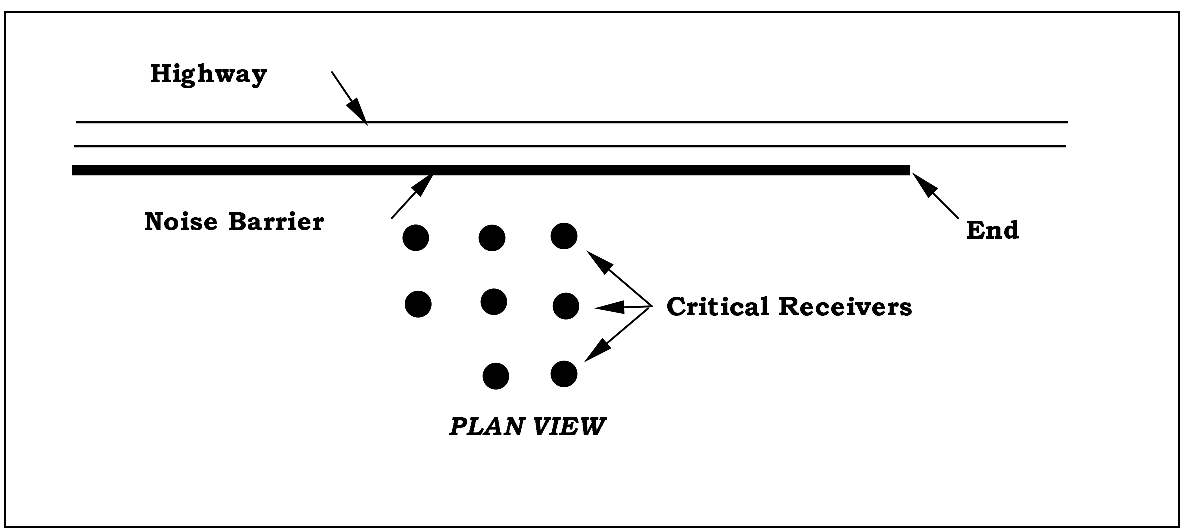
Figure N-6131.5 - Recommended L.O.S. Break Limits



N-6132 Noise Barrier Length

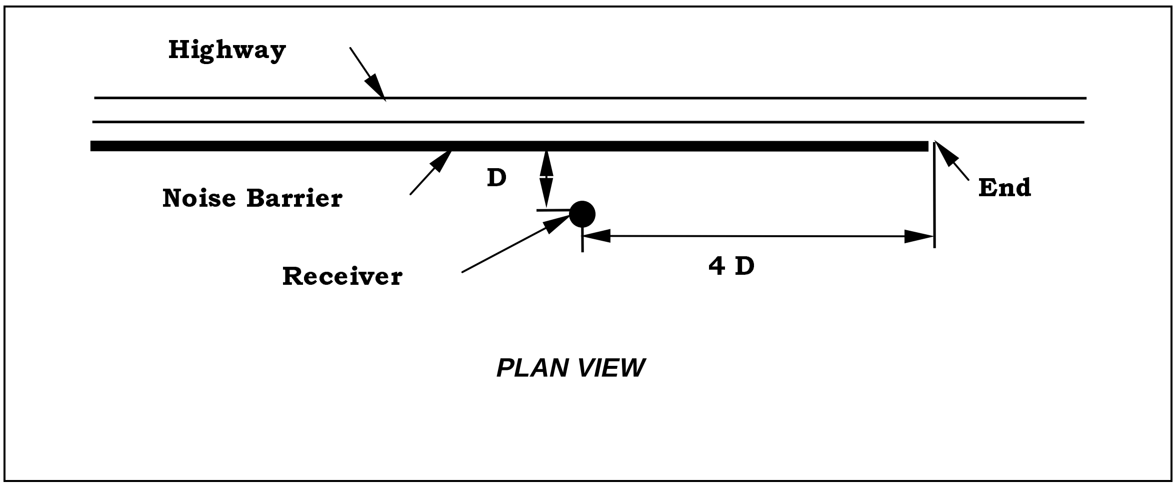
A noise barrier should be sufficiently long to protect the end receivers (See Figure N-6132.1). If the barrier is not long enough the exposed roadway segment will contribute a significant portion of noise energy and sharply reduce the effectiveness of the barrier. For example, if a barrier ends at the receiver, half of the roadway is exposed and the noise reduction by the barrier is 3 dBA or less.

Figure N-6132.1 - Barrier Extended Far Enough to Protect End Receivers



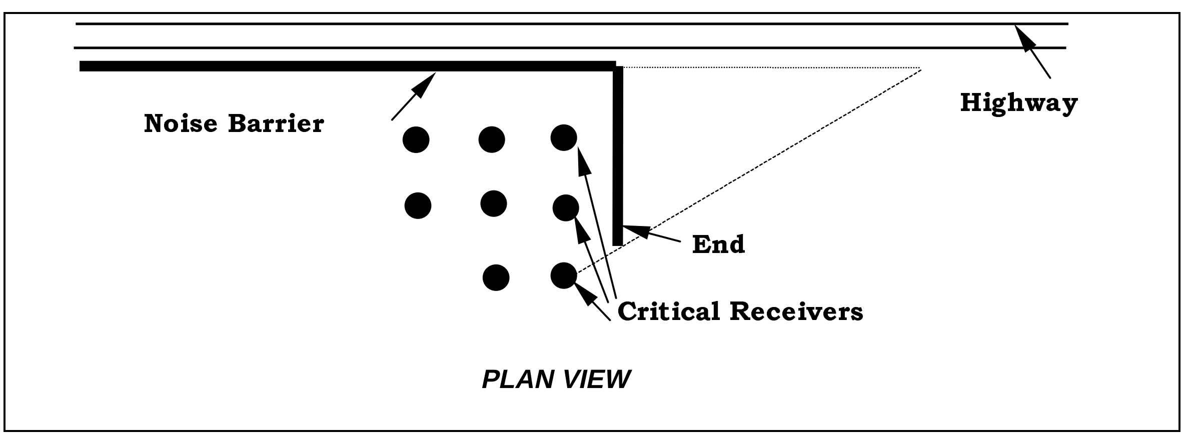
As a rule of thumb, a noise barrier should extend at least 4D beyond the last receiver, where "D" is the perpendicular distance from barrier to receiver (see Figure N-6132.2). The "4D rule", however, should be considered a starting point and the FHWA Model should be used to exactly locate the end of the barrier. Often the critical end receivers are not in the first row of homes, but perhaps several rows farther from the highway as is also shown In Figure N-6132.1. As the barrier to receiver distance increases, the highway noise becomes less, but the barrier segment angle also reduces, which makes a potential noise barrier less effective. The FHWA Model is needed to resolve these opposing factors.

Figure N-6132.2 - The "4D Rule"



Another way of dealing with end receivers is shown in Figure N-6132.3. The barrier is "hooked" around the critical receivers. The obvious advantage of this design is the shorter barrier length compared with the normal barrier extension. The disadvantage is the legal agreements between Caltrans and the private property owners, concerning the construction easements, barrier maintenance and responsibilities.

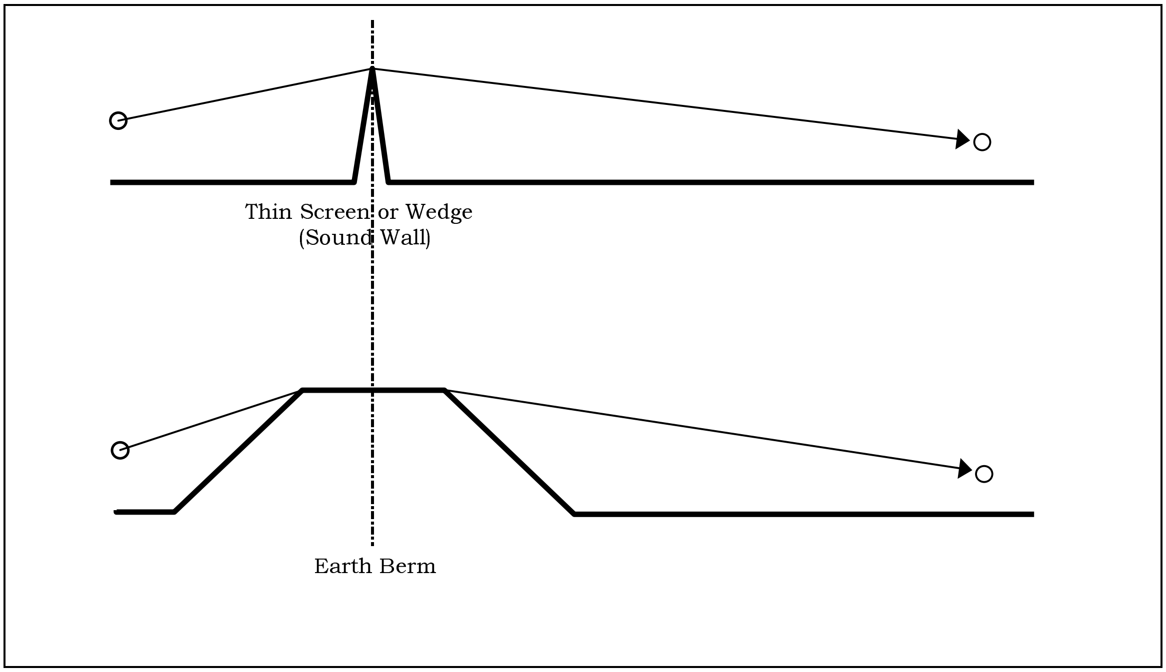
Figure N-6132.3 - Barrier Wrapped Around End Receivers, An Effective Alternative



N-6140 Barrier Shape

Section N-4510 indicated that FHWA Model distinguishes between two noise barrier shapes: the thin screen (wedge) shape, and the earth berm. Figure N-6140 shows representations of the two barrier shapes.

Figure N-6140.1 - Thin Screen Vs. Berm; a Berm Gives More Barrier Attenuation.

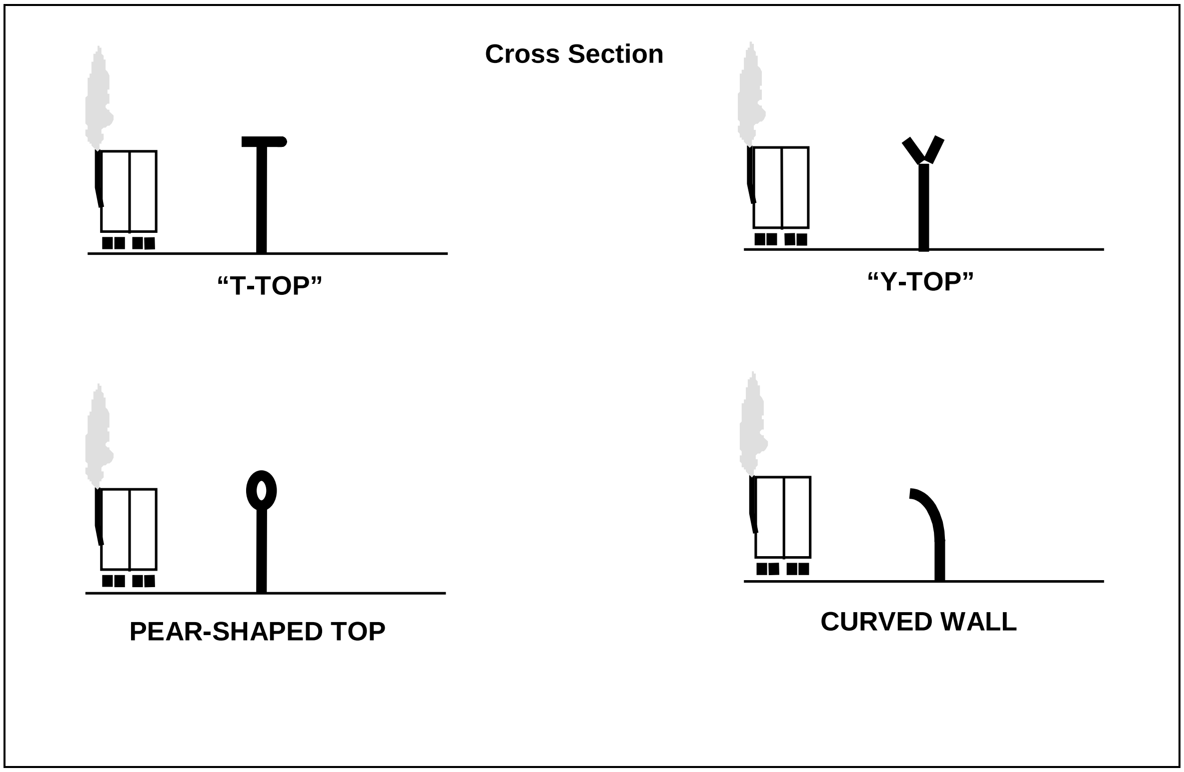


Given the same site cross section, distance between source and receiver, and barrier height, a berm allows a greater barrier attenuation than the thin screen (wedge), such as a sound wall. Although the FHWA assumes 3 dBA more attenuation for the berm than the thin screen, the actual extra attenuation may be somewhere between 1 and 3 dBA.

There are several probable causes for the extra 3 dBA attenuation for a berm. One reason is the shape of the berm. The flat top allows a double diffraction, resulting in a longer path length difference. Another cause may be that the noise path is closer to the ground (berm surface) than that for a thin screen, thus allowing more ground absorption by retaining soft site characteristics.

Other barrier shapes have been researched. These include “T-tops”, “Y-tops, pear shaped tops, curved walls, and others. Given the same total height of wall, these do little to improve barrier attenuation; usually only about 1 or 2 dBA maximum. (Figure N-6140.2 shows some different shapes. The extra cost of constructing these shapes usually does not warrant this small benefit.

Figure N-6140.2 - Various Wall Shapes; Minimal Benefit for the Extra Cost.

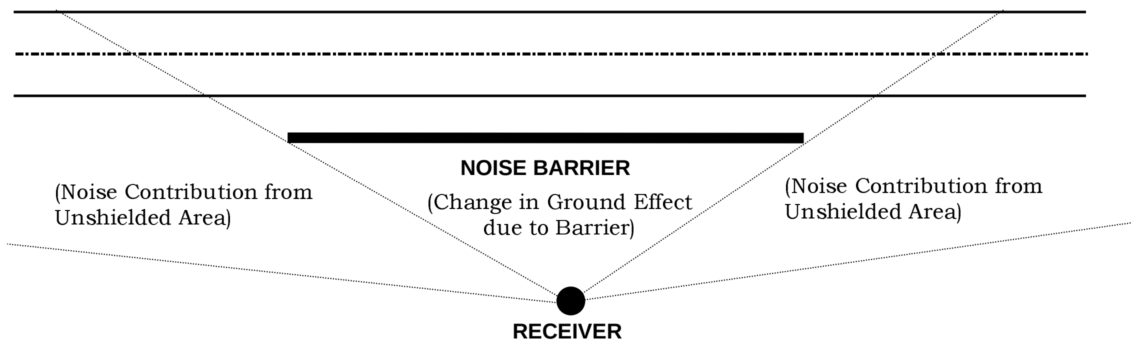


There is also a question of jeopardizing safety with any overhang, especially when the barrier is constructed near the edge of shoulder.

N-6150 Barrier Insertion Loss

In simple terms, barrier insertion loss is the difference in the noise levels before and after a barrier is constructed. It takes into account barrier attenuation, the contributions from unshielded roadway segments, changes in drop-off rates, and interaction with existing barriers (such as reflections, or additional shielding). For example, while the barrier attenuation in Figure N-4530.1 may be 10 dBA, when the change in ground effects and the contribution from the unshielded segments is accounted for the insertion loss is only, say 6 dBA. Section N-6000 "Acoustical Barrier Design Considerations discusses these factors in greater detail.

Figure 6150.1 - Barrier Insertion Loss Vs. Barrier Attenuation



Barrier Attenuation **=** Noise attenuation due to Barrier (diffraction) only.
Barrier Insertion Loss **=** Net effect of Barrier Attenuation, change in Ground Effect, and Noise Contribution from unshielded areas; i.e. *Before - After Barrier Noise Level.*

N-6160 Background Noise Levels

One important factor to be considered (and often overlooked) in noise barrier design is the background noise level within a community. A noise barrier cannot reduce noise levels below the noise level generated by local traffic on surface streets within a community. For instance, if the background level (without the highway) is 65 dBA (at the target receivers), and a proposed project will raise this level to 68 dBA at the same receivers, a noise barrier will not be able to lower the noise level down to below 65 dBA. Therefore, the community "background" noise level should always be added into the predicted noise levels and considered in the noise attenuation design process. Only if it is obvious that the background noise from local sources will not influence the noise barrier's insertion loss (i.e. is at least 10 dBA below the predicted noise level with the noise barrier), can the background noise be ignored.

The following two examples illustrates a method of including existing background noise levels. The first example involves a new facility in a residential area. The second involves a project along an existing facility.

Example 1. New Facility

Background noise level:	60 dBA at Receiver(s)
New facility (w/o background)	<u>68 dBA</u> at Receiver(s)
Total predicted:	69 dBA at Receiver(s)

From the above data we decide to design a noise barrier that will reduce the total noise level by 5 dBA. The model predicts noise levels without the background noise level. Yet, the latter should be accounted for in the total noise attenuation. Thus we must calculate what what predicted noise level is needed to reduce the total predicted noise level to 64 dBA.

Background noise level:	60 dBA at Receiver(s)
Predicted noise level:	?? dBA at Receiver(s)
Total desired noise level:	64 dBA at Receiver(s)

Predicted noise level = 64 dBA - 60 dBA = $10\text{Log}_{10}(10^{6.4}-10^{6.0})$= 61.8, say 62 dBA. The calculated insertion loss should then be 69 - 62 = 7 dBA to reduce the total noise level by 5 dBA.

The next example, involving an existing facility, is more complicated, because the background noise levels at the receivers located near the existing highway are contaminated by noise originating from the highway, and therefore not known. Background noise levels can, however, be estimated from measurements taken throughout the community at sites far enough from the highway to not be influenced by it. (see section N-3221). Once this is accomplished, the problem is essentially the same as example 1.

Example 2. Existing Facility

Background noise level:	60 dBA at Receiver(s) (estimated)
Existing noise level:	65 dBA at Receiver(s) (measured)
Existing noise level:	64 dBA at Receiver(s) (calculated, using the model).
With project noise level	68 dBA at Receiver(s) (predicted, without background)

It is obvious that the existing noise level is contaminated by the background noise level, because the difference between the two is less than 10 dBA . Therefore, model calibration is not allowed, and the predicted with project noise level is used without adjustment, as explained in section N-5600 (Model Calibration, “Cautions and Pitfalls”). The problem is then solved as shown in example 1.

N-6200 NON-ACOUSTICAL CONSIDERATIONS

Final selections of materials, locations, heights, lengths, and shapes of noise barriers include non-acoustical considerations such as safety, aesthetics, and maintenance.

N-6210 Safety

Safety considerations include lateral clearances, sight distance requirements, and guard rail or safety shape barrier requirements. These safety considerations are covered in Chapter 1100 of the Highway Design Manual.

The Office of Structure Design has developed standard sheets for noise barriers (sound walls). These have been distributed to the Districts. The standard designs include the following materials:

- Masonry block.
- Precast concrete panel (with post or mounted on safety shaped barrier).
- Wood (post and plank or framed plywood)
- Metal (ribbed steel).
- Composite beam (Styrofoam and wire mesh core with stucco exterior)

Other designs, retrofit treatments such as noise absorptive paneling, and alterations to noise barriers should be approved by the Office of Structure Design.

The standard sheets also include designs for gates providing emergency access to community fire hydrants, emergency access for stranded motorists, rapid access to accidents, etc.

A minimum height requirement of 1.8 m (6 ft) for sound walls in Chapter 1100 of the Highway Design Manual was partially designed to control pedestrian access to the freeway.

N-6220 Aesthetics

The visual impact of noise barriers on adjoining communities, as well as on the motorists is a major consideration in the design of noise barriers. A high noise barrier placed close to single story residences could have a severe visual effect. A high barrier can also create unwanted shadows, impede natural air flows, or block panoramic views. Chapter 1100 of the Highway Design Manual outlines maximum heights for noise barriers located at distances of 4.5 m (15 ft) or less and more than 4.5 m from the traveled way.

In general, visual dominance of high walls near residences is reduced when the sound wall is located at least 2 - 4 times its height from the nearest receiver. The visual impact is further softened with berms and landscaping (see Figure N-6220.1). Landscaped earth berms are acoustically and aesthetically superior to sound walls. However, in many locations they are not suitable because of space limitations.

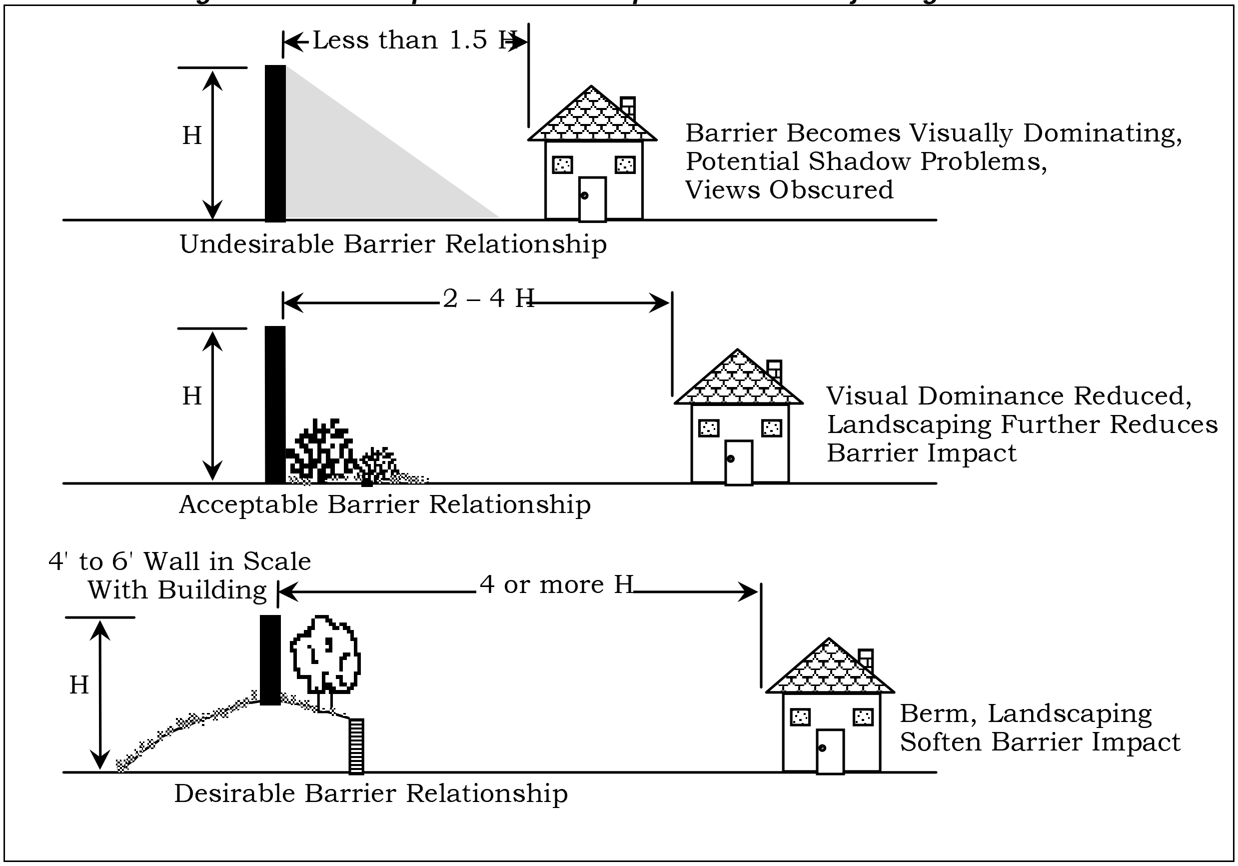
Sound walls should not have abrupt beginnings or endings. Instead they should be tapered or stepped. Only standard aesthetic treatments developed by the Office of Structure Design should be used. If landscaping is to be placed adjacent to the sound wall where it will eventually screen a substantial portion of the wall, only minimal aesthetic treatment is justified.

Walls should as much as possible reflect the character of the surroundings. In cases where the general architecture of a community has a certain character, sound wall material, texture and color should preferably fit this character at the community side of the wall. Ideally, the community should have some input in the aesthetic design of noise barriers.

On the motorist side of the wall the emphasis should be on the overall form of the wall, its color and texture. Small details will not be noticed at normal highway speeds. Instead, the emphasis should be on avoiding a tunnel effect through various forms, and visual treatments. Landscaping can be used effectively to accomplish this.

Further guidance on aesthetics can be found in Chapter 1100 in the Highway Design Manual, and "Instructions for using the Standard Aesthetics Features Sheets". The latter is available from the Aesthetics and Models unit of the Office of Structure Design.

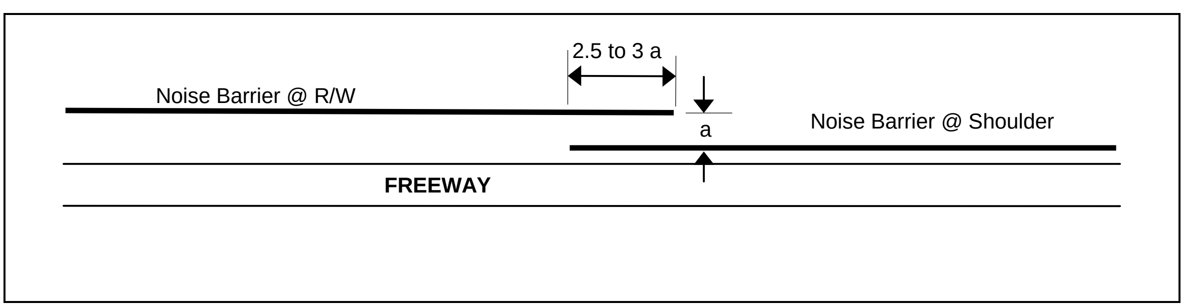
Figure N-6220.1 - Spatial Relationship of Barrier to Adjoining Land Use



N-6230 Maintenance

Access to the back side of noise barriers must be provided if the area is maintained by Caltrans. If access is not available from local streets access gates or openings from the highway must be provided along the noise barrier. Openings created by overlapping barriers must have an overlap distance of at least 2.5 to 3 times the width of the opening (distance between overlapping barriers) (see Figure N-6230.1).

Figure N-6230.1 - Barrier Overlap 2.5 to 3 times the Width of the Access Opening.



The alternate materials selected for noise barriers should be appropriate for the environment in which they are placed. For instance, for walls that are located near the edge of shoulder, the material above the safety-shape concrete barrier should be able to withstand the impact of an occasional vehicle riding up above the top of the safety barrier. Concrete block, cast-in-place concrete, or precast concrete panels are recommended in these locations. In areas of great fire danger, wood barriers should be avoided. See Chapter 1100 of the Highway Design Manual for further information.

N-7000 NOISE STUDY REPORTS

The primary function of a noise study report is to present the methods and results of a traffic noise analysis and the data supporting the conclusions to a target audience that includes both lay persons and technical noise analysts. One way to satisfy both audiences is to provide a summary for lay persons and decision makers, and a technical report for experienced noise analysts, or lay persons desiring more detail than that provided by the summary.

The summary, also called the Executive Summary, should briefly describe existing landuse and noise environment, the project alternatives, future noise environment, traffic noise impacts (if any) and noise abatement/mitgation considered.

The technical report needs to fully support the conclusions that are incorporated into the environmental document and should satisfy technical reviewers who wish to assess the validity of the noise study, including the methods used as well as any assumptions that have been made. Sufficient information should be presented to allow any trained noise analyst to come to the same conclusions.

As is the case with all technical environmental studies, the level of effort to be spend on the noise study report needs to be matched with the size and complexity of the project, and degree of controversy (if any) surrounding it.

N-7100 OUTLINE

Table N-7100-1 shows an outline for a typical noise study report. Not all reports will need this level of effort. On the other hand, some reports may require more information due to special circumstances.

Table N-7100-1 Noise Study Report Outline

I. SUMMARY (OR EXECUTIVE SUMMARY)

- Purpose of noise report
- Brief description of the project
- Brief description of the land use and terrain
- Existing noise levels (ambient and background)
- Future predicted noise levels
- Traffic noise impacts (if any)
- Noise abatement/mitigation considered (range of heights, lengths, insertion losses, and no. of benefited receivers
- Reasonable monetary allowances per benefited receiver for abatement considered
- Areas where abatement/mitigation are not feasible

- Construction noise

Table N-7100-1 Noise Study Report Outline (continued)

II. NOISE IMPACT TECHNICAL REPORT

A. Introduction

1. Purpose of report
2. Background

B. Project Description

1. Detailed description of all project alternatives
2. Maps showing alignment and profiles

C. Fundamentals of Traffic Noise

1. Decibels and frequency
2. Noise source characteristics (vehicles & roadways)
3. Noise propagation
4. Perception at the receiver, A-weighting, noise descriptors
5. Decibel scale

D. Federal & State Policies and Procedures

1. Traffic Noise Analysis Protocol
2. Technical Noise Supplement

E. Study Methods and Procedures

1. Selection of receivers and measurement sites
2. Field measurement procedures: **(Note: field data in appendices)**
   a. instrumentation and setups
   b. noise measurements
   c. traffic counts and speeds
   d. meteorology
   e. data reduction
3. Noise prediction method used:
   a. LEQV2 or SOUND32 based on FHWA RD-77-108 Report and Calveno (FHWA/CA/TL-87/03) Report, or
   b. TNM, based on FHWA-PD-96-009 and – 010 (when mandated)

F. Existing Noise Environment

1. Detailed description of noise sensitive land use
2. Maps showing receivers and noise measurement sites
3. Table showing existing noise levels at receivers:
   a) Field measured results (ambient and background)
   b) Modeled results
4. Discussion on model calibration (if appropriate) for adjusting modeled noise levels (existing or future)

G. Future Noise Environment, Impacts, and Cosidered Abatement/ Mitigation

1. Discuss future traffic data assumptions and site geometry
2. Table showing predicted noise levels, and identification of traffic noise impacts, if any
3. Discussion of noise abatement options

4. Table showing future noise levels and insertion losses (noise reduction) for various noise barrier heights, lengths and locations
5. Table summarizing data necessary for "Reasonableness" determination
6. Discussion of areas where abatement/mitigation is not feasible

Table N-7100-1 Noise Study Report Outline (continued)

H. Construction Noise

I. References

J. Appendices

1. Instrumentation, manufacturer(s),model, type, serial numbers, calibration
2. Measurement site details, instrument setups
3. Measurement procedures, duration, number of repetitions
4. Measured noise data, dates, times
5. Meteorological conditions
6. Traffic counts
7. Data reduction, measurement results
8. Details of computer modeling assumptions, inputs and outputs

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N-7200 SUMMARY (OR EXECUTIVE SUMMARY)

The noise study conclusions should be presented near the front of the Noise Study Report in the form of a summary, also called Executive Summary. The summary of findings and conclusions of the study should be extracted from the technical portion of the noise study report. This requires the technical portion to be written first. The executive summary should target the layperson who is interested in the noise impacts, if any, but does not want to read all of the technical details. Because the author of the Noise Study Report is usually not the same author of the project's environmental document, the executive summary should be written in such a manner, that it can be "cut and pasted" into the environmental document. This will help reduce misinterpretations or loss in translations. The Executive Summary should be short, usually only a few pages. Briefly describe the elements mentioned in the outline (Table N-7100-1). A table listing receivers, existing noise levels, future noise levels without noise barriers, future noise levels with noise barriers (various heights), and insertion loss should be sufficient to summarize the results of the noise study.

N-7300 NOISE IMPACT TECHNICAL REPORT

The noise impact technical portion is the main body of the Noise Study Report. It contains detailed descriptions of why and how the noise study was performed and how the conclusions were reached. Sufficient detail is needed for someone to be able to duplicate the study from the information included in report.

Depending on the size, location and type of project, it may be beneficial to combine the noise report with some of the other technical reports, such as air quality, in order to avoid repetition.

Following are suggested sections of the report with brief descriptions of their contents.

N-7310 Introduction

The introduction should include the purpose of the Noise Study Report, study objectives, and background information such as need for project and need for the study, or any other general information useful to the understanding of the Noise Study Report.

N-7320 Project Description

The project description should include a detailed description of all of the project alternatives. There should be enough information for the reader to understand the project and how it fits into the transportation system of the area. An appropriate location map showing alternative alignments studied and and their spatial relationship with noise sensitive receivers such as residences, schools, hospitals, churches and parks should be included.

N-7330 Fundamentals of Traffic Noise

A short review of the physical principles of traffic noise at the source and its propagation, and subjective human perception will provide a link for lay persons to understand the technical information. The contents of this section may be of standard format or tailored to specific studies.

Briefly describe sound pressure level, the logarithmic nature of decibel units, and frequency (pitch), and the noise characteristics of vehicles. Vehicle noise emissions increase with speed. Increased traffic volumes also increase traffic noise. However it takes a doubling of traffic to increase noise levels by only 3 dB.

Discuss the noise propagation (line source vs point source) over acoustically “hard” and “soft” ground, effects by meteorolgical factors such as wind and temperature gradients, shielding by terrain or noise barriers.

Human perception of noise is also frequency dependent, which leads to a discussion on “A-weighting”, its purpose and its use. Changes in noise levels are perceived as follows: 3 dBA barely perceptible, 5 dBA readily perceptible, and 10dBA perceived as a doubling or halving of noise. Follow this with a discussion on commonly used noise descriptors, such as L_{eq}(h).

Finally, the inclusion of a decibel scale showing a link between everyday activities and associated noise levels will provide the reader with a “yard stick” to evaluate the severity of traffic noise.

The fundamentals of traffic noise discussion need not be restricted to the above items. Other topics may be included as appropriate, some of which may be specifically tailored to the nature of the noise study. The information presented in this TeNS may be beneficial in explaining various phenomena. For instance, where parallel or single noise barrier noise reflections are an issue, it may prove to be beneficial to include selected text of section N-8000, *Special Considerations.*

N-7340 Federal & State Standards and Policies

This section covers the applicable Federal and State standards and policies. Caltrans noise analysis policies are in the Traffic Noise Analysis Protocol and the Highway Design Manual Federal requirements include NEPA and 23CFR772. State requirements and policies are contained in CEQA, California Streets and Highways Code Section 216, and. Terms used in the policies and standards should be mentioned in this section along with the Noise Abatement Criteria (NAC) and their significance, definitions of appropriate noise descriptors, and traffic noise impact criteria.

If the project involves local noise ordinances written in terms of a noise descriptor other than L_{eq}(h) an attempt should be made to equate the noise descriptors rather than duplicating most of the noise report using another descriptor (see Section N-2230 for a discussion of equating worst-hour L_{eq}'s to L_{dn}'s, etc.).

N-7350 Study Methods and Procedures

Study methods and procedures followed should be identified in the Noise Study Report. This section should describe selecting receivers and noise measurement sites, field measurement procedures, and noise prediction methods (Sections N-3000 and N-5000).

The discussion of selecting the receivers and noise measurement sites should focus on why they were selected. Selections are based on expectations of worst noise impacts, geometry of the project, representativeness, acoustical equivalence, and human use (Sections N-3200 and N-5310). The importance of selecting receivers outside the area of project influence must not be overlooked. These receivers are extremely useful for documenting background noise levels and – later, after the project is built - guard against unsubstantiated public claims that noise barriers constructed as part of the project increased noise levels at distant receivers (Section N-8200).

The discussion on field measurement procedures (Section N-3000) should include descriptions of instrumentation, set-ups, noise measurement procedures, traffic counts and speeds, meteorological observations and data reduction methods. Also discuss model calibration procedures (Section N-5400).

Include in the appendices to the noise report the measurement equipment used, calibration information and dates and times of measurements, and measured noise data, traffic counts and speeds, meteorological conditions, site topography, and detailed measurement locations (as a rule of thumb, the microphone locations should be retraceable within one meter horizontally, and 0.3 meter vertically). If measurements were taken at a time different from the worst noise hour, show the adjustment and procedure used (Section N-3312), any receivers modeled and calibrated, and the inputs for these.

Noise level predictions must be based on the methodology in the FHWA Highway Traffic Noise Prediction Model (FHWA-RD-77-108) with California reference energy mean emission (Calveno) levels, or when implemented for use by Caltrans the FHWA Traffic Noise Model (FHWA-PD-96-009 & -010; DOT-VNTSC-FHWA-98-1 & -2),. These, and other documents pertinent to the noise study should be referenced, as appropriate.

N-7360 Existing Noise Environment

Before traffic noise impacts can be evaluated, a detailed knowledge of the existing noise environment is required. A description of the project's surrounding land use (residential, commercial zones, undeveloped land, farm land etc.) should be included in this section. The number and type of receivers involved should be reported so that the reader understands the size and charcteristics of the area under study (e.g. "….approximately 75 first tier single family residences; 5 two-story apartments; 2 grammar schools and 3 parks…" etc. Mention any particularly sensitive land uses. For undeveloped land include future uses if known. Also note the presence of any ather stationary or mobile noise sources, e.g. arterials, airports, etc.

The general topography surrounding the project and any problems in noise measurements or modeling should be pointed out in this section, especially in complicated or unusual situations. A discussion on background noise levels, noise levels unaffected by the existing highway, is also appropriate. The importance of selecting measurement sites to document background noise levels is mentioned in the previous section N-7350.

For each receiver selected for the noise impact analysis, show:

- location or address
- type of development

- the number of units represented by the receiver
- landuse activity category and Noise Abatement Criterion
- existing noise level results (“raw” data should go into appendices)
- whether existing noise level was measured or modeled (predicted); if measured, also indicate if measurement was adjusted to worst hour noise (see Section N-3312); when predicted, indicate if prediction included model calibration (see Section 5400; the details

of the calibration, such as the calibration constant and any explanations of why they were excessiveley large, should be in the appendices).

Table N-7360.1 suggests how the information might be displayed in tabular form. The format shown is only an example. The information may be presented in many other ways, as long as the result is clear, concise and effective.

This section should only show a summary of the results. It is important to mention whether the existing noise levels reflect the worst noise hour, or other time periods. The text should include brief discussions on meteorological conditions during measurements, and meteorological criteria. "Raw" data of noise measurements, traffic counts, speeds, meteorological, site locations and topography should be included in the appendices.

N-7370 Future Noise Environment, Impacts, and Considered Abatement/ Mitigation

This section of the Noise Study Report deals with the future noise environment. A discussion of the assumptions and inputs used for the predicted noise levels is appropriate. Include the source of predicted future traffic volumes (such as: from traffic models, assumed level of service C or D, design hour traffic, etc.), vehicle mix, and speeds. The actual input/output data should be presented in the appendices.

The predicted results for future noise levels, traffic noise impacts, and considered abatement, if any, should be presented in a clear and concise manner. As was shown in Section N-7360, the summary information is most often best displayed in tables. An example of presenting predicted noise levels and impacts is shown in Table N-7370.1. The table shows receivers, receiver type, location, and or address, existing noise levels, predicted noise levels, noise increase or decrease, activity category, NAC, and impact type. Include a project map showing receivers and approximate locations of noise barrier locations considered.

The predicted noise and impact results table covers information for discrete receivers. The information must be expanded to include the entire study area. Table N-7360.1 in the previous section showed how many units were represented by each of the selected receivers. This information can be used to identify areas of traffic noise impacts and the acoustical design of noise barriers, (e.g. length, height, insertion loss). For projects where traffic noise impacts have been identified, show heights and lengths of all feasible noise barriers or other abatement measures, and enough information to determine the reasonable noise abatement allowance per benefitted residence for each noise barrier and height considered. The latter is necessary to determine whether abatement measures are reasonable. Although noise barriers are normally considered for abatement/mitigation, other measures may also be considered (see Protocol, Sec. 5.2), and in some instances a better option.

Table N-7360.1 Existing Noise Levels (Example)

Receiver I.D. No.	Location or Address	Type of Development	Number of Units Represented	Noise Abatement Category and Criterion ( )	Existing Worst Hour Noise Level, Leq(h), dBA	Noise Level Measured* or Modeled**?
1	1234 Elm Street, back yard, center of patio (first row residence)	Residential	15	B (67)	74	Measured
2	4321 Main Street, 5' from façade (first row residence)	Residential	9	B (67)	75	Measured
3	2336 Elm Street, center of backyard (first row residence)	Residential	24	B (67)	73	Modeled
4	3538 Elm Street, center of backyard (first row residence)	Residential	18	B (67)	74	Modeled
5	1212 Church Street, 10' N. of bottom front step	Church	1	B (67)	68	Measured
6	1723 Oak Street, center of front lawn (1/4 mile from the freeway, background noise level)	Residential	24	B (67)	56	Measured
7	1052 Sycamore Drive, middle of cul-de-sac, (1/4 mile from the freeway, background noise level)	Residential	30	B (67)	55	Measured

* Unless otherwise indicated, all measurements shown reflect worst hour noise levels, i.e. they were either measured during the noisiest hour (Section N-3311) or were adjusted to worst hour traffic characteristics (Section N-3312).

** Unless otherwise indicated modeled receivers include a calibration constant (Sections N-3120, N-5330 and N-5400)

Table N-7370.1 - Predicted Traffic Noise Impacts (Example)

Receiver I.D. No.	Type, Location or Address	Development Either Predates 1978, or Project is a New Highway Construction (Yes or No)	Existing Noise Level, Leq (h), dBA	Predicted Noise Level, Leq (h), dBA	Noise Increase (+) or Decrease (-)	Activity Category and NAC, Leq(h)	Impact Type * (S, A/E, CR or NONE)
1	1234 Elm Street, back yard, center of patio (first row residence)		74	75	+1	B (67)	A/E
2	4321 Main Street, 5' from façade (first row residence)		75	76	+1	B (67)	A/E
3	2336 Elm Street, center of backyard (first row residence)		73	74	+1	B (67)	A/E
4	3538 Elm Street, center of backyard (first row residence)		74	75	+1	B (67)	A/E
5	1212 Church Street, 10' N. of bottom front step		68	69	+1	B (67)	A/E
6	1723 Oak Street, center of front lawn (1/4 mile from the freeway, background noise level)		56	56	0	B (67)	NONE
7	1052 Sycamore Drive, middle of cul-de-sac, (1/4 mile from the freeway, background noise level)		55	55	0	B (67)	NONE

* **Impact Type:** **S** = **Substantial Increase (12 dBA or more)**
A/E = **Approach or Exceed NAC**
CR = **Class Room Noise (Sec 216 of Streets & Hwys Code)**

If noise barriers are be considered for the project, include in tabular form the future noise levels and noise insertion losses for various barrier heights, or alternate locations (such as: "…. At the shoulder", or: ….at the R/W". An example is shown in table N7370-2.

Section 2.8 of the Protocol discussed the procedure for determining the preliminary reasonableness of noise abatement. The process requires various inputs (for details, refer to Section 2.8.2.), most of which have been discussed. Table N-7370-3 is an example of how this information may be displayed.

The Protocol, particularly Section 2.9, 3, and 4 discuss further reporting requirements for draft and final environmental documentation.

Point out that barrier heights and locations are preliminary and subject to change (see Protocol Section 2.9.

If appropriate, it should be mentioned that noise barriers under consideration can have their own negative impacts. Barriers may interfere with the passage of air, interrupt scenic views, or create objectionable shadows. They can also create maintenance access problems, make it difficult to maintain landscaping, create drainage or snow removal problems and provide pockets for trash and garbage to accumulate. In certain circumstances they may raise concerns about safety by blocking areas from the view of patrolling police. Noise barriers can also raise concerns about traffic safety by reducing stopping or merging sight distance, or by reducing errant vehicle recovery room.

Include discussions and justifications for any locations where a noise impact has been identified, but where no feasible mitigation measures are available.

Table N 7370-2 - Noise Abatement
Predicted Noise Levels, $L_{eq}(h)$ and Insertion Loss (I.L., Noise Reduction), dBA For Sound Wall 1, at R/W.
(Example)

Receiver I.D.No.	W/o Wall	With Wall H=6' (1.8 m)		With Wall H=8' (2.4 m)		With Wall H=10' (3.0 m)		With Wall H=12' (3.7 m)		With Wall H=14' (4.3 m)		With Wall H=16' (4.9 m)	
		Leq(h)	I.L.	Leq(h)	I.L.	Leq(h)	I.L.	Leq(h)	I.L.	Leq(h)	I.L.	Leq(h)	I.L.
1	75	70	5	69	6	68*	7	66	9	65	10	64	11
2	76	70	6	69	7	68*	8	67	9	65	11	64	12
3	74	70	4	69	5	68*	6	66	8	65	9	63	11
4	75	70	5	69	6	68*	7	66	9	65	10	64	11
5	69	65	4	64	5	63*	6	61	8	60	9	59	10
6	56	56	N/A**	56	N/A**	56	N/A**	56	N/A**	56	N/A**	56	N/A**
7	55	55	N/A**	55	N/A**	55	N/A**	55	N/A**	55	N/A**	55	N/A**

- * **Breaks Line of Sight between 11.5 ft (3.5 m) truck stack and 5 ft (1.5 m) high receiver in the first row of residences.**
- ** **N/A = Not applicable (no barrier considered)**

Table N-7370-3 - Data For Reasonableness Determination (Example)

SOUND WALL I.D.: SW-1						
PREDICTED, W/O SOUND WALL						
Absolute Noise Level, L_{eq}(h), dBA*	75					
Build Vs. No-build, dBA*	+1					
PREDICTED, WITH SOUND WALL	**H=1.8 m**	**H=2.4 m**	**H=3.0 m**	**H=3.7 m**	**H=4.3 m**	**H=4.9 m**
Loss (Noise Reduction), dBA*	5	6	7	9	10	11
No. of Benefited Residences	24	24	24	48	72	96
New Highway, or More Than 50% of Residences Predate 1978? (Yes or No)	NO	NO	NO	NO	YES	YES
Reasonable Allowance Per Benefitted Residence	$21,000	$23,000	$23,000	$25,000	$35,000	$35,000

***At critical receiver(s)**

SOUND WALL I.D.: SW-2						
PREDICTED, W/O SOUND WALL						
Absolute Noise Level, L_{eq}(h), dBA*	74					
Build Vs. No-build, dBA*	+1					
PREDICTED, WITH SOUND WALL	**H=1.8 m**	**H=2.4 m**	**H=3.0 m**	**H=3.7 m**	**H=4.3 m**	**H=4.9 m**
Insertion Loss (Noise Reduction), dBA*	4	5	6	8	9	11
No. of Benefited Residences	0	24	24	48	48	96
New Highway, or More Than 50% of Residences Predate 1978? (Yes or No)	NO	NO	NO	NO	NO	YES
Reasonable Allowance Per Benefitted Residence	Not Feasible	$19,000	$21,000	$21,000	$23,000	$33,000

***At critical receiver(s)**

N-7380 Construction Noise

Construction noise impacts and likely abatement measures thereof (if necessary) should be discussed briefly. Unless the project involves construction activities that are likely to generate unusually high noise levels such as pile driving or pavement breaking, the discussion should be brief and concise. Detailed discussions of typical construction equipment noise levels are probably not necessary unless there are unusually sensitive receptors involved, or if the project is controversial.

N-7390 References

Typical references may include NEPA, CEQA, 23 CFR 772, Traffic Noise Analysis Protocol Highway Design Manual Chapter 1100, FHWA-RD-77-108 or (when TNM is mandated) FHWA-PD-96-009 & -010, DOT-VNTSC-FHWA-98-1 & -2, and other appropriate documents.

N-7400 APPENDICES

Include in the appendices any details that would support the conclusions of the Noise Study Report. Examples are instrumentation used, calibration data, field measurement data, site details and computer modeling input assumptions and results. If the analysis includes model calibrations (Section N-5400) these should be shown in simple table form (see Table 7340.1) Ideally the appendicies should fill in all of the details that are not in the main report such that the analysis could be repeated.

Table N-7340.1 Model Calibration (Example)

Receiver I.D.	Measured Noise Level, Leq(h), dBA	Predicted Noise Level, Leq(h), dBA	Calibration Constant, K (Meas-Pred), dBA
1	68	70	-2
2	66	69	-3
3	70	71	-1
4	69	72	-3

If measurements were taken at a time different from the worst noise hour, show the adjustment and procedure used (Section N-3312), any receivers modeled and calibrated, and the inputs for these.

N-8000 SPECIAL CONSIDERATIONS

This chapter is devoted to special considerations arising from certain site geometries, noise barrier configurations, intervening terrain, distant receivers, interactions with meteorology, and abnormal traffic conditions. Any one or more of these factors can affect noise measurements, analysis, and barrier design, with results that are predicted with more than routine methods.

Continuing research by Caltrans and others have provided some answers to these problems. However, there is a continued need for field research to verify prediction algorithms in new prediction models, alter those in existing ones, and investigate conditions which lead to newly identified problems.

The "special considerations" covered in this chapter include reflected noise and noise barriers, distant receivers, multiple barriers, and dealing with stop-and-go traffic.

N-8100 REFLECTED NOISE AND NOISE BARRIERS

Section N-6100 "Acoustical Design Considerations" briefly discussed the possibility of noise reflections by a single noise barrier causing noise problems at the opposite side of the highway. This is just one of the issues raised in recent years concerning negative effects of noise barriers. As is often the case, the solution of one problem gives rise to the possibility of creating other problems. In the case of noise barriers, reducing noise at receivers on one side of the highway could potentially increase the noise at receivers on the other side. The complex nature of noise barrier reflections, the difficulties in measuring them, and the controversy surrounding the significance of their impacts deserve a detailed discussion.

More noise barriers have been constructed in California than in any other state, in many different configurations of alignment, profile, and height. These barriers are located along one or both sides of highways of different widths, along ramps, connectors and interchanges, in urban, suburban, and sometimes rural regions under varying traffic conditions. The receivers for which they were designed are located in many different types of terrain, topography, and climatic conditions. The combinations and permutations associated with the vast variety of conditions inevitably increase the possibilities of creating controversies over the extent of noise reflections by barriers. Hence, it is only natural that noise reflection issues are on the rise in California, especially since almost all California barriers are made of noise reflective material with hard, relatively smooth surfaces (masonry, concrete). In most cases, the alleged noise increases due to reflections turn out to be so small that most people do not notice them. The people that do perceive increases in noise are usually suddenly made aware of freeway noise by some event that triggers the awareness, such as the construction of the noise barrier. Measured increases due to noise reflections of more than 2 dBA have never been measured by Caltrans, however, claims of 10 and even 20 dBA increases have occasionally been made.

Many of the alleged increases in noise were actually due to changes in meteorology. Atmospheric refraction due to wind shear and temperature gradients can account for 10 to 15 dBA variations when the same sources are measured from distances of 1.5 to 3 km (approximately 1 to 2 miles). In order to measure the effects of noise reflections, before and after barrier noise measurements have to be carefully matched by wind speed, wind direction, temperature gradients, air temperature, humidity, and sky cover. Likewise, if a person perceives a noticeable increase in noise levels due to a reflective noise barrier, he/she must be able to compare it mentally with a before condition that included the same meteorology. Needless to say, this process is very unreliable.

Section 8100 covers various aspects of noise reflection concerns in detail. The following classifications of reflective noise with respect to noise barriers and other structures will be discussed:

1. Single barrier (on one side of a highway)
2. Parallel barriers (on both sides of the highway)
3. Structures and canyon effects

When compared to reflections measured under similar conditions, results of theoretically modeled noise reflections normally show higher values. This over prediction of reflection models has been attributed to the inability of models to accurately account for all the variables, such as interactions with atmospheric effects and the unknown degree to which traffic streams interfere with reflections.

Reflective noise is not peculiar to noise barriers. Retaining walls and other structures reflect noise in the same manner as noise barriers do. The principles discussed in this section can be applied to reflective barriers, reflective retaining walls, or any other smooth, continuous and hard surface.

N-8110 Single Barrier Reflections

N-8111 Simple Terrain

Figure N-8111.1 is the simplest, two-dimensional representation of single barrier reflections. The presence of a reflective barrier on the opposite side of an at-grade highway essentially doubles the acoustic energy at the receiver. In addition to the direct noise "ray" "d", the barrier reflects a noise ray "r" of roughly the same acoustic energy (actually ”r” is longer than “d” and will result in slightly less acoustical energy). Theoretically, only one reflective ray reaches the receiver, because the angle of incidence equals the angle of reflection (both are depicted as ? in Figure N-8111.1). Thus, even if they are equal, “r” and “d” cause a doubling of energy increases the noise level by 3 dB at the receiver.

Figure N-8111.1 - Single Barrier Reflection (Simplest Representation)

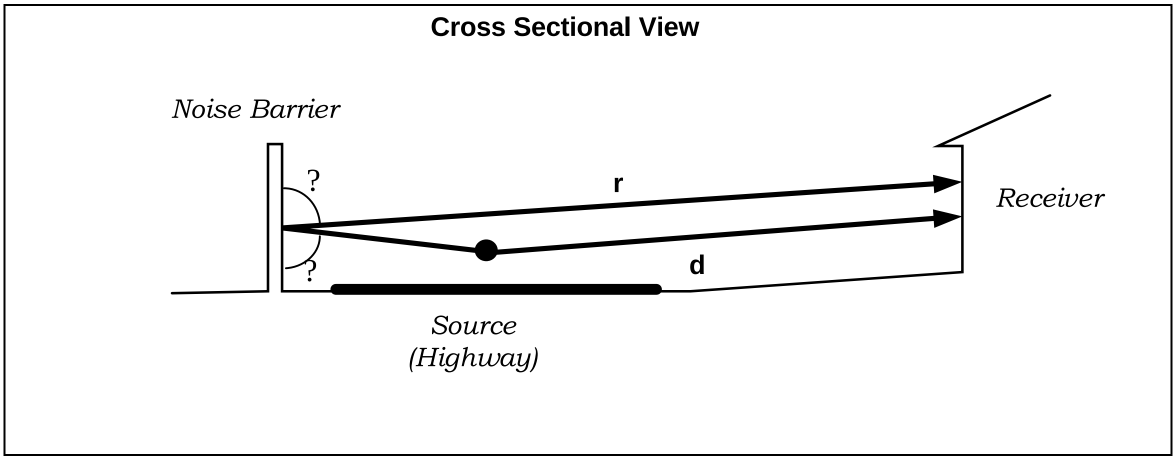


Figure N-8111.2 shows that for an infinite line source and noise barrier the reflections are also an infinite line source. At each point along the highway there is only one reflection ray that reaches the receiver and for which the angle of incidence equals the angle of reflection.

Figure N-8111.2 – Single Barrier Reflections – Infinite Line Source and Noise Barrier

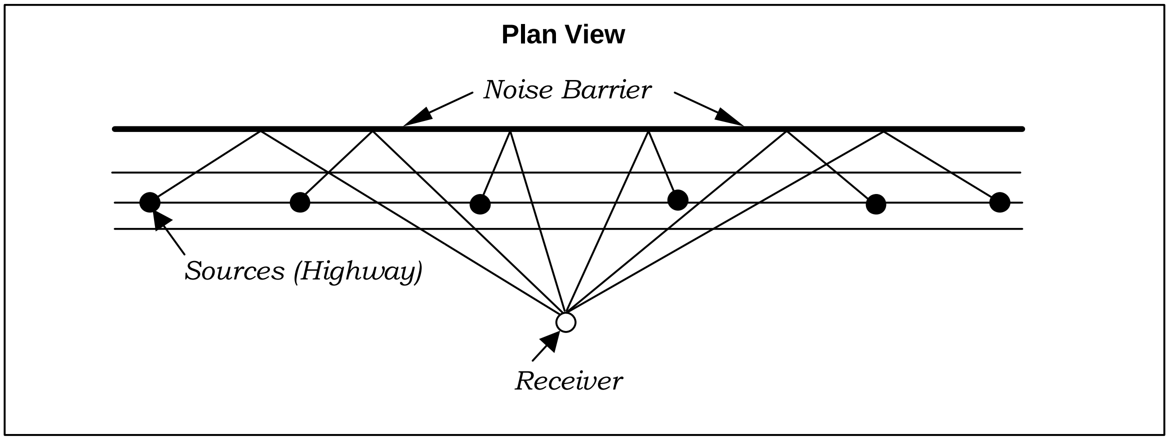
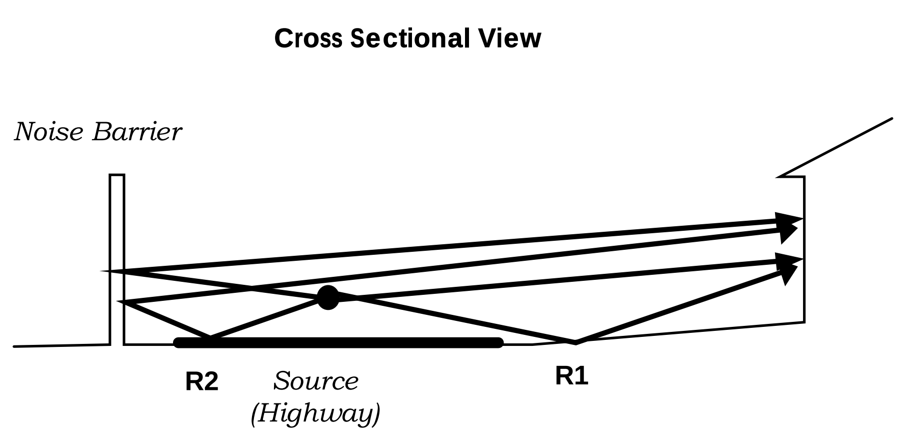


Figure N-8111.3 is a more realistic depiction, which includes pavement reflections. Note, however, that a noise barrier on the opposite side still increases the noise level by 3 dB, although the before and after noise levels are 3 dB higher (due to the pavement reflections) than in Figures N-8111.1 and N-8111.2. In plan view, the pavement reflections would also shown to be a line source.

The reflection point R1, shown on the pavement (Figure N-8111.3) may actually fall off the pavement on absorptive ground, reducing the before barrier noise levels at the receiver. The pavement reflection point R2, however, significant only after building the barrier, will usually be on the pavement. The difference between before and after barrier noise levels could therefore slightly exceed 3 dBA.

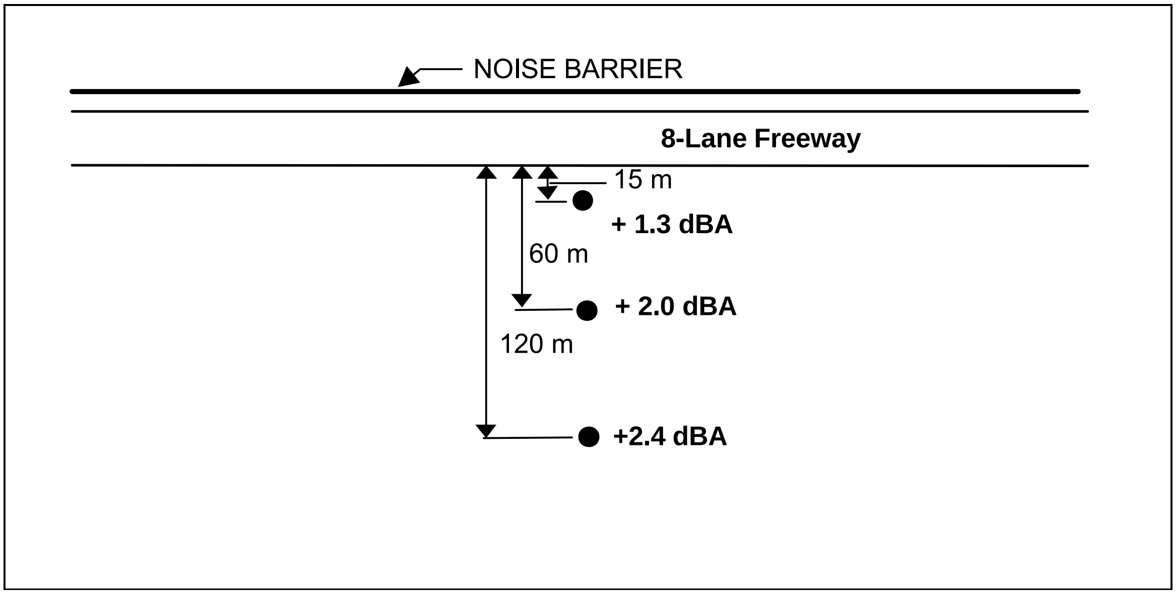
Figure N-8111.3 - Single Barrier Reflection (More Accurate Representation)



The effects of single noise barrier reflections are distance dependent. At distant receivers, the ratios of direct/reflected noise path lengths as well as those for near/far lane distances approach 1. When this is the case, contributions of direct and reflected noise from each lane contributes roughly the same energy (of course there will always remain a slight loss of acoustical energy due to imperfect reflections), with the result that the increase approaches 3 dBA for distant receivers. For receivers close to the highway, however, the distance ratios become less than 1 and the noise at the receiver is dominated by direct noise from the near lanes. The result is less contribution from reflected noise.

Figure N-8111.4 shows the distance dependency of the noise increases due to the barrier reflections, for a typical 8-lane at-grade freeway. At 15 m (50 ft) from the edge of the traveled way (ETW) the increase is only 1.3 dBA; at 60 m (200 ft) the increase is 2.0 dBA, and at 120 m (400 ft) from the ETW the increase is 2.4 dBA. The increases were calculated assuming equal noise source distributions in the near and far (E/B and W/B) lanes, and hard site propagation.

Figure N-8111.4 - Noise Increases due to Single Barrier Reflections.



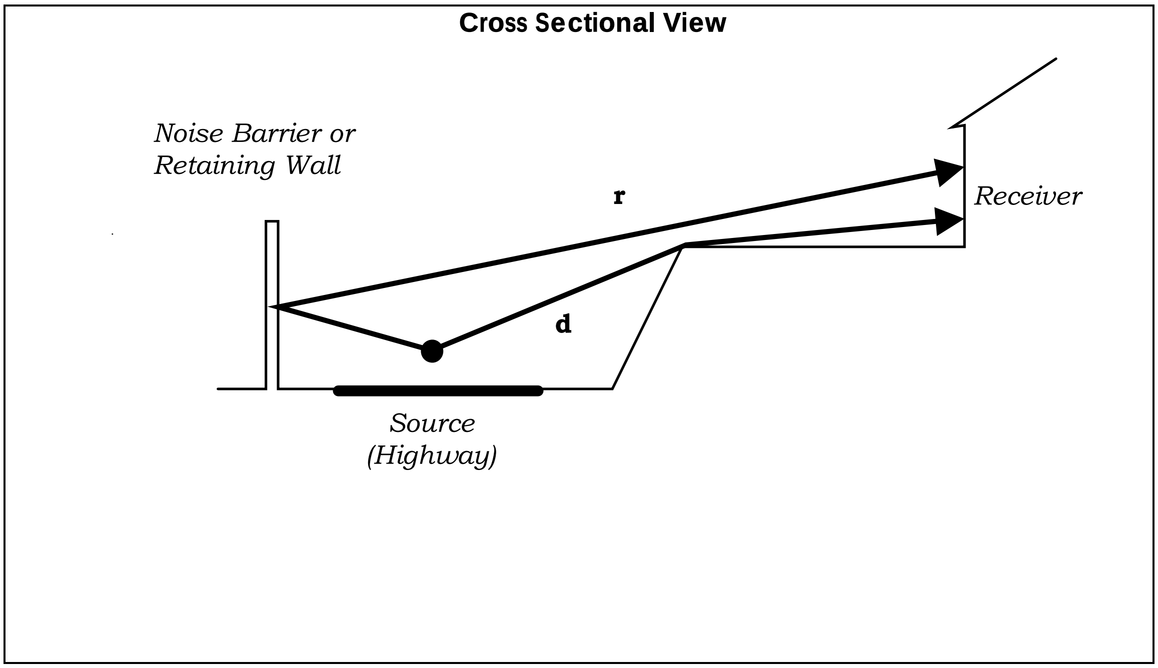
Actually, the "real world" is far more complicated than shown in figures N-8111.1 through N-8111.4. Consider that the noise sources are distributed over the width of the highway; that the paths of the barrier noise reflections are always longer than the direct noise paths; that reflective barriers are not perfect reflectors, and that the traffic stream most likely interfere with the reflections. Because of these factors, reflected noise contributions are less than those of direct noise, and seldom increase noise levels by more than 1 or 2 dB. The human ear cannot perceive such small increases.

N-8112 Complex Terrain

In more complex terrain there are, however, instances when single barrier reflected noise could increase noise levels perceptibly (3 or more dBA) at a receiver. One such case is shown in Figure N-8112.1, which depicts a receiver that is effectively shielded by terrain or top of a depressed highway cut. If a noise barrier or retaining wall were constructed on the opposite side of the highway, unshielded reflected noise ray “r” could contain significantly more acoustical energy than the shielded direct ray “d”, causing a noticeable increase in noise at the receiver. Once again, "real world" situations are far more complex than illustrated. Some of the noise sources may be shielded, while others may not. Similarly, some of the reflected noise paths may be shielded and others not.

In general, if most of the traffic cannot be seen from the receiver while most of the noise barrier is visible, there is a possibility that the barrier noticeably increased noise levels at the receiver.

Figure N-8112.1 - Single Barrier Reflection. Direct Noise Shielded, Reflected Noise Not Shielded.



Reflections off single barriers located at the top of cut (Figure N-8112.2) generally are directed over a 5 foot high receiver on the opposite side and therefore usually not a problem for low receivers. However, higher receivers, such as the second floor of a residence, or receivers located on a higher hill behind the front receivers may still be affected by the reflections, if the direct noise is shielded.

Situations depicted in Figures N-8112.1 and N-8112.2 (high receivers only) usually increase noise levels by a maximum of 3 to 5 dBA, depending on the angle of reflections and the height and length of reflective barrier. Since noise barrier heights are normally restricted to 16 feet by Caltrans policy, the maximum noise increases due to reflections are usually caused by retaining walls, which are not constrained in height.

Single barriers on top of fills (Figure N-8112.3) generally do not present any reflection problems. The reflected noise "ray" is usually well above the receiver.

Figure N-8112.2 - Single Barrier Reflection. Noise Barrier on Top of Opposite Cut.

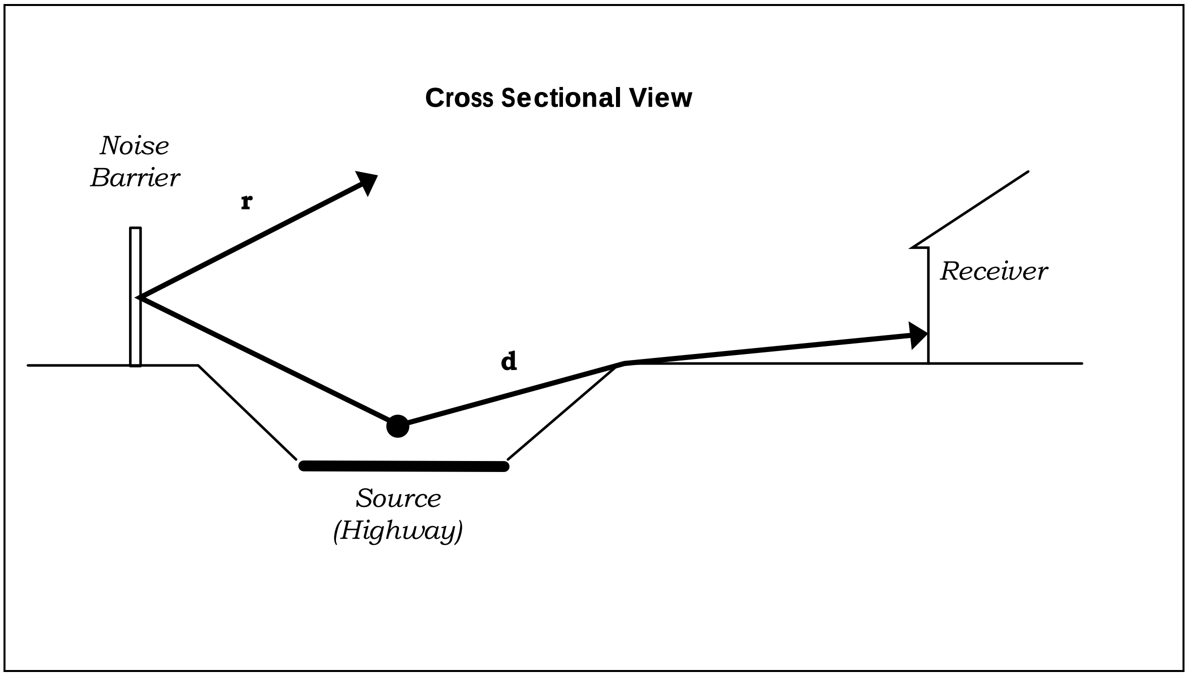
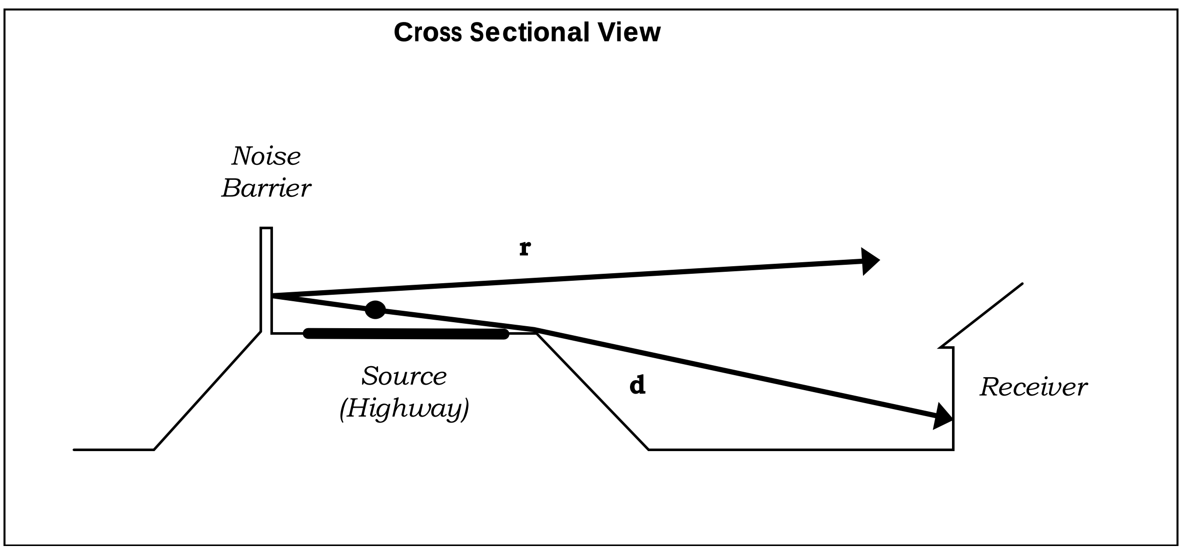


Figure N-8112.3 - Highway and Noise Barrier on Fill.



N-8113 Modeling Single Barrier Reflections

The FHWA Traffic Noise Model (TNM) has at this time no provisions for calculating single barrier reflections. In the future it will have that capability.

Caltrans versions of FHWA Highway Traffic Noise Prediction Model computer programs (LEQV2 and SOUND32), also have no provisions for calculating single barrier noise reflections directly. For simple situations, the effects of reflections can be evaluated in

LEQV2, SOUND32 and TNM using additional elements or coordinates of "image sources". Figures N-8113.1 and N-8113.2 illustrates these in cross section and plan view.

Figure N-8113.1 - Placement of Image Sources (Cross Sectional View)

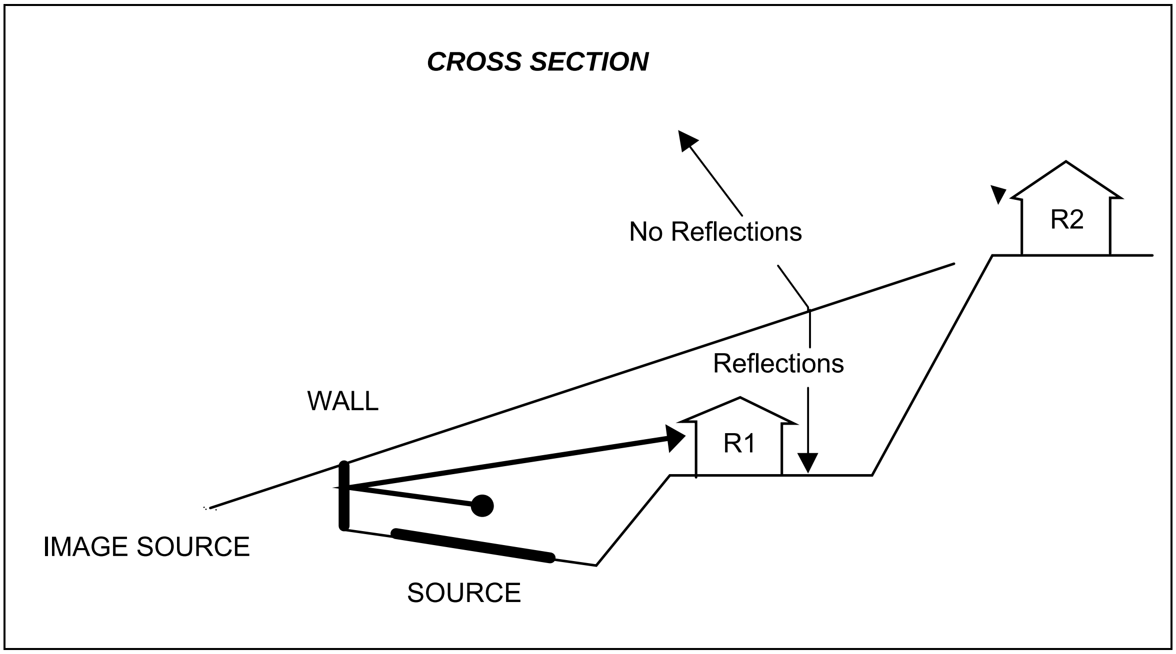
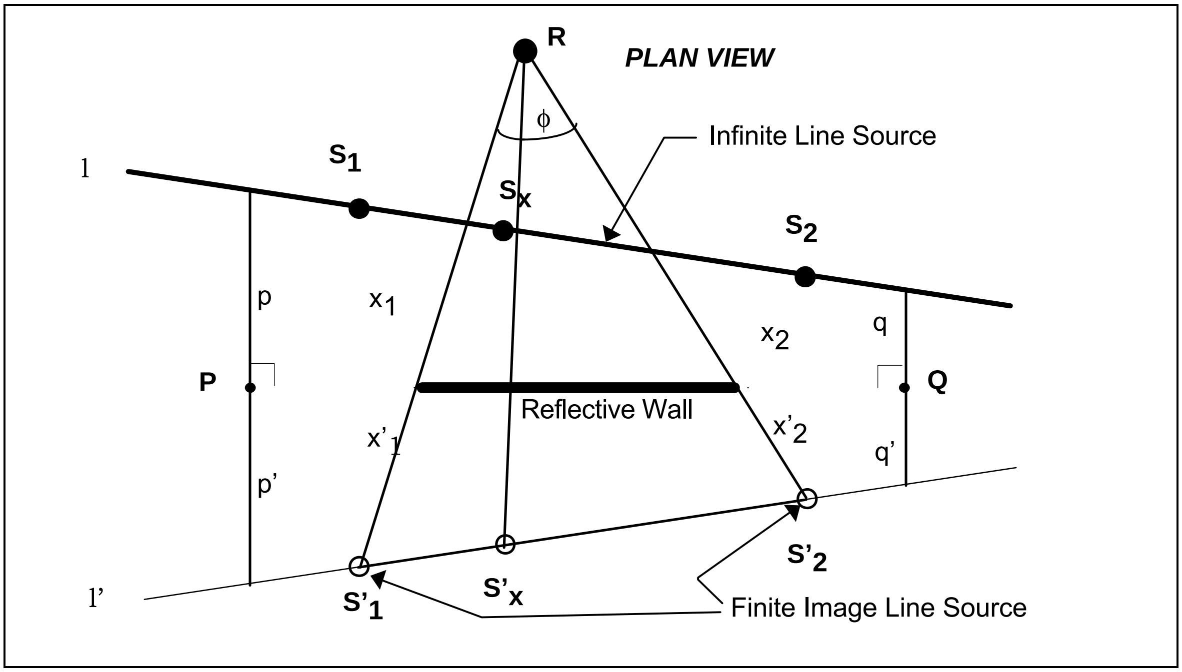


Figure N-8113.1 illustrates the placement of an image source in cross section, by drawing a line perpendicular to the reflective wall (or to its vertical extension) that passes through the real source. The image source is positioned on that line, at the same distance from the wall as the real source, but on the opposite side. The image source is analogous to a mirror image of the real source, with the wall being the "mirror".

It is important to point out that, just as mirror images cannot be seen from all angles, not all image sources necessarily contribute to reflections. A straight line drawn from the image source to the receiver must pass through the wall before the image source can contribute to the noise at the receiver. Note that R1 lies in the "zone of reflections", while R2 does not experience reflective noise. In some cases there are reflections from cars but not from heavy trucks, or vice versa, depending on the site geometry. In other cases only traffic noise from certain lanes will be reflected and others not. Accurate site cross sections will reveal which image sources are relevant.

Figure N-8113.2 shows plotting of image sources in a plan view. A general case is shown, with a finite wall that is not parallel to the roadway. This case was selected to illustrate how image sources are generated in the plan view. Examination of Figure N-8113.2 reveals that a finite wall creates a unique finite image line source for a particular receiver on the opposite side of a highway.

Figure N-8113.2 - Placement of Image Sources (Plan View)



To "construct" the finite image line source, lines perpendicular to the wall (or its extensions) at two different locations (say P and Q) can be drawn. Along these lines, distances "p" and "q" from the wall to the roadway line l, at P and Q respectively, can be drawn on the image side of the wall (p = p' and q = q'). A line l' connecting the two points defined by distances p' and q' establishes the direction of the image line source. Next, the termini of the infinite image line source can be determined by the intersections of line l' with two lines from the receiver R through both end points of the wall. S1' and S2' are now the end points of the finite image line source.

When using LEQV2 program the wall has to be parallel to the roadway. The above process can be used for this special case. The finite image line source will then run parallel to the roadway, and can be defined as an additional element(s), with a segment angle ϕ. A cross sectional drawing is needed to reveal if all image traffic (and image roadways) should be included. If, for instance the heavy trucks do not produce reflections, the heavy truck volume for the image source can be coded as 0.

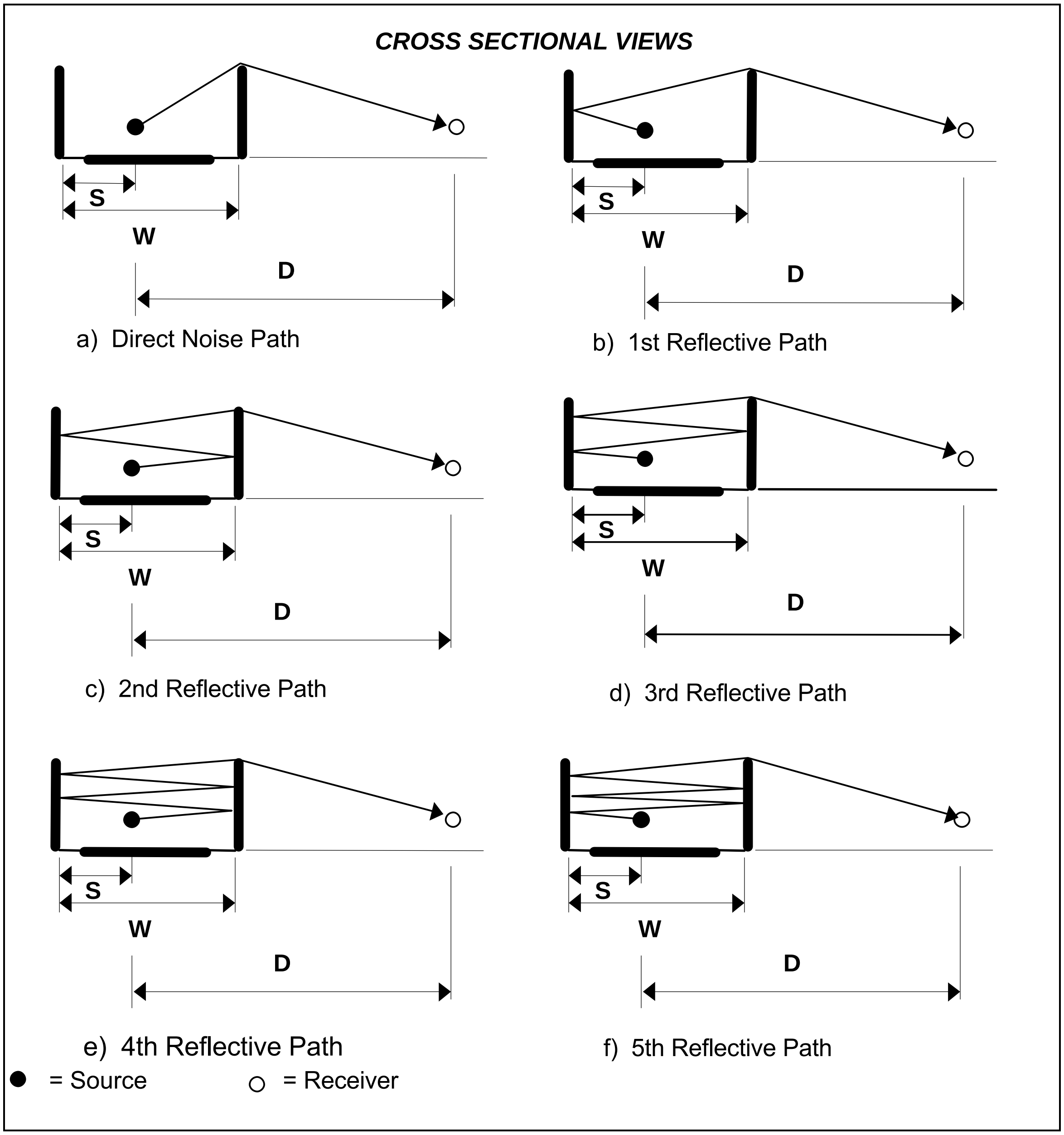
Needless to say, only primary reflections should be considered when employing the above methods. And since each receiver is affected by a different set of reflections, the number of receivers modeled should be kept to a minimum. Even then, modeling of reflective noise can be a very cumbersome process. FHWA Traffic Noise Model (TNM), presently being phased in, does not have, at this time, provisions for reflection calculations other than the parallel barrier analysis mentioned in the next section. However, it is anticipated that in the near future single barrier reflections will be included in routine calculations in TNM, eliminating the need for manipulating the input source data.

N-8120 Parallel Barrier Reflections

Multiple reflections between reflective parallel noise barriers (noise barriers on each side of the highway) can potentially reduce the acoustical performance of each individual barrier. Figure N-8120.1 shows a simple illustration of only five of the many possible reflective paths in addition to the direct path to the top of the barrier. Theoretically, there are an infinite number of possible reflective noise paths. Each reflection essentially becomes a new source, which may add to the noise diffracted by the barrier nearest to the receiver. This in turn may reduce the barrier's effectiveness.

Figure N-8120.1 clearly shows, however, that as the number of reflections for each possible path increases, the path length becomes significantly longer. However, in all instances the barrier to receiver distance is the same. Only that portion of the path length from source to receiver that lies between the barriers changes. For the direct path this distance is **W - S**, where **W** is the separation distance between the two barriers and **S** is the distance between the far barrier to the source. For the first reflective path the distance is approximately (**W + S**), and for the second reflective path approximately **3W - S**. Further examination of Figure N-8120.1 shows that the path length difference between the first reflective path and the direct path is **2S.** The difference between the second and first reflective paths is **2(W - S)**. The pattern repeats itself for subsequent reflections. These increases in path length distances for each subsequent reflection soon make their contribution to the total diffracted noise insignificant, i.e. only the first few reflections are important.

Figure N-8120.1 - Various Reflective Noise Paths for Parallel Noise Barriers



For instance, for the special case where W = 2S (source halfway between the barriers), each subsequent reflective path increases by W. Assuming the distance between the source and receiver D = W (a fairly typical situation) and the NRC is 0.05 (95% of energy reflected at each reflection point), the contribution of each subsequent reflection decreases rapidly due to increasing path length as shown in Table N-8120.1. The table assumes only the effects of increasing distances and a slight absorption by the walls (5% at each reflection point), and does NOT include the effects of the location of the final point of reflection with respect to the source location. This affects the amount of diffraction by the wall on the receiver side, which will be different for each of the reflective paths. Also ignored are pavement reflections, constructive and destructive interference of the sound waves, frequency shifts and the effects of the traffic mix, traffic stream, and lane distribution.

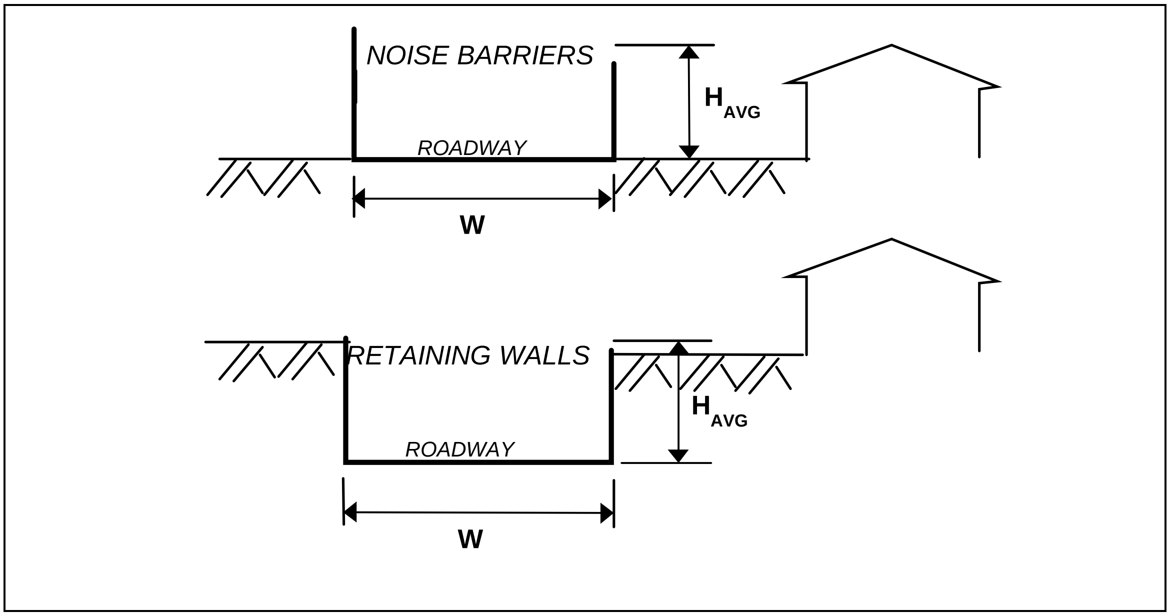
Table N-8120.1 - Contribution of Reflections for the Special Case where W=2S, D=W, and NRC=0.05.

NOISE PATH	*DISTANCE, (RE: W)* *(Source to Receiver)*	*DISTANCE ADJUSTMENT,(Direct to Reflective Path)* *10Log(W/XW) (X=2,3, ,11) dBA* **(1)**	*ABSORBED, (NRC=0.05),* *dBA* **(2)**	*CONTRIBUTION, (RE: Direct),* *dBA* **(1+2)**	*CUMULATIVE TOTAL NOISE LEVEL (RE: Direct),* *dBA* **(Direct + 1st Refl. + 2nd Refl., etc.)**
Direct	W	0 (Ref.)	0	0 (Ref.)	0 (Ref.)
1st Reflective	2W	-3.0	-0.2	-3.2	+1.7
2nd Reflective	3W	-4.8	-0.45	-5.25	+2.5
3rd Reflective	4W	-6.0	-0.7	-6.7	+3.0
4th Reflective	5W	-7.0	-0.9	-7.9	+3.3
5th Reflective	6W	-7.8	-1.1	-8.9	+3.6
6th Reflective	7W	-8.5	-1.3	-9.8	+3.8
7th Reflective	8W	-9.0	-1.6	-10.6	+3.9
8th Reflective	9W	-9.5	-1.8	-11.3	+4.1
9th Reflective	10W	-10.0	-2.0	-12.0	+4.2
10th Reflective	11W	-10.4	-2.2	-12.6	+4.3

Noise contributions from parallel barrier reflections are obviously depended on the source to receiver distance. For a fixed W, the relative distance attenuation for each reflective path decreases as the D increases. The contribution of each reflection also increases as W decreases in relation to D (Figure N-8120.1).

Noise contributions of reflections between parallel barrier degrade the performance (insertion loss) of each noise barrier. How much degradation takes place depends of course on the site geometry and barrier configurations. In addition to the factors shown in Figure N-8120.1 and Table N-8120.1, there is another important relationship between the ratio of the separation between two parallel barriers (W) and their average height (H_{AVG}), and the amount of insertion loss degradation. As a rule, if the W/H_{AVG} ratio is 10:1 or greater, the insertion loss degradation is less than 3 dBA, and not noticeable to the human ear. This has been supported by Caltrans research and research done by others. Because of noise barrier height restrictions of 5 m (16 ft), parallel noise barriers in California have a W/H of 10:1 or greater. Although there have been claims to this effect, there are no known instances where reflective parallel noise barriers in any configuration, anywhere, have ever measurably increased noise levels over those without noise barriers. The W/H_{AVG} guideline applies not only to noise barriers but also to retaining walls or combinations of both. Figure N-8120.2 shows these concepts.

Figure N-8120.2 - W/H_{AVG} Ratio Should be 10:1 or Greater

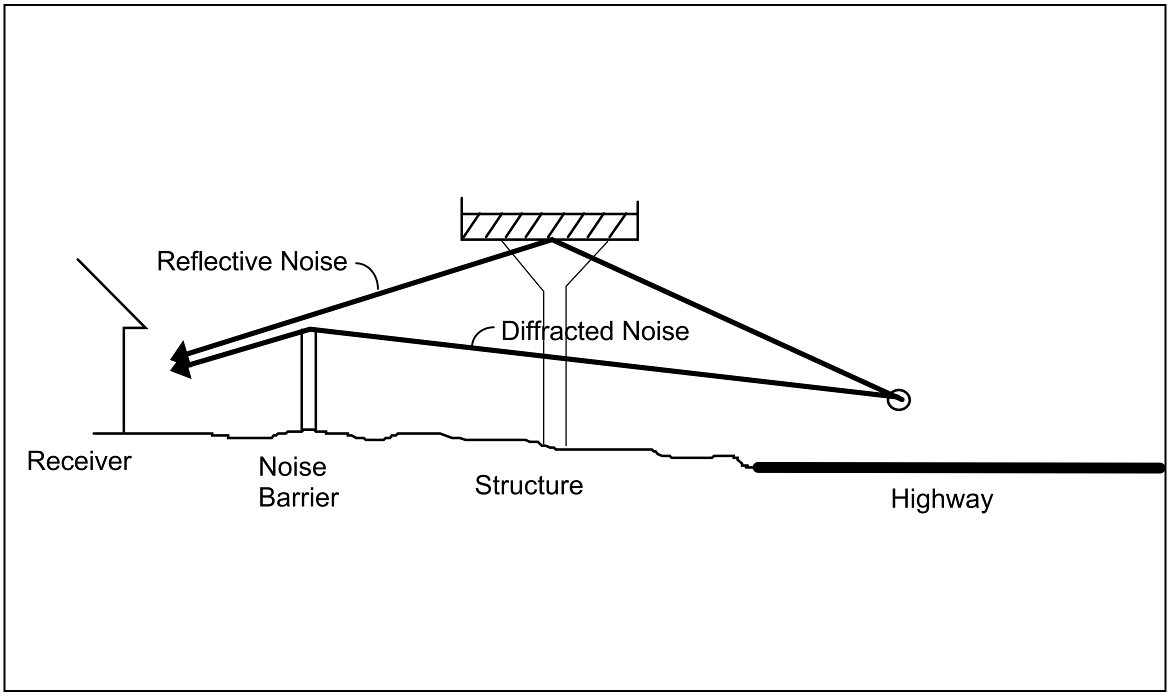


N-8130 REFLECTIONS OFF STRUCTURES AND CANYON EFFECTS

Generally, the same rules that apply to reflections off noise barriers apply to those off *retaining walls*. Since the height limitations to noise barriers do not pertain to retaining walls, there is a greater potential for noise reflections, especially when the retaining walls are along stretches of depressed freeways. However, no noise barriers in this configuration have ever been shown objectively and conclusively to result in higher noise levels than those of a similar, at-grade freeway because of reflective noise.

Complex multi-level highway interchanges can present some challenging problems in noise abatement design. The widespread spatial distributions of traffic noise sources and receivers make it difficult to design noise barriers that interrupt all direct noise paths between the many source-to-receiver combinations. Additionally, reflective surfaces of concrete structural components create many opportunities for noise reflections to circumvent noise barriers. Figure N-8130.1 shows one example of a *potential* problem created by the interaction of structures and noise barriers.

Figure N-8130.1 - Noise Reflection Off Structure (Potential Problem)



The structure in the illustration provides a point (or actually a "line") of reflection off the structure's soffit. This essentially creates a new line source with respect to the receiver shown. Unlike the highway noise sources which are shielded from the receiver by the noise barrier, the reflected noise (new source) is not shielded.

High median barriers (e.g. 5 foot high concrete glare screens) are not considered a problem. Because of the barriers' limited height, reflections are most likely scattered and interrupted by the traffic stream.

The effects of reflections near *tunnel portals* also have a very limited range. A Minnesota study showed that although noise levels are elevated immediately in front of the portal, they drop to ambient levels in about 20-25 m (65-80 ft) from the portal.

Thus far, Caltrans measurements have yet to <u>conclusively</u> uncover problems of interaction with structures and noise barriers. The effects of reflections off structures would be limited due to the small reflecting surface, and therefore affect only a relatively small group of receivers, due to the small reflecting surface.

Studies of highways through canyons typically have shown noise increases of less than 3 dBA from *canyon effects*. Noise increases generated from highways in narrow canyons with steep side slopes theoretically *could* be greater than 3 dBA, depending on ground cover and the steepness and smoothness of side slopes. The canyon walls, to some extent, act as parallel sound walls with respect to multiple reflections. However, unless the slopes are perfectly vertical, build up of reflections will be more limited due to the slope angles.

Highways on hill sides with near vertical rock cuts are somewhat similar to the single barrier situation discussed before. No perceptible noise increases are expected. Due to the angle of the cut slope, reflections are directed skyward, while receivers would most likely be below the highway.

N-8140 MINIMIZING REFLECTIONS

When designing reflective parallel noise barriers it is recommended that a minimum 10:1. W/H_{AVG} is maintained between the two barriers, in order to avoid the possibility of perceivable barrier performance degradations. Earth berm noise barriers are not reflective and are therefore not affected by W/H_{AVG} ratios of less than 10:1.

Sound absorption has been promoted as a solution for noise reflection where actual problems would be identified. As part of an on-going program Caltrans considers a variety of proprietary noise barrier products and systems, some of which have sound absorptive characteristics. For reasons of structural integrity, safety, cost, or other factors, no absorptive material has been approved yet. For more information on barrier materials and new products, the designer should check with HQ Design and Local Programs for availability of approved materials, and the Office of Structures Design to determine which materials have been approved for use on noise barriers. Sound-absorptive materials can either be an inherent property of the barrier, or it can be added on to an existing barrier (retrofit). Either way, the cost of the barrier will likely increase substantially.

The amount of noise absorption of the materials is rated by a noise absorption coefficient **a**. The coefficient is defined as the ratio of the acoustical energy absorbed by the material to the total energy incident upon that material. For any particular material, **a** is frequency-dependent, and its value for each specific frequency ranges from 0 (perfect reflector) to 1 (perfect absorber). In order to rate the overall absorptive characteristics of the material, a measure of the average **a** over the frequency range of interest is useful. For traffic noise frequencies, an appropriate measure is the Noise Reduction Coefficient (NRC), which is the arithmetic average of **a** in four octave bands with center frequencies of 250, 500, 1000, and 2000 Hz, calculated by:

$$\mathbf{NRC = (a_{250} + a_{500} + a_{1000} + a_{2000})/4}$$

If approved absorptive materials are considered, a minimum NRC of 0.85 should be used as a criterion. This value means that 85% of the incident noise energy is absorbed and only 15% reflected. For a single reflection this can only add a maximum of 0.6 dBA to the direct noise level, instead of the theoretical 3 dBA for a perfect reflector (NRC = 0).

N-8200 EFFECTS OF NOISE BARRIERS ON DISTANT RECEIVERS

N-8210 BACKGROUND

With the proliferation of noise barriers in California, some recent public concern has emerged that under certain conditions of topography and meteorology noise barriers increase noise levels at receivers between 1/2 km to 3 km (more than 1/4 mile to 2 miles) from freeways. The concerns are based on subjective perception only. No objective evidence based on noise measurements has ever been advanced that noise barriers increase noise levels at any distance, other than under the limited conditions described in section N-8100.

The concerns raised by various homeowner groups in the San Francisco Bay Area and the Los Angeles Area include all three possible categories of source/ barrier/ receiver configurations:

1. Reflective noise barriers on the sides of highways opposite from that of the receivers (i.e. highways between barriers and receivers)
2. Parallel reflective noise barriers on each side of highways
3. Noise barriers between highways and receivers

The first two issues involve reflective noise of single and parallel barriers, discussed in previous section N-8100. The third issue, however, deals with diffracted noise. All of the issues involve long noise propagation distances, which are difficult to study due to the numerous variables in topography and meteorology. Caltrans experience has been that atmospheric conditions can fluctuate noise levels at those distances by more than 10 dBA, <u>with or without</u> noise barriers.

Refraction is the principle atmospheric process responsible for the fluctuations. A vertical gradient of either temperature or wind velocity produces a corresponding vertical gradient of sound velocity. This causes sound waves to refract (bend) either upwards or downwards. Upward refraction occurs during sound propagation in upwind direction or normal temperature lapse conditions (air temperatures decreasing with height). This tends to send noise skyward, leaving a noise "shadow" near the ground and thereby reducing noise levels. This occurs with or without noise barriers. Downward refraction occurs during sound propagation in downwind direction, or in temperature inversions (temperature increasing with height above the ground). Downward refraction tends to send skyward noise down, concentrating noise near the ground, thereby increasing noise levels, both with and without a barrier. Atmospheric refraction of sound waves was discussed in section N-2143.

N-8220 COMPLETED STUDIES

N-8221 Caltrans Reflective Noise Studies

On the issue of reflective noise, Caltrans has done two very detailed studies, one along 07-LA-405 in the Los Angeles community of Brentwood, and another along 03-Sac-99 in south Sacramento. These studies dealt with the acoustical performance of parallel noise barriers and the possibility of noise reflection problems. The studies are described in the following reports:

1. Hendriks, R., J.Hecker, "Parallel Noise Barrier Report: A Noise Absorptive Demonstration Project - San Diego Freeway, Interstate Route 405 in the City of Los Angeles, Community of Brentwood", California Department of Transportation, District 7 Environmental Investigations Section (With Assistance of Transportation Laboratory), Los Angeles, CA., July 1989.
2. Hendriks, R., "Field Evaluation of Acoustical Performance of Parallel Noise Barriers Along Route 99 in Sacramento, California", Report No. FHWA/CA/TL-91/01, California Department of Transportation, Division of New Technology, Materials and Research, Sacramento, CA., January 1991.

The L.A. study (1) was part of a demonstration project to test acoustically absorptive treatment on one of two parallel masonry sound walls. The project was initiated by District 7 (Los Angeles) in response to concerned home owners living in Brentwood at distances of 0.3 - 0.6 km (0.2 to 0.4 miles) away from the freeway. The terrain between the residences and the freeway ranged in height from -6 to +15m (-20 to +50 ft) relative to the freeway and was occupied by single and multi-story residential units. Some homeowners perceived an increase in noise when the opposite sound wall was constructed about seven years after the near sound wall had been completed. Legal action was initiated to have Caltrans remove the wall or have it treated with a noise absorptive material. No noise level increase had been perceived when the first (near) barrier was constructed.

In 1987 the Division of New Technology, Materials and Research (NT,M&R), also known as TransLab - was contacted to perform the before and after treatment noise study. NT,M&R's approach was to take simultaneous noise measurements at 14 different locations, of which 11 were in the vicinity of the freeway sound walls, at distances up to 61 m (200 ft) from the near wall and at heights of up to 7m (23 ft) above the ground, and the remaining 3 near the residences. Concurrent meteorological observations (wind speed, direction, temperature and humidity) and lane-by-lane traffic counts on the Route 405 freeway, on/off ramps, and Sunset Boulevard were also taken. Fifteen "before" and ten "after" measurements were taken at the freeway sites; twenty-seven before and twenty-two after at the 3 distant sites. Each measurement lasted 15 minutes. About thirty District 7 and NT,M&R personnel participated in the study. At Caltrans' request an expert in the discipline of transportation noise, Dr. William Bowlby from Vanderbilt University, also participated in the study by analyzing the data independently. His results and method of analysis were reported the following document:

3. Bowlby, W., "Parallel Noise Barrier Study, 07-LN-405, Prediction and Analysis of Data Before and After Acoustical Treatment", Submitted to California Department of Transportation, District 7, Los Angeles, CA, Contract 07D527, Department of Civil and Environmental Engineering, Vanderbilt University, Nashville, Tennessee, June 2, 1989.

The before and after data were carefully matched by wind speed and direction, and normalized for traffic variations.

Analyses in (1) and (3) showed that the acoustical material reduced the noise by an average of 1 dBA. Human ears cannot perceive a change of 1 dBA. Since the acoustic material was an almost perfect noise absorber of the reflective noise, the after treatment condition, in essence, simulated a no wall condition on the opposite side of the freeway. From the results NT,M&R concluded that there was no reflection problem to begin with.

However, fluctuations in noise levels at 0.3 km (0.2 miles) and greater were as large as 8 dBA with relatively minor changes in wind speed and direction. Even at 61 m (200 ft) behind the barrier minor wind shifts were responsible for noise fluctuations of about 4 dBA. Wind was the single most important factor in changing noise levels at distances beyond 61 m (200 ft) from the barrier, even greater than differences in traffic volumes.

In 1991 NT,M&R completed the Sac-99 study (2), which represented one of the first systematic attempts to quantify the effects of multiple reflections between parallel masonry sound walls for configurations representative of many barrier locations in California. The research consisted of extensive noise, traffic, and meteorological measurements and analyses during three stages: 1) without any sound walls, 2) after construction of the near sound wall, and 3) after completion of the far sound wall. More than one-hundred 15-minute measurements were taken at 11 locations, simultaneously, ranging from 0 to 61 m (200 ft) behind the near barrier and at heights of 1.5 to 7 m (5 to 23 ft) above the ground. The objective was to determine how much the performance of the near barrier would be decreased by the reflections off the far barrier. Once again, the staged data were carefully matched by meteorology. The results indicated that the average reduction in near sound wall performance ranged from 0 to 1.4 dBA, well below the generally recognized 3 dBA human perception threshold of changes in noise levels. As was the case with the L.A. study, the data showed large fluctuations in noise that occurred during all three stages (i.e. with or without noise barriers) as a result of meteorological conditions. Under all measured conditions, however, the barrier provided adequate insertion loss.

The above studies were performed under carefully documented "real world" conditions and showed no evidence of reflection problems. However, the studies did clearly demonstrate the profound effect of meteorological conditions on traffic noise levels. Any before and after comparisons of noise data should therefore be matched as carefully as possible by meteorological conditions to be meaningful. Given the number of variables involved, the level of effort and cost that must go into a noise study involving long distances is substantial.

N-8222 Reflective Noise Studies by Others

The U.S. Department of Transportation, Volpe National Transportation Systems Center completed two parallel barrier studies during the period of October 1986 through April 1994. The studies were funded by the highway agencies of seventeen states, including Caltrans. The findings of the two studies are reported in:

4. Fleming, G.G., E. Rickley, "Performance Evaluation of Experimental Highway Barriers", Report Number DOT-VNTSC-FHWA-94-16, U.S. Department of Transportation, Research and Special Programs Administration, John A. Volpe National Transportation Systems Center, Cambridge, MA 02142, April 1994.

The first study examined the performance of two parallel experimental highway noise barriers constructed on opposite sides of a two-lane asphalt service road at Dulles International Airport near Washington, D.C. The barriers were constructed in such a way that they could be configured to have absorptive and/or reflective roadside facades, or be independently tilted outward, away from the roadway, at angles of 7, 15, and 90 degrees. A

90-degree tilt angle simulated effective removal of the barrrier. The barrier behind which noise measurements were made was 152 m (500 ft) in length; the barrier on the opposite side was 76 m (250 ft) long and centered on the 152 m barrier. For each of 12 individual barrier configurations, noise and meteorological measurements were made at 10 locations behind the 152 m barrier and 10 locations in an adjacent open field site, using the same distances from the noise sources and heights above the ground. The noise sources were four individual test trucks and an artificial fixed point source (speaker system) used to simulate a pass by of each test truck.

The Dulles site was not representative of the typical parallel barrier sites along California highways. Although the 4.3 m height of the barriers was typical, the 26 m (86 ft) separation (width) between the two barriers was much narrower than typical highway widths. This translates into a width/height (w/h) ratio of 6:1 for the Dulles barriers, while almost all parallel barrier sites in the U.S. have at least a 10:1 ratio. The Dulles study concluded that the worst insertion loss degradation reached as high as 6 dBA due to multiple reflections between the parallel reflective barrier facades.

A second site along I-495 in Montgomery County, Maryland, was used to measure parallel barrier degradation under more realistic yet still severe conditions of free-flowing traffic but a w/h ratio of 9:1 (still less than typical). The degradations were measured using 10 microphone locations behind a parallel barrier section and simultaneously at 10 locations behind a single wall adjacent to the parallel barriers. In this configuration the maximum degradation reached 2.8 dBA.

Together with the Caltrans studies (1 and 2) the report (4) concluded that parallel barrier sites with w/h ratios of 10 or more would have a degradation of less than 3 dBA, an imperceptible noise increase over a single barrier.

N-8223 Noise Levels Behind A Single Noise Barrier

The third issue, that of perceived increases in noise levels behind a single noise barrier on the same side of a freeway, relates in part to the above mentioned studies. The noise level fluctuations at distant receivers are far more influenced by varying meteorological conditions than the presence or lack of a noise barrier. Therefore, any study designed to examine with and without barrier conditions will certainly have to include detailed meteorological documentation. Atmospheric equivalency must first be established, before any comparisons of before and after barrier noise data should be made.

There is no question that noise barriers are effective in the vicinity of highways, say within 100 m (330 ft). Caltrans has collected enough data over the years to substantiate this. The following report compared before and after noise measurements at eleven noise barrier sites with those predicted by noise barrier acoustical design procedures:

5. Hendriks, R.W., "Evaluation of Noise Barriers", Report No. FHWA/CA/TL-81/07, California Department of Transportation, Office of Transportation Laboratory, Sacramento, California, June 1981.

The measurements were part of an overall evaluation of noise barriers' performances, noise barrier acoustical design procedures, and community acceptance.

Caltrans has also experienced, in the course of many measurements, that beyond 100 m or so, noise levels often approach ambient levels (the noise levels associated with normal day-to-day activities in the community). For obvious reasons, a sound wall cannot attenuate noise below these levels. However, Caltrans has never experienced noise <u>increases</u> (over no-barrier noise levels) at any distance behind noise barriers. Yet, some persist that noise barriers will increase noise levels at distant receivers.

Explanations have sometimes centered on noise waves "going over the wall and coming back to the ground". This is "diffraction" and is actually responsible for noise attenuation, rather than an increase in noise, when compared with the direct noise received without a noise barrier. (See sections N-2144, N-4510, and N-6100).

Another popular "explanation" for perceived increase in noise due to sound walls is that the sound wall "lifts" the noise over tiers of homes that normally would shield the receiver. Yet, a sound wall will no more elevate the noise source over tiers of homes than the intervening homes will. Sound walls in California are generally restricted in height to 16 feet, an amount approximately equal to the average height of residential development.

There is, however, a loss of "ground effect" behind a noise barrier (see sections N-4520 and N-6131). Without a noise barrier the direct path of the traffic noise to the receiver travels closer to the ground than after a noise barrier is built. Noise waves close to the ground are subject to excess attenuation due to absorption by the ground. Therefore, when a noise barrier is built there is a trade-off between barrier attenuation (a decrease in noise) and a loss of excess attenuation.

The net reduction of noise due to the barrier attenuation and loss of excess attenuation is called "barrier insertion loss"(Section N-6131). Close to a barrier, there is no question that the barrier attenuation benefit far outweighs the loss of excess attenuation. At further distances, however, barrier attenuation diminishes while the cumulative effects of the loss of excess attenuation increase. Our acoustical design procedures for noise barriers take these factors into consideration by applying different noise drop-off rates to with and without noise barrier cases. If we were to keep these drop-off rates constant and apply them to long distances, there would indeed be a distance at which the loss in ground effect would eventually exceed the barrier attenuation.

Extensive amounts of field data gathered during a Caltrans noise propagation research project shows that differences between excess attenuation rates of elevated sources (e.g. truck stacks, noise diffracted over a noise barrier) and those close to the ground (e.g. tire noise) diminish after a hundred meters (few hundred feet) or so. The findings can be applied to noise barriers which in essence “elevate” the source. The cumulative effect of decreasing differences in elevated and near-ground excess attenuation rates with distance appear to cause a “bulge” at about 60 - 90 m (200 - 300 ft) behind the barrier where the effect of the differences is the greatest. At greater distances the differences in elevated and near-ground noise levels appear to become smaller again until they disappear at some distance beyond 120m (400 ft). The research was documented in the following report:

6. Hendriks, R.W., “Traffic Noise Attenuation as a Function of Ground and Vegetation (Final Report)”, Report No. FHWA/CA/TL-95/23, California Department of Transportation, Engineering Service Center, Office of Materials Engineering and Testing Services, Testing and Technology Services Branch, Sacramento, CA, June 1995.

Questions have also been raised at times about whether noise “redirected” by noise barriers “bounces off” temperature inversion layers. Although NT,M&R did not have instrumentation to measure inversion layers in the L.A. study, the probability of the presence of one was very high during the early morning measurements under calm conditions. At any rate, “redirections” on the scale being discussed, involves a maximum of 5m (16 ft) high noise barriers and a distance of 400 m (1/4 mile) or more, are less than one degree and therefore negligible.

In July 1994, Caltrans contracted with a consulting firm to do a detailed before and after noise barrier study along I-680 near Walnut Creek. Caltrans had previously received complaints from residents in nearby Danville who claimed that recently constructed noise barriers increased noise levels more than 0.4 km (1/4 mile) from the freeway. The study was part of an on-going effort by Caltrans to find out if noise barriers do indeed increase noise levels at some distance from a freeway. The study concentrated on receivers from 0.4 to 1 km (1/4 to 2/3 mile) behind a 3.6 m (12 ft) high noise barrier, 1.2 km (3/4 mile) long.

The study included before and after noise barrier noise measurements of traffic noise, traffic volumes and speeds, traffic mix, and meteorological conditions. All before and after noise measurements were carefully matched by meteorology and normalized for different traffic conditions. Although the noise barrier actually decreased noise levels the amounts were insignificant and the conclusion was that the noise barrier did not affect the noise levels at the distant receivers. The results and methodology of the study are described in:

7. "Interstate 680 Livorna - Stonecastle Soundwall Study", Woodward-Clyde Consultants, Oakland, California, and Illingworth and Rodkin, Inc., Fairfax, California, Submitted to California Department of Transportation, Oakland, California, July 1994.

The study also included measurements on the opposite side of the freeway to measure reflections off the noise barrier. As expected, there was a noise level increase of 0-2.4 dBA, with an average of 1.5 dBA. Such a small increase is not noticeable by the human ear.

After years of research, Caltrans has found no objective evidence that noise levels increase perceptibly due to noise barriers. It is widely accepted by acousticians that changes in traffic noise levels need to be 3 dBA before they can be perceived by human ears. Such increases in noise levels due to noise barriers have never been measured.

N-8230 STUDYING THE EFFECTS OF NOISE BARRIERS ON DISTANT RECEIVERS

Allegations of noise barriers increasing noise levels at distant receivers based on perception only are at best unreliable. With possible noise fluctuations of more than 10 dBA due to meteorological factors alone, person(s) making such claims must remember not only the before barrier noise levels, but also have knowledge of the meteorological conditions associated with those noise levels. In order to confirm whether noise barriers indeed do increase noise levels in some instances, a complex before and after barrier field study must be undertaken.

Before and after noise barrier(s) noise measurements do not adequately address the previous issues unless the measurements are carefully matched by before and after conditions of meteorology, traffic, and topography. Such studies are not at this time considered routine. Technical Advisory TAN-97-01-R9301 "General Guidelines for the Effects of Noise Barriers on Distant Receivers", issued in 1997, gives guidelines and criteria to cover these studies. This Technical Advisory can be obtained from the Caltrans Environmental Program, Environmental Engineering – Noise, Air Quality,, and Hazardous Waste Management Office, in Sacramento, CA.

N-8300 STOP AND GO TRAFFIC

Section N-5510 covered the California version of the FHWA traffic noise prediction model per FHWA-RD-77-108. The computer programs SOUND32 and LEQV2 predict the hourly L_{eq} for constant-speed traffic. The model is not equipped to deal with "stop and go" driving conditions typical of ramps, arterials and city streets.

A model suitable for use with STAMINA 2.0 (Federal computerized version of the FHWA Model) has been developed by Dr. William Bowlby of Vanderbilt University under contract to the National Cooperative Highway Research Program (NCHRP). The former Division of New Technology Transportation Materials and Research further revised this model for use with SOUND32 (California version of the STAMINA 2.0). The full report in which the model and its use with STAMINA 2.0 is described is:

8. Bowlby, W., R.L.Wayson, and R.E. Stammer, Jr., "Predicting Stop-and-Go Traffic Noise Levels", NCHRP Report 311, Transportation Research Board, National Research Council, Washington, D.C., November 1989.

The report, excerpts from the report, and revisions for use with SOUND32 are available from Caltrans Environmental Program, Environmental Engineering – Noise, Air Quality, and Hazardous Waste Management Office, in Sacramento, CA.

When TNM (see Section N-5520) is mandated, the above method will be obsolete. TNM has provisions for dealing with interrupted-flow traffic.

N-9000 GLOSSARY

The terms and definitions in this glossary are either used in this Supplement, or are commonly found in environmental noise literature. To make this glossary more useful to the highway traffic noise analyst, the definitions herein are generally biased towards highway traffic noise and the abatement thereof, instead of general acoustics.

Absorption (of Sound) - The attenuation of sound (noise) caused by conversion of sound energy into other forms of energy (usually heat) within a medium. Absorption is a property of the medium (material). In noise barrier material, absorption can be thought of as the complement of reflection. A perfectly absorptive material does not reflect any sound energy; a non-absorptive (reflective) material reflects almost all of the sound energy. In either case, a small portion of sound energy is transmitted through the barrier and continues in roughly the same direction as the incident noise propagation. (See *Transmission Loss*). In typical highway traffic noise barriers, the sound energy passing through is less than 1% of the incident noise energy.

Absorption Coefficient - A term that approximately equals the ratio of sound energy absorbed by a material to the energy incident upon the material. Absorption coefficients range from 0 (no absorption) to 1 (perfect absorption). In highway noise barriers, material with an absorption coefficient of 0 will reflect back almost all the incident noise energy; material with a coefficient of 1 will not reflect back any sound energy. The absorption coefficient is dependent on material, the sound frequency and angle of incidence.

Absorptive Grounds - Types of ground (such as normal earth and most grounds with vegetation) that are absorptive to sound energy, and that reverse the phase of reflected energy at grazing angles of incidence. (See also *soft sites* and *ground effects*).

Acoustics - The broad field of science that deals with the production, propagation, reception, effects, and control of sound, audible and inaudible to the human ear, and occurring in all media.

Airborne Sound - Sound that reaches the point of interest primarily by propagation through the air.

Ambient Noise (Level) - All-encompassing noise (level) at a given place and time, usually a composite of sounds from all sources near and far, including any specific source(s) of interest.

Amplitude - The strength or magnitude of the pressure of a sound wave.

Anechoic Chamber (Room) - A room whose boundaries have been designed to absorb nearly all of the sound incident on them, thereby affording a test room essentially free from reflected sound, simulating a free field conditions for the limited space defined by the room's boundaries.

Angle of Diffraction - The angle through which sound energy is diffracted (bent) as it passes over the top of a noise barrier and then proceeds towards the receiver. Receivers deeper into the shadow zone have larger angles of diffraction, and therefore greater barrier attenuation. (See *Diffraction, Shadow Zone.*)

Angle of Incidence - The angle formed by the radial line of sound waves striking a surface at a specific location and the plane of that surface. (See *angle of reflection*).

Angle of Reflection - The angle formed by the radial line of sound waves reflecting off a surface at a specific location and the plane of that surface. (See *angle of incidence*).

Atmospheric Effects - Sound absorption by air molecules and water vapor, sound refraction caused by temperature and near-ground wind gradients, and air turbulence are collectively called atmospheric effects. Although atmospheric effects are mostly responsible for substantial noise fluctuations at distant receivers, they also can have a significant effect at distances within a 100 m (330 feet).

Audible (Frequency) Spectrum - The frequency range normally associated with human hearing, usually considered between 16 - 20,000 Hz. For noise control purposes, the audible spectrum of interest usually lies between 20 - 10,000 Hz.

Audiogram - A graph showing hearing loss as a function of frequency.

Audiometer - An instrument for measuring hearing sensitivity or hearing loss.

Automobile - A vehicle classification for the purpose of noise prediction modeling, defined as all vehicles with two axles and four wheels designed primarily for transportation of nine or fewer passengers (automobiles), or transportation of cargo (light trucks). Generally the gross weight is less than 10,000 lbs (4,500 kg).

Average (Noise) Level - Typically the “energy-averaged” noise level in dB, wherein the contributing levels are first converted to “relative energies” or “energy ratios”, and added and divided by the number of contributing levels. The result is then converted back to dB.

A-Weighted Sound Level (abbreviated dBA or dB(A)) - Frequency weighted Sound Pressure Level approximating the frequency response of the human ear. It is defined as the sound level, in decibels, measured with a sound level meter having the metering characteristics and a frequency weighting specified in the American National Standards Institute Specification for Sound Level Meters, ANSI S 1.4 - 1983. The A-weighting de-emphasizes lower frequency sound sounds below 1000 Hz (1kHz) and higher frequency sounds above 4 kHz. It emphasizes sounds between 1kHz and 4 kHz. A-weighting is the most generally used measure for traffic and environmental noise throughout the world.

Background Noise - The total of all noise in a system or situation, independent of the presence of the noise source of interest (i.e without the noise of interest).

Baffle - A shielding structure or series of partitions used to increase the effective external transmission path length between two points in an acoustic system.

Band - (See *Frequency Band*)

Band Center Frequency - The designated (geometric) mean frequency of a band of noise.

Band Pressure Level - The sound pressure level contained within a specified band.

(Noise) Barrier Attenuation - The noise reduction due to barrier diffraction only.

Broadband Noise - Noise with components over a wide range of frequencies.

Calibrator - A device used to calibrate -or properly adjust for valid measurement results- a sound level meter and microphone system. Calibration must be performed before and after sound level measurement sequence.

Community Noise Equivalent Level (CNEL) - A noise level that takes into account all the A-weighted noise energy from a source during 24 hours and weights the evening (7 to 10 p.m.) noise by adding 5 dBA, and night (10 p.m. to 7 a.m.) noise by adding 10 dBA, respectively, during these periods.

Compression (of Sound Wave) - The portion of a sound wave in which the air molecules are slightly compressed with respect to the barometric air pressure (opposite of rarefaction).

Cylindrical Divergence (- Spreading) - Sound waves generated by a line source, such as approximated by a highway, tend to form cylindrical wave fronts that propagate by radiating outward from their original line source in cylindrical pressure waves of ever increasing areas. This process is referred to as cylindrical divergence or spreading. The same sound energy distributed over an ever increasing cylindrical area is reponsible of reducing the sound's energy per unit area (intensity) by one half for each doubling of distance. This corresponds with a noise level decrease of 3 dB per doubling of distance.

Cycles Per Second - (See *Hertz*)

Day-Night Level - (See L_{dn})

Decibel *(Abbreviated dB)* - A decibel is one-tenth of a Bel. It is a measure on a logarithmic scale which indicates the squared ratio of sound pressure to a reference sound pressure (unit for *sound pressure level*), or the ratio of sound power to a reference sound power (unit for *sound power level*). (See *sound pressure level*, and *sound power level*).

(Noise) Descriptor - A generic term for a noise indicator such as L_{eq}, L_{max}, L_{dn}, etc.

Diffuse Sound Field - A sound field in which the time average of the mean-square sound pressure is everywhere the same and the flow of acoustic energy in all directions is equally probable. For example, a sound source in a reverberation room, where many reflected sound waves are present and the sound level is equal at any location in the room.

Diffraction - The bending of sound pressure waves around an obstacle. The ease with which the pressure waves diffract around an obstacle depends on the ratio of wavelength to the size of the obstacle. Pressure waves with a given wavelength diffract more readily around a small object than a large object. Pressure waves with a longer wavelengths diffract more easily around an object of a given size than pressure waves with a shorter wavelength. Due to the above principles, highway traffic noise barriers provide a more defined noise "shadow" behind the barrier (and more noise attenuation) for higher frequency noise than for lower frequency noise. (See Angle of Diffraction, Shadow Zone)

Doppler Effect - The change in observed frequency of a sound wave caused by a time rate of change in the effective path length between sound source and receiver. If the path length rate of change causes the source and receiver to approach each other, the observed frequency shifts upward. If the source and receiver recede relative to each other, the frequency shifts downward. The frequency shift is called the Doppler Shift, and the unit is Hertz.

Dosimeter - An instrument measuring noise exposure for compliance with OSHA standards.

Dynamic Range - The range in sound levels (in dB) through which a source or receiver can emit or receive sound. For example, the dynamic range of a sound level meter typically ranges from 20 - 140 dB.

Emission Level - A measure of the noise output of a single vehicle. It is the maximum noise level, in dBA, observed during a passby of the vehicle at 15 m (50 ft). (See also Reference Energy Mean Emission Level).

Energy Average (- Mean) - The (noise level) result of energy averaging, or a method of averaging various sound pressure levels on the basis of their squared pressures (energy). This method involves the conversion of decibels to equivalent relative energy or energy ratios, averaging and changing the values back to decibels.

Energy Ratio - (See *Relative Energy)*

Equivalent (Lane) Distance (D_E) - The distance to a specific receiver from an imaginary single lane which acoustically represents a multi-lane highway or a group of lanes, such as directional lanes.

Equivalent Level - (See L_{eq}).

Excess Attenuation - Sound attenuation in addition to that caused by geometric spreading (see *geometric spreading*). Usually meant to be the attenuation due to ground effects and sometimes also the atmospheric effects (see *ground effects, atmospheric effects*).

Existing Noise Levels - The noise, resulting from the natural and mechanical sources and human activity, considered to be usually present in a particular area.

Far (Sound) Field - The region beyond the near field, where the effects of source dimensions are less important and where the noise propagates with a simple relationship between sound level and distance.

Filter - A device for separating components of a signal on the basis of their frequency. It allows components in one or more frequency bands to pass relatively unattenuated, and it attenuates components in other frequency bands.

Flanking Noise - Refers to noise energy that arrives at an observer by some unexpected or unexamined pathway. For example, in the design of noise barriers, the calculations predict the energy that diffracts over the top of the barrier. If significant amounts of noise energy reach the observer by passing around its ends far up and down the roadway, this energy has flanked the barrier along unexpected “flanking paths”.

Free (Sound) Field - A sound field that is free from enclosures or boundaries, and in which there are no reflections and accompanying interference and reverberation effects such as found in auditoriums.

Frequency - The number of oscillations per second (a) of a periodic wave sound, and (b) of a vibrating solid; expressed in units of Hertz (abbreviated Hz), formerly cycles per second (cps). 1 Hz = 1cps = 1 oscillation per second. The value is the reciprocal (1/x) of the period of oscillations in seconds. The symbol for frequency is f.

Frequency Band - An interval of the frequency spectrum defined between an upper and lower cut-off frequency. The band may be described in terms of these two frequencies, or, preferably, by the width of the band and the geometric mean frequency of the upper and lower cut-off frequencies, e.g., an octave band "centered" at 500 Hz.

Frequency Response - The response (or sensitivity) to an oscillating phenomenon (e.g., sound pressure) by an object (e.g., microphone or ear) measured in decibels as a function of frequency. For example, the A-weighting curve (see A-weighted sound level) corresponds closely to the frequency response of human hearing at a certain constant level of sound energy.

Frequency Spectrum - The description of a sound wave's resolution into components, each of different frequency and (usually) different amplitude and phase.

Fresnel Number (N) - A dimensionless value used in predicting the attenuation of a noise barrier located between a noise source and a receiver. In its simplest mathematical form $N=2\delta/\lambda$, where δ is the path length difference between the sound path from source to receiver via the top of the barrier and the straight line between the source and receiver; λ = the wavelength of the sound (units of δ and λ must be the same). Generally, the larger the value of N, the greater the attenuation.

Fundamental Frequency - The frequency with which a periodic function (e.g., a sound wave) reproduces itself, sometimes called the first harmonic (see *harmonic*).

Geometric Divergence (- Spreading) - Refers to the shape of sound pressure wave fronts and the manner in which they propagate. Geometric divergence or spreading is a generic term used for specific types of divergence, such as cylindrical or spherical divergence. (see cylindrical divergence and spherical divergence).

Gradient (Re:Speed of Sound, Temperature, or Wind Velocity) - Variation of speed of sound, temperature, and wind velocity with height above the ground surface. A gradient in speed of sound can be caused by differences in temperature with height above the ground and/or differences in wind velocities with height above the ground. The speed of sound gradient in turn causes (atmospheric) refraction of sound which can create noise "shadows" (decreases) in certain areas and noise concentrations (increases) in others. (See *(atmospheric) refraction*)

Ground Effects - The effects of sound grazing absorptive ground (see *absorptive grounds*).

Hard Site (- Ground) - Term used for reflective characteristics of the ground surface between a noise source and receiver. The term is most often used in traffic noise prediction models, where it is associated with a 3 dB per doubling of distance line source attenuation (i.e. due to geometric spreading only, without excess attenuation).

Harmonic - A sinusoidal (pure tone) component whose frequency is a whole-number multiple of the fundamental frequency of the wave. If a component has a frequency twice that of the fundamental frequency it is called the second harmonic.

Heavy Truck (HT) - A vehicle type for the purpose of noise prediction modeling, defined as all vehicles with three or more axles designed for transportation of cargo. Generally the gross weight is greater than 12,000 kg (26,500 lbs.).

Hertz (Hz) - Unit of frequency, formerly called cycles per second (cps). 1 Hz = 1 cps. (See *frequency*).

Hourly Equivalent Sound Level - See ($L_{eq}(h)$)

Incident Sound - Direct sound striking a surface (see *angle of incidence*).

Infrasound, Infrasonic - Sound(s) with frequencies below the audible sound spectrum (generally lower than 16-20 Hz).

Insertion Loss (IL) - The actual noise level reduction at a specific receiver due to construction of a noise barrier between the noise source (traffic) and the receiver. Generally, it is the net effect of the (noise) barrier attenuation and the loss of ground effects.

Inverse First Power - The lessening (increasing) of sound amplitude due to the process of *cylindrical divergence* (see *cylindrical divergence*) from a *line source*. For a *line source*, the sound pressure level SPL_1 at distance D_1 is related to the sound pressure level SPL_2 at a distance of D_2 by the equation:

$$SPL_1 - SPL_2 = 10 \log (D_1 / D_2)$$

Inverse Square - The lessening (increasing) of sound amplitude due to the process of *spherical divergence* (see *spherical divergence*) from a *point source*. For a *point source*, the sound pressure level SPL_1 at distance D_1 is related to the sound pressure level SPL_2 at a distance of D_2 by the equation:

$$SPL_1 - SPL_2 = 10 \log (D_1 / D_2)^2$$

kHz - abbreviation for kilo Hertz, or 1,000 Hertz; e.g. 3 kHz is 3,000 Hertz (see *Hertz*).

L_{dn} - Abbreviation for the Day-Night Level noise descriptor. It is the energy-average of the A-weighted sound levels occurring during a 24-hour period, with 10 dB added to the A-weighted sound levels occurring during the period from 10 p.m. to 7 a.m.

Leq - The equivalent steady state sound level which in a stated period of time would contain the same acoustical energy as the time-varying sound level during the same period.

Leq (h) - The energy-average of the A-weighted sound levels occurring during a one hour period, in decibels, i.e., a one hour Leq (see *Leq*).

Level - In acoustics, the value of a logarithm of the ratio (or ratio squared) of that quantity t a reference quantity of the same kind, in decibels. The base of the logarithm is commonly 10. The reference quantity and the kind of level must be specified, e.g., sound pressure *level* of 60 dB re: 20 μPa, sound power *level*, re: 10^{-12} W, etc.

Line of Sight - A straight line between the observer location and a specific noise source.

Line Source (of Noise) - A source of noise spread out into a line, such as approximated by the combined traffic on a roadway.

L_{max} - The highest sound pressure level in a specific time period.

Logarithm (Log) - A mathematical operation which, for values greater than 1, condenses these into smaller values by doing the reverse of y^x, where x is the number which is being operated on. Normally the base, or value of y, is taken as 10 (common log). If the base is not specified, its value is usually considered as 10. Thus, if $10^x = a$, then $x = \text{Log}_{10} a$ or Log a. If $a > 1$, x is positive; if $a=1$, $x=0$, and if $0<a<1$, x is negative. Examples:

$10^2 = 100$; Log 100 = 2 (x=2, a=100)

$10^0 = 1$ Log 1 = 0 (x=0, a=1)

$10^{-2} = 0.01$ Log 0.01 = -2 (x=-2, a=0.01)

Note: *a* must never be 0!!

Loudness - The judgement of intensity of a sound in terms of which sounds may be ranked on a scale from soft to loud. On this scale, a doubling of a reference sound energy is barely perceptible to the human ear; a tripling of the sound energy is readily perceptible, and ten times the sound energy sounds about twice as loud. Decreasing the sound by the same factors has a reciprocal effect, i.e. reducing the reference sound energy to one tenth of the original energy the sound is perceived as half as loud. Although loudness depends primarily on the intensity of the sound, it also depends on the sound's frequency and wave form.

Loudness Level - Of a sound is defined as the median sound pressure level in a specified number of trials of a 1000 Hz tone that is judged equally loud to the listener as the sound in question. Described in units of phons.(See *phon*). NOTE: calculated loudness level, L in phons is related to loudness in *sones* (see *sone*) by the equation:

$L = 10 \log_2 n_s$,

where L is the loudness level in phons and n_s is loudness in sones (see *sone*)

(A twofold change in loudness corresponds to a n interval of 10 phons)

L_x *(where x= 1-99; e.g.* L_{10}, L_{50}*)* - The sound pressure level exceeded x percent of a specific time period. L_{10} is the level exceeded 10% of the time; L_{50} is the level exceeded 50% of the time.

Masking - The action of bringing one sound (audible when heard by itself) to inaudibility or to unintelligibility by the introduction of another sound.

Medium - A substance carrying a sound wave. For example: air, water, steel.

Medium Truck (MT) - A vehicle classification for the purpose of noise prediction modeling, defined as all vehicles with two axles and six wheels designed for transportation of cargo. Generally the gross weight is greater than 4,500 kg (10,000) lbs. and less than 12,000 kg (26,500 lbs.).

(Sound Level) Meter Response - Measure of the quickness with which the needle of an analog sound level meter, or the display of a digital sound level meter, follows changes in the actual sound level.

Microphone - An electroacoustic transducer that transforms sound waves into equivalent electric waves.

Natural Frequency - Frequency of free oscillation of a system, i.e. the frequency at which a system vibrates when given an initial excitation and then allowed to vibrate freely without constraints.

Near (Sound) Field - That part of a sound field, usually within about two wavelengths of the lowest sound frequency from a sound source, where the dimensions of the sound source have an important effect, and where there is no simple relationship between sound level and distance. For traffic noise, the near field usually exists within 7.5 m (25 ft) from the nearest traffic. Noise measurements or predictions should be avoided in the near field.

Noise - Sound that is loud, unpleasant, unexpected, or otherwise undesirable.

Noise Barrier - A generic term for any feature which blocks or diminishes sound in its path from the source to the receiver. Although the term can technically refer to any feature, man-made or natural, the two most common features included in noise barriers are *sound walls* and *earth berms* (see *sound walls; earth berms*). Almost all noise barriers in California are sound walls, and for this reason the terms noise barriers and sound walls are frequently interchanged, even though sound walls are a (albeit very large) sub set of noise barriers.

Noise Contour - An imaginary line shown on a plan along which sound levels are all equal.

Noise Floor - The level of noise (in dB) which represents the threshold of sensitivity for a sound level meter and below which the inherent, or the device's own noise, limits its detectability of low-level signals.

Noise Reduction Coefficient (NRC) - A value representing the arithmetic average of the absorption coefficients in four octave bands with respective center frequencies of 250, 500, 1000, and 2000 Hz.

Octave - The interval between two sounds having a frequency ratio of 1:2; e.g., 500 - 1,000 Hz; 440 - 880 Hz, etc.

Octave Band - A frequency band in which the interval between the upper and lower cut-off frequency is one octave. As is the case with all frequency bands, the octave band is usually described by its center frequency (See *frequency band).* Octave bands are centered by preferred frequencies described by ISO R 266. Example: the 500 Hz octave band.

One-Third (1/3) Octave (Also Third Octave) - The interval between two sounds having a frequency ratio of the cube root of 2 (approximately 1.26). Three contiguous one-third octaves cover the same frequency range as an octave.

One-Third (1/3) Octave Band - A frequency band in which the interval between the the upper and lower cut-off frequency is one third of an octave. As is the case with all frequency bands, the one-third octave band is usually described by its center frequency (See *frequency band).* Three contiguous octave bands make up one octave band. As is the case with octave bands, one-third octave bands are centered by preferred frequencies described by ISO R 266. Example: three one-third octave bands centered at 400, 500, and 630 Hz make up the 500 Hz octave band.

Overall (Noise) Level (Total Noise Level) - The sound pressure level which includes all the energy in all frequency bands of interest.

Pascal (Pa) - A unit of pressure (in acoustics, normally RMS sound pressure) equal to one Newton per square meter (N/m^2). A reference pressure for a sound pressure level of 0 dB is 20 μ Pa (20 micro Pascal, or 20×10^{-6} Pa).

Peak Sound (Noise) Level - (See *peak sound pressure level*).

Peak Sound Pressure - The maximum instantaneous (non-RMS) sound pressure for a transient or impulsive sound or short duration or in a specified time interval for a sound long duration. Unit is Pa.

Peak Sound Pressure Level - Level of peak sound pressure (see *peak sound pressure*). Peak sound pressure level may be frequency weighted (such as A-weighted). Note: sound pressure level should not be frequency weighted (see *sound pressure level*). Unit is dB with stated frequency weighting, if any.

Permanent Threshold Shift - Permanent hearing loss due to frequent exposures to noise of high intensities(see *temporary threshold shift*).

Phon - Unit of loudness, judged or calculated in definition of loudness level (see *loudness level*).

Pink Noise - Broadband noise that yields the same energy for each octave band over its entire range of frequencies. Since, going from low frequencies to high frequencies, each subsequent octave band contains twice the frequency range as the previous octave band, the energy decreases with increasing frequency to maintain equal energy per octave band. (Compare with *white noise*).

Point Source (of Noise) - A noise source essentially concentrated at a single point, from which noise propagates outward in all directions (see *spherical divergence, spreading*). A single vehicle observed from some distance can be approximated as a point source.

Propagation (of Sound, Noise) - The passage of sound energy from noise source to receiver through a medium (such as air).

Pure Tone - A sound wave whose waveform is that of a sine wave (single frequency).

Random Incidence (of Sound) - Refers to sound waves that strike the receiver randomly from all angles of incidence. Such waves are common in a diffuse sound field.

Random Noise - Noise that has random characteristics in both time and amplitude - that is, any occurrence of any amplitude is as likely to occur at any one moment as any other.

Rarefaction (of Sound Wave) - The portion of a sound wave in which the air molecules are rarefied or in a slight vacuum with respect to the barometric air pressure (opposite of compression).

Rate of Decay (of Sound) - The time rate at which a sound pressure level decreases at a given receiver after the sound source is turned off. The commonly used unit is decibels per second (dB/s). It is used in measuring reverberation time of a room. (See *reverberation* and *reverberation time).*

(Noise) Receiver (Receptor) - Most basically, a receiver (receptor) is defined as any natural or artificial sensor that can perceive, register or be affected by sound, such as a human ear, or a microphone. The definition of receiver is usually extended to a three dimensional location where such receiver is likely to be present. In noise analysis, a receiver is any location of interest to the analyst. In noise measurement, a receiver is the location of the measurement, i.e. microphone. Frequently, one receiver is selected to represent a group of receivers in the same vicinity and with the same acoustical site characteristics.

Reference Energy Mean Emission Level (REMEL) - The speed-dependent, energy-averaged maximum pass-by noise level generated by a defined vehicle type, as measured by a sound level meter at 15 m (50 ft) from the centerline of travel, at a height of 1.5 m (5 ft).

Reference (Sound) Pressure - 1) Any sound pressure to which a test pressure is being compared on a decibel scale, e.g. in the following expression:

dB = 10 $\mathrm{Log}_{10}\left(\frac{p_1}{p_0}\right)^2$,where P_0 is the reference pressure (usually defined as 20 μ Pa).

2) The sound pressure at 1000 Hz which normal young adults can just detect; taken as 20 μ Pa.

Reflection, Angle of - (See *angle of reflection*)

Reflection (of Noise, Sound) - Bouncing back of sound waves away from an object which is 1) larger in exposed section than the wavelengths and 2) of sufficient surface weight, density and stiffness to present a very large increase in impedance compared to the air surrounding it.

Reflective Ground - Opposite of absorptive ground (see *absorptive grounds*). Grounds that do not absorb sound energy and reflect back most of the energy. Examples are paved surfaces (asphalt, concrete) and hard-packed soils.

(Atmospheric) Refraction - The bending of sound waves in arcing curves, either downward or upward, due to different velocities of sound with respect to height above the ground. The sound velocity differences are caused either by differences in near-ground wind velocity due to wind shear, or vertical changes in temperature (sound velocity increases with air temperature). Downward refraction occurs for downwind sound propagation and also during near-ground temperature inversions (temperature increases with height), and is responsible for noise increases. Upward refraction occurs for upwind sound propagation and also during near-ground temperature lapses (temperature decreases with height), and is responsible for noise decreases.

Relative (Sound, Noise) Energy - The energy ratio between a sound level to that of a reference level. For example, the sound energy of 60 dB is 10^6, or 1,000,000 times larger than that of 0 dB; that of 67 dB $10^{6.7}$, or 5,011,872 times larger than that of 0 dB. To add or subtract sound levels, the (relative) energies (<u>not</u> the dB levels) may be added directly. So the total relative energy of 60 dB + 67 dB = 1,000,000 +5,011,872 = 6,011,872 (RE: 0 dB), or in decibels: 10 Log (6,011,872) = 67.8 dB. The same result would be obtained if a reference of 50 dB were selected. Then the addition would be set up as follows: Total sound level= 50 dB + 10 Log $[10^{(6-5)} + 10^{(6.7-5)}$ = 50 dB + 10Log$[10^1 + 10^{1.7})$ = 50 dB + 10Log(60.12) = 50 dB + 17.8 = 67.8 dB.

Resonance - The relatively large amplitude of sound or vibration produced when the frequency of the source of the sound or vibration "matches" or synchronizes with the natural frequency (see *natural frequency*) of vibration of an object.

Resonator - A device that resounds or vibrates in sympathy with a source of sound and vibration, i.e. the source frequency matches the natural frequency of the resonator.

Reverberant Field - The region in a room where the reflected sound dominates, as opposed to the noise source where the direct sound dominates.

Reverberation - The persistence of sound in an enclosed space, as a result of multiple reflections, after the sound source has stopped.

Reverberation Room - A room having a long reverberation time, especially designed to make a sound field inside it as diffuse (homogeneous) as possible. Also called a live room. The opposite of an anechoic chamber (room). (see *anechoic chamber*).

Reverberation Time (RT) - The reverberation time of a room is the time taken for the sound energy (or sound intensity) to decrease to one millionth (10^{-6}) (corresponding to a drop of 60 dB in sound pressure level) of its steady-state value when the sound source is suddenly stopped. It is a measure of the persistence of an impulsive sound in a room and of acoustical absorption present inside the room.

Root Mean Square (RMS) Pressure (of Sound)- The square root of the mean (average) of the squares of a set of instantaneous positive, negative or zero (sound) pressure amplitudes. The RMS value is calculated by squaring the pressure values at each instant, adding them, dividing the total by the number of values, and taking the square root of the result. The squaring of both the positive and negative values ensures a positive result. An RMS sound pressure is directly correlated with sound energy. For a single frequency (pure tone) sound, or sine wave, there is a simple relationship between the peak sound pressure and RMS value:

$$\text{Peak} = \sqrt{2} \times \text{RMS} \approx 1.414 \times \text{RMS}$$

$$\text{RMS} = 1/\sqrt{2} \times \text{Peak} \approx 0.707 \times \text{Peak}$$

(Sound, Noise) Shadow Zone - The area behind a noise barrier that is blocked from direct view of the source of noise on the roadway.

Shielding - A noise reduction at the receiver due to to the placement or existence of natural or artificial barriers, such as walls, berms, rows of buildings, or, if thick and dense enough, trees.

Sine-Wave - A sound wave, audible as a pure tone, in which the sound pressure is a sinusoidal function of time.

Soft Site (- Ground) (See Absorptive Ground)

Sound - *Sound* is a vibratory disturbance created by a moving or vibrating source, in the pressure and density of a gaseous, liquid medium or in the elastic strain of a solid which is capable of being detected by hearing organs. Sound may be thought of as mechanical energy of a vibrating object transmitted by pressure waves through a medium to human (or animal) ears. The medium of main concern is air. Unless otherwise specified, sound will be considered airborne sound, as opposed to for example, structureborne or earthborne sound.

Sound (Noise, Acoustic) Energy - (See *Relative Energy*)

Sound Insulation - 1) The use of structures and materials designed to reduce the transmission of sound from one room or area to another or from the exterior to the interior of a building. 2) The degree by which sound transmission is reduced by means of sound insulating structures and materials.

Sound Intensity - The average rate of sound energy transmitted in a specified direction through a unit area normal to this direction at a point considered.

Sound Level (Noise Level) - Frequency-weighted sound pressure level measured using metering characteristics and frequency weighting, such as A,B, or C, specified in the American National Standards Institute Specification for Sound Level Meters, ANSI S1.4 - 1983.

Sound Level Meter - An instrument that is used for measuring sound levels in a specified manner. It generally comprises a microphone, an amplifier, an output display, and frequency weighting networks.

Sound Power - The total amount of energy radiated into the atmosphere per unit time by a source of sound.

Sound Power Level - The level of sound power, averaged over a period of time, the reference being 10^{-12} watts.

Sound Pressure Level (SPL) - Ten times the logarithm to the base ten of the ratio of the time mean-square pressure of a sound, in a stated frequency band (or range of frequencies) to the square of the reference sound pressure in gasses, of 20 μPa. SPL represent only un-weighted RMS levels (see *root mean square*). Unit is dB.

$$\text{SPL} = 10 \text{ Log}_{10} \left(\frac{p_1}{p_0} \right)^2$$

Where: P_0 is the reference pressure of 20 μ Pa

P_1 is the sound pressure

(Sound, Noise) Source - A general term designating the sound energy generator. In transportation, noise sources are classified as point and line sources (see *point source* and *line source*), which have different propagation characteristics.

(Sound, Noise) Source Heights - The effective acoustic (centroid) height of vehicle noise sources. These heigths have been determined from vehicle noise emission data, and are programmed in the appropriate computerized noise prediction models. The heights represent the energy average of all subsources, such as exhaust, tires and engine noise, and are most important in evaluating noise barrier attenuation.

Sound Transmission Class (STC) - A single figure rating system designed to give an estimate of sound insulation properties of a partition or a rank ordering of a series of partitions. It is intended for use primarily when speech and office noise constitutes the principal problem.

Spectrum - (See *frequency spectrum*)

Speed of Sound (in Air) - The speed of sound for standard temperature of dry air at 0° C and standard air pressure of 760 mm Hg standard is 331.4 m/s, or 1087.3 ft/sec. From these base values, the variation of speed of sound with temperature is described by the following equations:

Metric Units (m/s): $$c = 331.4\sqrt{1 + \frac{Tc}{273}}$$

English Units (ft/sec): $$c = 1051.3\sqrt{1 + \frac{Tf}{459}}$$

Where:
c = speed of sound in m/s (metric) or ft/sec (English)
Tc = Temperature in degrees Celcius (include minus sign for below zero)
Tf = Temperature in degrees Fahrenheit (include minus sign for below zero)

Spherical Divergence (- Spreading) - Sound waves generated by a point source, such as approximated by a single vehicle, tend to form spherical wave fronts that propagate by radiating outward from their original point source in spherical pressure waves of ever increasing areas. This process is referred to as spherical divergence or spreading. The same sound energy distributed over an ever-increasing spherical area is responsible of reducing the sound's energy per unit area (intensity) by one quarter for each doubling of distance. This corresponds with a noise level decrease of 6 dB per doubling of distance. (See also cylindrical divergence).

Spherical Wave - A sound wave in which the surfaces of constant phase are concentric spheres. A small (point) source radiating into an open space produces a free sound field of spherical waves.

Steady-State Sound - Sounds whose average characteristics remain constant in time. Examples are the sound of an air conditioner, fan, pump, etc.

Structureborne Sound - Sound that reaches the receiver, over at least part of its path, by vibration of a solid structure.

Temporary Threshold Shift - A temporary hearing loss, evidenced by an increase in the threshold of audibility (see *threshold of audibility*) occurring after exposure to noise of high intensity. After a given time (usually up to several hours), the ear recovers to almost normal, but not quite so. After an excessive number of exposures of high intensity a hearing loss, or permanent threshold shift develops gradually..

Threshold of Audibility (- of Detectabilty) - The minimum sound pressure level at which a person can hear a specific sound for a specified fraction of trials.

Transducer - A device capable of being actuated by waves from one or more transmission systems or media, and supplying related waves to one or more other transmission systems or media. Examples are microphones, loud speakers, accelerometers, and seismometers.

Transient Sound - Transient sounds are those, whose average properties do not remain constant over time. Examples are aircraft fly-over, a passing train, a sonic boom and a gun shot.

Transmission Loss (TL) - The "loss" in sound energy at a specific frequency, expressed in decibels as sound passes through a barrier or a wall. TL may be expressed mathematically as:

$$TL = 10 \times Log\left[\frac{E_1}{E_2}\right]$$

Where: E_1 is the sound energy leaving the back of the wall, and E_2 is the sound energy as it strikes the front of the wall.

Transmission Loss is not a reduction in total energy, only a transformation from sound energy into heat. Almost all highway noise barriers provide a TL of at least 25 dBA, which means that less than 1/3 percent of the sound energy travels through the wall.

Wave - In acoustics, a propagation wave is a cyclic pressure variation in air. The waves move at a characteristic speed (speed of sound) through the medium (air) as an elastic response to a pressure perturbation at a source.

Wave front - A portion of any wave (whether in compression or rarefaction state) which can be followed as it propagates throughout the medium, analogous to the crest of a tidal wave as it crosses the ocean. At all points on the wave front, the wave is of equal amplitude and phase.

Wavelength - For a non-periodic wave (such as sound in air), the normal distance between analogous points of any two successive waves. The wavelength of sound in air or in water is inversely proportional to the frequency of the sound. Thus the lower the frequency, the longer the wavelength.

White Noise - Broadband noise, the energy of which is constant over a wide range of frequencies, i.e. energy/Hz = constant. Since each octave band range increases by a factor of two, going from low to high frequencies, each subsequent octave band contains twice the acoustical energy as the previous one. This corresponds with an increase of 3 dB in energy for each subsequent octave band. (Compare with *pink noise*).

Ultrasonic - Pertaining to sound frequencies above the audible sound spectrum (in general higher than 20,000 Hz).

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CHAPTER 1. INTRODUCTION AND BACKGROUND

This manual provides practical guidance to Caltrans engineers, planners, and consultants who must address vibration issues associated with the construction, operation, and maintenance of California Department of Transportation (Caltrans) projects.

Operation of construction equipment and construction techniques such as blasting generate ground vibration. Maintenance operations and traffic traveling on roadways can also be a source of such vibration. If its amplitudes are high enough, ground vibration has the potential to damage structures, cause cosmetic damage (e.g., crack plaster), or disrupt the operation of vibration-sensitive equipment such as electron microscopes and advanced technology production and research equipment. Ground vibration and groundborne noise can also be a source of annoyance to individuals who live or work close to vibration-generating activities. Pile driving, demolition activity, blasting, and crack-and-seat operations are the primary sources of vibration addressed by Caltrans. Traffic, including heavy trucks traveling on a highway, rarely generates vibration amplitudes high enough to cause structural or cosmetic damage. However, there have been cases in which heavy trucks traveling over potholes or other discontinuities in the pavement have caused vibration high enough to result in complaints from nearby residents. These types of issues typically can be resolved by smoothing the roadway surface.

Freight trains, mass-transit trains, and light-rail trains can also be significant sources of ground vibration and groundborne noise in the environment. Caltrans is usually not involved in the construction of rail projects. There are, however, instances in which construction or modification of a roadway requires the relocation of existing rail lines. In these cases, Caltrans must consider the effects on ground vibration associated with relocated existing tracks.

The guidance and procedures provided in this manual should be treated as screening tools for assessing the potential for adverse effects related to human perception and structural damage. General information on the potential effects of vibration on vibration-sensitive research and advanced technology facilities is also provided, but a discussion of detailed assessment methods in this area is beyond the scope of this manual. Most situations involving research and advanced technology facilities will require consultation with experts with specialized expertise in this area.

The information in this manual is meant to be informative and educational to those individuals who must address vibration from construction equipment, explosives, and facility operations. As such, the information presented herein is considered both reliable and accurate. However, because the authors have no control over the conditions under which the information might be used, any and all risk associated with the use of the information contained herein lies with the user of this manual. This document is not an official policy, standard, specification, or regulation and should not be used as such. Its content is for informational purposes only.

This manual does not supersede previous Caltrans publications on earthborne vibration. Rather, it is intended to supplement previous publications and to improve knowledge and information related to this issue. Caltrans has been involved in the evaluation of earthborne vibration since 1958 and has conducted numerous studies since that time. A Caltrans report titled *Survey of Earth-borne Vibrations due to Highway Construction and Highway Traffic* (Report CA-DOT-

TL-6391-1-76-20) compiled a summary of results, findings, and conclusions of 23 studies completed in the 17-year period between 1958 and 1975. A Caltrans technical advisory titled *Transportation Related Earthborne Vibrations (Caltrans Experiences)* (Technical Advisory TAV-02-01-R9601) that was prepared in 1996 and updated in 2002 provides information from these 23 studies and other Caltrans vibration studies. This technical advisory is provided in Appendix A.

The following is an overview of the information presented in this manual. Because of the unique nature and effects of blasting, a separate chapter on that topic is presented.

- **Chapter 1, "Introduction and Background,"** summarizes the layout of this manual and provides background information on groundborne vibration.
- **Chapter 2, "Basic Physics of Ground Vibration,"** discusses the basic physics of groundborne vibration.
- **Chapter 3, "Vibration Sources,"** discusses the various sources of groundborne vibration that are of concern to Caltrans.
- **Chapter 4, "Vibration Propagation,"** discusses groundborne vibration wave types and vibration propagation models.
- **Chapter 5, "Vibration Receivers,"** discusses vibration receivers that are of concern to Caltrans: people, structures, and equipment.
- **Chapter 6, "Vibration Criteria,"** summarizes various vibration criteria that have been developed over the years.
- **Chapter 7, "Vibration Screening Assessment for Construction Equipment,"** presents a simplified procedure for assessing groundborne vibration from construction equipment.
- **Chapter 8, "Methods for Reducing Vibration,"** presents approaches to reducing the adverse effects of construction vibration.
- **Chapter 9, "General Procedures for Addressing Vibration Issues,"** discusses general procedures that can be used to avoid vibration-related problems.
- **Chapter 10, "Vibration Measurement and Instrumentation,"** discusses methods and tools used to measure and analyze vibration effects.
- **Chapter 11, "Vibration and Air-Overpressure from Blasting,"** presents information on groundborne vibration and air overpressure generated by blasting.
- **Chapter 12, "References and Additional Reading,"** lists additional sources of information.
- **Appendix A, "Technical Advisory TAV-02-01-R9601."**

- **Appendix B, “Sample Construction Vibration Complaint Form**.**”**
- **Appendix C, “Sample Vibration Specification.”**
- **Appendix D, “Sample Blasting Vibration Specifications.”**

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CHAPTER 2. BASIC PHYSICS OF GROUND VIBRATION

A. Simple Vibratory Motion

Dynamic excitation of an elastic system, such as the ground or a structure, results in movement of the particles that compose the elastic system. An idealized system of lumped parameters is commonly used to describe and evaluate the response of the elastic or vibratory system to excitation. The simplest lumped parameter system is called a “single-degree of freedom system with viscous damping.” This system comprises a mass (to represent the weight of the system), a spring (to represent the elasticity of the system), and a dashpot (to represent damping in the system). Figure 1 is graphic representation of this idealized system.

The following equation, which excludes the effects of damping, can be used to describe the vibratory motion of a mass in this simple system:

$$D = D_{pk} \sin (2\pi f t) \qquad \textit{(Eq. 1.)}$$

Where:

D = displacement from the at-rest position at a given point in time
D_{pk} = maximum or peak displacement amplitude from the at-rest position
π = ~3.1416
f = rate of oscillation expressed in cycles per second, or Hertz (Hz)
t = time in seconds [sec.]

Figure 2 depicts the quantities that are used to describe the vibratory motion.

As the mass oscillates up and down past the at-rest position, the motion can be described as follows. When the mass is at the maximum point of displacement with the spring either compressed or extended, the velocity of the mass is zero and the acceleration of the mass is at a maximum. Conversely, as the mass passes through the point of zero displacement, the velocity is at a maximum and the acceleration is zero.

The velocity (V) of the mass can be determined by taking the time derivative of the displacement, which is equivalent to multiplying the displacement by $2\pi f$:

$$V = 2\pi f \times D \qquad \textit{(Eq. 2)}$$

The acceleration (A) of the mass can be determined by taking the second time derivative of displacement, or the time derivative of the velocity:

$$A = 2\pi f \times V = (2\pi f)^2 \times D \qquad \textit{(Eq. 3)}$$

Therefore, if the frequency and amplitude of displacement, velocity, or acceleration are known, the remaining amplitudes can be determined by differentiation or integration. For example, if the frequency and amplitude of velocity are known, the displacement amplitudes can be determined

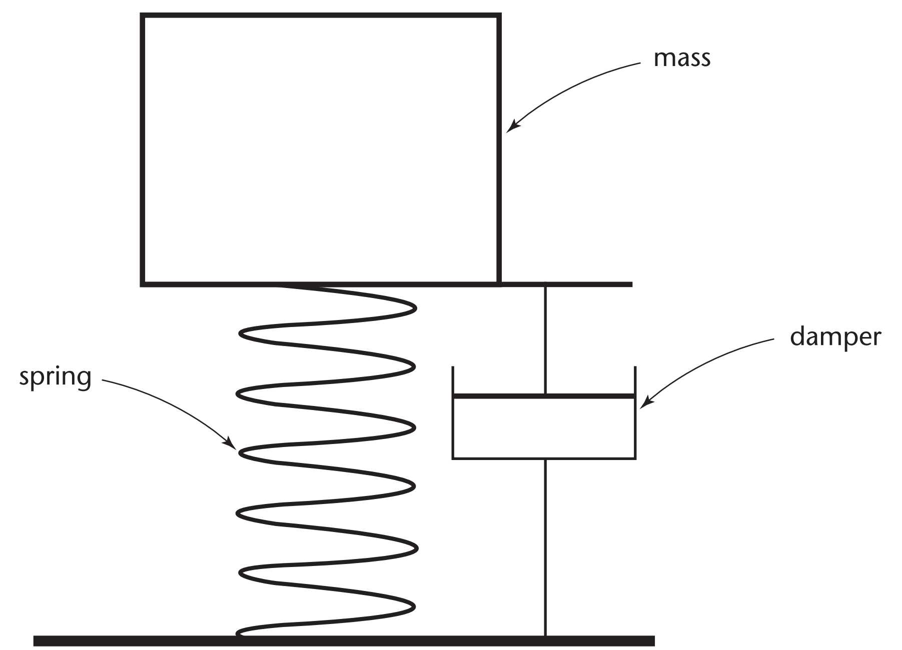

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Figure 1
Simple Lumped-Parameter Vibratory System

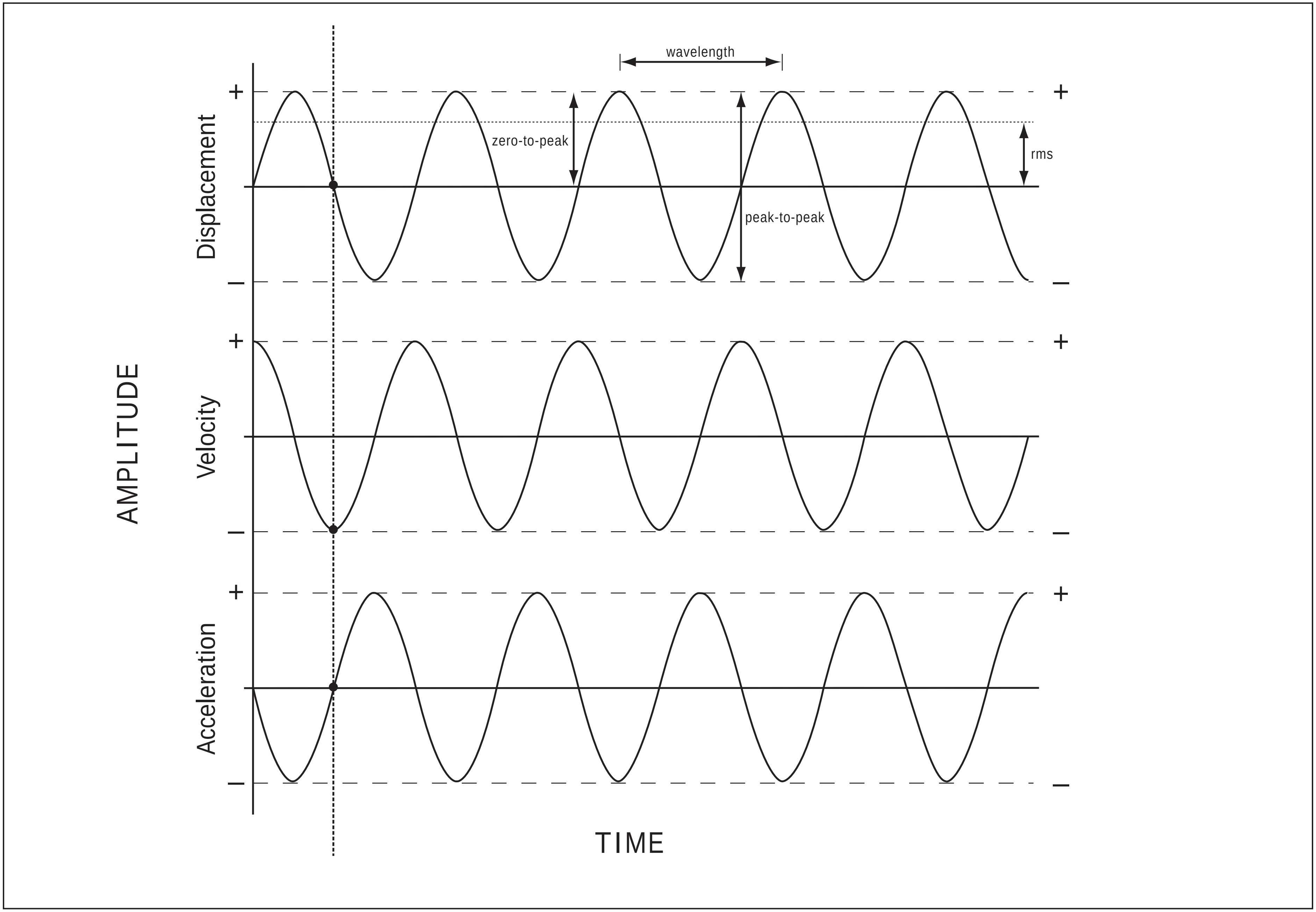

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Figure 2
Quantities Used to Describe Vibratory Motion

by integration (dividing by $2\pi f$) and the acceleration amplitude can be determined by differentiation (multiplying by $2\pi f$).

B. Amplitude Descriptors

In describing vibration in the ground and in structures, the motion of a particle (i.e. a point in or on the ground or structure) is used. The concepts of particle displacement, velocity, and acceleration are used to describe how the ground or structure responds to excitation. Although displacement is generally easier to understand than velocity or acceleration, it is rarely used to describe ground and structureborne vibration because most transducers used to measure vibration directly measure velocity or acceleration, not displacement. Accordingly, vibratory motion is commonly described by identifying the peak particle velocity (PPV) or peak particle acceleration (PPA). This is the zero-to-peak amplitude indicated in Figure 2.

PPV is generally accepted as the most appropriate descriptor for evaluating the potential for building damage. For human response, however, an average vibration amplitude is more appropriate because it takes time for the human body to respond to the excitation (the human body responds to an average vibration amplitude, not a peak amplitude). Because the average particle velocity over time is zero, the root-mean-square (rms) amplitude is typically used to assess human response. The rms value is the average of the amplitude squared over time, typically a 1-sec. period (Federal Transit Administration 1995). The rms value is always positive and always less than PPV; for a single frequency condition, the rms value is about 70% of the PPV. The rms amplitude is indicated in Figure 2. The crest factor is the ratio of the peak amplitude to the rms amplitude. For a sine wave, the crest factor is 1.414. For random ground vibration such as vibration from trains, the crest factor is 4. For vibration from pile driving and other impact sources, the crest factor cannot be readily defined because it depends on the averaging time of the rms measurement.

Displacement is typically measured in inches (in.) or millimeters (mm). Velocity is measured in inches per second (in/sec) or millimeters per second (mm/sec). Acceleration is measured in in/sec per second (in/sec^2), mm/sec per second (mm/sec^2), or relative to the acceleration of gravity (g) (32.2 feet [ft.]/sec^2 or 9.8 meters [m]/sec^2).

Decibels (dB) are also commonly used to compress the range of numbers required to describe vibration. Vibration velocity level (L_v) in dB is defined as follows (Federal Transit Administration 1995).

$$L_v = 20 \times \log_{10}(v/v_{ref}) \qquad \text{(Eq. 4)}$$

Where:

L_v = *velocity level in decibels (VdB)*
v = *rms velocity amplitude*
v_{ref} = *reference velocity amplitude*

In the United States, v_{ref} is usually 1 x 10^{-6} in/sec (1 µ-in/sec). For example, an rms value of 0.0018 in/sec is equal to a vibration velocity level of 65 VdB (re: 1 µ-in/sec). In this manual, all vibration velocity dB values are expressed relative to 1 u-in/sec rms. Vibration in terms of PPV is referred to as vibration velocity amplitude, whereas vibrations in terms of VdB is referred to as vibration velocity level.

When discussing vibration amplitude, the direction of the particle motion must be considered. Vibration amplitude can be described in terms a vertical component; a horizontal longitudinal component; a horizontal transverse component; and the resultant, which is the vector sum of the horizontal and vertical components. Caltrans most often uses a vertical PPV descriptor because vibration amplitude along the ground surface is usually, but not always, greatest in the vertical direction (Hendriks 2002). More importantly, the vertical component is usually representative of the vibration in all three orthogonal directions and is most easily measured.

In addition to the three translational axes discussed above, particle motion can also be rotational or angular along three rotational axes. Rotational particle motion is generally not a concern with regard to human or structure response. However, certain semiconductor tools, radar antennas, and telescopes are sensitive to rotational vibration. A detailed discussion of rotational particle motion is beyond the scope of this manual.

CHAPTER 3. VIBRATION SOURCES

The duration and amplitude of vibration generated by construction and maintenance equipment varies widely depending on the type of equipment and the purpose for which it is being used. The vibration from blasting has a high amplitude and short duration, whereas vibration from grading is lower in amplitude but longer in duration. In assessing vibration from construction and maintenance equipment, it is useful to categorize the equipment by the nature of the vibration generated. Various equipment categories according to type of vibration and/or activities in each category are discussed below.

Equipment or activities typical of continuous vibration include:

- excavation equipment,
- static compaction equipment,
- tracked vehicles,
- traffic on a highway,
- vibratory pile drivers,
- pile-extraction equipment, and
- vibratory compaction equipment.

Equipment or activities typical of single-impact (transient) or low-rate repeated impact vibration include:

- impact pile drivers,
- blasting,
- drop balls,
- "pogo stick" compactors, and
- crack-and-seat equipment.

Equipment typical of high-rate repeated impact vibration includes jackhammers and pavement breakers.

Because vehicles traveling on highway are supported on flexible suspension systems and pneumatic tires, these vehicles are not an efficient source of ground vibration. They can, however, impart vibration into the ground when they roll over pavement that is not smooth. Continuous traffic traveling on a smooth highway creates a fairly continuous but relatively low level of vibration. Where discontinuities exist in the pavement, heavy truck passages can be the primary source of localized, intermittent vibration peaks. These peaks typically last no more than a few seconds and often for only a fraction of a second. Because vibration drops off rapidly with distance, there is rarely a cumulative increase in ground vibration from the presence of multiple trucks. In general, more trucks result in more vibration peaks, though not necessarily higher peaks. Automobile traffic normally generates vibration amplitudes that are one-fifth to one-tenth the amplitude of truck vibration amplitudes. Accordingly, ground vibration generated by automobile traffic is usually overshadowed by vibration from heavy trucks.

Freight trains, commuter rail trains, mass-transit trains, and light-rail trains can also be significant sources of ground vibration in the environment. Although Caltrans is usually not involved in the construction of rail projects, there are instances in which construction or modification of a roadway requires the relocation or existing rail lines. In these cases, Caltrans must consider the effects on ground vibration associated with relocated existing tracks. Factors that affect the amount of vibration generated by a train include:

- stiffness of the vehicle suspension systems,
- unsprung mass of the wheel sets and trucks,
- roundness of the wheels,
- roughness of the rails and wheels,
- rail support system,
- mass and stiffness of the guideway structure, and
- stiffness and layering of soils supporting the rails.

For a detailed discussion of vibration effects from trains, refer to Federal Transit Administration 1995, Nelson 1987, and U.S. Department of Transportation 1982.

CHAPTER 4. VIBRATION PROPAGATION

A. Vibration Wave Types

When the ground is subject to vibratory excitation from a vibratory source, a disturbance propagates away from the vibration source. The ground vibration waves created are similar to those that propagate in water when a stone is dropped into the water. To assess ground vibration propagation over distance, the ground is modeled as an infinite elastic halfspace. The body of this type of medium can sustain two types of waves: "compression" or "primary" waves (P-waves), and "secondary" or "shear" waves (S-waves). These waves are called "body waves." The particle motion associated with a P-wave is a push-pull motion parallel to the direction of the wave front, whereas particle motion associated with an S-wave is a transverse displacement normal to the direction of the wave front.

In 1885, Lord Rayleigh discovered a third type of wave that can propagate in a halfspace. The motion of this wave, called a Rayleigh wave (R-wave), is confined to a zone near the surface or boundary of the halfspace. The R-wave consists of horizontal and vertical components that attenuate rapidly with depth (Richart 1970). Figure 3 depicts the deformation characteristics of P-, S-, and R-waves.

P-, S-, and R-waves travel at different speeds. The P-wave is the fastest, followed by the S-wave, then the R-wave. For a single short-duration disturbance, the characteristic wave system is shown in Figure 4 (Richart 1970). About 67% of energy is transmitted in the R-wave, 26% in the S-wave, and 7% in the P-wave (Richart 1970). As shown in Figure 5, the P-wave arrives first, followed by the S-wave, then the R-wave, with most of the energy in the R-wave. Along the surface of the ground, the P- and S-waves decay more rapidly than the R-wave. Therefore, the R-wave is the most significant disturbance along the surface of the ground, and it may be the only clearly distinguishable wave at large distances from the source (Richart 1970). However, at higher frequencies the R-wave may not be identifiable because inhomogeneities and layering complicate the propagation of these waves.

B. Vibration Propagation Models

When the ground is subject to vibratory excitation, body waves propagate outward radially from the source along a hemispherical wave front, while the R-wave propagates outward radially along a cylindrical wave front. All of these waves encounter an increasingly large volume of material as they travel outward, and the energy density in each wave decreases with distance from the source. This decrease in energy density and the associated decrease in displacement amplitude is called spreading loss. The amplitudes of body waves decrease in direct proportion to the distance from the source, except along the surface, where their amplitudes decrease in direct proportion to square of the distance to the source. The amplitude of R-waves decreases in direct proportion to the square root of the distance from the source.

The general equation for modeling spreading loss (often called "geometric attenuation") is as follows:

$$v_b = v_a\,(r_a/r_b)^{\gamma} \qquad \textit{(Eq. 5)}$$

Where:

v_a = vibration amplitude of the source at distance r_a
v_b = vibration amplitude at distance r_b
γ = geometric attenuation coefficient

As implied above, the geometric attenuation exponent depends on the wave type and propagation path. Table 1 summarizes the geometric attenuation coefficient by wave type and propagation path.

Table 1. Geometric Attenuation Coefficients

Source	Wave Type	Measurement Point	γ
Point on surface	R	Surface	0.5
Point on surface	Body (P or S)	Surface	2
Point at depth	Body (P or S)	Surface	1
Point at depth	Body (P or S)	Depth	1

Source: Amick 2000.

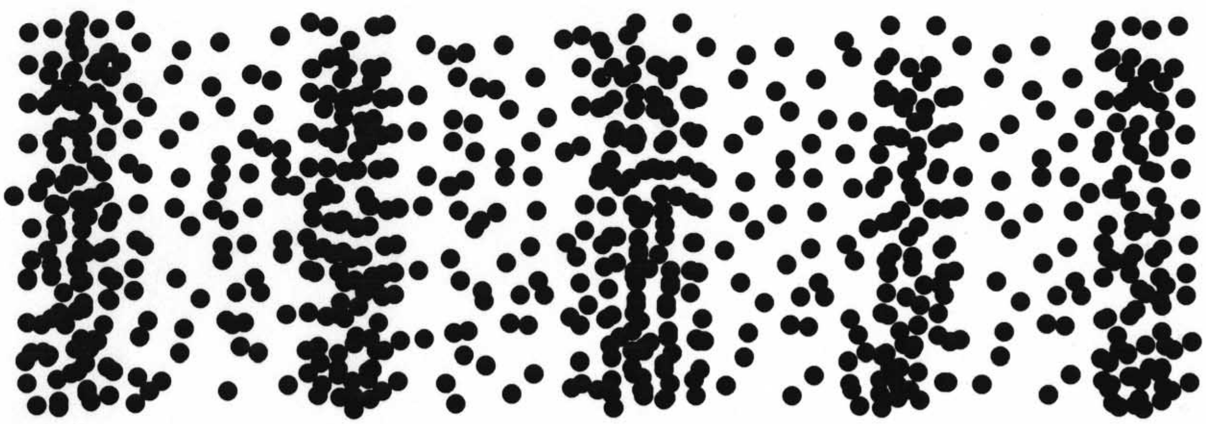
Given that two-thirds of the total input energy is transmitted away from a vertically oscillating source by the R-wave and that the R-wave decays much more slowly with distance than body waves, the R-wave is of primary concern for foundations on or near the ground surface (Richart 1970). Most construction settings involve surface or near-surface sources and receivers, making the R-wave the primary wave of concern. Even when the actual vibration source is below the surface, as with pile driving, R-waves are formed within a few meters of the point on the surface directly above the source (Dowding 1996). Accordingly, propagation of vibration from construction sources, including pile driving, is typically modeled in terms of R-waves (i.e., γ = 0.5). For a buried source, the R-wave emerges at a distance of about five times the depth from the source.

Because soil is not perfectly elastic, another attenuation factor influences attenuation of R-waves. In real earth materials, energy is lost by material damping (Richart 1970). Material damping is generally thought to be attributable to energy loss due to internal sliding of soil particles. Fluid motion in pores may also produce attenuation. Assuming R-waves are of primary consideration, the effect of material damping can be added to Eq. 5 as follows (Richart 1970):

$$v_b = v_a\,(r_a/r_b)^{0.5}\, e^{\,a(ra - rb)} \qquad \textit{(Eq. 6)}$$

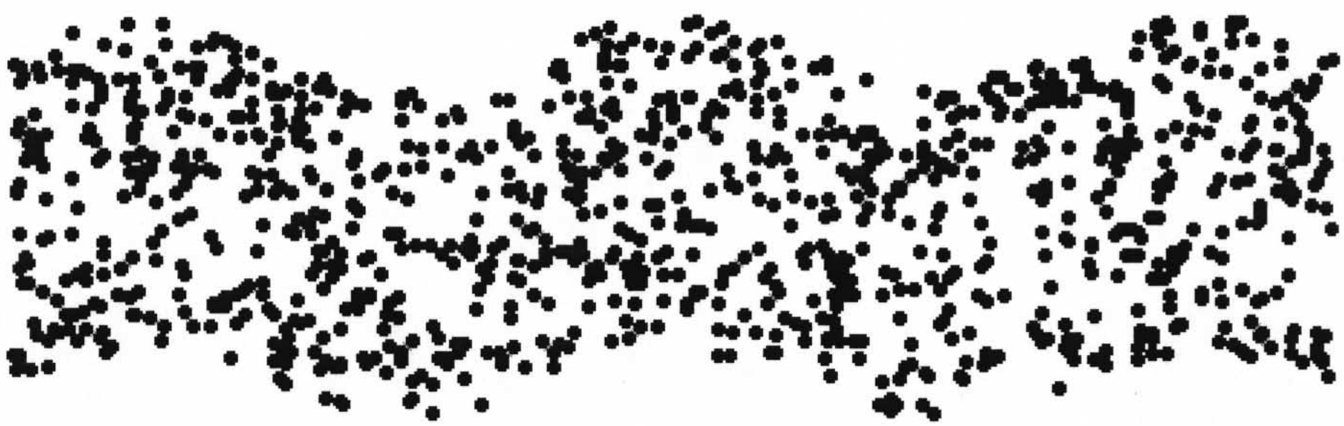
Where:

α = material damping coefficient



Compression or Primary Wave (P-Wave)

direction of wave propagation



Shear or Secondary Wave (S-Wave)

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Figure 3
Body Wave Types

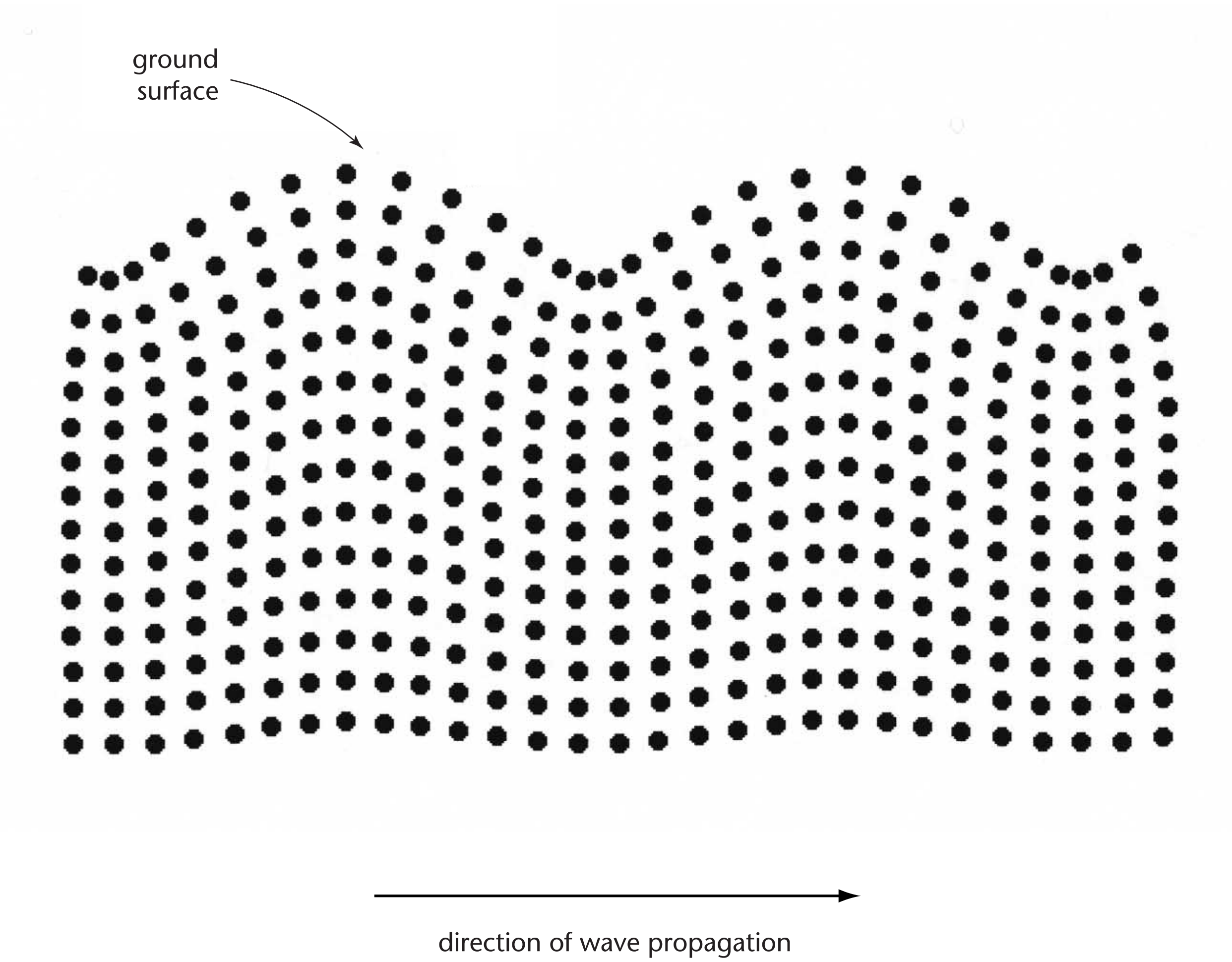

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Figure 4
Rayleigh Surface Wave

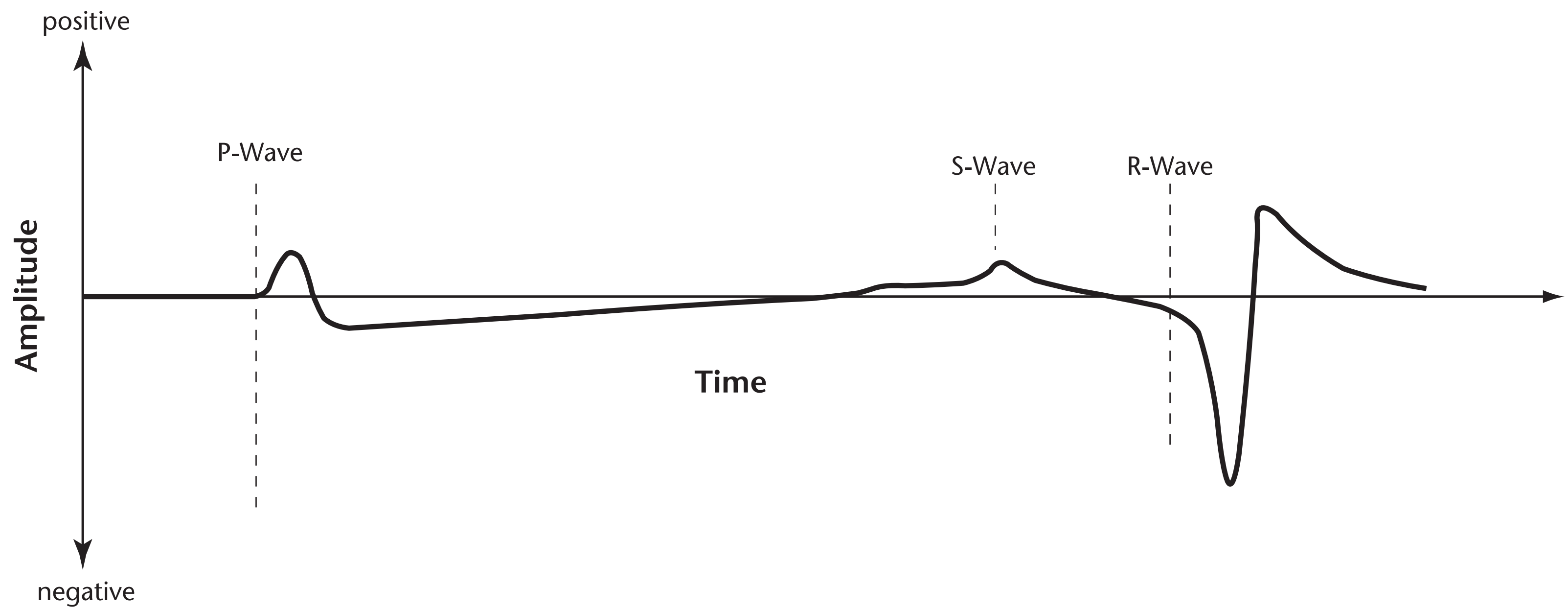

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Figure 5
Wave System from a Surface Point Source

Many factors affect material damping in soil, including soil type, moisture content, temperature, and the frequency of the vibration sources. Clays tend to exhibit higher damping than sandy soils (Wiss 1967). Wet sand attenuates less than dry sand because the combination of pore water and sand particles in wet sand does not subject compressional waves to as much attenuation by friction damping as does dry sand. Propagation of R-waves is moderately affected by the presence or absence of water (Richart 1970). Frozen soil attenuates less than thawed soil (Barkan 1962). Table 2 summarizes material damping coefficients for various soil types.

Table 2. Summary of Material-Damping Coefficients (Applies to Both P- and S-Waves)

Investigator	**Soil Type**	**α feet^{-1}**	**α meter^{-1}**
Forssblad	Silty gravelly sand	0.04	0.13
Richart	4-in. concrete slab over compact granular fill	0.006	0.02
Woods	Silty fine sand	0.079	0.26
Barkan	Saturated fine grain sand	0.003	0.010
	Saturated fine grain sand in frozen state	0.018	0.06
	Saturated sand with laminae of peat and organic silt	0.012	0.04
	Clayey sand, clay with some sand, and silt above water level	0.012	0.04
	Marly chalk	0.03	0.1
	Loess and loessial soil	0.03	0.1
	Saturated clay with sand and silt	0.0–0.037	0.0–0.12
Dalmatov	Sand and silt	0.079–0.11	0.026–0.36
Clough, Chameau	Sand fill over bay mud	0.015–0.061	0.05–0.2
	Dune sand	0.076–0.2	0.025–0.65
Peng	Soft Bangkok clay	0.079–0.13	0.026–0.44
Hendriks	Sand-silt, clayey silt, silty sand	0.006	0.021

Sources: Amick 2000, Hendriks 2002 (for Hendricks only).

A more simplified model has been suggested by Wiss (1981), who obtained a best fit of field data with the following equation:

$$V = kD^{-n} \qquad \textit{Eq. 7}$$

Where:

V = PPV of the seismic wave
k = value of velocity at one unit of distance
D = distance from the vibration source
n = slope or attenuation rate

The “n” value in this case is not equivalent to the material damping coefficient, but rather is a composite value or pseudo-attenuation coefficient that accounts for both geometric and material damping. Woods and Jedele (1985) developed values for “n” from field construction data. These values were related to generic soil types as indicated in Table 3.

Table 3. "n" Values Based on Soil Classes

Soil Class	Soil Type	"n" Value for Eq. 7
Class I	*Weak or soft soils:* lossy soils, dry or partially saturated peat and muck, mud, loose beach sand, dune sand, recently plowed ground, soft spongy forest or jungle floor, organic soils, topsoil (shovel penetrates easily)	None identified
Class II	*Competent soils:* most sands, sandy clays, silty clays, gravel, silts, weathered rock (can dig with a shovel)	1.5
Class III	*Hard soils:* dense compacted sand, dry consolidated clay, consolidated glacial till, some exposed rock (cannot dig with a shovel, need a pick to break up)	1.1
Class IV	*Hard, competent rock:* bedrock, freshly exposed hard rock (difficult to break with a hammer)	None identified

Source: Wood 1997.

There is a relationship between vibration amplitude and the energy of the driving force (Hendriks 2002). In general, if the energy of the driving force changes from E_1 to E_2, the vibration amplitude changes from V_1 to V_2 according to the following equation:

$$V_2 = V_1(E_2/E_1)^{0.5} \qquad \textit{(Eq. 8)}$$

In general, if the vibration amplitude of a source at a given distance is known, Eq. 6 or Eq. 7 can be used to estimate the resulting amplitude at various distances. This methodology, which does not account for the frequency dependence of the material-damping coefficient, provides a convenient and reasonable means of assessing vibration impact on structures and people. This method does not, however, have enough detail to be particularly useful for impact assessment for vibration-sensitive research or advanced technology facilities (Amick 2000). There is a significant body of knowledge that relates human response and building damage to the peak velocity amplitude measured in the time domain. Essentially, this is the function of Eq. 6 and Eq. 7. However, most assessment of the impact of vibration on research and advanced technology facilities is based on measurement and analysis in the frequency domain using frequency spectra (typically one-third octave spectra). The assessment of frequency-dependent vibration propagation is beyond the scope of this guidance manual.

For the purposes of assessing vibration effects on people and structures, use of a frequency-independent material-damping coefficient is supported by the fact that damage levels in terms of velocity in the frequency range of 1–80 Hz tend to be independent of frequency. This is also true for complaint levels in a frequency range of 8–80 Hz. Typical vibration from transportation and construction sources typically falls in the range of 10–30 Hz and usually centers around 15 Hz. (Hendriks 2002.) Within the narrow range of frequencies associated with most sources, frequency independence is a reasonable assumption.

Chapter 7 discusses a suggested method for applying propagation models to the assessment of groundborne vibration from construction equipment. Chapter 8 discusses a method relating to blasting.

CHAPTER 5. VIBRATION RECEIVERS

There are three primary types of receivers that can be adversely affected by ground vibration: people, structures, and equipment.

Ground vibration can be annoying to people. The primary effect of perceptible vibration is often a concern. However, secondary effects, such as the rattling of a china cabinet, can also occur, even when vibration levels are well below perception. Any effect (primary perceptible vibration, secondary effects, or a combination of the two) can lead to annoyance. The degree to which a person is annoyed depends on the activity in which they are participating at the time of the disturbance. For example, someone sleeping or reading will be more sensitive than someone who is running on a treadmill. Reoccurring primary and secondary vibration effects often lead people to believe that the vibration is damaging their home, although vibration levels are well below minimum thresholds for damage potential.

Vibration generated by construction activity has the potential to damage structures. This damage could be structural damage, such as cracking of floor slabs, foundations, columns, beams, or wells, or cosmetic architectural damage, such as cracked plaster, stucco, or tile.

Ground vibration also has the potential to disrupt the operation of vibration-sensitive research and advanced technology equipment. This equipment can include optical microscopes, cell probing devices, magnetic resonance imaging (MRI) machines, scanning electron microscopes, photolithography equipment, micro-lathes, and precision milling equipment. The degree to which this equipment is disturbed depends on the type of equipment, how it used, and its support structure. For example, equipment supported on suspended floors may be more susceptible to disturbance than equipment supported by an on-grade slab.

CHAPTER 6. VIBRATION CRITERIA

Over the years, numerous vibration criteria and standards have been suggested by researchers, organizations, and governmental agencies. There are no Caltrans or Federal Highway Administration standards for vibration, and it is not the purpose of this manual to set standards. Rather, the following discussion provides a summary of vibration criteria that have been reported by various researchers, organizations, and governmental agencies. The information is used in this chapter to develop a synthesis of these criteria that can be used to evaluate the potential for damage and annoyance from vibration-generating activities. In addition to the criteria discussed in this chapter, additional criteria that apply specifically to blasting are provided in Chapter 11.

A. People

Numerous studies have been conducted to characterize the human response to vibration. Table 4 summarizes the results of an early study (Reiher 1931) on human response to steady-state (continuous) vibration. Human response to vibration generated by blasting is discussed in Chapter 8.

Table 4. Human Response to Steady State Vibration

PPV (in/sec)	Human Response
3.6 (at 2 Hz)–0.4 (at 20 Hz)	Very disturbing
0.7 (at 2 Hz)–0.17 (at 20 Hz)	Disturbing
0.10	Strongly perceptible
0.035	Distinctly perceptible
0.012	Slightly perceptible

Table 5 summarizes the results of another study (Whiffen 1971) that relates human response to vibration from traffic (continuous vibration).

Table 5. Human Response to Continuous Vibration from Traffic

PPV (in/sec)	Human Response
0.4–0.6	Unpleasant
0.2	Annoying
0.1	Begins to annoy
0.08	Readily perceptible
0.006–0.019	Threshold of perception

Table 6 summarizes the results of another study (Wiss 1974) that relates human response to transient vibration.

Table 6. Human Response to Transient Vibration

PPV (in/sec)	Human Response
2.0	Severe
0.9	Strongly perceptible
0.24	Distinctly perceptible
0.035	Barely perceptible

The results in Tables 4–6 suggest that the thresholds for perception and annoyance are higher for transient vibration than for continuous vibration.

In 1981, the International Standards Organization (ISO) published *Guide to the Evaluation of Human Exposure to Vibration and Shock in Buildings (1 Hz to 80 Hz)* (ISO 2631). This document, based on the work of many researchers, suggested that humans are sensitive to particle velocity in the range of 8–80 Hz. This means that the same velocity at different discrete frequencies will elicit the same response, such as detection or discomfort. Below 8 Hz, the body is less sensitive to vibration, and therefore responds more uniformly to acceleration (i.e., higher velocities are needed to elicit the same response). Table 7 summarizes the vibration criteria in ISO 2631 for vibration sources with predominant frequencies in the range of 8–80 Hz. It is recommended in ISO 2631 that one-third octave band filtering be used when the vibration source has many closely spaced frequencies or contains broadband energy.

Table 7. ISO 2631 Vibration Criteria

Building Use	Vibration Velocity Level (VdB)	Vibration Velocity rms Amplitude (in/sec)
Workshop	90	0.032
Office	84	0.016
Residence	78 day/75 night	0.008
Hospital operating room	72	0.004

Also, FTA (1995) has developed vibration criteria based on building use. These criteria, shown in Table 8, are based on overall rms vibration levels expressed in VdB.

Table 8. Federal Transit Administration Vibration Impact Criteria

Land Use Category	Vibration Impact Level for Frequent Events (VdB)	Vibration Impact Level for Infrequent Events (VdB)
Category 1: Buildings where low ambient vibration is essential for interior operations	65	65
Category 2: Residences and buildings where people normally sleep	72	80
Category 3: Institutional land uses with primarily daytime use	75	83

Note: "Frequent events" is defined as more than 70 events per day. "Infrequent events" is defined as fewer than 70 events per day.

B. Structures

The effects of vibration on structures has also been the subject of extensive research. Much of this work originated in the mining industry, where vibration from blasting is a critical issue. The following is a discussion of damage thresholds that have been developed over the years. Mining industry standards relating to structure damage thresholds are presented in Chapter 7.

A study by Chae (1978) classifies buildings in one of four categories based on age and condition. Table 9 summarizes maximum blast vibration amplitudes based on building type. (The study recommends that the categories be lowered by one if the structure is subject to repeated blasting.)

Table 9. Chae Building Vibration Criteria

Class	PPV (Single Blast) (in/sec)	PPV (Repeated Blast) (in/sec)
Structures of substantial construction	4	2
Relatively new residential structures in sound condition	2	1
Relatively old residential structures in poor condition	1	0.5
Relatively old residential structures in very poor condition	0.5	—

The Swiss Association of Standardization has developed a series of vibration damage criteria that differentiates between single-event sources (blasting) and continuous sources (machines and traffic) (Wiss 1981). The criteria are also differentiated by frequency. Assuming that the frequency range of interest for construction and traffic sources is 10–30 Hz, Table 10 shows criteria for 10–30 Hz.

Table 10. Swiss Association of Standardization Vibration Damage Criteria

Building Class	Continuous Source PPV (in/sec)	Single-Event Source PPV (in/sec)
Class I: buildings in steel or reinforced concrete, such as factories, retaining walls, bridges, steel towers, open channels, underground chambers and tunnels with and without concrete alignment	0.5	1.2
Class II: buildings with foundation walls and floors in concrete, walls in concrete or masonry, stone masonry retaining walls, underground chambers and tunnels with masonry alignments, conduits in loose material	0.3	0.7
Class III: buildings as mentioned above but with wooden ceilings and walls in masonry	0.2	0.5
Class IV: construction very sensitive to vibration; objects of historic interest	0.12	0.3

Konan (1985) reviewed numerous vibration criteria relating to historic and sensitive buildings, and developed a recommended set of vibration criteria for transient (single-event) and steady-state (continuous) sources. Konan recommended that criteria for continuous vibration be about half the amplitude of criteria for transient sources. Table 11 summarizes the recommended criteria.

Table 11. Konan Vibration Criteria for Historic and Sensitive Buildings

Frequency Range (Hz)	Transient Vibration PPV (in/sec)	Steady-State Vibration PPV (in/sec)
1–10	0.25	0.12
10–40	0.25–0.5	0.12–0.25
40–100	0.5	0.25

Whiffen (1971) presents additional criteria for continuous vibration. These criteria are summarized in Table 12.

Table 12. Whiffen Vibration Criteria for Continuous Vibration

PPV (in/sec)	Effect on Buildings
0.4–0.6	Architectural damage and possible minor structural damage
0.2	Threshold at which there is a risk of architectural damage to normal dwelling houses (houses with plastered walls and ceilings)
0.1	Virtually no risk of architectural damage to normal buildings
0.08	Recommended upper limit of vibration to which ruins and ancient monuments should be subjected
0.006–0.019	Vibration unlikely to cause damage of any type

Siskind et al. (1980) applied probabilistic methods to vibration damage thresholds for blasting. Three damage thresholds have been identified and are described in Table 13 in terms of PPV for probabilities of 5, 10, 50, and 90%.

Table 13. Siskind Vibration Damage Thresholds

	PPV (in/sec)			
Damage Type	5% Probability	10% Probability	50% Probability	90% Probability
Threshold damage: loosening of paint, small plaster cracks at joints between construction elements	0.5	0.7	2.5	9.0
Minor damage: loosening and falling of plaster, cracks in masonry around openings near partitions, hairline to 3-mm (0–1/8-in.) cracks, fall of loose mortar	1.8	2.2	5.0	16.0
Major damage: cracks of several mm in walls, rupture of opening vaults, structural weakening, fall of masonry, load support ability affected	2.5	3.0	6.0	17.0

Dowding (1996) suggests maximum allowable PPV for various structure types and conditions. Table 14 summarizes these values.

Table 14. Dowding Building Structure Vibration Criteria

Structure and Condition	Limiting PPV (in/sec)
Historic and some old buildings	0.5
Residential structures	0.5
New residential structures	1.0
Industrial buildings	2.0
Bridges	2.0

The American Association of State Highway and Transportation Officials (AASHTO) (1990) identifies maximum vibration levels for preventing damage to structures from intermittent construction or maintenance activities. Table 15 summarizes the AASHTO maximum levels.

Table 15. AASHTO Maximum Vibration Levels for Preventing Damage

Type of Situation	Limiting Velocity (in/sec)
Historic sites or other critical locations	0.1
Residential buildings, plastered walls	0.2–0.3
Residential buildings in good repair with gypsum board walls	0.4–0.5
Engineered structures, without plaster	1.0–1.5

C. Equipment

The operation of equipment for research, microelectronics manufacturing, medical diagnostics, and similar activities can be adversely affected by vibration. For the purposes of designing facilities to house this equipment, vibration criteria that are generic (i.e., applicable to classes of equipment or activity) rather than specific have been developed (Gordon 1991; Institute of Environmental Science and Technology 1998). These criteria are expressed in terms of one-third octave band velocity spectra and are summarized in Table 16.

Table 16. Vibration Criteria for Sensitive Equipment

Criterion Curve (see Figure 1)	Max Level[1] (microinches/sec) (dB)	Detail Size[2] (microns)	Description of Use
Workshop (ISO)	32,000 (90)	NA	Distinctly feelable vibration. Appropriate to workshops and nonsensitive areas.
Office (ISO)	16,000 (84)	NA	Feelable vibration. Appropriate to offices and nonsensitive areas.
Residential Day (ISO)	8,000 (78)	75	Barely feelable vibration. Appropriate to sleep areas in most instances. Probably adequate for computer equipment, probe test equipment, and low-power (to 50X) microscopes.
Op. Theatre (ISO)	4,000 (72)	25	Vibration not feelable. Suitable for sensitive sleep areas. Suitable in most instances for microscopes to 100X and for other equipment of low sensitivity.
VC-A	2,000 (66)	8	Adequate in most instances for optical microscopes to 400X, microbalances, optical balances, proximity and projection aligners, etc.
VC-B	1,000 (60)	3	An appropriate standard for optical microscopes to 1,000X, inspection and lithography equipment (including steppers) to 3 μ line widths.
VC-C	500 (54)	1	A good standard for most lithography and inspection equipment (including electron microscopes) to 1 μ detail size.
VC-D	250 (48)	0.3	Suitable in most instances for the most demanding equipment including electron microscopes (TEMs and SEMs) and E-Beam systems, operating to the limits of their capability.
VC-E	125 (42)	0.1	A difficult criterion to achieve in most instances. Assumed to be adequate for the most demanding of sensitive systems including long path, laser-based, small target systems, and other systems requiring extraordinary dynamic stability.

[1] As measured in one-third octave bands of frequency over the frequency range 8 to 100 Hz. The dB scale is referred to 1 micro-inch/second.

[2] The detail size refers to the line width in the case of microelectronics fabrication, the particle (cell) size in the case of medical and pharmaceutical research, etc. The values given take into account the observation that the vibration requirements of many items of the equipment depend upon the detail size of the process.

The information given in this table is for guidance only. In most instances, it is recommend that the advice of someone knowledgeable about the applications and vibration requirements of the equipment and process be sought.

CHAPTER 7. VIBRATION PREDICTION AND SCREENING ASSESSMENT FOR CONSTRUCTION EQUIPMENT

To assess the potential for vibration to annoy people and damage structures, a reasonable means must be available for estimating or predicting the PPV from various sources at various distances. This section describes a simple method for predicting vibration amplitudes from construction equipment, in terms of PPV, for a variety of vibration sources and soil types. A method for evaluating vibration from blasting is provided in Chapter 8. The evaluation of potential vibration impacts on research and advanced technology production equipment is beyond the scope of this manual. Individuals with specialized expertise in the evaluation of these impacts should be contacted in cases where research and advanced technology equipment could be affected.

This assessment of effects relates to the direct effects of vibration on people and structures. For pile driving, there are few cases of direct damage to structures located farther from a pile than the length of that pile. Settlement of soil as the result of pile driving, however, has potential to damage surface and buried structures at greater distances. Assessment of effects related to vibration-related soil settlement is beyond the scope of this manual. Individuals with specialized expertise in vibration-related soil settlement should be consulted in cases where construction-induced vibration could result in soil settlement or liquefaction.

The method presented in this chapter uses reference vibration source amplitudes and the simplified Wiss propagation model (Eq. 7) described in Chapter 4. The following discussion is separated into the following equipment categories: pile drivers, hydraulic breakers, and other construction equipment. Vibration amplitudes estimated using the method presented in this chapter are expected to be *typical worst-case values* and should be viewed as guidelines only. Actual values from equipment used by a contractor may result in vibration amplitudes that exceed or are lower than the estimated values.

A. Pile Driving Equipment

A wide variety of impact and vibratory pile driving hammers is used for driving or extracting various types of piles. Commonly used types of pile drivers are described below.

Drop hammer: The simplest form of pile driving hammer is a falling weight called a gravity or drop hammer. In this case, a weight is raised to the desired height by an attached crane hoist line and dropped directly or indirectly onto the pile. The weight can be enclosed in a steel cylinder.

Pneumatic hammer: A pneumatic impact hammer, also called a compressed-air hammer, is essentially a drop hammer in which a ram/piston in a cylinder is propelled upward by compressed air. The ram strikes the pile cap at the end of a downward stroke, which may be in a free fall under gravity (single-acting) or assisted in downward stroke by pressurized air over the piston head to accelerate the ram (double-acting).

Diesel hammer: Diesel impact hammers are similar to pneumatic hammers. However, whereas pneumatic hammers are one-cylinder drivers that require compressed air from an

external source, diesel hammers carry their own fuel, from which they generate their power internally. The falling ram compresses the air in the cylinder, and the impact atomizes a pool of diesel fuel at the end of the cylinder. The atomized fuel ignites with the compressed air and propels the ram upward, ready for the next downward stroke. The burnt gases are scavenged from the cylinder on the upward stroke of the ram. Some diesel hammers are provided with an adjustable fuel pump that serves to regulate the jumping height, and thereby the impact energy.

Hydraulic hammer: Hydraulic impact hammers are a relatively new type of hammer. They are similar to the pneumatic impact hammers, except that the ram is lifted hydraulically, using an external hydraulic source, and then is left to fall freely or is accelerated downward by pressurized gas above the piston.

Vibratory pile driver: Vibratory pile drivers advance the pile by vibrating it into the ground. They are especially effective for soils that are vibratorily mobile, such as sands and silts. Vibration is created in the gear case by rotating eccentric weights powered by hydraulic motors, and sometimes by electric motors. Only vertical vibration is created in the gear case. Horizontal vibration is canceled by the paired eccentrics, which are interconnected with gears to maintain synchronization. The vibration created in the gear case is transmitted into the pile being driven or extracted by means of a hydraulic clamp attached to the bottom of the gear case. The complete vibrator assembly is held by crane. To prevent the vibration created in the gear case from affecting the crane line, a vibration suppresser assembly is attached to the top of the gear case.

The rated energies of most pile drivers are in the range of about 20,000–300,000 foot-pounds (ft-lbs.) (Woods 1997). One very large driver, the Vulcan 6300, has a rated energy of 1,800,000 ft-lbs. Smaller drivers have rated energies as low as 300 ft-lbs. (Woods 1997.)

Vibration Amplitudes Produced by Impact Pile Drivers

An extensive review of the available literature (Martin 1980; Wood and Theissen 1982; Wiss 1967, 1974, 1981; Dowding 1996; Federal Transit Administration 1995; Woods 1997; Schexnayder and Ernzen 1999) and information provided by the manufacturers (Preston 2002; Morris 1991, 1996, 1997) indicates that the PPV from impact pile drivers can be estimated by the following equation:

$$PPV_{Impact\ Pile\ Driver} = PPV_{Ref}\,(25/D)^{n} \times (E_{equip}/E_{Ref})^{0.5} \quad (in/sec) \qquad (Eq.\ 9)$$

Where:

PPV_{Ref} = 0.65 in/sec for a reference pile driver at 25 ft.
D = distance from pile driver to the receiver in ft.
n = 1.1 is a value related to the vibration attenuation rate through ground
E_{Ref} = 36,000 ft-lb (rated energy of reference pile driver)
E_{equip} = rated energy of impact pile driver in ft-lbs.

The above equation is based on extensive review of the actual data points at various distances, measured for a wide range of impact pile drivers. The data were measured at the ground surface outside or within various types of buildings.

Literature indicates that the value of “n” in the above equation is generally 1 to 1.5. The suggested value for n is 1.1. The use of values greater than 1.1 would likely result in overestimation of amplitudes at distances closer than 25 ft and would be slightly conservative at distances beyond 25 ft.

If vibration impacts, based on the above approach, are expected to exceed the vibration assessment criteria, vibration estimates may be refined further by using values of “n” that are based on soil type classification, ranging from Class I–IV soils as outlined in the National Cooperative Highway Research Program (NCHRP) Synthesis 253 (Woods 1997), and based on data developed by Woods and Jedele (1985). This step would require detailed information on soil conditions at the site. Table 17 describes soil materials, soil classes, values of “n” determined by Woods and Jedele (1985), and suggested values for “n” for the purposes of estimating vibration amplitude.

Table 17. Measured and Suggested “n” Values Based on Soil Class

Soil Class	Description of Soil Material	Value of “n” measured by Woods and Jedele	Suggested Value of “n”
I	Weak or soft soils: loose soils, dry or partially saturated peat and muck, mud, loose beach sand, and dune sand, recently plowed ground, soft spongy forest or jungle floor, organic soils, top soil. (shovel penetrates easily)	Data not available	1.4
II	Competent soils: most sands, sandy clays, silty clays, gravel, silts, weathered rock. (can dig with shovel)	1.5	1.3
III	Hard soils: dense compacted sand, dry consolidated clay, consolidated glacial till, some exposed rock. (cannot dig with shovel, need pick to break up)	1.1	1.1
IV	Hard, competent rock: bedrock, freshly exposed hard rock. (difficult to break with hammer)	Data not available	1.0

As indicated by Wood and Theissen (1982), the use of published attenuation relationships, based primarily on Wiss (1967) and Attewell and Farmer (1973), relating hammer energies, scaled distances, and PPVs to predict vibration levels in moderately large commercial buildings or in buried structures would probably result in overly conservative estimates. Wiss (1967, 1974, 1981) does not report data points for complete evaluation, but rather presents only generalized curves.

Research by Wood and Theissen (1982) and an evaluation of the available literature indicate that predictions based on Wiss and Attewell and Farmer are likely to be overly conservative. Therefore, it is prudent to be cautious about the upper range of values presented in FTA’s *Transit Noise and Vibration Impact Assessment* guidance manual (Federal Transit Administration 1995) and the NCHRP Synthesis 218 (Schexnayder and Ernzen 1999) for the impact pile drivers, because these higher values appear to be based on Wiss's curves. The typical values for impact pile drivers, reported in these publications, appear to be based on the actual measured data reported by Martin (1980) and form the basis for Eq. 9 above.

Vibration Amplitudes Produced by Vibratory Pile Drivers

Information regarding vibration amplitudes produced by vibratory pile drivers is scarce in published literature. However, Wood (1982) presents some data for vibratory pile drivers. International Construction Equipment (ICE) has also provided some data for the vibratory pile drivers (Morris 1991, 1996, 1997). ICE conducted tests in 1991 with three different vibratory pile drivers and measured vibration levels at several distances between 3 and 100 ft. Wiss (1967, 1974, 1981) also presents some data curves for vibratory pile drivers. A lack of actual data points and inconsistency in the curves presented in different publications suggests that some caution be applied in evaluating the data.

Based on review of the available literature (Wood and Theissen 1982; Wiss 1967, 1974, 1981) and information provided by ICE (Morris 1991, 1996, 1997), vibration amplitudes produced by vibratory pile drivers can be estimated by the following equation:

$$PPV_{Vibratory\ Pile\ Driver} = PPV_{Ref}\,(25/D)^{n} \quad (in/sec) \qquad \text{(Eq. 10)}$$

Where:

PPV_{Ref} = 0.65 in/sec for a reference pile driver at 25 ft
D = distance from pile driver to the receiver in ft.
n = 1.1 (the value related to the attenuation rate through ground)

The suggested value for "n" is 1.1, the same value used for impact pile drivers. If desired and if soil information is available, the value of "n" may be changed to reflect soil type classification, as shown in Table 17.

Vibratory pile drivers generate the maximum vibration levels during the start-up and shut-down phases of the operation because of the various resonances that occur during vibratory pile driving (Woods 1997). Maximum vibration occurs when the vibratory pile driver is operating at the resonance frequency of the soil-pile-driver system. The frequency depends on properties of the soil strata being penetrated by the pile.

As indicated in the NCHRP Synthesis 253 (Woods 1997), vibration from vibratory pile drivers is related to the centrifugal force, which is proportional to the mass of the rotating eccentric elements, the radius of eccentricity of rotating elements, and the frequency of the rotating elements. Because of the scarcity of available data, the effect of centrifugal force on vibration from vibratory pile drivers could not be evaluated. In the absence of any reliable data, it is recommended that vibration from vibratory pile drivers be estimated by using Eq. 10 above.

Eq. 10 can be used to estimate the vibration amplitude during the resonant start-up and shut-down phases of the pile driving operation. Although there are no actual data that show the relative magnitude of vibration during the primary driving phase, away from the resonance effects, it is estimated that it could be 50% or less of the maximum levels that may occur during the start-up and shut-down phases. The maximum levels during the start-up and shut-down phases are the important values that should be evaluated when assessing potential impacts. Vibration generated during these start-up and shut-down phases is often very perceptible and is the source of most complaints from vibratory pile driving activity.

The FTA's *Transit Noise and Vibration Impact Assessment* (Federal Transit Administration 1995) and NCHRP Synthesis 218 (Schexnayder and Ernzen 1999) state that continuous operation at a fixed frequency may be more noticeable to nearby residents, even at lower vibration levels. In addition, the steady-state excitation of the ground may increase the response at the resonance frequency of building components. Response may be unacceptable in cases of fragile historical buildings or vibration-sensitive manufacturing processes. Impact pile drivers, conversely, produce high vibration levels for a short duration (0.2 second) any may have sufficient time between impacts to allow any resonant response to decay.

Wood and Theissen (1982) state that vibration levels from vibratory pile drivers may be at least as severe as those from impact pile drivers, and that the potential for damage from vibratory pile drivers may be greater than that from impact hammers because of sustained vibration levels. Vibration data provided by ICE (Morris 1991, 1996, 1997) support the fact that vibratory pile drivers generate vibration levels that are somewhat similar to those produced by impact pile drivers. The use of resonance-free vibratory pile drivers may be an exception to this inference (see "Vibration Mitigation Measures for Pile Drivers" section below).

Vibration Amplitudes Produced by Hydraulic Breakers

Review of available literature indicates that there is no information available about measured vibration amplitudes from hydraulic breakers used in pavement and concrete demolition projects. Hydraulic breakers (also called hoe-rams, hydraulic hammers, or mounted impact hammers) are generally rated by the amount of energy being delivered, typically in the range of 70–15,000 ft-lbs. Because the breakers are rated in a similar manner to impact pile drivers, it is reasonable to assume that the approach presented in Eq. 9 can be used for estimating vibration amplitude from hydraulic breakers. Because hydraulic breakers generally have much lower energy ratings than impact pile drivers, Eq. 9 should be adjusted for typical reference energy of only 5,000 ft-lbs. for hydraulic breakers.

Based on the above discussion, vibration produced by hydraulic breakers can be estimated by the following formula:

$$PPV_{Hydraulic\ Breaker} = PPV_{Ref}\,(25/D)^n\ x\ (E_{equip}/E_{Ref})^{0.5}\quad (in/sec) \qquad (Eq.\ 11)$$

Where:

PPV_{Ref} = 0.24 in/sec for a reference hydraulic breaker at 25 ft.
D = distance from hydraulic breaker to the receiver in ft.
n = 1.1 (the value related to the attenuation rate through ground)
E_{Ref} = 5,000 ft-lbs. (rated energy of reference hydraulic breaker)

E_{equip} = *rated energy of hydraulic breaker in ft-lbs.*

The suggested value for "n" is 1.1. Because vibration from the hydraulic breakers originates primarily near the ground surface, a value of **"**n**"** based on soil classification may not necessarily be applicable; however, a higher value of "n" based on site-specific soil conditions could be used for a less-conservative estimation of vibration amplitude.

B. Vibration Produced by Other Construction Equipment

Review of available literature indicates that there is limited information available on vibration source levels from general construction equipment. The most comprehensive list of vibration source amplitudes is provided in the document entitled *Transit Noise and Vibration Impact Assessment* (Federal Transit Administration 1995). This document lists vibration source amplitudes at 25 ft. for various types of construction equipment. Table 18 summarizes these and other source levels.

Caltrans has conducted several studies related to ground vibration produced by crack-and-seat operations. A study conducted by Caltrans (2000) measured and evaluated ground vibration generated by crack-and-seat operations along State Route 101 near Santa Maria. A Walker Megabreaker Model 8-13000 was used. This machine drops an 8-ft-wide by 10-ft-tall steel plate weighing 13,000 lbs. approximately 4 ft. Operation of this machine produced the following results:

At 12 m, PPV = 1.25 in/sec.

At 27 m, PPV = 0.422 in/sec, 0.62 in/sec, and 0.412 in/sec.

At 34 m, PPV = 0.290 in/sec.

At 63 m, PPV = 0.083.

Another study (Ames et al. 1976) conducted in 1972 produced the following results:

At 10 ft., PPV = 2.99 in/sec.

At 38 ft., PPV = 0.275 in/sec.

The Santa Maria data has been used to develop a reference vibration amplitude for crack-and-seat operation. Using the measurement at 12 m as the reference distance, the data corresponds to Eq. 12 with N = 1.5. The reference amplitude at 25 ft. extrapolated from this is 2.4 in/sec and is shown in Table 18.

Table 18. Vibration Source Amplitudes for Construction Equipment

Equipment	Reference PPV at 25 ft. (in/sec)
Vibratory roller	0.210
Large bulldozer	0.089
Caisson drilling	0.089
Loaded trucks	0.076
Jackhammer	0.035
Small bulldozer	0.003
Crack-and-seat operations	2.4

Sources: Federal Transit Administration 1995 (except Hanson 2001 for vibratory rollers) and Caltrans 2000 for crack-and seat-operations.

Using these source levels, vibration from this equipment can be estimated by the following formula:

$$PPV_{Equipment} = PPV_{Ref}\,(25/D)^{n} \quad (in/sec) \qquad \text{(Eq. 12)}$$

Where:

PPV_{Ref} = reference PPV at 25 ft.
D = distance from equipment to the receiver in ft.
n = 1.1 (the value related to the attenuation rate through ground)

The suggested value for “n” is 1.1. Because vibration from this equipment originates primarily near the ground surface, modifying the value of “n” based on soil classification may not necessarily be applicable; however, a higher value of “n” based on site-specific soil conditions could be used for a less-conservative estimation of vibration amplitude. FTA recommends a value of “n” of 1.5 for vibration assessment. Using a value of 1.5 is less conservative than using a value of 1.4 or less (as indicated in Table 17) because it assumes that vibration will attenuate at a greater rate.

C. Evaluating Potential Vibration Impacts

As shown in Chapter 6, there is limited consistency between the categorization of effects and damage thresholds; however, it is apparent that damage thresholds for continuous sources are less than those for single-event or transient sources. It is also apparent that the vibration from traffic is continuous and that vibration from a single blasting event is a single transient event; however, many types of construction activities fall between a single event and a continuous source. An impact pile driver, for example, continuously generates single transient events. As a practical matter and based on the nature of available criteria, the criteria can only be reasonably separated into two categories: continuous and transient.

To assess the damage potential from ground vibration induced by construction equipment, a synthesis of various vibration criteria presented in Chapter 6 has been developed. This synthesis of criteria essentially assumes that the threshold for continuous sources is about half of the threshold for transient sources. A vibration amplitude predicted using Eqs. 9–12 can be compared the criteria in Tables 19 and 20 to evaluate the potential for damage.

Table 19. Guideline Vibration Damage Potential Threshold Criteria

Structure and Condition	Maximum PPV (in/sec) Transient Sources	Maximum PPV (in/sec) Continuous/Frequent Intermittent Sources
Extremely fragile historic buildings, ruins, ancient monuments	0.12	0.08
Fragile buildings	0.2	0.1
Historic and some old buildings	0.5	0.25
Older residential structures	0.5	0.3
New residential structures	1.0	0.5
Modern industrial/commercial buildings	2.0	0.5

Note: Transient sources create a single isolated vibration event, such as blasting or drop balls. Continuous/frequent intermittent sources include impact pile drivers, pogo-stick compactors, crack-and-seat equipment, vibratory pile drivers, and vibratory compaction equipment.

A similar synthesis of criteria relating to human perception has also been developed and is summarized in Table 19. A vibration amplitude predicted with Eqs. 1–4 can be compared to the criteria in Table 20 for a simple evaluation of the potential for annoyance and adverse impact. Some individuals may be annoyed at barely perceptible levels of vibration, depending on the activities in which they are participating.

Table 20. Guideline Vibration Annoyance Potential Criteria

Human Response	Maximum PPV (in/sec) Transient Sources	Maximum PPV (in/sec) Continuous/Frequent Intermittent Sources
Barely perceptible	0.04	0.01
Distinctly perceptible	0.25	0.04
Strongly perceptible	0.9	0.10
Severe	2.0	0.4

Note: Transient sources create a single isolated vibration event, such as blasting or drop balls. Continuous/frequent intermittent sources include impact pile drivers, pogo-stick compactors, crack-and-seat equipment, vibratory pile drivers, and vibratory compaction equipment.

Example Calculations

Example 1: An 80,000 ft-lb. pile driver will be operated at 100 ft. from a new office building and 100 ft. from a historic building known to be fragile. Evaluate the potential for damage to the buildings and annoyance to the building occupants. No information on the soil conditions is known.

Use Eq. 10 to estimate the PPV from the pile driving at 100 ft. In the absence of soil information, use N = 1.1.

$$PPV = 0.65\ (25/100)^{1.1}\ X\ (80{,}000/36{,}000)^{0.5} = 0.21\ in/sec$$

Table 19 suggests that an appropriate damage potential threshold for new commercial buildings is 0.5 in/sec when the source is continuous. The predicted vibration amplitude of 0.21 in/sec is well below this value, indicating low potential for structural damage to the building.

Table 19 suggests that an appropriate damage potential threshold for a fragile building is 0.1 in/sec when the source is continuous. The predicted vibration amplitude of 0.21 in/sec exceeds this value, indicating potential for structural damage to the building.

Table 20 suggests that a transient vibration amplitude 0.21 in/sec would be strongly perceptible, indicating that pile driving could lead to annoyance of building occupants.

Example 2: A vibratory roller will be operated 50 ft. from residences constructed in the 1940s. A detailed soil study is available indicating that the soil is hard competent rock. Evaluate the potential for damage to the buildings and annoyance to the building occupants.

Use Eq. 12 and data from Table 18 to estimate the vibration amplitude. Hard competent rock is in Soil Class IV. Therefore, N = 1.0 should be used.

$$PPV = 0.210\ (25/50)^{1} = 0.11\ in/sec$$

Table 19 suggests that an appropriate damage potential threshold for older residential structures is 0.3 in/sec when the source is continuous. The predicted vibration amplitude of 0.11 in/sec does not exceed this value, indicating low potential for structural damage to the building.

Table 20 suggests that a continuous vibration amplitude 0.11 in/sec would be strongly to severely perceptible, indicating that operation of the roller could lead to a high level of annoyance of residences.

Example 3: Crack-and-seat operations will be conducted on a freeway located 75 ft. from newly constructed residences and residences constructed in the 1940s. Soil conditions are known to be dense, compacted sand. Evaluate the potential for damage to the residences and annoyance to the building occupants.

Use Eq. 12 to estimate the PPV from the pile driving at 120 ft.. Dense, compacted sand is in Soil Class IV. Therefore, N = 1.1 should be used.

$$PPV = 2.4\ (25/120)^{1.1} = 0.43\ in/sec$$

Table 19 suggests that an appropriate damage potential threshold for older residential structures is 0.3 in/sec when the source is continuous. The threshold for new residential construction is 0.5 in/sec. The predicted vibration amplitude of 0.43 in/sec is below the 0.5 in/sec threshold for new residential construction but above the threshold of 0.3 for older construction, indicating low potential for structural damage to the newer residences but potential for damage to the older structures.

Table 20 suggests that a transient vibration amplitude 0.43 in/sec would be severely perceptible, indicating that pile driving could lead to annoyance of residents.

CHAPTER 8. METHODS FOR REDUCING VIBRATION

This chapter discusses methods for reducing ground vibration. For the most part, the methods involve reducing vibration at the source. Wave barriers treat the transmission path between the source and the receiver. Once ground vibration is transmitted to a receiver, there are few, if any, means for reducing the vibration.

A. Wave Barriers

The following discussion is a summary of the discussion of wave barriers provided in NCHRP Synthesis 253 (Woods 1997). Richart (1970) also provides useful information on this subject.

The purpose of a barrier is to reflect or absorb wave energy, thereby reducing the propagation of energy between a source and a receiver. A wave barrier is typically a trench or a thin wall made of sheet piles or similar structural members. The depth and width of a wave barrier must be proportioned to the wavelength of the wave intended for screening. The wavelength of a seismic wave is a function of propagation velocity and frequency. Pile driving typically generates ground vibration with frequencies in the range of 4–30 Hz. With common wave velocities in the range of 61–610 m/s, typical wavelengths can be in the range of 3–152 m.

Studies indicate that the depth of a wave barrier must be at least two-thirds of the seismic wavelength to be screened and that the length of the barrier must be at least one wavelength to screen even a small area. In one case, a trench wave barrier that was 1.19 wavelengths deep by 1.79 wavelengths long resulted in an 88% reduction in amplitude in two small areas behind the trench. Wave barriers must be very deep and long to be effective, and they are not cost effective for temporary applications such as pile driving vibration mitigation.

B. Vibration Reduction for Impact Pile Drivers

Impact pile driving can be the most significant source of vibration at construction sites. The principal means of reducing vibration from impact pile driving are listed below. Some of these methods may not be appropriate in specific situations, but where they are practical, they can often be used to reduce vibration to an acceptable level.

- **Jetting:** Jetting is a pile driving aid in which a mixture of air and water is pumped through high-pressure nozzles to erode the soil adjacent to the pile to facilitate placement of the pile. Jetting can be used to bypass shallow, hard layers of soil that would generate high levels of vibration at or near the surface if an impact pile driver was used.

- **Predrilling:** Predrilling a hole for a pile can be used to place the pile at or near its ultimate depth, thereby eliminating most or all impact driving.

- **Using cast-in-place or auger cast piles:** Using cast-in-place or auger cast piles eliminates impact driving and limits vibration generation to the small amount generated by drilling, which is negligible.

Using nondisplacement piles: Use of nondisplacement piles such as H piles may reduce vibration from impact pile driving because this type of pile achieves its capacity from end bearing rather than from large friction transfer along the pile shaft.

Using pile cushioning: With pile cushioning, a resilient material is placed between the driving hammer and the pile to increase the period of time over which the energy from the driver is imparted to the pile. Keeping fresh, resilient cushions in the system can reduce the vibration generated by as much as a factor of 2 (Woods 1997).

Scheduling for specific times to minimize disturbance at nearby vibration-sensitive sites: Adverse effects can be avoided if pile driving is not scheduled for times at which vibration could disturb equipment or people. For example, if pile driving near a residential area can be scheduled during business hours on weekdays, many people will be at work and will therefore not be affected.

Using alternative nonimpact drivers: Several types of proprietary pile driving systems have been designed specifically to reduce impact-induced vibration by using torque and down-pressure or hydraulic static loading. These methods would be expected to significantly reduce adverse vibration effects from pile placement. The applicability of these methods depends in part on the type of soil. The following information is provided for informational purposes only. This discussion is not intended to favor any commercial product; inclusion of information on these products does not constitute endorsement or approval by Caltrans.

- The first nondynamic system is the Fundex Tubex piling system, manufactured by Fundex in the Netherlands and marketed by American Piledriving in California. Tubex piles are installed with minimal vibration by using torque and down-pressure to produce true soil displacement piles. A patented cast-steel boring drill tip is welded to the pipe casing; then, the Tubex machine installs the pile by gripping the outside of the pipe casing with hydraulic clamps and, in essence, screwing the pile into the ground. Grout injection ports are located at the base of the tip, which allows for the injection of water as a drilling medium and for the injection of grout to produce a soil-cement mixture around the steel casing. Once the steel shell is installed and grouted, concrete and reinforcing are conventionally placed inside the pipe as structurally required by design, or the pile is left unfilled as a simple pipe pile.

  Based on vibration tests performed in 2001 by American Piledriving, the vibration amplitude generated by the Tubex system is expected to be about 0.05 in/sec at 25 ft. This amplitude is significantly lower than vibration generated by conventional impact or vibratory pile drivers. Tubex piles were evaluated by Caltrans in a test project conducted near Interstate 280 in the San Francisco Bay Area. The ultimate capacity of the Tubex pile in terms of tension and compression exceeded all other pile types evaluated.

- The second nondynamic system is the Still Worker (Liddy 2002), a static load piling system, marketed by the Ken-Jet Corporation in New Jersey. This system hydraulically installs and retrieves H-piles, pipe, and sheet piles, generating significantly less vibration than is generally associated with conventional impact and vibratory pile drivers. The system uses hydraulics to push in piles in a smooth, fluid motion that virtually eliminates vibration commonly associated with the installation of piling. Although there are no available vibration data for the system, it appears to substantially reduce vibration from pile driving. A product developed by Giken Engineering Group called the “Silent Piler” operates in a similar fashion.

- Using a vibratory pile driver instead of an impact pile driver can reduce some vibration problems, but vibration amplitudes are similar to those of an impact pile driver because a resonance can occur as the vibratory pile driver starts up and shuts down. One alternative to conventional vibratory pile drivers is a resonance-free vibrator, or variable eccentric moment vibrator. ICE manufactures two such models. These vibrators do not vibrate during start up and shut down, thereby avoiding the excessive vibrations that are commonly associated with traditional vibratory units. By changing the static moment, these vibrators can vary the frequency of operation and the force amplitude. Before the vibrator is started, two parallel rows of eccentric weights are shifted out of phase, resulting in no vibration during start up. By changing the relative orientation of the two rows of parallel eccentric masses, the static moment is changed. After the vibrator reaches full speed, the eccentric masses are shifted into phase, resulting in maximum eccentric moment and maximum amplitude to drive the pile efficiently. Before shut down, the two rows of eccentric weights are again shifted out of phase, resulting in no vibration during shut down.

C. Vibration Reduction for Hydraulic Breakers

If vibration levels from hydraulic breakers are expected to exceed applicable vibration limits, the following vibration-reducing measures can be considered. Some of these methods may not be appropriate in particular situations, but they can often be used to reduce vibration levels to an acceptable limit where they are practical.

A hydraulic crusher (also called smasher, densifier, processor, or pulverizer) can be used to break up the material. A hydraulic crusher is an attachment that is generally mounted on the end of a backhoe, excavator, or skid-steer. It has large jaws that open and close. When closed, the attachment can cut through and crush concrete and any rebar used in the concrete. The attachment can be used for demolition of concrete dividers, such as those used between roadways, and at locations where the concrete can be placed between the jaws. For demolition of a sidewalk or pavement, digging or breaking up of the surface may be required to allow the concrete to be placed between the jaws.

Saws or rotary rock-cutting heads can be used to cut bridge decks or concrete slabs into small sections that can be loaded onto trucks for disposal.

Hydraulic splitters can be used to break up concrete. These devices apply lateral force against the inside of holes drilled into the concrete.

Chemicals can be used to split concrete.

- # Pavement and concrete demolition can be scheduled for certain times to minimize the disturbance at the nearby vibration-sensitive sites.

D. Vibration Reduction Measures for Other Construction Equipment

In most cases, vibration induced by typical construction equipment does not result in adverse effects on people or structures. Noise from the equipment typically overshadows any meaningful ground vibration effects on people. Some equipment, however, including vibratory rollers and crack-and-seat equipment, can create high vibration levels.

Because of the nature of these types of devices, the options for reducing vibration are limited. Maximizing the distance between the source and receiver might be possible, but there is usually little or no flexibility in this regard. Conducting work when most people are not in the area (e.g., at work) or when sensitive equipment is not operating can avoid or minimize adverse impacts with this type of equipment, but pavement crack-and-seat operations often must be conducted at night to avoid disrupting traffic. As such, little can be done to avoid adverse impacts on people. In some circumstances, temporary relocation of residents during these operations may be appropriate; this is often done by offering hotel vouchers to potentially affected residents.

In the absence of measures than can physically reduce induced ground vibration, informing the public about the project and the potential effects of construction activities is, in many cases, the best way to avoid adverse reactions from the public. The suggested process for engaging the public is discussed in Chapter 9.

E. Vibration Reduction for Vehicle Operations

Vehicles traveling on a smooth roadway are rarely, if ever, the source of perceptible ground vibration. However, discontinuities in roadway pavement often develop as the result of settling of pavement sections, cracking, and faulting. When this occurs, vehicles passing over the pavement discontinuities impart energy into the ground, generating vibration. In most cases, only heavy trucks, not automobiles, are the source of perceptible vibration. Trucks traveling over pavement discontinuities also often rattle and make noise, which tends to make the event more noticeable when the ground vibration generated may only be barely noticeable.

Because vibration from vehicle operations is almost always the result of pavement discontinuities, the solution is to smooth the pavement to eliminate the discontinuities. This step will eliminate perceptible vibration from vehicle operations in virtually all cases.

F. Vibration Reduction for Train Operations

Methods for reducing ground vibration generated by rail operations are described in FTA 1995. These methods include:

- # maintaining wheel and rail smoothness;

- # locating special trackwork for turnouts and crossovers away from vibration-sensitive areas;

specifying vehicles with low unsprung weight, soft primary suspension, minimum metal-to-metal contact between moving parts of the truck, and smooth wheels; and

use of special track-support systems such as:

- resilient fasteners,
- ballast mats,
- resiliently supported ties,
- floating slabs, and
- speed reduction.

Special track support systems require engineering to ensure optimal effectiveness in reducing vibration.

CHAPTER 9. GENERAL PROCEDURES FOR ADDRESSING VIBRATION ISSUES

Concerns about vibration generally arise because of complaints about existing operations or construction and maintenance activities. (Construction and maintenance activities are collectively referred to here as “construction activities.”) Concerns can also arise in response to planned activities, such as the construction and operation of a new facility or the modification of an existing facility. This chapter discusses the recommended procedures for addressing vibration concerns about both existing and planned activities and operations.

A. Vibration Concerns about Existing Activities and Operations

Pile driving and crack-and-seat operations near homes or businesses are the primary subjects of vibration complaints. Vibration complaints can also be generated in response to traffic operations if pavement is in poor condition. Increases in traffic, heavy truck, or bus operations resulting from opening of new transportation facilities or the redirection of traffic can also trigger complaints. Although complaints can come from any type of receiver, most are from occupants of residences and from businesses that have vibration-sensitive equipment or operations. Complaints about vibration require a response from Caltrans.

The first step in investigating complaints is to interview the individuals making the complaints (i.e., the complainants) and to assess the severity of the vibration concern. A list of questions, a screening procedure to determine the severity of the concern, and a vibration complaint form are provided in Appendix B for this purpose. In assessing the severity of a vibration concern, the most important issues are:

- The type and location of the vibration source(s)
- The complainant’s concerns (e.g., annoyance, damage, disruption of operations)
- The location that is most sensitive, or where vibration is most noticeable

The screening procedure may indicate that vibration monitoring should be conducted. Vibration monitoring of existing operations or construction activity can range from simple, single-location measurements to more complex, simultaneous, multi-instrument measurements. The simple approach consists of taking measurements at the most sensitive location or the location perceived by the complainant to have the worst level of vibration. Sufficient data should be collected for each location of interest. For highway traffic vibrations, 10 heavy-truck pass-bys (preferably worst-case combinations of several trucks) for each location should be measured. For pile driving or crack-and-seat operations, several minutes of equipment operation should be monitored at each location of interest. The measurement results can then be compared to the applicable vibration criteria.

If the simple measurement indicates that vibration approaches or exceeds applicable criteria, a more detailed study should be conducted. This study involves placing a sensor close to the source as a reference and one or more sensors at the critical locations. The reference sensor remains fixed in one location near the source, whereas the response sensors may be moved to different locations. The simultaneous measurements can then be used to positively identify the vibration source, the drop-off rate, and the response (i.e., vibration level) at the locations of interest. This information can be used to identify unusual conditions that may be contributing to the high vibration condition and to identify a course of action to reduce the impact.

B. Vibration Concerns about Planned Activities and Operations

Avoiding adverse vibration effects regarding planned construction activities and facility operations involves using physical methods to reduce the actual vibration and good public relations to ensure that the public is well informed about the work and its potential effects. In general, literature on the subject shows that only blasting, pile driving, and pavement breaking have documented examples of potential damage to buildings (American Association of State Highway and Transportation Officials [AASHTO] 1990). For pile driving and pavement breaking, the potential for damage from vibration is at locations in relatively close proximity to the activity. However, because the threshold of perception for vibration is much lower than the threshold for damage, claims of damage often arise because of perceptible vibration and not because of actual damage.

Chapter 11 outlines a process for avoiding and addressing potential problems from the public related to blasting. The following process, which focuses on vibration from construction activities and facility operations, is modeled after that process. Every attempt should be made to mitigate the adverse vibration effects from construction activities through the use of modern techniques, procedures, and products. It is equally important to develop a process to avoid and, if necessary, address problems identified by the public that can arise from construction activities, even when the levels of vibration are well below the levels at which damage to structures or excessive annoyance to humans are expected to occur. The following steps should be taken:

1. Identify potential problem areas surrounding the project site
2. Determine conditions that exist before construction begins
3. Inform the public about the project and potential vibration-related consequences
4. Schedule work to reduce adverse effects
5. Design construction activities to reduce vibration
6. Notify nearby residents and property owners that vibration-generating activity is imminent
7. Monitor and record vibration from the activity
8. Respond to and investigate complaints

These steps are described below.

Step 1. Identify Potential Problem Areas Surrounding the Project Site

The first step is to identify the types of dynamic equipment that will be used on the project. As previously discussed, pile drivers and crack-and-seat equipment tend to be the most common source of vibration concerns. In some cases, vibration from the operation of a new or modified highway may need to be evaluated. Prediction methods discussed in Chapter 7 should then be used to estimate distances at which vibration could exceed perception thresholds and structural damage thresholds.

A question that must be answered before determining a preconstruction survey radius is whether the intent is to prevent structural damage or to prevent the perception that structural damage is occurring. In general it is impractical to survey all locations where vibration could be perceptible or where there could be the perception of damage. Regardless of the radius selected for preconstruction surveys, there have been numerous instances where claims of damage came from locations far beyond the surveyed areas. Hence, there is no reasonable standard distance beyond which no complaints can be assured.

Bearing in mind human perceptions and economic considerations, the best solution might be to select structures for preconstruction surveys as follows:

- those structures or groups of structures closest to the vibration source,
- structures within a radius where the effects are estimated to be strongly perceptible and,
- any structures at greater distances that, because of historic value or special conditions, are deemed to deserve special attention.

If the surrounding residents do not view the project as necessarily beneficial to them, or if the project is otherwise unpopular, the distances should probably be increased accordingly.

After the decision has been made as to the limit of preconstruction surveys, anticipate that damage claims may come from residents outside the limit that would have to be resolved through forensic investigation. This is discussed in Step 8.

In some special circumstances, an assessment of the vibration propagation characteristics of the project site may be warranted to improve the accuracy of the vibration predictions. These special circumstances may include situations with special receivers, such as a hospital, research facility, or high-technology facility with vibration-sensitive equipment. Other circumstances might include situations where vibration is known to propagate efficiently though the soil on the site.

A method that Caltrans has used to determine site-specific vibration drop-off characteristics involves the generation of vibration on the site and measurement of the response of the ground at various distances. To generate a strong vibration signal, Caltrans has driven a heavily loaded water truck or dump truck at high speed over a series of five 2- by 4-in. or 2- by 6-in. wood boards spaced 25 ft. apart. This method has been proven to generate a recognizable signal at 90 m (300 ft.). Other methods of generating vibration are also available and include drop-balls, impact hammers, and vibratory rollers.

With this method, a minimum of two sensors must be used simultaneously: one reference sensor and one or more response sensors. Refer to Chapter 10 for a discussion of vibration measurement instrumentation. The reference sensor remains fixed at 5 m (16 ft.) from the centerline of travel (or any convenient distance near the source) opposite the last board to be run over (most forward in line with the direction of travel). The response sensors are positioned at various distances from the source. Because of the steepness of the drop-off curve near the source, it is a good idea to cover shorter-distance intervals near the source and longer ones away from the source. To adequately cover the entire range of the drop-off curve, six to eight locations should be monitored and at least five truck pass-bys measured at each location. Frequently, simulations are not possible on the site of interest because of space limitations. Nearby empty lots or open fields, or data from other sites known or judged to have similar soil conditions, can then be used. However, care must be exercised in choosing a representative site because subsurface conditions can vary substantially.

Once the measurements have been made, the data at each location should be averaged. Using the reference position and at least two others (including the farthest one), the soils coefficient of attenuation (or alpha value, α) can be calculated using Eq. 6. Ideally, the alpha value should remain constant for each location, but in reality it will vary as a function of frequency and position. The average of several values can then be used to develop a drop-off curve. The vibration amplitudes at all measured locations should then be plotted to determine how well they fit this curve. Assuming they fit reasonably well, a normalized drop-off curve can be developed and used with any source reference level, to predict the future level at any distance within the range of the curve.

Another method that can be used to determine vibration propagation characteristics on a site involves measuring the transfer mobility of the ground. This procedure involves dropping a heavy weight on the ground, and then measuring the forces into the ground and the response at several distances from the impact. This procedure is discussed in detail in Federal Transit Administration 1995.

If it is possible to do the simulations at the site, measurement locations both inside and outside the buildings of concern should be included to measure the effects of building amplification or attenuation. Ambient vibration should also be measured both inside and outside the building to document vibration before the construction activity. Any claims that a Caltrans activity or project has increased ground vibration can then be assessed by comparing project-related vibration compared to the existing vibration.

Using the information collected from this study, future vibration can be predicted and compared to existing ambient vibration, perception and damage thresholds, or any other applicable criteria. In some cases where disturbance thresholds for sensitive equipment are not known, vibration measured near the sensitive equipment can be correlated with the disturbance of the equipment to establish a threshold.

The methods described here are generally sufficient for identifying the potential for adverse effects on sensitive equipment. Most situations involving construction operations near sensitive equipment will require consulting experts with specialized expertise in this area.

Step 2. Determine Conditions That Exist Before Construction Begins

There are various methods that can be used to conduct preconstruction surveys, but all must meet the primary purpose of documenting all the defects and existing damage in the structures concerned. An inadequate preconstruction survey can be worse than no preconstruction survey at all. Preexisting defects that are not listed in the preconstruction survey will probably then be attributed to the construction by the property owner. Unless these can be refuted through forensic investigation, the complainant will probably be successful.

Secondary purposes of the preconstruction survey include answering any questions the homeowner may have regarding the project and looking for anything that might require correcting before construction starts or that may place an unexpected limit on blast design. Examples include antique plates that are leaning against a wall or precariously balanced figurines. These should be secured for the duration of the project if there is any concern.

Surveys can consist of drawings on paper, high-resolution video, black and white photography, or any other method that adequately documents existing defects and damage. It is also helpful if the possible cause of the defect can be determined and listed. Oriard (1999) and Dowding (1996) describe preconstruction survey methods in detail.

In some instances, homeowners will prefer that their homes not be surveyed. This is usually for the sake of the owners' privacy, and a notation should be made for that structure as to the time and date, the specific comment made and the person who made it. On some occasions, a homeowner may terminate a preconstruction survey before it is complete. Again, the survey should be annotated accordingly.

It is usually advantageous to conduct postconstruction surveys to verify that no additional damage has been caused by the construction activity.

All residential structures suffer from normal shrinkage of materials caused by diurnal thermal strains and possible settling that start to occur soon after construction. This can present a problem on long-term projects when relatively new homes are included in the preconstruction survey. The normal shrinkage cracks and defects may not show up before the preconstruction survey, but may be there for any postconstruction inspection. The only solution is to investigate them thoroughly to determine whether it was possible that construction activity caused the defect. This will normally require the services of an experienced forensic investigator.

It is also good practice to examine homes both near and far from the construction activity. If cracks or other defects are consistent throughout the area, they are likely the result of thermal stresses or settlement. Cracks or defects that diminish with distance from the vibration source may be indicative of effects caused by the source. Cracks that occur only on surfaces exposed to the sun are indicative of thermal cracking.

There is a tendency for insurance companies to settle smaller claims rather than pay the cost involved in determining the actual cause. This is not only technically and philosophically unsound, but also an open invitation for additional claims from surrounding neighbors.

Step 3. Inform the Public about the Project and Potential Construction-Related Consequences

Good public relations with the neighbors nearest the project, as well as all interested parties, are always beneficial. Most homeowners do not have experience with construction vibration, and may have concerns about their own safety and the safety of their homes.

If the situation warrants, a meeting should be held and a presentation made that explains the reason for the project, that construction will be necessary, what the residents can expect to hear and feel from the construction, any specific warning signals that will be used, and the intent of the preconstruction survey. Knowledgeable persons should attend to answer questions. There should be a handout that explains all of the above information and includes phone numbers to call if there are problems or questions. The person or company that will conduct the preconstruction surveys should be introduced. The main purpose of such a meeting is to educate the neighbors and to put their minds at ease. Such a meeting, conducted properly, can greatly reduce the potential for problems with neighboring property owners.

Another opportunity to conduct good public relations is during the preconstruction survey. The informational sheet from the meeting should be distributed during the survey. The person or persons that conduct the survey should be conversant enough about the project to answer any questions that homeowners might have.

Homeowners should be provided with a procedure for registering complaints with Caltrans in the event that vibration is found to be excessive. This procedure should identify a contact person and phone number or email address.

Step 4. Schedule Work to Reduce Adverse Effects

As long as safety considerations can be met, construction activity should be scheduled to occur during times of maximum human activity, rather than during times of extreme quiet. In some cases, nearby sources of noise and/or vibration can be used to mask the noise from construction activities. For example, if highway work can be conducted during daytime hours, normal traffic noise may mask much of the construction noise. Night work should be avoided, although night work is required to avoid disruption of commute traffic flows in many cases.

Other factors may need to be considered as well. A survey of the area should disclose locations with critical activities that might require close coordination. For example, if a hospital where surgery is conducted or other facilities with equipment highly sensitive to vibration are nearby, coordination is necessary so that construction does not interfere with operations of those facilities. Medical equipment that is particularly sensitive to vibration include magnetic resonance imaging (MRI) systems, scanners, and microscopes.

Step 5. Design Construction Activities to Minimize Vibration

Where adverse vibration effects are anticipated, reasonable efforts should be made to reduce those effects. Chapter 8 discusses methods to reduce vibration from construction.

Step 6. Notify Nearby Residents and Property Owners That Vibration-Generating Activity Is Imminent

Once work has been scheduled, nearby residents and property owners should be notified about the specific times and dates that vibration-generating activity will occur. Many complaints occur because a resident or property owner was not aware that the construction activity would occur.

Step 7. Monitor and Record Vibration Effects from Construction

Although it is possible to estimate the levels of construction-induced vibration with some confidence, field monitoring and recording of vibration effects is sometimes warranted. Monitoring records provide excellent tools for evaluating the potential for damage from construction activities. The monitoring and recording should be conducted with equipment specifically intended for this purpose, including accelerometers, velocity sensors, and data-recording or data-logging devices. Equipment used to collect and evaluate vibration data is discussed in Chapter 10.

In situations in which there is considerable opposition to a project and damage claims are anticipated, monitoring and recording should be conducted by a third party. In situations in which there is little chance for claims or where monitoring is being done solely to ensure that specifications are being met, the construction contractor could conduct the monitoring, although it is advisable for the contractor to have a third-party vibration consultant oversee and approve the monitoring and recording process.

Step 8. Respond to and Investigate Complaints

An adequate process for handling complaints should be established. Neighboring residents should know whom to contact with a concern or complaint, regardless of whether it involves a claim of damage. In all instances, a form that documents the details should be initiated on receipt of a complaint. A sample construction vibration complaint form is provided in Appendix B.

For minor complaints, responsible, knowledgeable contractor personnel might conduct the investigation. It is advisable to have a qualified forensic investigator look into claims of damage. The investigator might be the same party that conducted the preconstruction survey or conducted the monitoring. Prompt investigation is advisable. Correction of the problem, if caused by the construction activity, should also be handled promptly.

A vibration specification can be valuable in avoiding problems resulting from construction vibration. Because it is impossible to foresee all variables that may be encountered on various project sites, specifications should be developed specifically for each construction site. A sample vibration specification developed for a construction site with nearby historic structures is provided in Appendix C.

C. Vibration Study Reports

Any time a vibration field study is conducted, the results should be documented in a report. Depending on the number of sites measured, amount of data collected, methodologies used, and the importance of the study, the report may range from a simple one or two paged memo, to a report of twenty or more pages long. A vibration study can be considered a mini-research project, and should contain enough information for the reader to independently come to the same conclusions.

Normally, a vibration report should contain the following topics:

- project title and description;
- introduction;
- objectives;
- background;
- study approach;
- instrumentation;
- measurement sites;
- measurements;
- data reduction;
- measurement results;
- data analysis;
- results and comparison with criteria;
- conclusions and recommendations;
- tables showing all measured data, summaries of results, analysis, and standards;
- figures showing site layouts and cross sections, instrument setups, drop-off curves, and other pertinent illustrations; and
- references cited.

In short and simple vibration studies, the above topics may be described within a few sentences in a memorandum. In more complex studies, a fairly extensive report is usually required. Refer to Appendix A for more detailed information on vibration study reports.

CHAPTER 10. VIBRATION MEASUREMENT AND INSTRUMENTATION

A. Vibration Measurement Equipment

Ground vibration is typically measured with a sensor that produces an electrical signal that is proportional to amplitude amplitude of the ground motion. These sensors are called transducers because they "transduce" the ground motion into an analogous electronic signal. Transducers can be designed to produce a signal that is analogous to the displacement, velocity, or acceleration of the ground motion. Velocity transducers (seismometers) and acceleration transducers (accelerometers) are the most widely used transducers for measuring ground motion. Vibration transducers measure vibration in one axis. These transducers can be combined into a triaxial array to simultaneously measure vibration in three orthogonal axes.

During the period between 1958 and 1994, all vibration monitoring conducted by Caltrans was performed by staff from the Caltrans Translab. A transducer calibration system consisting of a shaker table mounted on a concrete vibration isolation pad and a camera/amplifier system that measured displacement allowed Translab to calibrate its own transducers with traceability to the National Institute of Standards and Technology (NIST), formerly known as the National Bureau of Standards (NBS). Transducers were calibrated by mounting them on the shaker table and running the table at a known frequency and displacement. Translab is no longer responsible for vibration studies. These studies are now conducted by Caltrans headquarters staff and vibration consultants retained by Caltrans.

Historically, Caltrans used both seismometers and accelerometers to measure ground motion. Seismometers used by Caltrans measure vibration at relatively low frequencies, usually between 1 and 200 Hertz (Hz), through magnetic induction that produced a voltage proportional to velocity. Because seismometers are typically large and can weigh as much as about 7 kilograms (kg) (15 pounds [lbs]), they typically can be placed directly on the ground without special mounting attachments if the mounting surface is stiff, such as hard soil, a concrete sidewalk, flagstone, or asphalt. If used on soil, the seismometer should be firmly embedded in the soil by embedding the entire base in the soil.

An accelerometer measures acceleration directly. When used with an integrator, an accelerometer can also measure velocity and displacement. Accelerometers used by Caltrans have piezoelectric (charge-generating) crystals. As the transducer vibrates with the surface it is mounted on, acceleration changes the compression of the crystal, which in turn causes variations in the electrical charge across the crystal faces. These charge variations are proportional to acceleration.

Accelerometers are typically small and not as sensitive as seismometers. The advantage is that they have a wider frequency range, typically from 1 Hz to several kilo-Hertz (kHz). Because of their small size and lack of mass, accelerometers should not be placed directly on the ground, floor, or other vibrating surface without proper mounting. Accelerometers can be mounted in various ways, depending on the surface. Accelerometers can be adhered to a vibrating surface such as floors, sidewalks, or walls using scientific wax, beeswax, or other special wax provided by the accelerometer manufacturer can be used. Threaded studs adhered to the surface with epoxy can also be used. For good high frequency (up to 100 Hz) coupling to soil, accelerometers should be mounted to an aluminum spike.

An accelerometer can also be mounted via a magnet (or adhesive) to a heavy block of steel weighing 5–10 kg (10–20 lbs). The steel block can then be placed directly on the ground or other surface if the steel block does not rock. The mass of the steel block provides adequate coupling of the accelerometer with the ground for the low-frequency, low-level vibrations generated by transportation facilities and construction activities. Other mounting options are also available. Refer to the accelerometer manufacturer's recommendations for other mounting options.

The signal from a vibration transducer can be directly conditioned and displayed with stand-alone equipment or it can be recorded with an analog or digital recording device for subsequent analysis. Stand-alone or software-based digital fast fourier transform (FFT) analyzers are commonly used to evaluate the recorded signal. Most analyzers can integrate the signal so that velocity and displacement values can be determined from an acceleration signal. Overall peak amplitudes (i.e., PPV) in the time domain can be displayed or, if desired, the frequency spectrum of the signal can be evaluated in the frequency domain (i.e., one-third octave band or narrow band spectrum). A variety of averaging methods is often available.

CHAPTER 11. VIBRATION AND AIR OVERPRESSURE FROM BLASTING

A. Introduction to Blasting

Often, the only means of loosening a rock mass and reducing it to a material of manageable size is to blast using explosives placed within drilled holes. Many variables relate to the execution of a blast, only some of which are within the control of the blaster. Some of these variables are difficult, if not impossible, to adequately define. As such, blasting is still part "science" and part "art," based on the laws of physics and the capability and experience of the blaster.

Blasting Terminology

The following terms are commonly used in blasting and should be understood by anyone involved in the subject.

- **Downhole blasting:** Downhole blasting is a type of blasting in which explosives are loaded into drilled holes, as opposed to charges being placed on the surface. Surface charges do not have application in conventional construction blasting situations, especially in urban settings.

- **Burden:** Burden represents that volume of material that a detonating hole or holes are expected to fragment and shift. There are two types of burdens: drilled burden and shot burden. Drilled burden is the distance between a row of holes and the nearest free face, and is measured perpendicular to the row of holes. It is also the distance between two rows of holes. Shot burden represents the distance between a hole that is detonating and the nearest free face that is developing in the blast. Unless otherwise specified, the term usually refers to the drilled burden.

- **Spacing:** Spacing represents the distance between holes in a row. A drill pattern is always described in terms of (in order) burden and spacing (e.g., a 6-foot by 8-foot pattern has a burden of 6 ft. and a spacing of 8 ft.)

- **Subdrilling:** Subdrilling is the amount of hole that is drilled below the intended floor of the excavation. Except in situations in which the rock is in flat bedding planes, the detonating charge usually leaves a crater at the bottom of the hole rather than shearing the rock on a horizontal plane. Accordingly, it is not uncommon to subdrill a distance that approaches half of the burden distance to be able to excavate to the intended depth.

- **Stemming:** To confine the energy from the explosive, the top portion of the hole is stemmed (back-filled) with inert material. Because of their proximity to the hole, drill cuttings are usually used, although other material such as stemming plugs can be used. Crushed stone chips are superior to drill cuttings for stemming material because they tend to lock in place under pressure.

- **Decks or decking:** Decks or decking is a means of separating two or more charges within a hole. This step is usually taken to (1) reduce the amount of explosive detonating in a given instant by having the decks fired on different delays, or (2) to avoid loading explosives in weak zones or mud seams in the rock. Decks are separated by inert stemming material and require some means of initiating each deck. Most blasters prefer to avoid the use of decking, however, because it increases the chances for misfired holes and is fairly labor intensive.

- **Primary (production) blast:** A primary (or production) blast is intended to adequately fragment a given volume of rock. The rock may be removed in one or more primary blasts. If the depth of an excavation is sufficient to require removal in more than one lift, each lift would be removed using one or more primary blasts.

- **Secondary blast:** Secondary blasts may be required to remove or reduce material that is not adequately fractured in primary blasts (i.e., trimming blasts or removing high bottom). Also secondary blasts are used for boulders whether or not primary blasting was conducted.

- **Powder factor:** The powder factor is the ratio between explosives consumed and material blasted, usually defined in pounds per cubic yard for construction blasts. When discussing powder factors, it is important to know whether one is using "shot powder factor" or "pay [or yield] powder factor". Shot powder factor includes the material in the subdrilling zone in the calculations, while pay powder factor does not.

- **Detonator:** Detonators are devices, either electric or nonelectric, that are used to detonate the explosive charges.

- **Delay:** The delay is the time interval between detonators (and their corresponding explosive charges) exploding. Because modern initiation systems provide for further subdividing of the delay times in conventional detonators, delay times can be tuned for specific blasting needs.

- **Initiation system:** The initiation system is the entire system for initiating the blast, including the blasting machine or starter, detonators, delay devices, and interconnecting parts.

- **Dynamite:** Dynamite was one of the earliest explosive charges. It was originally sensitized with nitroglycerin, but now uses other sensitizers.

- **Slurry, watergel, emulsion:** These products are modern explosive products in which portions of the ingredients have been replaced with water and various emulsifiers, gums, and other substances. These products come in either packaged or free-flowing form, and poured or pumpable forms.

- **ANFO:** ANFO is an inexpensive blasting agent consisting of 94% prilled ammonium nitrate and 6% #2 diesel fuel (by weight). There are variations of this product in which other materials are added to increase the energy yield. Because of the reduced sensitivity of this material, it requires the use of a more-sensitive explosive for initiation.

- **Booster:** A booster is a fairly sensitive charge that is used to initiate less-sensitive explosive charges. A booster is often in a cast form with a detonator well or detonating cord tunnel, but it can also be a cartridge product.

- # **Detonating Cord:** Detonating Cord consists of a core charge of pentaerythritol tetranitrate (PETN) wrapped with layers of plastics and textiles. It is available in various core loadings, all of which detonate at approximately 23,000 ft/sec. Originally developed as an initiation system, it has also been used in specialized blasting situations as the primary charge. Because of the extremely high noise level, this product is not normally used on urban blasting projects. (PETN is also the base charge in most detonators and is an ingredient in most cast boosters.)

- # **Presplitting:** Presplitting is a procedure in which a row of lightly loaded holes is detonated ahead of the main production blast. It is intended to propagate a crack along the row of holes to protect the final perimeter wall by allowing expanding gases to vent and preventing back-break from subsequent detonating production holes. It has been shown that a presplit crack has little or no effect in reducing vibration from subsequent blasts; in fact, a presplitting blast creates more vibration per unit of explosive than other forms of blasting.

- # **Smooth blasting:** Smooth blasting is similar to presplitting, except that the holes are detonated after the production holes in the main blast. The intent is not to form a crack, but to blast loose the remaining burden with the lighter charges without causing excessive damage to the perimeter wall. In this instance, the charge weights in the nearest production holes are usually reduced.

- # **Sinking cut:** A sinking cut is a blast in which no free vertical (or sloped) face exists and in which it is necessary to ramp down into a horizontal surface. In this type of blast, a portion of the blasted material must be expelled upward to make room for the expanding material from subsequent holes detonating. Some flyrock may occur and must be taken into account.

- # **Throw or heave:** Throw or heave is movement or shifting of the blasted material an intended distance and direction.

- # **Flyrock:** Flyrock is material that is expelled from the blast and travels farther than expected or intended.

- # **Blasting mats:** Blasting mats are mats used to cover a blast in an urban situation where flyrock cannot be tolerated and where the situation dictates that explosives be loaded fairly high in the holes. (It is not practical to cover large blast areas, and prevention of flyrock is best addressed in blast design for those situations.) Blasting mats are usually fabricated from sections of rubber tires, manila rope, used conveyor belting, or other similar materials. Many contractors cover the blast with soil, sand, or other fine material; this step can be successful, but it is necessary to use a sufficient amount of covering and to use covering that does not contain rock or other projectiles. Blast covering with any of these materials or devices must be done carefully so that the initiation system is not damaged.

- # **Scaled distance (square root or cube root):** Scaled distance is a means of scaling a ratio of distance and charge weight so that effects from various blasts can be compared or estimated. Once a blaster has recorded data from a given blast site, scaled distance can be used as a tool to assist in designing future blasts. Square-root scaled distance is derived by dividing the distance between the detonating charge and the object of interest by the square root of the charge weight. Square root scaling is used for vibration estimations where linear charges (length is more than twice the diameter) are used. Cube-root scaled distance is derived similarly, using the cube root of the charge weight instead of the square root. It is conventional to use cube root scaling for estimating air overpressure and for infrequent instances in which vibration estimations involve a spherical charge (diameter is greater than half the length).

Overburden: Overburden is soil and other materials that overlay the rock to be blasted. Overburden is usually removed before drilling, but it is occasionally left in place to confine the blast and to allow loading explosives higher in the hole (nearer to the top of the rock).

Blasting Process

After the decision has been made to conduct blasting at a construction site, the necessary permits obtained, and arrangements made for explosives storage, the first consideration is usually the size of the drill that will be used. For large excavations, large-diameter drills (4–6 in.) will provide better production than smaller drills, but will result in larger material. A larger number of smaller holes (2–3 in.) will take longer to drill and load, but will provide better fragmentation and easier handling of material. Other considerations are the size of the digging and hauling equipment, the location of any local utilities, nearby structures, vibration and air overpressure or airblast limitations for the specific site, and the lengths of drill steel available.

The blaster uses the borehole diameter and the considerations above to formulate blast designs—laying out burden and spacing, depth of hole (including subdrilling), type of initiation system, explosive products, and sequence of initiation. The blaster often uses timing and the sequence of initiation to control the direction of heave and to allow time for the earlier rows' burden to begin to move before the later rows detonate.

At this point, the blaster can document his intentions on a blasting plan, but he must have the latitude to make changes as drilling progresses and more is learned about the site geology. One or more test blasts are not unusual. The rock from a preceding blast will usually be removed before the succeeding blast is loaded and shot, thus providing a space for the expansion, or swell, of the material in the succeeding blast. If circumstances dictate, however, a portion of the shot rock may be left in place to help contain the material in the front row of the succeeding blast.

The actual loading process will depend on the type of explosives to be used, but will generally consist of the following. (Please note that only the blaster and those persons necessary for the loading process are allowed within 50 ft. of a blast while it is being loaded.)

1. The detonators are laid out near the holes according to the desired initiation sequence.

2. The primer is made up by inserting the detonator securely into the priming charge and is lowered to the bottom of the hole.

3. A denser bottom charge (if desired) is loaded. If there is water in the holes, a water-resistant explosive is loaded until the column builds up out of the water. The main explosive charge then is loaded. Holes are normally loaded to a specific height; however, in cases where the exact quantity of explosive is critical, holes might be loaded with a specific number of cartridges or containers of bulk product. If bulk loading equipment is used, the density of the product and the quantity loaded can be controlled by the operator.

4. A second primer is added, if desired.

5. After a hole is loaded with the desired quantity of explosive, the remainder of the hole is stemmed or backfilled with inert material.

6. After all holes are loaded and stemmed, the initiation system, except for the starter or blasting machine, is connected and checked. In the case of electric detonators, a Blaster's Galvanometer or Blaster's Multimeter is used to check the resistance of the system. Other systems are usually checked visually.

7. Blasting mats or other coverings are put in place, if they are to be used.

8. When the blast is ready to be detonated, the area is cleared, the blasting signals are initiated, and the blaster prepares to connect the starter or blasting machine.

9. Just before initiation, the blaster connects the starter or blasting machine, then detonates the blast at the proper time.

10. During and immediately following the blast, the blaster and his crew watch for any sign of a possible misfire. If a misfire is suspected, the area remains secured and no one, including the blaster, is allowed to approach the blast for at least 30 minutes. (This is a California Occupational Health and Safety Administration–mandated time period. Although seldom used in construction blasting, the use of cap and fuse would mandate a 60-minute wait).

11. As soon as it is safe to do so (and following the mandatory wait if a misfire is suspected), the blaster inspects the site.

12. After any misfires are cleared and the site inspection is complete, the "all clear" signal can be given and personnel are allowed back into the blast area.

As blasting proceeds through the project, the blaster can fine-tune his blast designs. Quite often, the best blasts will occur near the end of the blasting program because the blaster will have gradually increased his or her knowledge of how the rock on the site breaks.

B. Vibration and Air Overpressure Concerns that Arise from Blasting

When a blast is detonated, only a portion of the energy is consumed in breaking up and moving the rock. The remaining energy is dissipated in the form of seismic waves expanding rapidly outward from the blast, either through the ground (as vibration) or through the air (as air overpressure or airblast). While a blaster can quite easily design his blasts to stay well below any vibration or air overpressure levels that could cause damage, it is virtually impossible to design blasts that are not perceptible by people in the vicinity.

As seismic waves travel outward from a blast, they excite the particles of rock and soil through which they pass, causing them to oscillate. Spherical spreading, imperfect coupling, and other factors cause seismic waves to dissipate rapidly with distance, normally by two-thirds for each doubling of distance from the source. The motion of particles at a given point in the earth is measured when blast vibration is recorded. Blast vibration is described using the following terms.

Displacement: Displacement is the farthest distance that the ground moves before returning to its original position. For blasting, displacement is usually only a few thousandths or ten-thousandths of an inch.

Particle velocity: Particle velocity is the velocity at which the ground moves.

Peak particle velocity (PPV): PPV is the greatest magnitude of particle velocity associated with an event.

Acceleration: Acceleration is the rate at which particle velocity changes. Acceleration is measured in in/sec^2, mm/sec^2, or g.

Frequency: Frequency is the number of oscillations per second that a particle makes when under the influence of seismic waves. Frequency is measured in Hz.

Propagation velocity: Propagation velocity is the speed at which a seismic wave travels away from the blast. Propagation velocity is measured in ft/sec. (Please note that propagation velocity is several orders of magnitude greater than particle velocity.)

When blast vibration is recorded with a seismograph, three mutually perpendicular sensors record particle velocities in longitudinal (radial), transverse, and vertical axes; the PPVs recorded for each axis are the main data of interest for comparison with damage criteria. Because the data are recorded against a time base, other information such as frequency, displacement, acceleration, and true vector sum (resultant) can be calculated and included on the record.

The resultant particle velocity is the highest particle velocity in any direction. Although the resultant particle velocity is the highest particle velocity in any direction, the conventions and standards currently in use are based on data that were gathered when it was impractical to obtain true resultant data. Resultant values have become easily obtainable since the development of the digital seismograph and digital recording techniques. Therefore, when using modern prediction curves or blasting level criteria that are based on older data, one should use individual axis peaks rather than the resultant. If it is desirable to use the resultant instead of individual peaks, allowances need to be made that consider the higher numbers that would be obtained. (The true resultant PPV could be as much as 1.73 times the highest individual peak, although in actual practice it is usually only about 10–20% greater.)

In all instances, body waves (compression and shear waves that pass through the ground) and surface waves (waves that travel along the surface of the ground) diminish with distance, although they dissipate at differing rates. Body waves typically have a higher frequency than surface waves and are dominant close to the blast; therefore, the frequencies of the PPVs closer to the blast will be higher. As the distance from the blast increases, body waves dissipate faster than surface waves; therefore, the surface waves become dominant and the frequencies (and intensities) of the PPVs are lower. Exceptions can occur when waves propagate in underlying stiff soil or rock, and emerge as the dominant wave at large distances.

When the distance between the recording point and the blast is large enough, waves that have traveled different paths arrive at different times with spreading and some overlap. Recorded at greater distances, the entire blast begins to take on the characteristics of a single point detonation of relatively long duration.

Although residential structures may not be as strongly constructed as engineered structures, it is unusual to find damage to them from blast vibration. In numerous instances, vibration levels far greater than the maximum levels recommended by the U.S. Bureau of Mines (USBM) or Office of Surface Mining and Reclamation Enforcement (OSMRE) failed to cause damage. With regard to residences, the main issue with blast vibration is the perception of some residents that, because they could hear and feel the blast vibration, the vibration must have caused some damage to their residence. It is not unusual for a homeowner to be unaware of cracks or other defects in his or her residence that have developed slowly because of settlement or thermal strains. When a nearby blast is detonated and the homeowner examines his or her structure more closely, it is not surprising that defects are attributed to the event.

Homeowners with wells, especially in times of drought, can have major concerns over the effects of blast vibration on their water source, although vibration alone would not be expected to damage a well. If a blast was detonated in close enough proximity that rock-block movement pinched off a well, the well could sustain damage, but it would not have been caused by vibration (Robertson 1980, Rose 1991). In some situations, vibration is used by the oil industry to enhance permeability and well production.

C. Methods of Predicting Blast Vibration and Air Overpressures

To predict the intensities of blast-induced vibration and air overpressures from blasting, a scaling method is usually used that considers the energy released, the distance to the blast, and their relationship to the intensities derived. Other variables affect the intensities to a lesser extent.

Predicting Blast Vibration

Square-root scaled distance is a scale that divides the distance from the point of interest to the blast by the square root of the largest charge weight detonated on one delay period. All explosives detonating within any given 8-millisecond (ms) time period are typically counted as having been detonated on the same delay. (The blaster may be separating his detonating charges by more or less than 9 ms. In any case, all explosives detonating within any 8-ms period are combined for typical prediction calculations.)

The most commonly accepted blast vibration prediction curves in use were developed by Lewis L. Oriard, a noted seismologist from Huntington Beach, California (now retired), and are based on data gathered from a large number of blasts in various geological settings. Other researchers have come to similar conclusions, with their estimations falling within Oriard's parameters.

Figure 6 contains curves representing Oriard's upper and lower bounds for typical down-hole blasting, with a higher approximation for those instances where there is very high confinement, such as in presplitting. Because of the many variables involved in blast design and site-specific geology, data points could fall above or below the bounds for typical data shown on the graph.

Oriard's basic formula for predicting blast vibration is:

$$PPV = K\,(D_S)^{-1.6} \qquad \textit{(Eq. 13)}$$

Where:

PPV = peak particle velocity (in in/sec),
D_S = *square-root scaled distance (distance to receiver in ft. divided by square root of charge weight in lbs.)*
K = a variable subject to many factors, as described below

This equation is similar to Eq. 7 presented in Chapter 4 and Eqs. 1–4 in Chapter 2. The K factor (and the resulting PPV) decreases with the following:

decreased confinement of energy,

decreased elastic moduli of the rock,

increased spatial distribution of the energy sources,

increased time of energy release or timing scatter, and

decreased coupling of the energy sources.

PPV increases when these changes are reversed. Of the factors listed above, confinement of the explosive energy will probably be the most-important factor after charge weight and distance. Confinement of the energy is increased as the burden, depth of burial, and quality of rock increase. The combined K factor for Oriard's upper and lower bounds are 242 and 24, respectively. Most conventional blasts will fall between these bounds. The combined K factor for a blast under extremely high confinement is 605.

An exponent of –1.6 is typical. This exponent may be more negative for body waves in very close proximity to the blast or less negative where surface waves dominate.

The exponent –1.6 is more negative than the value of –1.0 to –1.4 recommended for construction equipment in Table 17. This suggests that blast vibration amplitudes in general attenuate at a higher rate than vibration from construction equipment. Persons experienced in blast vibration prediction will use the range given in the curves (or formulas) as a basis and adjust them for any blast-specific variables that they can quantify through experience. They will need information from the blaster (or the blaster's records) regarding charge weights per delay, timing schemes, and other factors.

In addition to ensuring that the charge weights obtained from the blaster are accurate, the correct number of holes per delay should be verified and, if more than one hole or deck will detonate simultaneously, the spatial separation of those holes or decks should be noted. Two holes that detonate simultaneously will not generate the same vibration as a single hole containing the same weight as the two holes combined; the greater the distance between holes detonating simultaneously, the less they cooperate in increasing vibration.

With regard to distance measurements, blast-induced ground vibration can travel only through the ground; it cannot jump across an open space. The shortest path through the ground between the detonating hole and the object of interest should be the distance used. The correct square-root scaled distance is the lowest number calculated for various configurations within the blast and will more closely relate to the intensity of vibration. Technically speaking, there are as many square-root scaled distances as there are holes detonating. If all the holes are loaded identically and are detonated on individual delays, the closest hole will naturally yield the lowest number. If the blast has varying charge weights (the shot may be deeper in some areas), the lowest square-root scaled distance may actually be calculated from a hole that is farther away.

A site-specific prediction curve is initiated when results from several recorded blasts have been plotted on a graph, although it should not be assumed that all future blasts will follow the results of just a few blasts. The confidence level increases as additional data are added, although some scatter in the data points can be expected. It is also helpful to have PPV readings over a wide range of distances (and square-root scaled distance) to provide linearity to the plot. If all recordings are made at one distance, the data points will be clustered in a general zone on the chart and it will be difficult to obtain a reasonable regression plot.

Predicting Air Overpressures from Blasting

Air overpressures from blasting can be predicted by using curves in a manner similar to vibration prediction; however, cube-root distance scaling, not square-root distance scaling, is normally used. Figure 7 depicts curves that are based on data gathered from blasts in various locations and from research conducted by various individuals and organizations, including USBM. Again, because of the variables, many of which are difficult to quantify, data points for a given event may fall above or below the bounds shown on the graph. The prediction curves were established using the basic formula for estimating air overpressures:

$$\textit{Peak air overpressure (in pounds per square inch [psi])} = K\,(D_S)^{-1.2} \qquad \textit{(Eq. 14)}$$

Where:

D_S = cube-root scaled distance (distance to receiver in ft, divided by cube root of charge weight in lbs.)

The curves representing the normal upper and lower bounds for confined charges use combined K factors (intercepts at a D_s of 1) of 2.5 and 0.78, respectively. The curve for unconfined charges uses a combined K factor of 82.

The attenuation slope of –1.2 is typical for static conditions and represents a reduction of approximately 7.2 dB for each doubling of distance. Some researchers have used attenuation slopes as flat as –1.0 (corresponding to 6 dB per doubling of distance), but the difference does not become a major factor until a considerable distance has been reached. Atmospheric variables such as wind and temperature inversions have a greater effect on attenuation.

In addition to charge weight and distance (which affect the cube-root scaled distance), the following factors affect air overpressure intensity.

depth of burial of the charge;

terrain features, trees, foliage, and other screening;

orientation of the blast face (facing toward the recording point increases intensity);

velocity of blast progression (across the face or along the surface);

explosive composition (elapsed time of energy release, a minor effect that can normally be disregarded for conventional explosive products);

atmospheric conditions:

- changes in barometric pressure (a minimal effect normally disregarded), and

- humidity (normal daily fluctuations may be disregarded, but the difference between a very dry day and a rainy one can be quite noticeable); and

temperature gradients:

- normal or lapse conditions (temperature decreases with elevation; sound energy is refracted upwards and the air overpressure will attenuate at a greater rate than isothermal conditions),

- inversion conditions (temperature decreases with elevation; sound energy is refracted downwards and air over pressure will attenuate at a lower rate than for isothermal conditions; a temperature inversion has little effect in the immediate area of the blast and

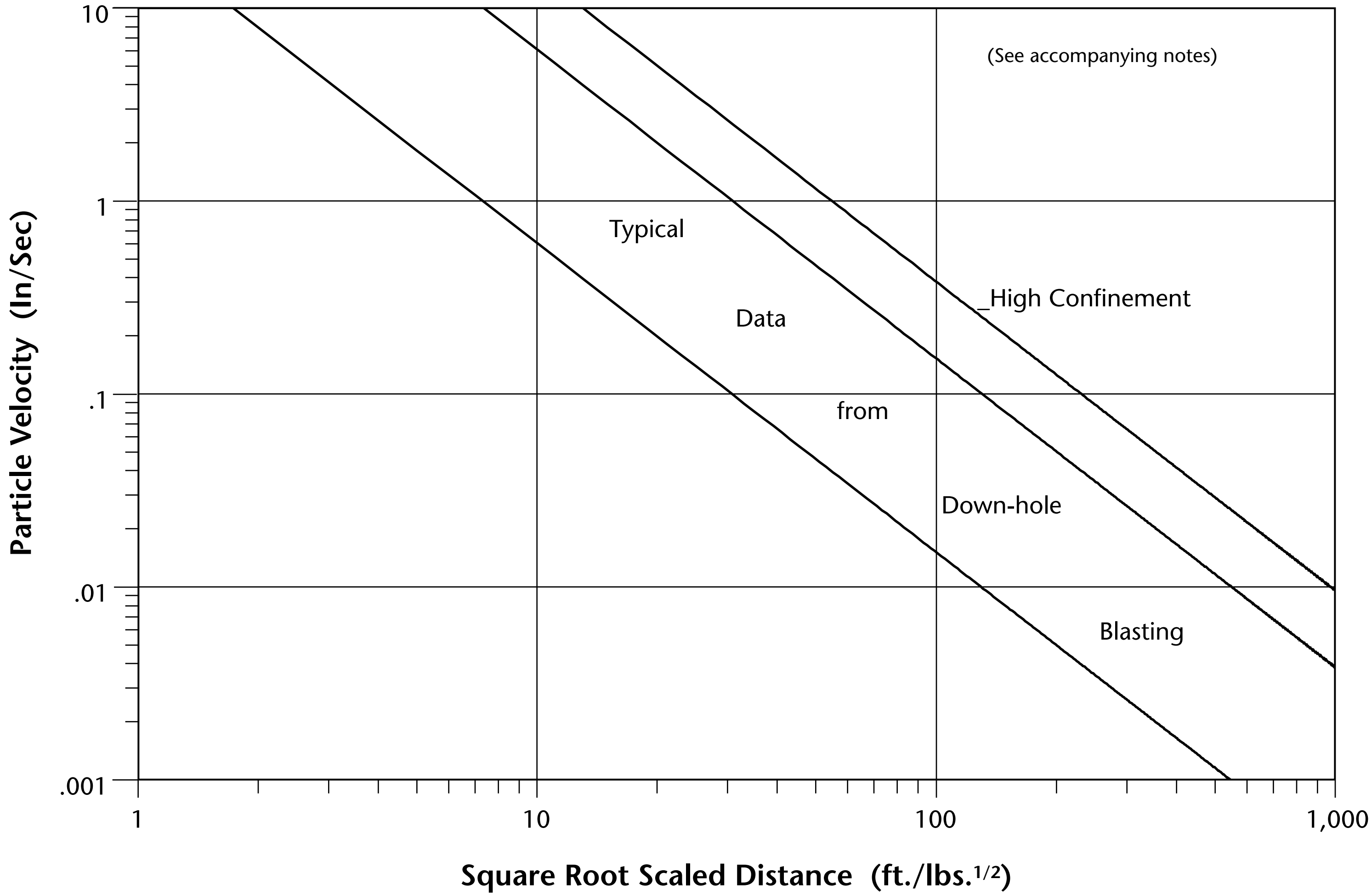

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Figure 6
Blast Vibration Prediction Curves (Oriard, 1999,2000)

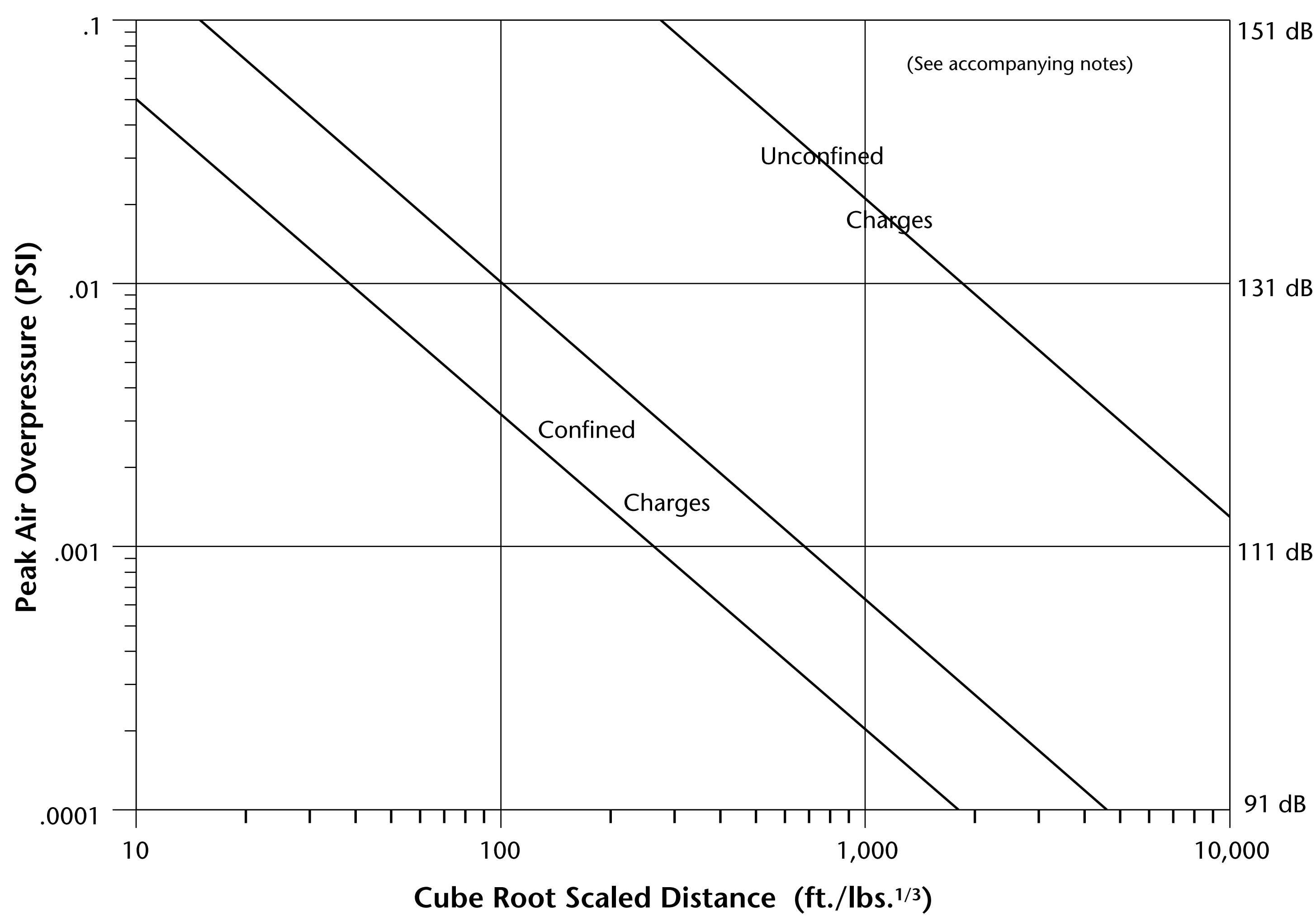

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Figure 7
Air Overpressure Prediction Curves

usually only affects air overpressure beyond a radius equal to the height of the inversion layer), and

- wind direction and velocity (wind can have a major impact on air overpressure; downwind from the blast, the overpressure will not attenuate as rapidly as it would upwind from the blast because the wave front and the sound energy is being refracted or bent downward; this can add from several to as much as about 20 dB to the overpressure).

If it is desirable to convert psi to decibels, the following formula can be used:

$$dB = 20 \log (psi / 2.9 \times 10^{-9}) \qquad \text{(Eq. 15)}$$

In addition to the cautions concerning charge weights and delays discussed above, the shortest distance through the air should be used. Depending upon terrain, this may not always be a straight line.

The estimation of air overpressures is more difficult than estimating vibration due to variables that can change from moment to moment. For this reason, allow a greater margin of error when estimating air overpressures. Gathering data for specific sites and accurately noting weather conditions at blast times can assist in building prediction curves for specific operations or specific sites.

D. Criteria for Assessing Human Response to Blasting and Potential for Structural Damage

Human Response

Human response to blast vibration and air overpressures from blasting is difficult to quantify. Ground vibration and air overpressures can be felt at levels that are well below those required to produce any damage to structures. The duration of the event has an effect on human response, as does the frequency. Events are of short duration, 1–2 seconds, for millisecond-delayed blasts. Typically, the longer the event and the higher the frequency, the more adverse the effect on human response. Factors such as frequency of occurrence, fright or “startle factor,” level of personal activity at the time of the event, health of the individual, time of day, orientation of the individual (standing up or lying down), the perceived importance of the blasting operation, and other political and economic considerations also affect human response.

Although the duration of an event affects human response, some researchers have found that fewer blasts of a longer duration are preferable to many blasts with shorter durations. There would be fewer times of perceived disturbance. Fixed locations such as quarries may be able to take advantage of this. Construction projects, however, usually have constraints such as smaller volumes of material to be blasted and sequence of the work that would preclude this.

Table 21 indicates the average human response to vibration and air overpressures that may be anticipated when the person is at rest, situated in a quiet surrounding.

Table 21. Human Response to Blasting Ground Vibration and Air Overpressure

Average Human Response	PPV (in/sec)	Airblast (dB)
Barely to distinctly perceptible	0.02–0.10	50–70
Distinctly to strongly perceptible	0.10–0.50	70–90
Strongly perceptible to mildly unpleasant	0.50–1.00	90–120
Mildly to distinctly unpleasant	1.00–2.00	120–140
Distinctly unpleasant to intolerable	2.00–10.00	140–170

In reviewing the above responses, one must distinguish between the average individual and those who may reside at either end of the human response spectrum. At one end are persons who might perceive some financial benefit or common good from the project. Although they may not appreciate the inconvenience of the blasting, unless they are physically damaged in some manner, they may not complain. At the other end of the spectrum, individuals who do not want the project to take place may be disturbed by the slightest inconvenience and will generally make their feelings known.

The listing of vibration levels and air overpressure levels on the same comparison chart above does not indicate that there is any connection between the two, except as the particular levels apply to human response. In blasting, an increase in vibration can often be accompanied by a decrease in air overpressures, and vice versa.

Effect of Blast Vibration on Materials and Structures

Table 22 summarizes the effects of peak particle velocities on structures and materials that have been documented by various researchers and organizations. The listing is intended to provide some idea of what various particle velocities represent and the effects that might be expected. This listing is not intended to be used to establish specific limits. In some instances equivalent velocity levels were derived from strain measurements.

Several valuable points can be drawn from review of Table 22 and associated references:

Concrete is difficult to damage with normal construction blast vibration, although unsupported concrete slabs can eventually crack from their own weight. Extremely close blasts could damage concrete from rock block movement, but this would not be considered vibratory damage.

The average residence experiences far greater stress from daily environmental changes than from construction blasting if blast vibration intensities are kept at or below USBM or OSMRE limits.

Water wells and buried pipelines can survive rather high-vibration intensities because they are constrained by the soil and bedding materials surrounding them.

Table 22. Effect of Blasting Vibration on Materials and Structures

PPV (in/sec)	Application	Effect	Reference
600	Explosives inside concrete	Mass blowout of concrete	Tart et al. 1980
375	Explosives inside concrete	Radial cracks develop in concrete	Tart et al. 1980
200	Explosives inside concrete	Spalling of loose/weathered concrete skin	Tart et al. 1980
>100	Rock	Complete breakup of rock masses	Bauer and Calder 1978
100	Explosives inside concrete	Spalling of fresh grout	Tart et al. 1980
100	Explosives near concrete	No damage	Oriard and Coulson 1980
50–150	Explosive near buried pipe	No damage	Oriard 1994
25–100	Rock	Tensile and some radial cracking	Bauer and Calder 1978
40	Mechanical equipment	Shafts misaligned	Bauer and Calder 1977
25	Explosive near buried pipe	No damage	Siskind and Stagg 1993
25	Rock	Damage can occur in rock masses	Oriard 1970
10–25	Rock	Minor tensile slabbing	Bauer and Calder 1978
24	Rock	Rock fracturing	Langefors et al. 1948
15	Cased drill holes	Horizontal offset	Bauer and Calder 1977
>12	Rock	Rock falls in underground tunnels	Langefors et al. 1948
12	Rock	Rock falls in unlined tunnels	E. I. du Pont de Nemours & Co. 1977
<10	Rock	No fracturing of intact rock	Bauer and Calder 1978
9.1	Residential structure	Serious cracking	Langefors et al. 1948
8.0	Concrete blocks	Cracking in blocks	Bauer and Calder 1977
8.0	Plaster	Major cracking	Northwood et al. 1963
7.6	Plaster	50% probability of major damage	E. I. du Pont de Nemours & Co. 1977
7.0–8.0	Cased water wells	No adverse effect on well	Rose et al. 1991
>7.0	Residential structure	Major damage possible	Nichols et al. 1971
4.0–7.0	Residential structure	Minor damage possible	Nichols et al. 1971
<6.9	Residential structure	No damage observed	Wiss and Nichols 1974
6.3	Residential structure	Plaster and masonry walls crack	Langefors et al. 1948
5.44	Water wells	No change in well performance	Robertson et al. 1980
5.4	Plaster	50% probability of minor damage	E. I. du Pont de Nemours & Co. 1977
4.5	Plaster	Minor cracking	Northwood et al. 1963
4.3	Residential structure	Fine cracks in plaster	Langefors et al. 1948
>4.0	Residential structure	Probable damage	Edwards and Northwood 1960
2.0–4.0	Residential structure	Plaster cracking (cosmetic)	Nichols et al. 1971
2.0–4.0	Residential structure	Caution range	Edwards and Northwood 1960
2.8–3.3	Plaster	Threshold of damage (from close-in blasts)	E. I. du Pont de Nemours & Co. 1977
3.0	Plaster	Threshold of cosmetic cracking	Northwood et al. 1963
1.2–3.0	Residential structure	Equates to daily environmental changes	Stagg et al. 1980
2.8	Residential structure	No damage	Langefors et al. 1948
2.0	Residential structure	Plaster can start to crack	Bauer and Calder 1977
2.0	Plaster	Safe level of vibration	E. I. du Pont de Nemours & Co. 1977
<2.0	Residential structure	No damage	Nichols et al. 1971
<2.0	Residential structure	No damage	Edwards and Northwood 1960
0.9	Residential structure	Equivalent to nail driving	Stagg et al. 1980
0.5	Mercury switch	Trips switch	Bauer and Calder 1977
0.5	Residential structure	Equivalent to door slam	Stagg et al. 1980
0.1–0.5	Residential structure	Equates to normal daily family activity	Stagg et al. 1980
0.3	Residential structure	Equivalent to jumping on floor	Stagg et al. 1980
0.03	Residential structure	Equivalent to walking on floor	Stagg et al. 1980

Government-Published Vibration Limits

U.S. Bureau of Mines

In 1974, USBM began a study to gather and update available blast vibration data. Work was included in the area of structural and human response to vibration. This resulted in the publishing in 1980 of USBM RI 8507, "Structure Response and Damage Produced by Ground Vibration From Surface Mine Blasting." Some of the conclusions contained in the report are as follows:

- PPV is the most practical descriptor of vibration as it applies to the damage potential for residential structures.

- The potential for damage to residential structures is greater with low-frequency blast vibration (below 40 Hz) than with high frequency blast vibration (40 Hz and above).

- The type of residential construction is a factor in the vibration amplitude required to cause damage.

- For low-frequency blast vibration, a limit of 0.75 in/sec for modern drywall construction and 0.50 in/sec for older plaster-on-lath construction was proposed. For frequencies above 40 Hz, a limit of 2.0 in/sec for all types of construction was proposed.

- Alternative blasting-level criteria were also proposed that used the above limits over a wide range of frequencies and included some limits on displacement.

Figure 8 depicts the alternative blasting level criteria proposed by USBM. (These curves also have been applied to impact rate driving vibration.)

Office of Surface Mining and Reclamation Enforcement

In 1983, OSMRE established regulations controlling vibration at all surface coal mining operations. Three optional methods of limiting vibration are allowed:

1. The first option limits PPV based on the distance to the nearest protected structure. Each blast must be monitored by a seismograph. With this option, velocities must be kept at or below the following levels:

   - Distances up to 300 ft.: 1.25 in/sec

   - Distances of 301–5,000 ft.: 1.00 in/sec

   - Distances beyond 5000 ft.: 0.75 in/sec

2. The second option does not require monitoring, but requires the operator to design his blasts utilizing Square-Root Scaled Distances (D_s). The calculated Scaled Distances must not fall below the following values:

Distances up to 300 ft.: 50

Distances of 301–5000 ft.: 55

Distances beyond 5000 ft.: 65

3. The third option requires an operator to monitor his blasts with a seismograph and use PPV limits that vary with frequency, similar to the alternative blasting level criteria proposed in USBM Report of Investigations (RI) 8507. The OSMRE option differs from RI 8507 in two areas: (1) it does not differentiate between drywall and plaster-on-lath construction, allowing 0.75 in/sec in the medium frequencies for either case, and (2) it allows a particle velocity of 2.0 in/sec down to a frequency of 30 Hz rather than 40 Hz.

Figure 9 depicts OSMRE optional criteria. An analysis of the OSMRE options discloses the following:

Option 1 is reasonable for mine-type blasts, which are usually larger than construction blasts and generally result in larger charge weights and lower frequencies. The nearest structures of concern are usually at greater distances than would be expected in construction blasts where charges are usually smaller and frequencies higher. Option 1 would be somewhat conservative for construction blasts.

Option 2 is quite conservative and uses blast design criteria rather than limiting the effects of the blast. Because no recording is required, a larger safety factor is built into this option. Unfortunately, this option also has the unintended effect of limiting the blaster’s use of modern technology to improve blast efficiency while at the same time keeping adverse effects within acceptable limits.

Option 3, which requires vibration recording with a capability of determining frequencies, is a more practical limit and can be equally applied to both mine and construction blasting.

Vibration Limits for Other than Residential Structures

Massive concrete structures, bridges, and other well-engineered structures are far more capable of withstanding blast vibration intensities than residential structures. Massive structures do not respond adversely to the relatively high-frequency and low-displacement vibration waves that result from nearby construction blasting. (On the other hand, the large displacements and low frequencies encountered in earthquakes must always be considered when designing these structures.) A PPV limit of 4.0–10.0 or 12.0 in/sec is not uncommon where the mass of a structure precludes it from being damaged by blast vibration, and it is unusual to find situations in which rock has been blasted away at the base of such structures without causing damage. Blast vibration limits are best addressed for engineered structures on a case-by-case basis.

Buried pipelines, being constrained by the bedding material and soil surrounding them, can also withstand high-vibration intensities (Oriard 1994, Siskind and Stagg 1993). When blasting in close proximity to these pipelines or in close proximity to most structures, rock block movement and cracks emanating from the crater zone toward the object can become more of a concern than vibration.

Special care should be taken when blasting in close proximity to historically important structures. Such structures are usually of older, less-competent construction, and lower vibration limits for them are often justified. These should be addressed on a case-by-case basis.

Effects of Air Overpressure (Airblast)

Although the term “airblast” has been used to describe all air overpressures from blasting, it is more correctly applied only to high-frequency air overpressures resulting from the detonation of explosives on the surface or in the air and that result in high intensities in close proximity to the detonation. Detonation of such charges should not have a part in construction blasting, especially in urban settings. Air overpressures from fully confined charges in normal down-hole blasting are lower-frequency pressure pulses that result from movement or bulking of the blasted material, bench-face movement, and the vertical component of ground vibration waves in the vicinity of an air overpressure recording device. All blasting involves expanding cases that induce a positive pressure pulse (hence the term “overpressure”).

Overpressure at higher frequencies can be startling in a quiet surrounding, but it will not normally cause damage unless it exceeds approximately 150 dB (linear, unweighted). Low-frequency overpressures, although they might be below the range of human hearing, can impact the side of a residential structure, resulting in windows rattling and other noise. On hearing this noise, the average homeowner will not be able to distinguish between air overpressure or ground vibration as the source but will generally incorrectly attribute the effect to the latter.

Government-Published Air Overpressure Limits

USBM RI 8485 (1980), “Structure Response and Damage Produced by Airblast From Surface Mining,” generally recommends a maximum safe overpressure of 0.014 psi (134 dB, linear, unweighted) for residential structures. The first occurrence of airblast damage is usually the breakage of poorly mounted windows at approximately 152 dB (0.11 psi). A limit of 134 dB is sufficiently low to prevent damage but may not address the annoyance of individuals.

OSMRE also addressed air overpressure limits in its 1983 regulations. It considered the characteristics of the recording systems and established the following limits:

Table 23. OSMRE Overpressure Limits

Recording Device Characteristics	Limit
Lower Limit of 0.1 Hz*	134 dB
Lower Limit of 2.0 Hz	133 dB
Lower Limit of 6.0 Hz	129 dB
C-weighted, slow response*	105 dBC

* To be used only with prior approval of OSMRE.

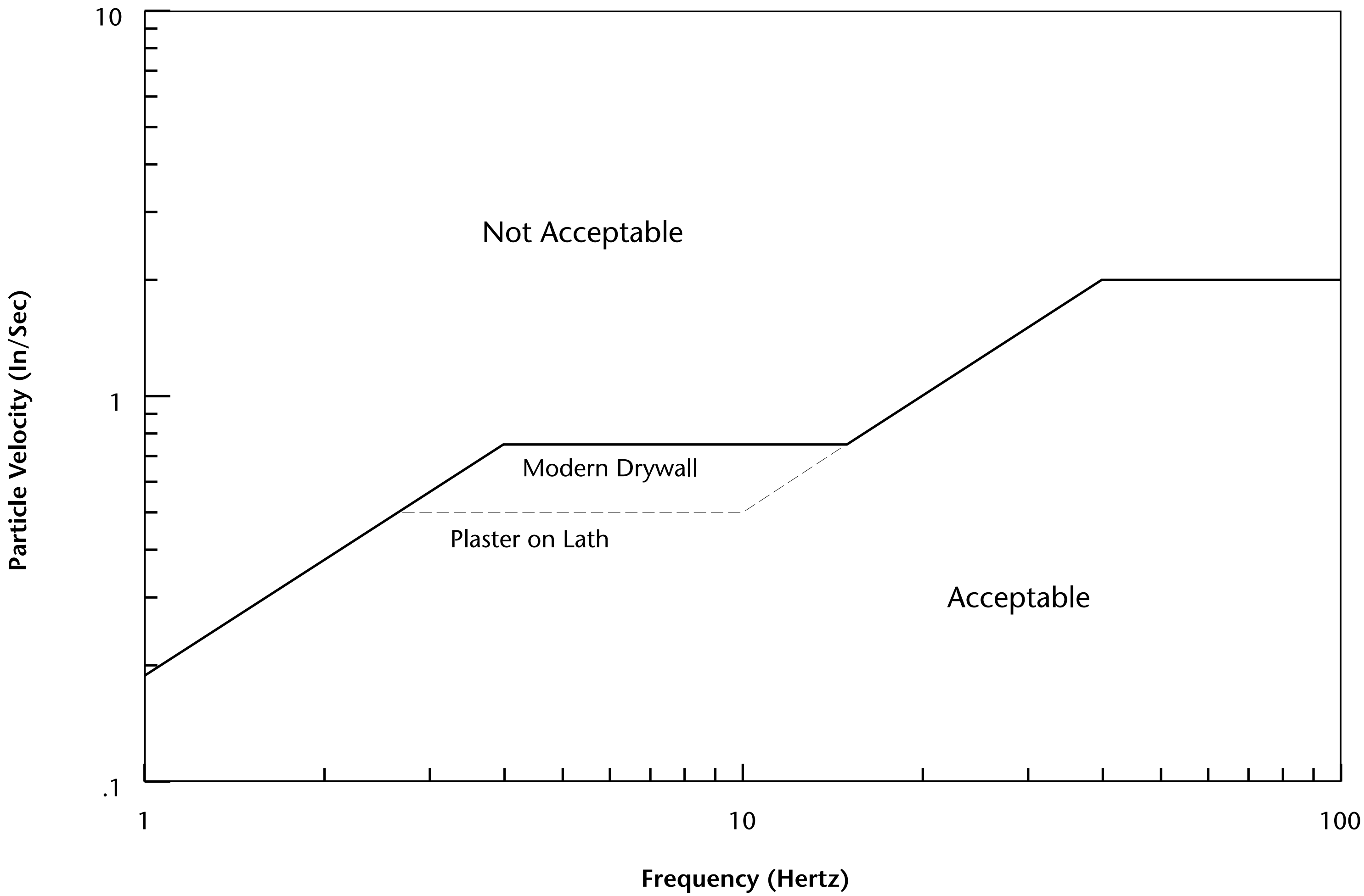

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Figure 8
R18507 Alternative Blasting Level Criteria

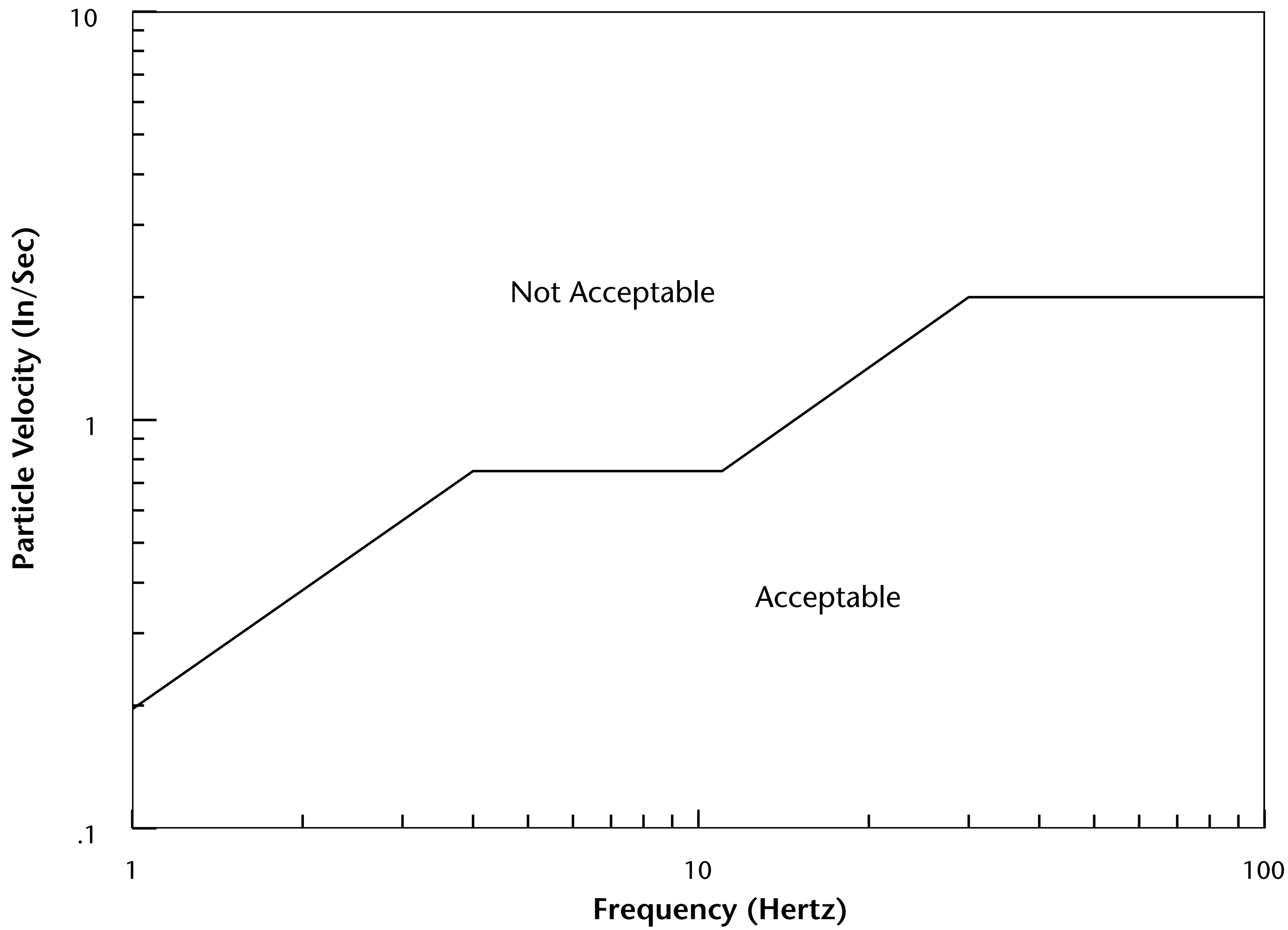

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Figure 9
OSMRE Alternative Blasting Criteria
(30 CFR Part 816.67(d)(4)

Most modern seismographs with air overpressure recording capability have a frequency response of from 2–250 Hz; hence, the 133-dB limit would be appropriate where they were used for recording.

For several years, an air overpressure limit of 140 dB was used primarily to prevent injury to workmen's' hearing; it also successfully prevented damage to structures. In recent times, lower limits have been used, mostly in attempts to reduce annoyance.

E. Procedures for Mitigating Blast Vibration and Air Overpressures from Construction Blasting

Every attempt should be made to mitigate the adverse effects from blasting on construction projects by using modern techniques, procedures, and products. It is equally important to put in place a process to avoid and, if necessary, deal with problems from the public that can arise from blasting, even when the levels of vibration and air overpressure are well below the levels at which damage to structures or excessive annoyance to humans is expected to occur. Taking the following steps is suggested to avoid and/or deal with potential problems from the public.

1. Identify potential problem areas surrounding the project site

2. Determine the conditions that exist prior to commencement of construction

3. Inform the public about the project and potential blasting-related consequences

4. Schedule the work to reduce adverse effects

5. Design the blast to reduce vibration and air over pressure

6. Use blast signals to notify nearby residents that blasting is imminent

7. Monitor and record the vibration and air overpressure effects of the blast

8. Respond to and investigate complaints

Steps 1–3 are closely related. Step 1 involves determining the radius within which a preblast survey should be conducted. Step 2 involves the actual preblast survey. Step 3 is related to the preblast survey but incorporates a larger radius and should be offered to all interested parties.

A blasting specification is a tool that can be used to identify blast vibration limits, surveys, monitoring instruments, and other key methods to avoid and minimize the effects of blasting. This chapter concludes with a discussion of blasting specifications.

Step 1. Identify Potential Problem Areas Surrounding the Project Site

The scope of blasting anticipated for a project will be part of the process of identifying potential problem areas. If only a very small portion of rock would be blasted at one end of the project, for example, there may be no need for a preblast survey of structures at the other end. Therefore, it must be determined how far away from the proposed blasting the surveys must be conducted. There is no standard distance that would be appropriate for all projects or all locations.

One method of determining the preblast survey radius is to estimate the blast vibration and survey to a radius at which the anticipated vibration levels drop below the threshold of human detection (0.01–0.02 in/sec PPV). This method would be economically feasible in rural areas where such a radius might include only a few structures, but may not be economically feasible in more densely populated areas. In a study conducted by Caltrans (Egan et al. 2001), it was suggested that a preblast survey radius of 100 m (328 ft.) appeared to be reasonable to take in all structures susceptible to blast vibration damage. Any distance selected must consider the volume of material to be blasted and the probable charge weights to be used.

One question that must be answered before any preblast survey radius is mandated is whether the intent is to prevent structural damage or to prevent the perception that structural damage is occurring. Egan (2001) notes in his study that structures beyond 35 m (115 ft.) would not have experienced blast vibration in excess of 2.0 in/sec, the Caltrans threshold for damage prevention at the time. Although this may have served well to prevent damage to structures, such vibration levels will usually result in claims of perceived damage from nearby neighbors. It would not prove excessively costly to base the preblast survey radius on preventing actual damage, but it could be very expensive if the radius were based on preventing human perception.

Regardless of the radius selected for preblast surveys, there have been numerous instances in which claims of damage came from locations far beyond the surveyed areas. Therefore, there is no reasonable standard distance beyond which no complaints can be assured.

Bearing in mind human perceptions and economic considerations, the best solution might be to select structures for preblast surveys as follows:

1. those structures or groups of structures closest to the blasting,

2. structures within a radius where the effects are estimated to be strongly perceptible and,

3. any structures at greater distances that, because of historic value or precarious condition, are deemed to deserve special attention (if the project is viewed by the surrounding residents as not necessarily being to their benefit or is otherwise unpopular, the distances should probably be increased accordingly).

After a decision has been made about the limit of preblast surveys, damage claims should be anticipated from residents in other structures that will probably need to be resolved through forensic investigation. This is discussed in Step 8.

Step 2. Determine the Conditions That Exist Before Construction Begins

Oriard (1999) and Dowding (1996) describe preblast survey methods in detail. Various methods can be used to conduct preblast surveys, but all must meet the primary purpose of documenting all defects and existing damage in the structures concerned. Secondary purposes of preblast surveys are to answer any questions homeowners have about the project, and to look for anything that might require correction before construction begins or that may unexpectedly limit blast design, such as antique plates that are leaning against a wall or precariously balanced figurines (which could probably be secured for the duration of the project). It is usually advantageous to conduct postblast surveys to verify that no additional defects have been caused by the blasting.

Surveys can be documented using drawings on paper, high-resolution video, black-and-white photography, or any other method that adequately documents existing defects and damage. It is also helpful if the possible causes of defects can be determined and listed. All residential structures suffer from normal shrinkage of materials, possible settling, and thermal stresses, which start to occur soon after their construction. Both factors can present problems on long-term projects for which relatively new homes are included in the preblast survey. Normal shrinkage cracks and defects might not be apparent during the preblast survey while being apparent during a postblast inspection. To determine whether it is possible that blasting caused the defect, the only solution is to investigate the defects thoroughly, which will normally require an experienced forensic investigator.

It is also good practice to examine homes both near and far from the construction activity. If cracks or other defects are consistent throughout the area, they are likely the result of regional settlement. Cracks or defects that diminish with distance from the vibration source may be indicative of effects caused by the source.

An inadequate preblast survey can be worse than no preblast survey at all; preexisting defects not listed in the preblast survey will likely be attributed to the blasting by the property owner. Unless such claims can be refuted through forensic investigation, the complainant will probably be successful. Insurance companies tend to settle smaller claims rather than pay the costs involved in determining the actual cause. Such action is technically and philosophically flawed, and is effectively an open invitation for additional claims from surrounding neighbors.

Homeowners will sometimes prefer that their homes not be surveyed, usually for the sake of privacy. A notation should be made for that structure as to the time and date, the specific comment made, and the person who made it. A homeowner might also terminate a preblast survey before it is complete. Again, the survey should be annotated accordingly.

Step 3. Inform the Public about the Project and Potential Blasting-Related Consequences

Establishing good public relations with those nearest the project and any other interested parties is always beneficial. Most homeowners do not have experience with blasting or its effects (other than spectacular events on television) and may have concerns for the safety of themselves and their homes.

A meeting should be held and a presentation made that explains the reason for the project, the necessity of blasting, the effects that the residents might experience (hear and/or feel), the specific blasting signals that will be used, and the intentions of the preblast survey. Knowledgeable persons should attend to answer questions. A handout should be provided that explains all of the above and includes phone numbers in case of a problem or questions. The person or company that will conduct the preblast surveys should be introduced. The main purpose of this meeting is to educate the neighbors, but it also tends to put their minds at ease. Such a meeting, conducted properly, can greatly reduce the potential for problems with neighboring property owners.

Another opportunity to establish good public relations is the preblast survey. The informational sheet that was used in the meeting should be distributed in the course of the survey. The person or persons conducting the survey should be conversant enough about the project to answer any questions from homeowners.

Homeowners should be provided with a procedure for registering complaints with Caltrans in the event that vibration is found to be excessive. This procedure should identify a contact person and phone number or email address.

Step 4. Schedule the Work to Reduce Adverse Effects

As long as safety considerations can be met, blasting should be scheduled for times of maximum human activity rather than times of extreme quiet. In some cases, other nearby sources of noise and/or vibration can be used to mask construction activities. (In one case, blasting complaints on a project near Reno were eliminated by detonating blasts only when planes were taking off from the nearby airport. Although this is an extreme example, it illustrates the concept well.)

In situations where only one blast is needed on a project (which are infrequent), providing a safe viewing location and invite neighboring residents to view the event can be beneficial. The residents will appreciate being included and will better understand the blasting process. A safe viewing location is key; there cannot be any chance that flyrock could reach the spectators.

There are other considerations in scheduling blasting. A survey of the area should disclose locations that might require close coordination. If hospitals where surgery is conducted or other facilities with equipment highly sensitive to vibration are nearby, coordination is necessary so that blast effects do not interfere with the operations of these facilities. Also, in areas prone to lightning storms, blasting schedules must be adjusted so that there is minimal interruption to the work. Blasts may need to be loaded and detonated during times when thunderstorms are not likely to occur.

Step 5. Design the Blast to Minimize Vibration and Air Overpressure

Most of the factors involved in blast design are interrelated or interactive; correcting one problem may prompt others. Safety is paramount. The first consideration in blast design must be the safety of all personnel and surrounding structures and objects.

Blast vibration is affected by the following list of variables. These are in turn affected by blast design factors as indicated. Fixed variables, which cannot be controlled by the blaster, are listed below.

Distance: As the distance from the blast increases, the vibration decreases. However, the blasting must be conducted where it is needed, and smaller charge weights may be necessary if blasting is needed in close proximity to structures.

Site geology: As the distance between the blast and the recording point increases, geology plays a more dominant role in determining the frequency of the blast vibration and the speed at which the vibration dissipates.

Weather: The blaster cannot control the weather, but can work to avoid blasting when windy conditions might increase the intensity of air overpressures at nearby residences.

Variables that the blaster can control are listed below.

Quantity of explosive per delay: The quantity of explosive per delay is one of the major variables in blast design for mitigating vibration. Blast design factors that can affect this include hole diameter and depth, the number of explosive decks, and the method of initiation. Generally, reducing this quantity will reduce the vibration generated, but the powder factor must remain high enough to adequately fracture the material (see third item in list below).

Confinement of the explosive energy: Confinement is affected by burden and spacing, the quantity (and quality) of stemming, amount of subdrilling, and the location of the initiating device. Highly confined blasts, such as presplitting, generate higher vibration levels per unit weight of explosive. If a certain amount of throw or heave is acceptable or if means are employed to prevent excessive throw, reducing burdens can lower vibration levels appreciably. If confinement is reduced to any great extent, one must be careful of increased air overpressures. Bottom initiation will generally result in slightly more vibration than top initiation. However, any vibration benefit that might be gained from shooting from the top down or from reducing the amount of subdrilling can be offset by any additional blasts that may be required if the primary blast does not fracture rock to the full depth.

Powder factor: The powder factor is affected by almost all blast design factors. The keys are to use as close to the optimum amount of explosive as possible and to distribute it through the material to be blasted in such a way that it will adequately fracture and shift the mass. If the powder factor is too low, it will not adequately fragment the material and a large portion of the available energy will be lost as seismic energy, resulting in excessive blast vibration. If the powder factor is too high, it can result in flyrock and excessive air overpressures, as well as increased vibration intensities.

Explosive/borehole coupling: Although explosive/borehole coupling can affect vibration, the effect is minimal. For example, presplitting uses decoupled charges (there is an annular space between the charge and the wall of the borehole), but results in high vibration levels because the increased burden has a greater impact than the decoupling. Decoupling of explosive charges normally is not used to reduce vibration.

Spatial distribution of the energy source: The spatial distribution of the energy source can affect vibration in terms of intensity and frequency. There are two examples of this. In the

first example, two holes separated by a reasonable distance and detonated simultaneously will generate less vibration than one hole containing as much explosive as the two holes combined. The resulting vibration will also be of a higher frequency. The extent of this effect depends largely on the separation distance between the two holes. In a second example, a long column of explosive will generate less vibration than a spherical charge of the same weight. Although the detonation velocity of a column of explosive has some effect on the spatial distribution of energy (and time of energy release), it is not usually a large enough factor to consider in blast design. The explosive properties are usually selected to match the rock conditions. As stated above, it is not wise to select a low-energy explosive to reduce adverse effects if more blasts would be needed to excavate the material to grade.

Timing of detonating charges: Some regulatory agencies specify a minimum of 9 ms between detonating charges and consider all explosives detonating in any given 8-ms period to have detonated in the same instant; this is done solely for determining explosive weight for scaled distance calculations and has no basis in reducing vibration. In actual practice, while 9 ms may be used in some situations, various delay intervals may be appropriate depending on the conditions. It is not unusual for delay intervals of as little as 5 ms to be used in very close-in blasting situations. When the nearest structures are at greater distances, longer delay periods are often used. After first considering safety issues, the blaster should try to determine a delay timing scheme that would minimize vibration or air overpressures, although this might not always be possible. Extending the delay time can reduce the amount of energy released per unit of time, reducing vibration to some extent.

Timing of blast progression: Air overpressures from blasting can be excessive when the velocity of initiation along a free face meets or exceeds the speed of sound; this occurs to a lesser extent on the surface of the blast. Reducing the velocity of the blast progression along the face to half the speed of sound reduces the effect considerably. The delay timing must not be increased, thereby reducing the blast progression, to the point of causing misfires through cutoff in initiation systems or explosive columns. The blaster must incorporate into the design a buffer zone that consists of several or more rows of holes between a hole that is detonating and detonators in holes in which the initiation signal has not been received. If this step is not taken, misfires often result. Although not required, many successful blasters prefer to use delay timing between holes in a row of 2–5 ms per foot of burden. Many also prefer to use delay timing from row to row that is double (or nearly double) the delay timing in a row.

Blast orientation: Blast orientation is usually mandated by terrain and the physical layout of the rock. As a general rule, the highest vibration amplitudes will usually be in a direction opposite of that in which the rock is being heaved or thrown, although local geology may affect the actual direction of maximum intensity. In side-hill situations, the rock movement would be downhill or along the side-hill, almost never uphill. Site safety conditions will dictate the actual design, but blasting against gravity can increase problems for flyrock and vibration.

Step 6. Use the Blast Signals to Notify Nearby Residents That Blasting Is Imminent

Although blasting signals were originally intended to provide a means of clearing a blast site before the blast is detonated, they also serve to alert nearby residents that a blast is about to occur. This helps to reduce the "startle" effect. After hearing 5- and 1-minute warnings, the average resident will anticipate the event and the intensities will not appear as severe as they would have if the person had not been warned. The blasting signals currently mandated by the California Occupational Safety and Health Administration for blasting on construction sites are contained under "Sample Specifications" in Appendix D.

Step 7. Monitor and Record the Vibration and Air Overpressure Effects of the Blast

Although blast-induced vibration and air overpressures can be estimated with some confidence, monitoring and recording these effects is far more effective. Records from blasting seismographs, when combined with the written blaster's report, provide excellent tools for evaluating the potential for damage from blast-induced vibration and air overpressure. Recording should be conducted with calibrated seismographs specifically intended for the purpose. Such instruments include a microphone channel for recording air overpressures; most have the ability to print a graph that compares vibration magnitudes and frequencies against accepted national standards.

In situations where there is considerable opposition to a project and damage claims are anticipated, third-party monitoring should be conducted. In situations where there is little chance for claims or where monitoring is being done solely to ensure that specifications are being met, the contractor might conduct his or her own monitoring. In such a case, a third-party vibration consultant is advisable to oversee and approve the contractor's monitoring and recording process. Damage claims should always be anticipated.

Step 8. Respond to and Investigate Complaints

An adequate process for handling complaints should be established. Neighboring residents should know whom to contact with a concern or complaint, whether or not it involves a claim of damage. In all instances, a form that documents the details of a complaint should be initiated when the complaint is received. A sample construction/blast complaint form is provided in Appendix B.

For minor complaints, responsible, knowledgeable contractor personnel might conduct the investigation. A qualified forensic investigator is advisable to look into claims of damage. The investigator could be the same person that conducted the preblast survey, the monitoring, or both. A prompt investigation is advisable. If the problem was caused by the blasting, correction of the problem should also be handled promptly.

F. Blasting Specifications

Anticipation of all variables that may be encountered on various project sites is not possible. For each project, a site-specific blasting specification should be developed that considers the peculiarities of the project location. In particular, the areas of blast vibration limits, preblast surveys, the number of recording instruments and their locations, the times and days of scheduled blasting, and cautious blasting techniques (if any) should be addressed. A sample blasting specification has been developed to provide a starting point for writing a blasting specification for construction blasting; the sample is provided in Appendix D.

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APPENDIX A. TECHNICAL ADVISORY TAV-02-01-R9601

California Department of Transportation
Division of Environmental Analysis
Office of Noise and Hazardous Waste Management
Sacramento, CA

TRANSPORTATION RELATED EARTHBORNE VIBRATIONS

(Caltrans Experiences)

Technical Advisory, Vibration

TAV-04-01-R0201

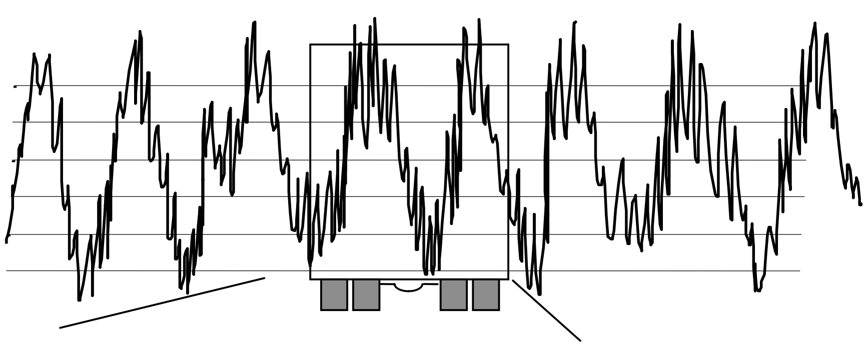
January 23, 2004

Prepared by Rudy Hendriks – Caltrans Retired Annuitant

NOTICE:

This document is a revision of technical advisory TAV-02-01-R9601 with the same title, prepared by the same author, dated February 20, 2002. As a result of a final review, minor editorial changes were made and a cautionary note was added to a method of coupling an accelerometer to the measuring surface. The basic information was not changed from the earlier version. This version of the technical advisory is included as Appendix A in the Transportation and Construction-Induced Vibration Guidance Manual, prepared by Jones & Stokes, Sacramento, CA, for Caltrans.

<u>This document is not an official policy, standard, specification or regulation and should not be used as such.</u> Its contents are for informational purposes only. Any views expressed in this advisory reflect those of the author, who is also responsible for the accuracy of facts and data presented herein. The latter were derived from Caltrans vibration studies from 1958 to 1994, and the author's vibration experiences from 1980 to 1994 at the Caltrans Transportation Laboratory (Translab) in Sacramento, CA.



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INTRODUCTION

This Technical Advisory is intended to give district environmental, materials, design, construction and other concerned personnel a basic understanding of transportation related earthborne vibrations. The advisory covers general vibration principles, vibrations caused by construction and operation of transportation facilities, criteria used by the California Department of Transportation (Caltrans), impacts, vibration study approaches, possible mitigation, and screening procedures to identify potential vibration problems in the field.

District personnel are usually the first to be contacted by the public when vibration problems occur. Until 1994, the district personnel in turn contacted the Caltrans laboratory (TransLab) and requested either an assesment of the problem or a vibration field study. In 1994, Translab discontinued the field studies because of a reorganization. Presently, HQ Division of Environmental Analysis, Noise, Air Quality and Hazardous Waste Management Office, Noise and Vibration Branch is responsible for providing guidance on potential vibration problems.

The information in this advisory will enable district personnel to participate in assessing and screening routine vibration complaints as well as provide background information for the oversight of more complex studies. This advisory will also be a useful source of information for developing contract specifications and oversight.

BACKGROUND

Caltrans has performed earthborne vibration studies since 1958. In 1976, a landmark TransLab vibration research report titled "Survey of Earth-borne Vibrations due to Highway Construction and Highway Traffic", Report No. CA-DOT-TL-6391-1-76-20, compiled a summary of results, findings, and conclusions of 23 studies completed in the 17 year period between 1958 and 1975. Since then many more studies have been performed. Most of these fall into the following three categories:

- Highway traffic vibrations
- Construction vibrations
- Train/light rail vibrations

The main concerns of vibrations involve:

- Annoyance
- Damage
- Disruption of vibration sensitive operations or activities
- Triggering of land slides

The sites investigated included private residences, factories, aerospace and defense plants, electronic laboratories, radio station, movie studio, etc., and even a major cake and pastry bakery.

Because of similarities between the disciplines of noise and vibrations, the former Noise Section took over the responsibilities for vibration studies from the Electrical Instrumentation Testing and Research Section in July, 1980. Almost two-thirds of the above mentioned studies were performed by the Noise Section, which, in 1994 was absorbed by the newly created Office of Environmental Engineering of the Environmental Program. The individual study reports are on file at the Office of Environmental Engineering. This advisory incorporates information and experience gained in all Caltrans vibration studies from 1958-1994.

FUNDAMENTALS OF EARTHBORNE VIBRATIONS

Vibration Sources

Sources of earthborne vibrations include natural phenomena (earthquakes, volcanic eruptions, sea waves, landslides, etc.), or manmade causes (explosions, machinery, traffic, trains, construction equipment, etc.). Vibration sources may be continuous such as factory machinery, and transient, such as explosions.

A distinction must be made between earthborne and airborne vibrations. Some sources, such as jet aircraft, rockets, explosions, sonic booms, locomotives, and even trucks under certain conditions, can create low frequency airborne noise of enough intensity to be felt, as well as heard. These low frequency airborne blasts or rumbles are often erroneously perceived as earthborne vibrations.

As is the case with airborne sound, earthborne vibrations may be described by amplitude and frequency.

Amplitude and Frequency

In airborne sound, amplitude is described by common logarithm of the square of the ratio of pressure fluctuations around mean air pressure divided by a reference pressure, and is expressed in logarithmic units of decibels. The pressure fluctuations propagate in waves of alternating compressed and rarefied air. The rate at which these waves radiate outward from their source is called the speed of sound, which is the wave velocity. Air is an elastic medium through which the waves travel.

In earthborne vibrations, amplitude is described by the local movement of soil particles. This movement must not be confused with wave velocity.

To distinguish between wave velocity and particle motion, consider the analogy of ripples on a lake and a floating cork. Wave velocity (in air, speed of sound) is analogous to the velocity of the ripples. Particle motion may be compared to the bobbing of the cork as the ripples pass by. The bobbing of the cork represents the local movement of the soil particles as earthborne vibration waves pass through the soil. The soil acts as an elastic medium.

The amplitude of particle motion may be described three ways:

1. **Particle displacement** - the distance the soil particles travel from their original position. Units are millimeters (mm). inches (in)

2. **Particle velocity** - the velocity of the soil particles. Units are inches per second (in/sec) or millimeters per second (mm/sec). Sometimes expressed logarithmically in decibels (dB) with reference to a specified unit of velocity such as .001 in/sec (1μ in/sec), or 0.001 mm/sec.

3. **Particle acceleration** - the acceleration of the soil particles. Units are inches per second per second (in/sec^2), millimeters per second per second (mm/sec^2), or g-force (g = acceleration of gravity = 32.2 feet per second per second (ft/sec^2) = 9.81 meter per second per second (m/sec^2). Sometimes expressed logarithmically in decibels (dB) with reference to a specified unit of acceleration, such as 1 g, or 0.001g (1μg).

For a perfect sine wave produced by a single vibration frequency there exists a simple relationship between the above three measures of amplitude (see Appendix). If the frequency and amplitude of one descriptor is known, the other two can easily be calculated. For waves consisting of many frequencies, and therefore not sine waves, the relationships become much more complicated.

There is a 90 degree phase shift between the three descriptors, i.e. velocity is 90 degrees out of phase with displacement, acceleration is 90 degrees out of phase with velocity, and acceleration is 180 degrees out of phase with displacement. To illustrate this, we might imagine a pendulum just released from a point furthest away from its stationary position. If we arbitrarily call this position the extreme positive (+) position of the pendulum, the stationary point 0, and the region beyond the stationary point a negative (-) position, we observe the following:

- at the point of release, the displacement (distance from stationary or 0 displacement position) is maximum and positive (+).
- the velocity at the point of release is 0.
- the acceleration at the point of release is at its maximum, in the direction towards the negative (-).

This can be worked out the same for other pendulum positions. For instance, as the pendulum swings through the stationary position, the displacement is 0, the velocity is maximum in the negative (-) direction, and the acceleration is 0. Once past the stationary point the pendulum decelerates in the negative (-) direction which is the same as increasing acceleration in the positive (+) direction.

Vibration amplitudes are usually expressed as either "peak", as in peak particle velocity, or "rms" (root mean square), as in rms acceleration. The relationship between the two is the same as with noise. The rms value is approximately 0.71 x the peak value for a sine wave representing either displacement, velocity, or acceleration.

Finally, the direction in which vibrations are measured, analyzed or reported should be specified (vertical, horizontal longitudinal, horizontal transverse, or the resultant of all three motions). For example, Caltrans most often uses a peak vertical particle velocity descriptor, because vibrations along the ground surface are most often (although not always) greatest in the vertical direction.

Propagation

Propagation of earthborne vibrations is complicated because of the endless variations in the soil through which waves propagate.

The relationship between frequency (**f**), period (**T**), wave length (λ), and wave velocity (**c**) is the same as that in noise, that is:

$f=1/T$ and $f=c/\lambda$

However, the wave velocity (c, sometimes also called the phase velocity) in soils varies much more than the speed of airborne sound does, and is often also frequency dependent (in the atmoshere, the speed of sound only varies with temperature). As a consequence, wavelength cannot readily be calculated when frequency is known and vice versa, unless the wave velocity happens to be known also.

There are three main wave types of concern in the propagation of earthborne vibrations:

1. **Surface or Rayleigh waves**, which as the name implies, travel along the ground surface. They carry most of their energy along an expanding cylindrical wave front, similar to the ripples produced by throwing a rock into a lake. The particle motion is retrograde elliptical, more or less perpendicular to the direction of propagation.
2. **P-waves, or compression waves.** These are body waves that carry their energy along an expanding spherical wave front. The particle motion in these waves is longitudinal, "push-pull". P-waves are analogous to airborne sound waves.
3. **S-waves, or shear waves.** These are also body waves, carrying their energy along an expanding spherical wave front. Unlike P-waves, however, the particle motion is transverse, or perpendicular to the direction of propagation.

As wave fronts move outward from a vibration source, their energy is spread over an ever increasing area. The more rapidly this area increases, the more quickly the energy intensity (energy per unit area) decreases. The areas of cylindrical Raleigh wave fronts do not increase as rapidly with distance as do the body (P- and S-) waves. Consequently, the energy intensities of Raleigh waves attenuate at a lesser rate with distance than those of body waves.

The spreading of energy over ever increasing areas is called geometric spreading (geometric attenuation) and the difference in attenuation rates between surface and body waves is analogous to that of line sources and point sources, respectively, in airborne sound. Geometric attenuation also results of encountering more soil mass as the area of the wave front increases.

Geometric attenuation is not the only attenuation encountered with distance. Hysteretic attenuation, or material damping, results from energy losses due to internal friction, soil layering, voids, etc. The amount of hysteretic attenuation varies with soil type, condition, and frequency of the source.

These variations make it much more difficult to predict vibration amplitudes at specific locations, than it is to predict noise levels.

In general, manmade earthborne vibrations attenuate rapidly with distance from the source. Even the more persistent Rayleigh waves decrease relatively quickly. Manmade vibration problems are therefore confined to short distances from the source.

In contrast, natural vibration problems are often wide spread. An obvious example is an earthquake which can cause damage over large areas, due to the release of enormous quantities of energy at longer wavelengths.

TRANSPORTATION RELATED EARTHBORNE VIBRATIONS

Sources

Caltrans is most commonly concerned with three types of transportation related earthborne vibration sources:

- Normal highway traffic - heavy trucks, and quite frequently buses, generate the highest earthborne vibrations of normal traffic. Vibrations from these vary with pavement conditions. Pot holes, pavement joints, differential settlement of pavement, etc., all increase the vibration amplitudes.
- Construction equipment - pile driving, pavement breaking, blasting, and demolition of structures generate among the highest construction vibrations.
- Heavy and light rail operations - diesel locomotives, heavily loaded freight cars, and operations such as coupling create the highest rail traffic vibrations.

Of the above three types, construction vibrations are of greatest concern. The four operations mentioned under construction vibrations are potentially damaging to buildings at distances of less than 7.5 m (25 ft) from the source.

Descriptor Used By Caltrans

With the exception of some construction operations such as pile driving, pile hole drilling, and perhaps some deep excavations, all vibrations generated by construction or operation of surface transportation facilities are mainly in the form of surface or Raleigh waves. Studies have shown that the vertical components of transportation generated vibrations are usually the strongest and that peak particle velocity correlates best with damage and complaints. For these reasons, Caltrans adopted the Peak Vertical Particle Velocity descriptor, with units of mm/sec or in/sec.

A great advantage of using this descriptor is that for a frequency range of 1 - 80 Hz damage amplitudes in terms of velocity tend to be independent of frequency. The same is true for complaint amplitudes within a range of 8 - 80 Hz. Velocity is the product of frequency, displacement and a constant (see appendix). It appears that within the above frequency ranges a doubling of frequency will offset a halving of displacement and vice versa; i.e. the effects of the product of the two tend to remain equal. Typical transportation and construction vibrations fall within the above frequency ranges. They typically range from 10 - 30 Hz, and usually center around 15 Hz.

From the above we can surmise that not only the effects of displacement are frequency dependent, but also those of acceleration. The latter is related to the former by the frequency times a constant squared (see appendix). Thus, criteria amplitudes in terms of displacement or acceleration need to be accompanied by a frequency.

Propagation of Transportation Related Vibration

Raleigh (Surface) Wave Drop-off - Surface waves generated by traffic, trains, and most construction operations tend to attenuate with distance according to the following equation:

$$V = V_0 (D_0/D)^{0.5} e^{\alpha(D0-D)} \quad \textbf{(eq. 1)}$$

where: V = Peak particle velocity at distance D
V_0 = Peak particle velocity at reference distance D_0
D_0 = Reference distance
D = Distance for which vibration amplitude needs to be calculated
e = Base of natural logarithm = 2.718281828
α = Soil parameter

The soil parameter α can be determined by simultaneous vibration measurements at a minimum of two different distances from a source. One distance should be near the source, ideally between4.5 and 7.5 m (15 -25 ft). The other should be farther away from the source, ideally at or beyond the farthest point of interest, but at a location where the source is still measurable and not contaminated by other vibrations. A third point in between is recommended for confirmation. Note that the value of α depends on the distance units used. The reason for this is that the exponential $(D_0 - D)\ \alpha$ needs to be a constant value while the value of $(D_0 - D)$ changes with the units used (normally, m or ft). Therefore, the relationship between α (based on m) and α (based on ft) is:

α (based on m) = 3.281α (based on ft), and
α (based on ft) = 0.305 α (based on m)

α can be calculated from the vibration measurements by rewriting eq. 1 as:

$$\alpha = (\ln V^2 + \ln D - \ln V_0^2 - \ln D_0)/2(D_0 - D) \qquad \textbf{(eq. 2)}$$

where "ln" denotes "natural logarithm"

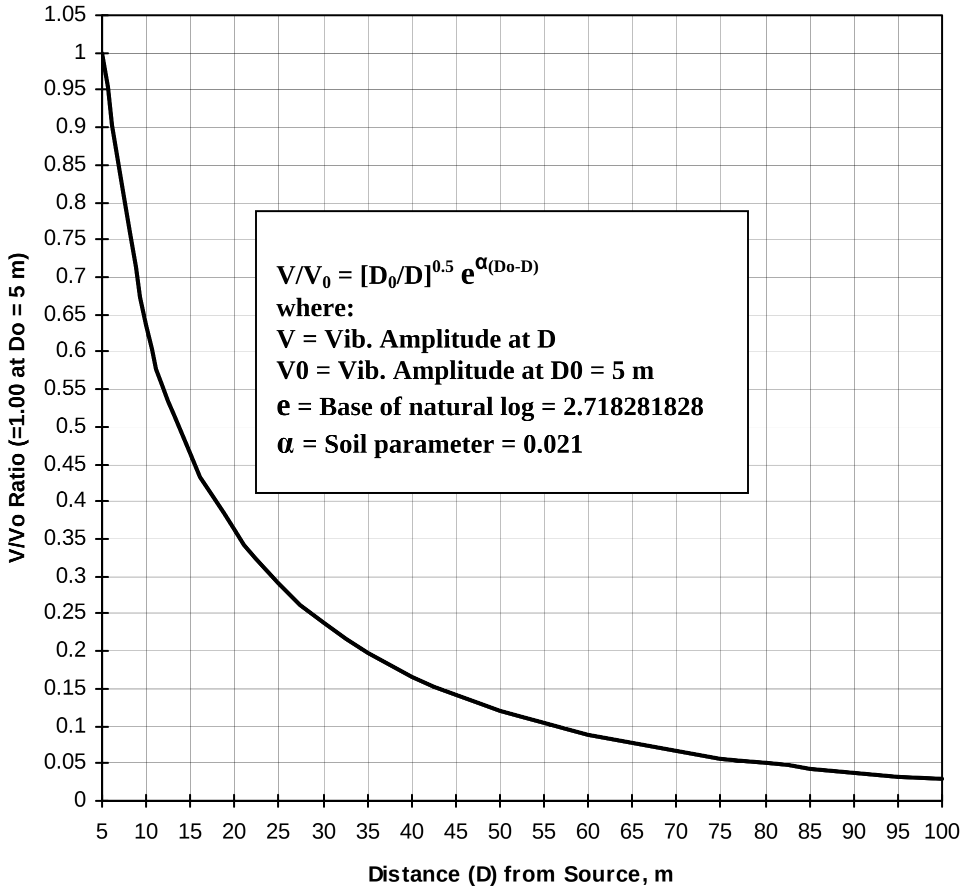
Once α is calculated from the measurements it can be used in eq. 1 to calculate vibrations for any other distance, given the same reference source.

Figure 1 shows a drop-off curve expressed as a ratio of V/V_0, using a reference distance D_0 of 5 m (16 ft). This is a normalized curve for α **= 0.021** (distance in m), or α **= 0.006** (distance in ft), derived from data measured in the City of Lynwood to calculate α for the LA-105 Alameda Viaduct vibration study, involving traffic effects on Westech Gear Corporation (formerly Western Gear) close tolerance manufacturing operations. The attenuation curve in Figure 1 is valid for the soils stratification derived from Caltrans boring logs for the Alameda Viaduct, shown in Table 1.

Table 1. - Soils Classifictaions for Figure 1.

Depth, m (ft)	Soil Description
0	
	Sand-Silt
1.5 (5)	
	Clayey Silt
9 (29)	
	Silty Sand
12 (40)	
	Sandy Silt
15.5 (51)	
	Sand
19.5 (64)	

Figure 1. Typical Normalized Distance Attenuation Ratio Curve of Earthborne Surface Vibrations (Reference Distance, Do = 5 m)



The curve is representative of many locations in the L.A. Basin, and also of various locations in Sacramento, and can be used for estimating traffic, train, and most construction vibration drop-offs with distance. To use the curve, the vibration amplitude V_1 must be known at a given distance D_1 near the source, preferably between 5 and 15 m (16 and 50 ft). The vibration amplitude V_2 at the distance of interest D_2 can then be calculated as follows:

$$V_2 = (V_2/V_0)/(V_1/V_0) \cdot V_1$$

(the ratio's V_2/V_0 and V_1/V_0 can be obtained from Figure 1)

For example, if the vibration amplitude is known to be 3.2 mm/s (peak particle velocity) at a distance of 12 m, the vibration amplitude at 58 m can be estimated from (0.09/0.55) x 3.2 mm/s = 0.5 mm/s.

Pile Driving Vibration Drop-off **-** During pile driving, vibration amplitudes near the source depend mainly on the soil's penetration resistance. In soils such as sand and silt, this resistance is relatively low with the result that a large portion of the impact energy is used to advance the pile. Less energy is then available for generating ground vibrations. In clay soils, however, the penetration resistance is higher and more energy is available for ground vibrations. The resistance provided by the soils consists of friction along the sides of the pile as well as compressional resistance due to the transfer of energy of the pile tip to the soil. This appears to generate body waves as opposed to surface waves by other construction operations.

The energy of a pile driver is of course also influential on the vibration amplitude at the source. There is a relationship between vibration amplitude and energy. If pile driver energy changes from E_1 to E_2, the vibration amplitude at a certain location changes from V_1 to V_2, where:

$$V_2 = V_1\left(\sqrt{\frac{E_2}{E_1}}\right) \qquad \textbf{(Eq. 3)}$$

Example: E_1 = 68,000 J (50,000 ft lbf)

E_2 = 111,900 J (82,500 ft lbf)

V_1 = 2.8 mm/s

Then: $V_2 = 2.8\left(\sqrt{\frac{111{,}900}{68{,}000}}\right) = 3.6$ mm/sec

Vibrations of pile driving appear to drop off differently than the Raleigh waves, probably due to the presence of a significant proportion of body waves. Pile driving vibrations tend to drop off with distance according to the following equation:

$$\mathbf{V = V_0.(D_0/D)^k} \qquad \textbf{(Eq. 4)}$$

where: V, V_0, D_0, and D are same as defined in Eq. 1, and
k = soil parameter (no units)

(Note that α and **k** are different parameters; whereas the value of α is dependent on the distance units used (m or ft), the value of k - which depends only on the ratio of distances - is independent of distance units used.)

Generally, the values of "k" lie between 1 to 1.5 (approaching 1 for sandy soils and 1.5 for clay soils), although values < 1 and > 1.5 have been encountered.

The value of "k" can be determined experimentally at different distances from a pile driver, similarly to the previously described derivation of α. For this purpose, Eq. 4 can be rewritten as:

$$\mathbf{k = (LogV - LogV_0)/(Log\ D_0 - LogD)} \qquad \textbf{(eq. 5)}$$

Caltrans Vibration Criteria

There are no FHWA or state standards for vibrations. The traditional view has been that highway traffic and construction vibrations pose no threat to buildings and structures, and that annoyance to people is no worse than other discomforts experienced from living near highways.

Damage - A considerable amount of research has been done to correlate vibrations from single events such as dynamite blasts with architectural and structural damage. The U.S. Bureau of Mines has set a "safe blasting limit" of 50 mm/s (2 in/sec). Below this amplitude there is virtually no risk of buiding damage.

“Safe” amplitudes for continuous vibrations from sources such as traffic are not as well defined. The Transport and Road Research Laboratory in England has researched continuous vibrations to some extent and developed a summary of vibration amplitudes and reactions of people and the effects on buildings (Table 2). These are the criteria used by Caltrans to evaluate the severity of vibration problems. Traffic, train, and most construction vibrations (with the exception of pile driving, blasting, and some other types of construction/demolition) are considered continuous. The "architectural damage risk amplitude" for continuous vibrations (peak vertical particle velocity of 5 mm/sec or 0.2 in/sec) shown in Table 2 is one tenth of the maximum “safe” amplitude of 50 mm/sec (2 in/sec) for single events.

All damage criteria for buildings are in terms of ground motion at the buildings' foundations. No allowance is included for the amplifying effects of structural components. Obviously, the way a building is constructed and the condition it is in determines how much vibration it can withstand before damage appears. Table 2 shows a recommended upper amplitude of 2.0 mm/s (0.08 in/sec) for continuous vibrations to which "ruins and ancient monuments" should be subjected. This criterion amplitude may also be used for historical buildings, or buildings that are in poor condition.

Relatively little information is available concerning the damaging effects of pile driving. Although technically a series of single events, pile driver blows occuring often enough in a confined area could cause damage at a lower amplitude than the single event criterion of 50 mm/s (2 in/sec). Caltrans has experienced minor damage from sustained pile driving at about 7.5 - 9 mm/s (0.30 - 0.35 in/sec) peak vertical particle velocity vibration on the ground next to an existing parking structure. The extent of the damage was some crumbling of mortar used to fill wall joints. In that instance the

Table 2 - Reaction of People and Damage to Buildings at Various Continuous Vibration Amplitudes

Vibration Amplitude (Peak Particle Velocity)*			
mm/s	in/sec	Human Reaction	Effect on Buildings
0.15-0.30	0.006-0.019	Threshold of perception; possibility of intrusion	Vibrations unlikely to cause damage of any type
2.0	0.08	Vibrations readily perceptible	Recommended upper amplitude of the vibration to which ruins and ancient monuments should be subjected
2.5	0.10	Amplitude at which continuous vibrations begin to annoy people	Virtually no risk of “architectural” damage to normal buildings
5.0	0.20	Vibrations annoying to people in buildings (this agrees with the amplitudes extablished for people standing on bridges and subjected to relative short periods of vibrations)	Threshold at which there is a risk of “architectural” damage to normal dwelling - houses with plastered walls and ceilings Special types of finish such as lining of walls, flexible ceiling treatment, etc., would minimize “architectural” damage
10-15	0.4-0.6	Vibrations considered unpleasant by people subjected to continuous vibrations and unacceptable to some people walking on bridges	Vibrations at a greater amplitude than normally expected from traffic, but would cause “architectural” damage and possibly minor structural damage.

** The vibration amplitudes are based on peak particle velocity in the vertical direction. Where human reactions are concerned, the value is at the point at which the person is situated. For buildings, the value refers to the ground motion. No allowance is included for the amplifying effect, if any, of structural components.*

Source: “A Survey of Traffic-induced Vibrations” by Whiffen and Leonard, Transport and Road Research Laboratory, RRL Report LR418, Crowthorne, Berkshire, England, 1971.

distance to the pile driving was slightly greater than 5 m (17 ft). The pile driver energy and the soil conditions were unknown. It is likely that the ground vibrations were amplified by the structure, causing the damage.

On the whole, the architectural damage criterion for continuous vibrations, 5 mm/s (0.2 in/sec) appears to be conservative even for sustained pile driving. Pile driving amplitudes often exceed 5 mm/s (0.2 in/sec) at distances of 15 m (50 ft), and 13 mm/s (0.5 in/sec) at 7.5 m (25 ft). Pile driving has been done frequently at these distances without apparent damage to buildings (with the previously mentioned exception). The criterion amplitude for pile driving is therefore somewhere between 5 and 50 mm/s (0.2 and 2 in/sec). The 50 mm/s (2 in/sec) single event criterion is still being used by some organizations and engineering firms as a safe amplitude for pile driving. Although never measured by Caltrans, calculations show that this amplitude will be probably exceeded within 2 m (6 ft) from a 68,000 J (50,000 ft lbf) pile driver. This amplitude is probably a "safe" criterion to use for well engineered and reinforced structures. For normal dwellings, however, pile driving peaks should probably not be allowed to exceed 7.5 mm/s (0.3 in/sec). In any case, **extreme care must be taken when sustained pile driving occurs within 7.5 m (25 ft) of <u>any</u> building, and 15-30 m (50-100 ft) of a historical building, or building in poor condition.**

When high amplitudes of construction vibrations (such as from pile driving, demolition, and pavement breaking) are expected at residences or other buildings, it is recommended that a detailed "crack survey" be undertaken BEFORE the start of construction activities. The survey may be done by photographs, video tape, or visual inventory, and should include inside as well as outside locations. All existing cracks in walls, floors, driveways, etc. should be documented with sufficient detail for comparison after construction to determine whether actual vibration damage has occurred.

<u>Annoyance</u> - The annoyance amplitudes in Table 2 should be interpreted with care. Depending on the activity (or inactivity) a person is engaged in, vibrations may be annoying at much lower amplitudes than those shown in Table 2. Elderly, retired, or ill people staying mostly at home, people reading in a quiet environment, people involved in vibration sensitive hobbies or other activities are but a few examples of people that are potentially annoyed by much lower vibration amplitudes. Most routine complaints of traffic vibrations come from people in these categories. To them, even vibrations near the threshold of perception may be annoying.

Frequently, low amplitude traffic vibrations can cause irritating secondary vibrations, such as a slight rattling of doors, windows, stacked dishes, etc. These objects are often in a state of neutral equilibrium and readily respond to very low amplitudes of vibrations. The rattling sound gives rise to exaggerated vibration complaints, even though there is very little risk of damage.

Other criteria - At times, other criteria may be necessary to address very specific concerns. For example, vibration sensitive manufacturing or calibration processes, such as close tolerance machining, laboratories calibrating sensitive electronic equipment, use of electron microscopes, etc. often require vibration criteria that are much lower than the threshold of perception amplitude.

Determining the specific criterion amplitude for such sites is no easy task, and requires the cooperation of the engineers, technicians, or managers involved with the operations. Frequently, even those experts do not know at what amplitude of vibrations their operations will be disturbed, and tests involving generation of vibrations (such as running a heavy truck over 2"x4" wooden boards outside the plant), vibration monitoring equipment, and a test operation must be performed.

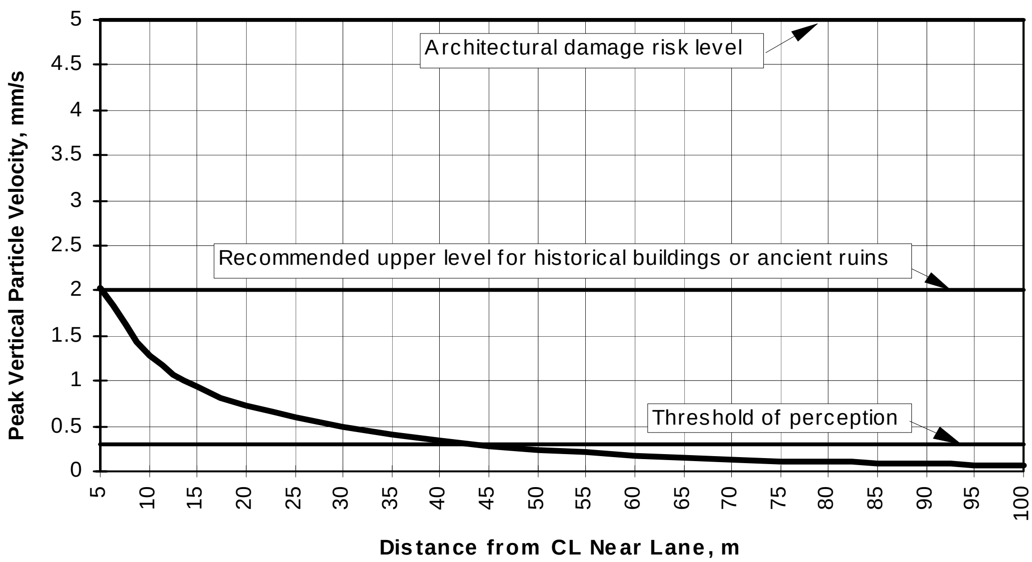
Typical Traffic Vibration Amplitudes

From Figure 1 typical relationships of traffic vibrations vs. distance from a freeway can be developed. For instance, vibration data of truck passbys are characterized by peaks that are considerably higher than those generated by automobiles. These peaks last no more than a few seconds and often only a fraction of a second, indicating a rapid drop-off with distance. Figure 1 showed that at 15 m (50 ft) from the centerline of the nearest lane, truck vibrations are about half of those measured near the edge of shoulder (5 m, or about 15 ft from the centerline of the near lane). At 30 m (100 ft) they are about one fourth, at 60 m (200 ft) about one tenth, and at 90 m (300 ft) less than one twentieth. These rough estimates are supported by years of measurements throughout California.

Because of the rapid dropoffs with distance, even trucks traveling close together often do not increase peak vibration amplitudes substantially. In general, more trucks will show up as more peaks, not necessarily higher peaks. Wavefronts emanating from several trucks closely together may either cancel or partially cancel (**destructive interference**), or reinforce or partially reinforce (**constructive interference**) each other, depending on their phases and frequencies. Since traffic vibrations can be considered random, the probabilities of total destructive or constructive interference are extremely small. Coupled with the fact that two trucks cannot occupy the same space, and the rapid drop-off rates, it is understandible that two or more trucks normally do not contribute significantly to each other's peaks. It is, however, good practice to try and include the worst combinations of truck clusters with heavy loads in traffic passby vibration measurements. This obviously requires a good view of the traffic, or an observer who is in communication with the instrument operator.

Figure 2 is a plot of maximum highway truck traffic vibrations vs. distance from the centerline of the nearest freeway lane. The curve was compiled from the highest measured vibrations available from previous studies. Some of the Table 2 criteria are also plotted, for comparison. The graph indicates that the highest traffic generated vibrations measured on freeway shoulders (5 m from center line of nearest lane) have never exceeded 2.0 mm/s, with worst combinations of heavy trucks. This amplitude coincides with the maximum recommended "safe amplitude" for ruins and ancient monuments (and historical buildings). The graph illustrates the rapid attenuation of vibration amplitudes, which dip below the threshold of perception for most people at about 45 m (150 ft).

Figure 2. Maximum Highway Truck Traffic Vibration Levels vs. Distance



Automobile traffic normally generates vibration peaks of one fifth to one tenth of truck vibrations. Traffic vibrations generally range in frequencies from 10-30 Hz, and tend to center around 15 Hz. However, it is not uncommon to measure lower frequencies, even down to 1-2 Hz. Due to their suspension systems, city buses often generate low frequencies around 3 Hz, with high velocities (indicating high displacements). It is more uncommon, but possible, to measure frequencies above 30 Hz for traffic.

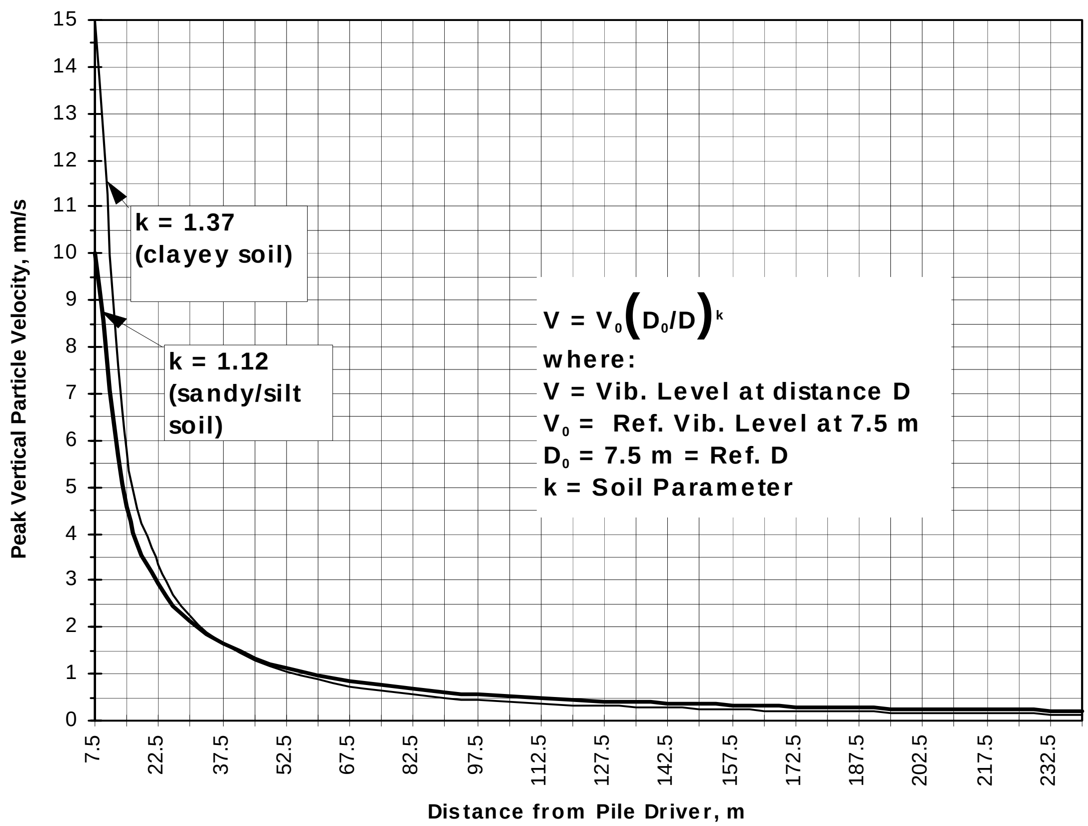
Construction Vibration Amplitudes

With the exception of a few instances involving pavement breaking, pile driving, all Caltrans construction vibration measurements have been below the 5 mm/s (0.2 in/sec) architectural damage risk amplitude for continuous vibrations. The highest measured vibration amplitude was 73.1 mm/s (2.88 in/sec) at 3 m (10 ft) from a pavement breaker. This instance marked the only time that the single event safe amplitude of 50 mm/s (2 in/sec) was exceeded during vibration monitoring by Caltrans.

Other construction activities and equipment, such as D-8 and D-9 Caterpillars, earthmovers and haul trucks have never exceeded 2.5 mm/s (0.10 in/sec) or one half of the architectural damage risk amplitude, at 3 m (10 ft)). Depending on the activity and the source, construction vibrations vary much more than traffic vibrations.

Figure 3 shows typical pile driving vibrations with distance, for a 68,000 J (50,000 ft lbf) energy impact pile driver, for two different soils (clayey and sandy with silt). Clay

Figure 3. Expected Vibration Levels Generated by a 68,000 J (50,000 ft lbf) Impact Pile Driver



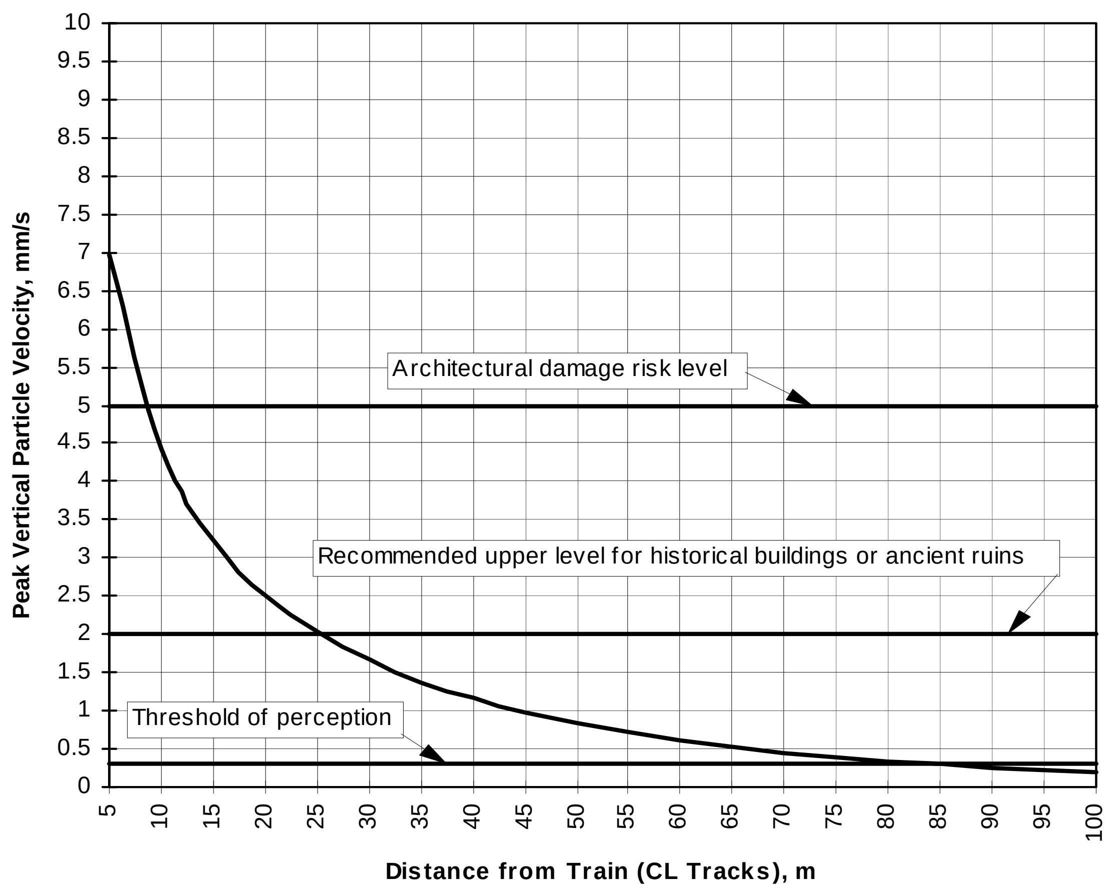
soils provide more resistance to advancing piles and therefore generate higher vibration amplitudes near the source than those in sandy soils. Vibrations in clay soils, however, tend to drop off more rapidly with distance than those in sandy soils.

Frequency ranges of construction vibrations, (including pile driving) tend to be the same as for traffic vibrations, mostly in the 10-30 Hz range, centered around 15 Hz, once in a while lower than 10 Hz, and rarely higher than 30 Hz.

Train Vibration Amplitudes

Train vibration amplitudes may be quite high, depending on the speeds, load, condition of track, amount of ballast used to support the track, and the soil. The highest train vibration measurement was 9.1 mm/s (0.36 in/sec) at 3 m (10 ft), in Sacramento. Using this information with the drop-off curve in Figure 1, we can construct a train vibration curve vs. distance. This is shown in Figure 4, beginning at 5 m (16 ft) where

Figure 4. Maximum Train Vibration Levels vs. Distance



the vibration amplitude is calculated at 7 mm/s. The curve represents maximum expected amplitudes from trains, and thus is very conservative. Measurements at various distances at other locations and different freight trains averaged about two-thirds of those shown in the curve.

Train vibrations tend to be in the same frequency ranges as traffic and construction vibrations. In some cases higher frequencies are encountered, especially in curves, caused by wheel chatter and squeal.

Impacts

Architectural and Structural Damage - The above discussions indicate that in any situation the probability of exceeding architectural damage risk amplitudes for continuous vibrations from construction and trains is very low and from freeway traffic practically non-existent. However, if vibration concerns involve pavement breaking, extensive pile driving, or trains, 7.5 m (25 ft) or less from normal residences, buildings, or unreinforced structures, damage is a real possibility. This may also be true if these operations occur within 15 m – 30 m (50 ft- 100 ft) from historical buildings, buildings in poor condition, or buildings previously damaged in earthquakes.

Pile driving in close proximity (say within 3 m or 10 feet) of structures can cause additional problems, depending on the soils and configurations of substructures. An example was the reconstruction of San Francisco-Oakland Bay Bridge Toll Plaza in June 1987. A number of piles were driven in soft clay soils ("bay mud") close to the existing booth access tunnel underneath the freeway. Due to the large number of piles, and the proximity and configuration of the old substructure, the lateral soil movement, caused by piles permanently displacing the clay, was resisted. The resulting conflict of forces was relieved by structure uplift and damage (cracks in the reinforced concrete tunnel).

Annoyance **-** As was discussed before, the annoyance amplitude shown in Table 2 is highly subjective, and does not take into consideration elderly, retired, ill, and other individuals that may stay home more often than the "average" person. Nor does it account for people involved in vibration sensitive hobbies or activities, and people that like to relax in quiet surroundings without noticing vibrations. The threshold of perception, or roughly 0.25 mm/s (0.01in/sec) may be considered annoying by those people. Low amplitude vibrations may also cause secondary vibrations and audible effects such as a slight rattling of doors, windows and dishes, resulting in additional annoyance. Annoying low frequency airborne noise can sometimes accompany earthborne vibrations.

Vibration Sensitive Operations - Aerospace and electronic laboratories, close tolerance manufacturing, calibration of sensitive instruments, radio & TV stations, recording studios, etc., require additional attention. Shutting down their operations, even temporarily, could be extremely costly to the state. As was previously discussed vibration criteria for these operations are not well defined, for two main reasons. First, the operations are often classified and their precise nature is therefore not always known. Secondly, the engineers involved in the critical operations often do not know how much vibration can be tolerated, or what operations they may be involved with in the future.

Heavy truck traffic on freeways within 30 m (100 ft), major construction within 60 m (200 ft), freight trains within 90 m (300 ft) and pile driving within 180 m (600 ft) may be potentially disruptive to sensitive operations.

Mitigation

Unlike with noise, there are no easy ways to mitigate earthborne vibrations. There are, however, a limited number of options available.

When designing new transportation facilities, reasonable amounts of care should be taken to keep these facilities away from vibration sensitive areas.

When dealing with existing transportation facilities, obvious vibration causes, such as pot holes, pavement cracks, differential settlement in bridge approaches or individual pavement slabs, etc., may be eliminated by resurfacing. In certain situations a ban of heavy trucks may be a feasible option.

The use of alternate construction methods and tools may reduce construction vibrations. Examples are predrilling of pile holes, avoiding cracking and seating methods for resurfacing concrete pavements near vibration sensitive areas, using rubber tired as opposed to tracked vehicles, placing haul roads away from vibration sensitive areas.

Scheduling construction activities (particularly pile driving) for times when it does not interfere with vibration sensitive operations (e.g. night time) may be another solution, especially in industrial areas.

Train vibrations may be reduced by using continuous, welded rails, vibration damping pads between rails and ties, and extra ballast.

Link With Historical Data

A considerable amount of effort has gone into the field measurements, reduction, documentation and reporting of vibration data since 1958. As data sets are accumulated with each vibration study, a more complete picture emerges of the generation and propagation of vibration waves under various conditions of geometry, soil, and source types.

Due to the lack of accurate subsurface information, empirical data is of utmost importance and can be used for future estimates when conditions are alike. Historical data that can be linked to the present and future play a very important role in estimates and predictions of future vibrations.

Present and future personnel charged with the responsibility of performing vibration studies and maintaining vibration files should make every effort necessary to maintain a good correlation between any new and old instrument systems, calibration procedures, and measuring methods. The link between present and valuable historical data must be preserved.

Vibration Monitoring Equipment

During the period of 1958 - 1994 all of Caltrans vibration monitoring was performed by Translab. A transducer calibration system consisting of a shake table mounted on a concrete vibration isolation pad, and an Optron camera/amplifier system, measuring displacement allowed Translab to calibrate its own transducers with traceability to the National Institute of Standards and Technology (NIST), formerly known as the National Bureau of Standards (NBS). Transducers were calibrated by mounting them on the shake table and running the latter at a known frequency and displacement.

Two types of sensors (transducers) were used by Caltrans. The first type was the **seismometer**. A seismometer measures vibrations at relatively low frequencies usually 1 - 200 Hertz (Hz), is very sensitive to low amplitudes of vibrations and, through magnetic induction produces a voltage proportionally to velocity. It measures velocity directly via a signal conditioner, and is therefore called a velocity transducer. It is large, weighs about 7 kg (15 lbs), and, because of its mass, can be placed directly on the ground without further mounting attachments.

The second type of transducer was an **accelerometer**. As the name implies, this type of transducer measures acceleration directly. Used with an integrator it can also measure velocity and displacement.

The type of accelerometer used by Caltrans has a piezoelectric (pressure sensitive) crystal. As the transducer vibrates with the surface it is mounted on, acceleration changes the compression of the crystal, which in turn causes variations in the electrical charge across the crystal faces. These charge variations are proportional to acceleration.

An accelerometer is small, not as sensitive as the seismometer and has a wide frequency range, from 1 Hz to several KHz (1 KHz = 1000 Hz). Larger, more sensitive accelerometers, weighing about 1 lb, are available with a narrower frequency range from 0.1 Hz to 1KHz. Due to their small size and lack of mass, accelerometers should not be placed directly on the ground, floor, or other vibrating surface without proper mounting. When properly mounted, accelerometers are excellent transducers for vibration monitoring. They can be mounted various ways, depending on the surface.

For earthborne vibration work an accelerometer can be mounted via a magnet (supplied with it) to a block of steel of, say 5-10 kg (10-20 lbs). The steel block can then be placed directly on the ground, or other surface. However, the steel block should be firmly embedded in loose soil. On harder surfaces such as pavements, the block can only be used on friction surfaces that are perfectly amplitude without high spots to avoid rocking of the block. Correlation tests conducted by Caltrans using this method and the heavy seimometers, concluded that the mass of the steel block provided adequate coupling of the accelerometer with the ground for the low frequency, low amplitude vibrations generated by transportation facilities and construction.

Vibration Study Approach and Instrument Setup

Vibration studies can be classified into two main categories:

1. Studies involving existing transportation operations and facilities
2. Studies involving future transportation operations and facilities

Vibration Studies for Existing Construction Operations and Transportation Facilities - These studies consist of mainly addressing vibration complaints due to existing traffic, or construction operations. Understandably, pile driving near homes or businesses will normally generate many noise and vibration complaints. Other construction operations can also be responsible. Traffic vibration complaints are often due to poor pavement conditions. Other reasons may be increases in traffic, heavy trucks, buses, etc. Sudden increases in traffic vibrations may be due to opening of new transportation facilities, or redirecting traffic.

Although complaints can originate from the entire spectrum of receptors, most are from residences, or businesses that have vibration sensitive equipment or operations.

The first step in investigating complaints should be interviewing the complainant(s). The screening procedures outlined later in this document cover the most important questions to ask. For the purposes of performing a vibration study, the most important issues are:

- The type and location of the vibration source(s)
- The complainant(s)' concerns, i.e., annoyance, damage, disruption of operations.
- The location that is most sensitive, or where vibrations are most noticeable.

Vibration monitoring of existing operations or facilities ranges from simple, single location measurements to more complex multi-instrument, simultaneous measurements. The former consists of taking measurements at the most sensitive location, or location perceived by the complainant to have the worst vibrations. The latter usually involves placing a sensor close to the source as a reference, and one or more sensors at the critical location(s) ("response sensors"). Simultaneous measurements will then positively identify the vibration source, the drop-off and the response (vibration amplitude) at the location(s) of interest. The reference sensor remains fixed in one location near the source, while the response sensor(s) may be moved to different locations.

Sufficient data should be collected for each location. For highway traffic vibrations, 10 passbys of heavy trucks (preferably worst case combinations of several trucks) for each location should be sufficient. For pile driving, at least one pile closest to the receptor should be monitored at each location of interest.

The highest vibration amplitude at each location can then be compared to Caltrans or other appropriate criteria.

Vibration Studies for Future Construction Operations and Transportation Facilities - Studies involving predictions of construction and operation vibrations of future transportation facilities often require vibration simulations to determine a site-specific drop-off curve. In order to generate vibrations that can still be measured at 60-90 m (200 to 300 ft) to develop the curve, the site must be free of high ambient vibrations (preferably less than 0.13 mm/s or 0.005 in/sec at the 90 m or 300 ft distance), and the generated vibrations must be relatively high. From Figure 1 we can calculate approximately how high the reference vibration V_0 at 5 m should be to detect the vibrations at 90 m. The V/V_0 ratio at that distance = 0.038; assuming we want V to be at least 0.13 mm/s; then V_0 = 1/0.038 x 0.13 = 3.4 mm/s (0.13 in/sec). If a low-vibration site cannot be found, either the distance for the drop off curve must be shortened, or the reference vibrations increased. Caution must be used to apply the drop-off curve to pile driving projections, due to the previously discussed differences in propagation characteristics.

To generate data for the drop-off curve, a heavily-loaded water truck, or dump truck (preferably 25 tons or greater GVW) is run at high speed over 2" x 4", or 2" x 6" wooden boards. Normally, five boards are laid perpendicular to the direction of travel, and spaced 7.5 m (25 ft) apart along the direction of travel. The advantage of this arrangement is that the generated vibration "signature" is normally recognizable at 90 m (300 ft).

A minimum of two sensors must be used simultaneously: one reference sensor, and one or more response sensors. The reference sensor remains fixed at 5 m (16 ft) from centerline of travel, (or any convenient distance near the source) opposite the last board to be run over (most forward in line with the direction of travel). The response sensor(s) is (are) positioned at various distances away from the source. Because of the steepness of the curve near the source it is a good idea to cover shorter distance intervals near the source and longer ones away from the source. To adequately cover the entire range of the drop-off curve, 6 to 8 locations must be monitored, and at least 5 truck passbys per location.

Frequently it is not possible to do the simulations on the site of interest, because of space limitations. Nearby empty lots or open fields, or data from other sites known or judged to have similar soil conditions can then be used.

Once the measurements have been made, the data at each location should be averaged. Using the reference location, and at least two others (including the furthest one), the soil parameter "**α**" can be calculated using equation 2. Ideally, "**α**" should remain constant for each location, but in reality it will vary. The average of several values can then be used to develop a drop-off curve. The vibration amplitudes at all measured locations should then be plotted to determine how well they fit this curve. Assuming they fit reasonably well, a normalized drop-off curve using V/V_0 ratios and distances (similar to Figure 1) can then be developed and used with any source reference amplitude, to predict the future amplitude at any distance within the range of the curve.

If it is possible to do the simulations at the site, inside/outside building locations should be included to measure the building amplification or attenuation ratio.

The next step is to measure ambient amplitudes at the site. Outside as well as inside building locations should be included for these measurements.

Using all the above information, future amplitudes can be predicted and compared to existing ambient amplitudes, Caltrans guidelines, or any other appropriate or required standard.

Concerns for vibrations of future transportation facilities are usually raised by vibration sensitive factories, laboratories, or other vibration sensitive sites. Unless construction activities are expected to occur very close to residential or other structures, or near historical buildings, these receptors are not routinely included in vibration studies for future facilities.

Vibration field studies including simulations are expensive. Unless the consequences of transportation and construction generated vibrations may be costly to Caltrans, the curves and techniques described in this document can be used to estimate "ball park" vibration amplitudes, in lieu of field studies.

Vibration Reports

Each vibration field study should be documented in a report. Depending on the amount of sites measured, amount of data collected, methodologies used, and the importance of the study, the report may range from a simple one or two paged memo, to a report of twenty or more pages. A vibration study can be considered a mini-research project, and should contain enough information for the reader to independently come to the same conclusions.

As a norm, vibration reports contain the following topics, which will be described in greater detail:

* Project title and description
* Introduction
* Objectives
* Background
* Study Approach
* Instrumentation
* Measurement Sites
* Measurements
* Data Reduction
* Measurement Results
* Data Analysis
* Results and Comparison with Standards
* Conclusions and Recommendations
* Tables showing all measured data, summaries of results, analysis and standards
* Figures showing site layouts and cross sections, instrument setups, drop-off curves, and other pertinent illustrations
* References cited

In short, simple vibration studies, the topics may be described in a few sentences in a memo. In more complex studies, a fairly extensive report is usually required.

Project Title and Description - If the report consists of a short memo this info. can be put in the "Subject:" space. In a long report it should be put on a separate title page, with the date, who did the study (Div.or District, Branch, and personnel involved), and author of report.

Introduction **-** Typical opening sentences: "This report (memo) presents the results of a vibration study at .... The study was requested by ......, in response to concerns by .... that vibrations of .... would interfere with ....operations. The study was performed by ..... (branch or section) on .... (dates)."

Objectives - This is often combined with the introduction. Example: "The purpose of the study was to provide baseline data for estimating vibration amplitudes in sensitive areas of Hughes Aircraft facility generated by construction and traffic of the proposed LA-105 Freeway."

Background - Used only when there is a long and complicated history connected with the reasons for the studies. Useful for documenting all the facts leading up to the study for litigation purposes. Dates first contacted, correspondence, actions taken, and other pertinent details may be appropriate in this section. Not necessary in most studies.

Study Approach - May be combined with other sections. A short description of how the study was done. Example:

"First, vibrations generated by a 25 ton GVW three-axle water truck driven over five 2"x4" wooden boards .... were measured at various distances to measure the vibration attenuation with distance. This info. was then used to develop a drop-off curve....., etc." For simple studies, such as residential complaints: "The sensor was set up at four different locations where, according to the homeowner, vibrations were most noticeable. Five heavy truck passbys on Route ..... were measured at each of the locations. ..."

Instrumentation **-** Always include description, manufacturer, model, serial no. of each vibration equipment components used. It is also extremely important to include the date instruments were last calibrated, by whom, where the records are on file, and whether calibration was traceable to the NIST (National Institute of Standards and Technology, formerly NBS). Essential in court cases!

Measurement Sites - Include a sketch, preferably to scale, of the relationship between source and measurement locations. Plot and number the sites on the sketch. Include typical cross sections if there are significant elevation differences between source and receptors. Plot significant structures. Show enough dimensions to pinpoint each measurement location. Show detailed descriptions, and instruments or sensors used at each location in the text, or in a separate table if there are many. Once locations are numbered and described, they can be referred to by number only.

Measurements **-** This section may also include the study approach. Basically explains the methods used, how sensors were mounted, number of measurements taken, what sources were measured (e.g. heavy trucks on Route 5), descriptor used and why, and other pertinent information concerning the vibration measurements. When possible, include a description of soil type and structure. This info. can often be extracted from nearby boring logs. Be sure to include ambient or background measurements.

Data Reduction - A short description of how the data was reduced can effectively be combined with the measurement section. Only if the reduction method is unusual or complex should it be discussed in a separate section.

Measurement Results **-** May also be combined with the measurement section. Briefly summarize data in the text by giving highest values, ranges, and averages. Should be accompanied by a table summarizing measurement run No. (or just Run No.), date and time, measurement location, source (heavy truck in N/B lane No.4), distance, vibration amplitude, dominant frequency, and optional remarks. This table may be put in the text or in an appendix with all other tables and figures. All individual measurements should be included as part of the report, for possible future use. Ambient or background vibration measurements can be expressed as a range of vibrations, typical frequency ranges, time period during which they were measured, and if possible the range of sources and distances.

Data Analysis **-** Developing drop-off curves, predicting future amplitudes, calculating amplitudes at specific distances not measured, etc. all should be in this section. May not be necessary for simple studies involving residential complaints, monitoring for compliance with a standard, or any other study involving vibration measurements only.

Results and Comparisons to Standards **-** Existing measured, projected, and predicted vibration amplitudes and frequencies are summarized and compared to pertinent standards in this section. This is usually done in tabular form, and accompanied by Table 1, which shows the vibration criteria used by Caltrans.

Conclusions and Recommendations - Conclusions are drawn from the previous comparisons with standards. Typically for highway vibration complaints would be: "Although vibrations generated by heavy trucks on I-5 may at times be felt, they are far below the 'architectural damage risk amplitude' criterion of 0.2 in/sec used by Caltrans."

Recommendations for mitigation are rather limited (see "Mitigation" section). However, in some cases strategies such as pile driving at night may solve interference with vibration sensitive manufacturing processes during day time. When ever possible, such recommendations should be included.

References **-** In complex reports, relying partly on previously gathered data, it may be beneficial to cite other reports or references by number. A listing of these references should then be included at the end of the report.

Field Review and Screening of Possible Vibration Problems

The following procedures were designed to screen vibration complaints near existing transportation facilities. They are intended to accomplish two things: 1) to evaluate the severity of the vibration problem, and 2) obtain preliminary information for a vibration study, should one be necessary.

The procedures are divided in two parts: problem definition and actions to take. An outline of the steps in each part follows:

I. Problem Definition

A. Interview resident at the site of concern. Ask the following questions:

1. What is the exact problem in the resident's opinion?

   Many people confuse low frequency airborne noise with earthborne vibrations.

2. What are the sources in the resident's opinion?

   Trucks on freeway?; city traffic?; trains? (sources may not be our jurisdiction.)

3. What are the specific concerns?

   Annoyance?, interference with activities?, damage to the residence? If damage is the main concern, ask for evidence look for stucco cracks, cracks in driveways, walkways, walls, stucco, etc. Compare with other residences further away from the transportation facility. If these also have cracks, then it is safe to assume that the facility is not responsible.

4. Where are the vibrations most noticeable?

   Which room?; which part of the yard? (Let resident point out the critical locations.)

5. What time of the day and/or what day of the week does the resident feel vibrations the most?

6. When did the resident become aware of the vibrations?

Try to correlate with changes in nearby traffic patterns, due to truck bans elsewhere, new industrial development, or other reason for truck increases.

B. Feel the vibrations

1. Stand at critical locations and try to feel vibrations when trucks pass by.

Place finger tips on furniture, walls, uncarpeted floor, ground outside the residence, patio floor, etc.

2. Have someone walk nearby; feel these vibrations and compare with the traffic vibrations. Also compare other in-house generated vibrations.

Walking, air conditioners, heater blowers, and garbage disposals, etc. often generate more vibrations than traffic.

3. Stand on freeway shoulder, sidewalk next to highway, or anywhere close to the suspect source. Feel vibrations and compare with those felt at the receptor.

Place finger tips on ground or pavement surface.

4. Look for obvious causes of excessive vibrations.

Pot holes, pavement joints, sag, and pavement cracks, or anything that could cause above normal vibrations; also look for drainage or other structures transmitting vibrations to the receptor without benefit of soil attenuation.

C. Evaluate severity of the problem.

The graphs in Figures 1 - 4 show typical vibration attenuations with distance for various sources. Use these to evaluate typical relationships of near and far source vibration amplitudes. If vibrations appear to dropoff at a significantly lesser rate, then suspect that something unusual is going on. For instance, vibrations may be transmitted by underground structures, which can cause problems at the receptor.

1. If vibrations feel as strong (or almost as strong) at the receptor as they do near the source (such as on a freeway shoulder), consider problem severe.

2. If vibrations at the receptor are readily noticeable and appear to interfere with activities or vibration sensitive operations, consider problem severe.

3. If vibrations of any amplitude are an issue in litigation, consider the problem severe.

4. If after this screening procedure uncertainty still exists, consider problem severe.

II. Actions To Take

A. If problem is not severe:

1. If there are obvious causes for excessive vibrations, such as pot holes, etc., contact Maintenance or other departments and find out if scheduled for repair or resurfacing.

2. Write memo to resident explaining your findings.

If there are obvious solutions such as patching or resurfacing, tell the resident. If there are no obvious solutions, explain to the resident that although vibrations may be felt, they are not damaging. Use background info. in this document.

B. If problem is considered severe, or if the resident keeps insisting on actual monitoring, consider contracting out vibration monitoring or a complete vibration study.

APPENDIX
BASIC VIBRATION FORMULAE

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APPENDIX

BASIC VIBRATION FORMULAE

Symbols

A = Zero-to-Peak, or Peak Acceleration (Units: m/sec^2, mm/sec^2, ft/sec^2, in/sec^2)

A_g = Zero-to-Peak, or Peak Acceleration (Units: "g" = acceleration of gravity), where:

1 g = 9.807 m/sec^2

= 9807 mm/sec^2

= 32.174 ft/sec^2

= 386.102 in/sec^2

D = Peak-to-Peak Displacement (Units: m, mm, ft, in) (Normally of interest)

D/2 = Zero-to-Peak, or Peak Displacement (Units: m, mm, ft, in)

f = Frequency (Units: Hertz)

V = Zero-to-Peak, or Peak Particle Velocity (Units: m/sec,mm/sec, in/sec)

π = 3.14159etc.....

Formulae for Sinusoidal Waves

Units need to be consistent; for example, if D is in mm, then V must be in mm/sec, and A either in mm/sec^2 or units of "g" (9807 mm/sec^2).

With **displacement**, we are normally interested in the peak-to-peak value or in other words, the total displacement (distance between the + peak and - peak) soil particles travel. Sometimes, however we may also be interested in the zero-to-peak displacement, or displacement relative to a stationary (zero) reference position. For sinusoidal waves, the + side of reference and the - side are symmetrical, and zero-to-peak values are D/2.

With **velocity** and **acceleration**, however, we are always interested in the zero-to-peak values. These give an indication of maximum value, without regard of the direction.

Acceleration is most commonly used in units of **g**.

Following are formulae expressing the relationships between displacement, velocity, and acceleration for sinusoidal vibration waves.

Velocity and Displacement:

$V = 2\pi f(D/2)$ (Eq.A-1)

$V = \pi fD$ (Eq.A-2)

$D/2 = V/(2\pi f)$ (Eq.A-3)

$D = V/(\pi f)$ (Eq.A-4)

Acceleration and Displacement:

$A = (2\pi f)^2(D/2)$ (Eq.A-5)

$A = 2\pi^2 f^2 D$ (Eq.A-6)

$A_g = (2\pi^2 f^2 D)/g$ (Eq.A-7)

If D is in inches:

$A_g = (2\pi^2 f^2 D)/386.102 = 0.0511 f^2 D$ (Eq.A-8)

If D is in mm:

$A_g = (2\pi^2 f^2 D)/9807 = 0.00201 f^2 D$ (Eq.A-9)

Acceleration and Velocity:

$A = 2\pi fV$ (Eq.A-10)

$A_g = (2\pi fV)/g$ (Eq.A-11)

If V is in inches per second:

$A_g = (2\pi fV)/386.102 = 0.0163 fV$ (Eq.A-12)

If V is in mm per second:

$A_g = (2\pi fV)/9807 = 0.000641 fV$ (Eq.A-13)

Acceleration or Velocity in Decibels:

$A(dB) = 20Log(A/A_0)$; $V(dB) = 20Log(V/V_0)$ (Eq.A-14)

where A = acceleration, A_0 = reference acceleration,

V = velocity, and V_0 = reference velocity (units must be consistent)

APPENDIX B. SAMPLE VIBRATION SCREENING PROCEDURE AND VIBRATION COMPLAINT FORM

Vibration Screening Procedure

The vibration screening procedure is divided in two parts: problem definition and actions to take.

I. Problem Definition

A. Interview resident at the site of concern. Ask the following questions.

1. *What is the exact problem, in the resident's opinion?*

   Confirm that the vibration is from a Caltrans facility or activity and that vibration is really the issue. Many people confuse low frequency airborne noise with earthborne vibrations.

2. *What are the sources of vibration, in the resident's opinion?*

   Identify the sources of vibration (e.g., trucks on freeway, city traffic, trains, construction equipment). Sources such as trains may not be within Caltrans' jurisdiction.

3. *What are the specific concerns?*

   Identify the specific concern (e.g., annoyance, interference with activities, damage to the residence). If damage is the main concern, ask for evidence and look for cracks in driveways, walkways, walls, stucco, etc. Compare these conditions with other residences farther away from the transportation facility or construction activity. If distant locations have similar conditions, it is likely that the damage is not the result of the facility or construction activity.

4. *Where is the vibration most noticeable?*

   Identify where the vibration is most noticeable (e.g., specific rooms, yard outside). Let resident point out the critical locations.

5. *What time of the day and what day of the week does the resident feel vibrations the most?*

   Identify when the vibration is most noticeable.

6. *When did the resident become aware of the vibrations?*

   Try to correlate the detection of vibration with changes in nearby traffic patterns, changes in heavy truck percentages, or the presence of new vibration sources.

B. Feel the vibrations.

1. *Stand at critical locations and try to feel vibrations when trucks pass by.*
   Place fingertips on furniture, walls, uncarpeted floor, ground outside the residence, patio floor, etc., to sense where vibration is most noticeable.

2. *Have someone walk nearby; feel these vibrations and compare with the traffic vibrations. Also compare other vibrations generated in-house.*
   People walking, air conditioners, heater blowers, garbage disposals, etc. often generate more vibrations than traffic. Try to see how vibration from these sources compares to vibration from the sources identified by the resident.

3. *Stand on freeway shoulder, sidewalk next to highway, or anywhere close to the suspected source. Feel vibrations and compare with those felt at the receptor.*
   Place fingertips on ground or pavement surface to sense vibration near the source of concern.

4. *Look for obvious causes of excessive vibrations.*
   Identify potholes, pavement joints, sag, pavement cracks, or anything that could cause above-normal vibration. Also look for drainage pipes or other structures that can transmit vibration directly to the receptor without benefit of soil attenuation.

C. Evaluate the severity of the problem.

If the vibration level appears to drop off at a significantly lower rate than would be expected, something unusual may be occurring on the site. For example, vibration may be transmitted by underground structures, which can cause vibration to be transmitted over longer-than-normal distances. A vibration problem should be considered severe if:

1. vibration feels as strong (or almost as strong) at the receptor as it does near the source (such as on a freeway shoulder),

2. vibration at the receptor is readily noticeable and appears to interfere with activities or vibration-sensitive operations,

3. vibration at the receptor is readily noticeable and appears to have resulted in structural or cosmetic damage,

4. vibration of any amplitude is an issue in litigation, or

5. uncertainty still exists as to the source of vibration.

II. Actions to Take

A. If problem is not severe:

1. *Identify the obvious causes for excessive vibrations.* These causes could include pavement imperfections that result in vibration from truck pass-bys or unusual building resonances that amplify vibration at the receiver. For issues within Caltrans' control, such as pavement conditions, contact the appropriate Caltrans department and find out whether the pavement is scheduled for repair or resurfacing.

2. *Prepare a memo to explain your findings.* If there are obvious solutions, such as pavement patching or resurfacing, explain these, along with actions that will or will not be taken to address the issue. If there are no obvious solutions, explain that, although vibration may be felt, it is not enough to cause damage.

B. If problem is considered severe, or if the resident keeps insisting on actual monitoring, conduct a vibration monitoring study to further investigate the issue.

Vibration Complaint Report

Complaint received: Date: ________________ Time: _______________

Complainant's name: ____

Address: ____ Phone: ______________

Specific complaint: ____

____

____

____

Date and specific time of occurrence (as reported by Complainant):

Date: _______________ Time: ________________

Complaint received by: ____

Results of Investigation: ____

____

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____

____

____

Investigated by: ____

Disposition of Complaint: ____

____

____

____

APPENDIX C. SAMPLE VIBRATION SPECIFICATIONS

VIBRATION MONITORING

DESCRIPTION

1.01 GENERAL

A. The Work of this Section includes furnishing, installing and maintaining vibration-monitoring instrumentation; collecting vibration data; and interpreting and reporting the results. The Contractor shall implement required remedial and precautionary measures based on the vibration-monitoring data.

B. The purpose of the vibration-monitoring program is to protect the following properties from excess vibration during demolition and construction activities associated with the ___________________________ Project:

1. Building name and address

2. Building name and address

3. Building name and address

4. Building name and address

C. Caltrans is not responsible for the safety of the Work based on vibration-monitoring data, and compliance with this Section does not relieve the Contractor of full responsibility for damage caused by the Contractor's operations.

1.02 RESPONSIBILITIES OF CONTRACTOR

A. Furnish and install vibration-monitoring instrumentation.

B. Protect from damage and maintain instruments installed by the Contractor and repair or replace damaged or inoperative instruments.

C. Collect, interpret and report data from instrumentation specified herein.

D. Implement response actions.

1.03 QUALIFICATIONS OF VIBRATION MONITORING PERSONNEL

A. The Contractor's vibration-monitoring personnel shall have the qualifications specified herein. These personnel may be on the staff of the Contractor or may be on the staff of a specialist subcontractor. However, they shall not be employed nor compensated by subcontractors, or by persons or entities hired by subcontractors, who will provide other services or material for the project.

B. The Contractor's vibration-monitoring personnel shall include a qualified Vibration Instrumentation Engineer who is a registered Professional Engineer in the State of California, who has a minimum of a Bachelor of Science degree in civil engineering, and who has at least 4 years of experience in the installation and use of vibration-monitoring instrumentation and in interpreting instrumentation data. The Vibration Instrumentation Engineer shall:

1. Be on site and supervise the initial installation of each vibration-monitoring instrument.

2. Supervise interpretations of vibration-monitoring data.

C. The Contractor's vibration-monitoring personnel shall be subject to the review of the Engineer.

1.04 QUALITY ASSURANCE

A. A record of laboratory calibration shall be provided for all vibration-monitoring instruments to be used on site. Certification shall be provided to indicate that the instruments are calibrated and maintained in accordance with the equipment manufacturer's calibration requirements and that calibrations are traceable to the U. S. National Institute of Standards and Technology (NIST).

1.05 SUBMITTALS

A. As soon as feasible after the Notice to Proceed, submit manufacturer's product data describing all specified vibration-monitoring instruments to the Engineer for review, including requests for consideration of substitutions, if any, together with product data and instruction manuals for requested substitutions.

B. Within 3 weeks after the Notice to Proceed, submit to the Engineer for review the resumes of the Vibration Instrumentation Engineer and any vibration monitoring technical support personnel, sufficient to define details of relevant experience.

C. Within 5 Workdays of receipt of each instrument at the site, submit to the Engineer a copy of the instruction manual and the laboratory calibration and test equipment certification.

D. Prior to the start of construction and prior to performing any vibration monitoring, the Contractor shall submit to the Engineer for review a written plan detailing the procedures for vibration monitoring. Such details shall include:

1. The name of the Firm providing the vibration monitoring services.

2. Description of the instrumentation and equipment to be used.

3. Measurement locations and methods for mounting the vibration sensors.

4. Procedures for data collection and analysis.

5. Means and methods of providing warning when the Response Values, as specified in Article 3.07, are reached.

6. Generalized plans of action to be implemented in the event any Response Value, as specified in Article 3.07, is reached. The generalized plans of action shall be positive measures by the Contractor to control vibrations (e.g. using alternative construction methods).

E. Submit data and reports as specified in Article 3.04.

MATERIALS

2.01 GENERAL

A. Whenever any product is specified by brand name and model number, such specifications shall be deemed to be used for the purpose of establishing a standard of quality and facilitating the description of the product desired. The term "acceptable equivalent" shall be understood to indicate a product that is the same or better than the product named in the specifications in function, quality, performance, reliability, and general configuration. This procedure is not to be construed as eliminating other manufacturers' suitable products of equal quality. The Contractor may, in such cases, submit complete comparative data to the Engineer for consideration of another product. Substitute products shall not be used in the Work unless accepted by the Engineer in writing. The Engineer will be the sole judge of the suitability and equivalency of the proposed substitution.

B. Any request from the Contractor for consideration of a substitution shall clearly state the nature of the deviation from the product specified.

C. The Contractor shall furnish all installation tools, materials, and miscellaneous instrumentation components for vibration monitoring.

2.02 SEISMOGRAPHS

A. Provide portable seismographs for monitoring the velocities of ground vibrations resulting from construction activities. Provide model DS-477 Blastmate II as manufactured by Instantel Inc., Kanata (Ottawa), Ontario, Canada, model VMS-500 as manufactured by Thomas Instruments, Inc., Spofford, NH, or model NC5310/D, as manufactured by Nomis Inc., Birmingham, AL, or acceptable equivalent. The seismograph shall have the following minimum features:

1. Seismic range: 0.01 to 4 inches per second with an accuracy of ±5 percent of the measured peak particle velocity or better at frequencies between 10 Hertz and 100 Hertz, and with a resolution of 0.01 inches per second or less.

2. Frequency response (±3 dB points): 2 to 200 Hertz.

3. Three channels for simultaneous time-domain monitoring of vibration velocities in digital format on three perpendicular axes.

4. Two power sources: internal rechargeable battery and charger and 115 volts AC. Battery must be capable of supplying power to monitor vibrations continuously for up to 24 hours.

5. Capable of internal, dynamic calibration.

6. Direct writing to printer and capability to transfer data from memory to 3-1/2 inch magnetic disk. Instruments must be capable of producing strip chart recordings of readings on site within one hour of obtaining the readings. Provide computer software to perform analysis and produce reports of continuous monitoring.

7. Continuous monitoring mode must be capable of recording single-component peak particle velocities, and frequency of peaks with an interval of one minute or less.

CONSTRUCTION METHODS

3.01 INSTALLATION OF SEISMOGRAPHS

A. The Contractor shall install seismographs at four points near the corners of the buildings that are closest to the project site; these points are denoted as locations 1 through 4 in Figure 1.

B. The seismograph vibration sensors shall be located at points on the ground between 3 and 6 feet from the building facades.

C. The seismograph vibration sensors shall be firmly mounted on the surface slab of concrete or asphalt, or firmly set in undisturbed soil

3.02 FIELD CALIBRATION AND MAINTENANCE

A. The Contractor’s instrumentation personnel shall conduct regular maintenance of seismograph installations.

B. All seismographs shall have been calibrated by the manufacturer or certified calibration laboratory within one year of their use on site. A current certificate of calibration shall be submitted to the Engineer with the Contractor's data.

3.03 DATA COLLECTION

A. The Contractor shall collect seismograph data prior to any vibration-producing demolition or construction activities to document background vibrations at each monitoring location. This monitoring shall consist of a continuous recording of the maximum single-component peak particle velocities for one-minute intervals, which shall be printed on a strip chart. The background monitoring shall be performed for a minimum of two non-consecutive workdays, spanning the hours during which demolition and construction activities will take place.

B. The Contractor shall monitor vibration during demolition and other significant vibration-producing construction activities as determined by the Engineer. This monitoring shall consist of a continuous recording of the maximum single-component peak particle velocities for one-minute intervals, which shall be printed on a strip chart. During the monitoring, the Contractor shall document all events that are responsible for the measured vibration levels, and submit the documentation to the Engineer with the data as specified in Article 3.04. A record form for documenting these events is included herein as Figure 2.

C. All vibration monitoring data shall be recorded contemporaneously and plotted continuously on a graph by the data acquisition equipment. Each graph shall show time-domain wave traces (particle velocity versus time) for each transducer with the same vertical and horizontal axes scale.

D. The Contractor shall notify the Engineer at least 24 hours prior to starting a new vibration-producing construction task, and shall have the seismographs in place and functioning properly prior to any such activity within 200 feet of the monitoring locations. No significant vibration-producing activity shall occur within this zone unless the monitoring equipment is functioning properly.

E. The equipment shall be set up in a manner such that an immediate warning is given when the peak particle velocity in any direction exceeds the Response Values specified in Article 3.07. The warning emitted by the vibration-monitoring equipment shall be instantaneously transmitted to the responsible person designated by the Contractor by means of warning lights, audible sounds or electronic transmission.

3.04 DATA REDUCTION, PROCESSING, PLOTTING AND REPORTING

A. Within 10 working days after the completion of the background vibration monitoring, the Contractor shall submit to the Engineer a hard copy report documenting the results at each of the monitoring locations.

B. During bridge demolition and construction, the Contractor shall provide weekly, hard copy reports summarizing any vibration monitoring data collected at the specified vibration-monitoring locations. The reports for each week shall be submitted on or before the end of the following week.

C. All reports shall be signed by the approved Vibration Instrumentation Engineer, and shall include the following:

1. Project identification, including District, County, Route, Post Mile, Project Name and Bridge number as shown on the project plans.

2. Location of the monitoring equipment, including address of adjacent building.

3. Location of vibration sources (e.g. traffic, demolition equipment, etc.)

4. Summary tables indicating the date, time and magnitude and frequency of maximum single-component peak particle velocity measured during each one-hour interval of the monitoring period.

5. Field data forms (construction vibration monitoring only).

6. Appendix graphs of the strip charts printed during the monitoring periods.

D. In addition to the hard copy data specified herein, the Contractor shall provide data on 3.5-inch diskettes with each report. Electronic data files for all instrument data shall be provided in dBASE IV (.DBF) format.

3.05 DAMAGE TO INSTRUMENTATION

A. The Contractor shall protect all instruments and appurtenant fixtures, leads, connections, and other components of vibration-monitoring systems from damage due to construction operations, weather, traffic, and vandalism.

B. If an instrument is damaged or inoperative, the Contractor’s instrumentation personnel shall repair or replace the damaged or inoperative instrument within 72 hours at no additional cost to Caltrans. The Contractor shall notify the Engineer at least 24 hours prior to repairing or replacing a damaged or inoperative instrument. The Engineer will be the sole judge of whether repair or replacement is required.

3.06 DISCLOSURE OF DATA

A. The Contractor shall not disclose any instrumentation data to third parties and shall not publish data without prior written consent of Caltrans.

3.07 DATA INTERPRETATION AND IMPLEMENTING PLANS OF ACTION

A. The Contractor shall interpret the data collected, including making correlations between seismograph data and specific construction activities. The data shall be evaluated to determine whether the measured vibrations can be reasonably attributed to construction activities.

B. The Response Values for vibration include a Threshold Value of 0.2 inches per second and a Limiting Value of 0.3 inches per second. The actions associated with these Response Values are defined below. Plans for such actions are referred to herein as plans of action, and actual actions to be implemented are referred to herein as response actions. Response Values are subject to adjustment by the Engineer as indicated by prevailing conditions or circumstances.

C. If a Threshold Value is reached, the Contractor shall:

1. Immediately notify the Engineer.

2. Meet with the Engineer to discuss the need for response action(s).

3. If directed by the Engineer during the above meeting that a response action is needed, submit within 24 hours a detailed specific plan of action based as appropriate on the generalized plan of action submitted previously as part of the vibration-monitoring plan specified in Article 1.05.

4. If directed by the Engineer, implement response action(s) within 24 hours of submitting a detailed specific plan of action, so that the Limiting Value is not exceeded.

D. If a Limiting Value is reached, the Contractor shall:

1. Immediately notify the Engineer and suspend activities in the affected area, with the exception of those actions necessary to avoid exceeding the Limiting Value.

2. Meet with the Engineer to discuss the need for response action(s).

3. If directed by the Engineer during the above meeting that a response action is needed, submit within 24 hours a detailed specific plan of action based as appropriate on the generalized plan of action submitted previously as part of the vibration-monitoring plan specified in Article 1.05.

4. If directed by the Engineer, implement response action(s) within 24 hours of submitting a detailed specific plan of action, so that the Limiting Value is not exceeded.

3.08 DISPOSITION OF INSTRUMENTS

A. The Contractor shall remove salvageable instruments only when directed by the Engineer.

B. All salvaged instruments shall become the property of the Contractor.

COMPENSATION

4.01 BASIS OF PAYMENT

A. The contract lump sum price paid for vibration monitoring shall include full compensation for furnishing all labor, materials, tools, equipment, and incidentals and for performing all work involving vibration monitoring, as specified in the Standard Specifications and these special provisions, and as directed by the Engineer.

B. Any additional areas where vibration monitoring is required will be paid for as extra work as provided in the Standard Specifications.

[Show vibration monitoring locations here.]

FIGURE 1. VIBRATION MONITORING LOCATIONS

CONSTRUCTION VIBRATION MONITORING FIELD DATA FORM

Contract Number: ____________________

Contract Name: ____________________

Contractor: ____________________

Observer: ____________________

Seismograph Information

Manufacturer and Model: ____________________

Serial Number: ____________________

Current Calibration Date: ____________________

Monitoring Location

Building: ____________________

Address: ____________________

Sensor Location (describe location and attach sketch)

____

Data Collection: 1-minute ppv Strip Chart (attach data)

Monitoring Period (date and time) Start: __________ End: __________

Observed Events

Date	Time	Source of Vibration (e.g. demolition, pile driving, compaction, excavation, tracked vehicles, etc.)	Distance From Sensor (ft)	Peak Particle Velocity (in./sec)	Frequency (Hz)

Attach additional sheets as necessary

FIGURE 2. CONSTRUCTION VIBRATION MONITORING DATA FORM

APPENDIX D. SAMPLE BLASTING VIBRATION SPECIFICATIONS

Sample Blasting Specifications

It is impossible to foresee all of the variables that may be encountered on various project sites. A site-specific Blasting Specification should be developed for each project that takes into consideration the peculiarities of that project location. In particular, the areas of blast vibration limits, pre-blast surveys, the number of recording instruments and their locations, the times and days of scheduled blasting, and cautious blasting techniques (if any) should be addressed.

Considering the foregoing, the following represents a generic blasting specification that provides a starting point for writing a blasting specification for construction blasting.

1. GENERAL

    All blasting operations on this project, including the storage, on-site transportation, loading and firing of explosives, shall be in strict compliance with this section.

2. PERMITS AND LICENSES

    A. All blasting operations shall be conducted under the direct supervision of a blaster holding a current license issued by the California Division of Occupational Safety and Health (CALOSHA). The class of license held by the blaster shall include the type of blasting that is to be accomplished. Prior to commencing blasting operations, a copy of the Blaster's License shall be provided to the Engineer.

    B. The Contractor shall be responsible for obtaining any explosives or blasting permits that may be required by state or local laws.

3. STORAGE OF EXPLOSIVES

    Storage of explosives, if anticipated, shall comply with the applicable provisions of CALOSHA's Construction Safety Orders and with Title 27 CFR 181, Part 55, Subpart K, Commerce in Explosives. Adequate magazine records shall be maintained for stored explosives.

4. TRANSPORTATION OF EXPLOSIVES

    A. Transportation of explosives to the project site shall be in accordance with current Federal Department of Transportation and California Highway Patrol regulations.

    B. Transportation of explosives on the project site shall comply with provisions of the CALOSHA Construction Safety Orders.

5. BLASTING OPERATIONS

A. All blasting operations shall be conducted in compliance with the CALOSHA Construction Safety Orders and the provisions of this Section.

B. The time and date of blasting shall be coordinated in advance with the Engineer in order to minimize the impact on traffic and nearby residents.

C. Due to the potential presence of RF emitting devices in the vicinity, only initiation systems that are not affected by stray current or RF energy shall be utilized. Initiation systems consisting solely of cap and fuse shall not be used. Procedures in the use of the initiation system selected shall conform to the system manufacturer's recommendations. Regardless of other exclusions in this section, if deemed safe by the Contractor, an electric detonator may be utilized to start the initiation system. The electric cap or other starter shall not be brought onto the blast site nor shall it be connected to the initiation system until the area has been cleared and the blast is ready to be detonated.

D. Before commencing loading operations, warning signs shall be posted at points of access to the blasting site. Only the blaster, his loading crew and necessary supervisory personnel shall be allowed within 50 feet of the blast site during loading.

E. Only a reasonable quantity of explosives for each blast shall be brought to the blast loading site. When loading is complete, all excess explosive materials shall be removed from the site and returned to the storage magazine or the supplier's storage facility. In no instance shall explosives, blasting agents, detonators or loaded holes be left unguarded or unattended.

F. A lightning detector of a type approved by CALOSHA shall be utilized to detect the presence of lightning immediately prior to and during blast loading operations. Prior to commencing loading operations, if an electrical storm is detected whose approach is estimated to interfere with loading operations, loading shall not commence and the blast shall be rescheduled. If an approaching electrical storm is detected during loading that will present a hazard to loading operations, loading shall be discontinued and all personnel moved to a safe area. All approaches to the blast site shall be guarded and no one shall be allowed to return to the blast site until the storm has passed safely out of range.

G. All refuse from explosives loading such as empty boxes, bags, plastic, paper and fiber packing shall be removed from the project site and destroyed in accordance with the provisions of the Construction Safety Orders.

H. Prior to firing a blast, all personnel shall be cleared to a safe distance and all approaches to the blast site shall be guarded. Traffic shall be stopped at a safe distance and held until the all-clear signal. The blaster firing the blast shall be in a position where he can see the blast site and approaches and shall not detonate the blast until he is certain that no one remains in a hazardous location.

I. Blasting signals shall be conspicuously posted at the site. The signaling device shall be sufficiently loud so that the signals can be heard throughout the area to be cleared. The following blasting signals shall be used:

WARNING SIGNAL
5 minutes prior to the blast...a 1-minute series of long signals

BLASTING SIGNAL
1 minute prior to the blast.....a series of short signals

ALL-CLEAR SIGNAL
Following inspection of the blast....a prolonged signal

J. Misfires.

1. After the blast has been fired, an inspection shall be made by the blaster to determine that all charges have detonated. Only after the blaster is satisfied that the area is safe shall the ALL-CLEAR signal be given.

2. If, after a blast has been fired, the blaster suspects that a misfire has occurred, the Engineer shall be notified. The ALL CLEAR signal shall NOT be given, traffic shall not be released and the blast site shall continue to remain guarded. The blaster shall be in charge of investigating the misfire. He shall do so in accordance with the Construction Safety Orders.

3. If no misfire is found to exist after adequate inspection by the blaster, he shall so notify the Engineer and the ALL CLEAR signal can be sounded.

4. If a misfire is found to exist, the blaster shall immediately notify the Engineer and he shall then proceed to clear the misfire. While this is being accomplished, the blast site shall remain guarded.

5. Following the successful clearing of the misfire and a subsequent inspection of the blast site by the blaster, he shall give the order to sound the ALL CLEAR signal.

6. BLAST DOCUMENTATION (BLAST REPORT)

A. At least 24 hours prior to the loading of a blast, the Contractor shall submit to the Engineer a copy of the proposed blasting scheme for that particular blast. As a minimum, the Blast Report shall include:

1. A plan view of the blast showing the number and location of all holes.

2. The hole diameter(s) and depth(s).

3. The burden and spacing dimensions.

4. The type(s) of explosive to be used and the anticipated total quantity of each.

5. The quantity of explosive to be loaded in each hole and in each deck if decking of charges is anticipated.

6. The type and depth(s) of stemming material to be used.

7. The type, layout and timing of the initiation system to be used.

8. The method of starting the initiation system.

9. The maximum quantity of explosive that will be detonated within any 8 millisecond time period during the blast.

10. The name of the licensed blaster and his license number.

B. It is anticipated that minor changes could be necessary during loading of the blast due to lost holes, etc. Immediately following the blast, the blaster shall annotate a copy of the Blast Report with such changes, if any, and shall sign the Report and deliver it to the Engineer.

7. PROTECTION OF NEIGHBORING FACILITIES

A. The Contractor shall conduct his blasting operations in a manner that will preclude his causing damage to neighboring facilities. Compliance with the provisions of these specifications or acceptance by the Engineer of any blasting procedures or techniques shall not absolve the Contractor from full responsibility for any damage that may result from his blasting operations.

B. Blasts shall be designed so that vibration and air overpressure levels and flyrock do not exceed the limits stated in this Section.

C. All blasts shall be monitored by the Contractor with ___(qty)___ blast vibration seismograph(s). Each seismograph shall record blast-generated vibration in three mutually perpendicular axes and have a frequency response range of from 2 to 250 Hertz.

D. The seismograph(s) shall have received a factory calibration within the 12 month period preceding the blast recorded. Each seismograph shall produce a real-time graphical depiction of the particle velocities recorded for each individual axis for the duration of the event. The seismograph(s) shall also produce a numeric record of the peak particle velocities and principle frequencies of the vibration recorded for each axis during the event.

E. For each blast, the seismograph(s) shall be located in accordance with instructions from the Engineer. As a minimum, one seismograph shall be located at the nearest critical structure.

F. The peak particle velocities recorded on each of the three axes shall not exceed the frequency-dependent limits contained in Bureau of Mines RI 8507 Alternative Blasting Level Criteria (Figure _____) at any of the monitoring locations.

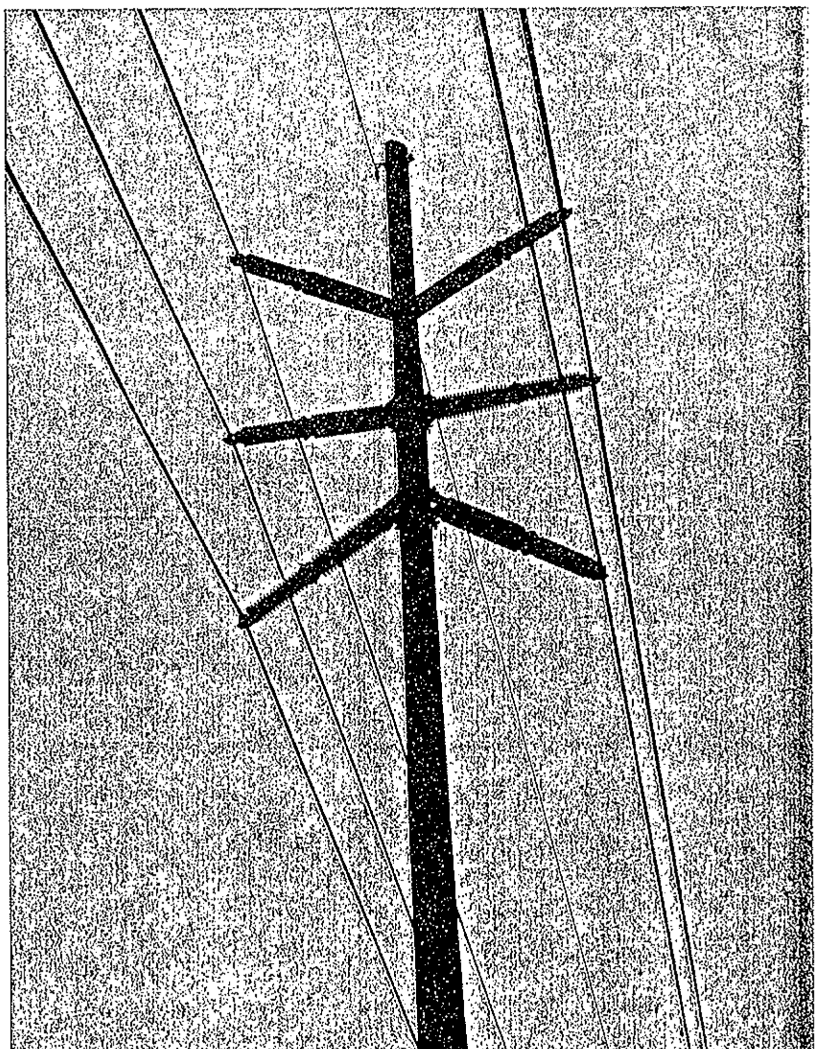
G. Air overpressures from each blast shall be recorded at the monitoring locations using the airblast channel of the blasting seismographs or with other suitable means. Readings shall be in decibels or in pounds per square inch (psi) and shall be recorded as a linear, unweighted value.

H. Air overpressures from blasting shall not exceed 133 dB (0.013 psi) at any of the monitoring locations.

I.   Flyrock will not be tolerated and shall be controlled through proper blast design. If flyrock occurs, the cause shall be investigated by the blaster. Blasting shall not continue until satisfactory corrective measures have been taken to preclude further flyrock incidents.

Transmission Line Reference Book

115-138 kV Compact Line Design



Electric Power Research Institute

Transmission Line Reference Book

115-138 kV Compact Line Design

Based on
EPRI Research Project 260

Prepared by
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AUDIBLE NOISE

Audible noise is due to point source corona, as are RI and TVI, and is a function of conductor voltage gradient and the number of irregularities on the conductor or on energized hardware. The major cause of irregularities is water droplets on the underside of the conductor. These droplets deform to point sources under the influence of the electric field, producing high local gradients and corona. Since water droplets are requisite to the primary mechanism, audible noise is generally limited to periods of heavy fog, rain, or immediately following rain.

The noise manifests itself as a sizzle, crackle, or hiss and a low-frequency hum. The first three are "white" noise, extending over the entire aural range (20 Hz to 2×10^4 Hz) and are caused by random point source discharges. The low-frequency hum is caused by space charge movement around the conductor at a frequency of 120 Hz and harmonics of 120 Hz. Unlike RI and TVI, audible noise is more localized; the noise is propagated via air and discharges a few spans away do not affect local measurements. This allows local remedial action, if necessary.

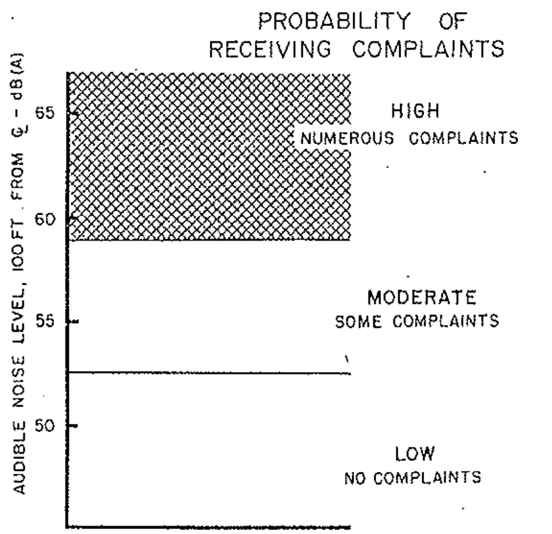
Annoyance caused by the audible noise depends on a number of qualitative factors, resulting in difficulty in specifying design levels. Such general factors as land use characteristics and ambient noise, together with individual activity and duration of exposure, must be recognized. For example, it would be unreasonable to use the same criteria for a line adjacent to an industrial facility as one near a hospital. Similarly, a line in a populous area has more potential for annoyance than one in an unpopulated area.

Audible noise is generally measured by the dB(A) scale (the "A" suffix refers to the weighting network used in the measurement). The dB(B) weighting network gives a better correlation with juror annoyance ratings of transmission line noise than the "A" network, probably because of the lower attenuation of the low-frequency noise with the "B" network (*7-11*). However, the dB(A) scale is in universal use for general noise ordinances, with excellent results.

Criteria for audible noise (AN) design is based on experience with other lines, present noise regulations, and typical ambient levels in the different areas of land usage. These criteria should recognize the statistical nature of the noise generation (*7-12*). Audible noise varies from being imperceptible in fair weather, to being noticeable over ambient during wet conditions, to higher but imperceptible over ambient during rain conditions. The line noise during heavy rain may be 6 dB(A) higher than when the conductor is merely wet (as after rain, during heavy fog, etc.). However, it is unlikely that heavy rain would cause annoyance because of the high ambient noise level and low exposure. Therefore it is more appropriate to consider the wet-conductor level because of its higher exposure probability.

A general guideline to acceptability is given in Reference *7-13* and is reproduced in Figure 7.16. It is based on public response to noise from existing lines at 100 feet from the center of the ROW and shows that less than 52.5 dB(A) resulted in no complaints. This is supported by other experience (*7-14*).

The method of calculation used on the compact line project is similar to that reported in Reference *7-15*. From single-phase cage tests, the generated acoustic power can be measured as a function of the conductor gradient. These can be summed for the three phases to give a lateral audible noise profile. Comparison with measured results indicates an accuracy to within ±3 dB. The results are presented in Figure 7.17 for Dove conductors (556.5 kcmil) at 30 feet effective height, with 3-foot phase-to-phase spacing (horizontal configuration), operating at 145 kV. This represents the most compact 138-kV design and a small conductor and therefore has the highest AN to be expected in practice. Noise levels are calculated at approximately 5 feet above the ground.



SOURCE: "An Analysis of Transmission Line Audible Noise Levels Based upon Field and Three-Phase Test Line Measurements," D. E. Perry, *IEEE Transactions on Power Apparatus and Systems*, 1972.

Figure 7.16 Probability of complaints about audible noise.

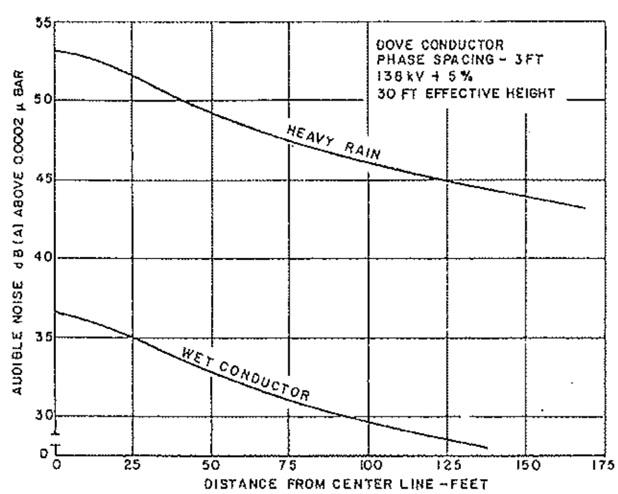


Figure 7.17. Audible noise for 3-phase compact line.

TRANSIT NOISE AND VIBRATION IMPACT ASSESSMENT

FTA-VA-90-1003-06 **May 2006**

Office of Planning and Environment
Federal Transit Administration

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13. ABSTRACT (Maximum 200 words)

This report is the second edition of a guidance manual originally issued in 1995 which presents procedures for predicting and assessing noise and vibration impacts of proposed mass transit projects. All types of bus and rail projects are covered. Procedures for assessing noise and vibration impacts are provided for different stages of project development, from early planning before mode and alignment have been selected through preliminary engineering and final design. Both for noise and vibration, there are three levels of analysis described. The framework acts as a screening process, reserving detailed analysis for projects with the greatest potential for impacts while allowing a simpler process for projects with little or no effects.

This updated guidance contains noise and vibration impact criteria that are used to assess the magnitude of predicted impacts. A range of mitigation measures are described for dealing with adverse noise and vibration impacts. There is a discussion of noise and vibration during the construction stage and also discussion of how the technical information should be presented in the Federal Transit Administration's environmental documents. This guidance will be of interest not only to technical specialists who conduct the analyses but also to transit agency staff, federal agency reviewers, and members of the general public who may be affected by the projects.

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TRANSIT NOISE AND VIBRATION IMPACT ASSESSMENT

FTA-VA-90-1003-06 May 2006

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PREFACE

This guidance manual on transit noise and vibration impact assessment is an updated edition of a document originally published in 1995. The manual details the procedures for producing accurate impact assessments for proposed federally-funded mass transit projects and discusses ways of reducing excessive noise and vibration caused by projects. While the manual is intended primarily for acoustics professionals who conduct the analyses as part of the environmental review process, it is written for a broader audience. Sections on noise and vibration fundamentals and a glossary of terms allow lay readers to gain a better understanding of one of the more technical subjects covered in the Federal Transit Administration's environmental documents.

The revisions in this manual are based on practitioners' experience in using the procedures and on developments that have occurred in this field over the past decade. The basic procedures for prediction and impact assessment remain the same; however, changes have been made throughout the document to clarify the procedures and to add new content. Some of the more significant changes involve: inclusion of noise reference levels for several new transit modes; fuller explanation of how to handle multimodal highway/transit projects; methods for assessing locomotive horn noise at grade crossings; expanded discussion of noise and vibration mitigation measures including costs; refined vibration impact criteria expressed in one-third octave bands for Detailed Analysis; and more examples on how to use the General Noise Assessment procedures for different types of transit projects.

This updated guidance manual supersedes the original document and should be used for addressing noise and vibration impacts for all construction projects seeking funding from FTA. For the great majority of projects, the results obtained from application of the methods described in this manual will not depart significantly from results obtained from the old manual. This document is also available in the Planning and Environment section of FTA's Web site (www.fta.dot.gov).

1. INTRODUCTION

1.1 PURPOSE

Noise and vibration assessments are key elements of the environmental impact assessment process for mass transit projects. Experience has shown that noise and vibration are among the major concerns with regard to the effects of a transit project on the surrounding community. A transit system is of necessity placed near population centers and often causes significant noise and vibration at nearby residences and other sensitive types of land use.

This manual provides guidance for preparing and reviewing the noise and vibration sections of environmental documents. In the interest of promoting quality and uniformity in assessments, the manual will be used by project sponsors and consultants in performing noise and vibration analyses for inclusion in environmental documents. The manual sets forth the methods and procedures for determining the level of noise and vibration impact resulting from most federally-funded transit projects and for determining what can be done to mitigate such impact. Since the methods have been developed to assess typical transit projects, there will be some situations not explicitly covered in this manual. The exercise of professional judgment may be required to extend the basic methods in these cases.

1.2 THE ENVIRONMENTAL REVIEW PROCESS

The Federal Transit Administration (FTA) provides capital assistance for a wide range of mass transit projects – from completely new rail rapid transit systems to bus maintenance facilities and vehicle purchases. The extent of environmental analysis and review will depend on the scope and complexity of the proposed project and the associated environmental impacts. FTA's environmental impact regulation classifies the most common projects according to the different levels of environmental analysis required, ranging from an environmental impact statement (EIS) to little or no environmental documentation (categorical exclusion). FTA's environmental impact regulation is codified in Title 23, Code of Federal Regulations, Part 771.[(1)*]

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[*]References are located at the end of each chapter.

Environmental Impact Statements. Large fixed-guideway projects, such as heavy rail, light rail, commuter rail and automated guideway transit systems, normally require environmental impact statements, including an in-depth noise and vibration assessment. While there may be exceptions to the EIS requirement, in the great majority of cases new rail starts or extensions to existing systems involve significant environmental effects in the context of the National Environmental Policy Act (NEPA). Because they are located in dense urban areas, noise and vibration impacts are a frequent concern; thus it is likely that for the major infrastructure projects requiring an EIS, the most detailed treatment of noise and/or vibration impacts will also be required.

There are other projects as well which may require a detailed analysis of noise and vibration impacts even if an EIS is not required to comply with NEPA. These could be bus/high-occupancy-vehicle (HOV) lanes built on existing highways or construction of certain bus or rail terminals and storage and maintenance facilities. If the project is proposed to be located in or very close to a sensitive area or site, it is prudent to use the most detailed procedures contained in the manual to predict noise and/or vibration levels since this will provide the most reliable basis for considering measures to mitigate excessive noise/vibration at a specific site.

Categorical Exclusions. At the other extreme is a host of smaller transit projects which normally do not cause significant environmental impacts and do not require noise and vibration assessment. These projects are listed as "categorical exclusions" in FTA's environmental regulation, meaning that FTA has determined that there are no significant environmental impacts for those types of projects and no environmental document is required. Examples are: vehicle purchases; track and railbed maintenance; installation of maintenance equipment within the facility, etc. Section 771.117(c) contains a list of transit projects predetermined to be categorical exclusions.

Other types of projects may also qualify as categorical exclusions, for example, certain transit terminals, transfer facilities, bus and rail storage and maintenance facilities (see 23 CFR 771.117(d)). These projects usually involve more construction and a greater potential for off-site impacts. They are presented in the regulation with conditions or criteria which must be met in order to qualify for categorical exclusion. The projects are reviewed individually by FTA to assure that any off-site impacts are properly mitigated. Depending on the proposed project site and the surrounding land use, a noise and vibration assessment may be needed even though the project may ultimately qualify as a categorical exclusion. The screening process in Chapters 4 and 9 will be helpful in pointing out potential noise and vibration concerns and the general assessment procedures may then be used to define the level of impact.

Environmental Assessments. When a proposed project is presented to FTA, if it is uncertain whether the project requires an EIS or qualifies as a categorical exclusion, FTA will direct the project sponsor to prepare an environmental assessment (EA). Generally, an EA is selected (rather than trying to process the project as a categorical exclusion) if the FTA reviewer feels that several types of impacts need further investigation, for example, air quality, noise, wetlands, historic sites, traffic, etc. An EA is a relatively brief environmental study which helps determine the magnitude of the impacts that will likely be caused by the project. If, during the analysis, it appears that any impacts are significant, an EIS will be prepared. If the analysis shows that none of the impacts is significant or if mitigation measures are incorporated in the project to adequately deal with adverse impact, the EA will fully document this and serve as the basis for a Finding of No Significant Impact issued by FTA. It is important to note that when mitigation measures are relied on, they must be described in detail in the EA since FTA's finding is based on the inclusion of these measures in the project.

FTA's environmental regulation does not list typical projects that require EA's. An EA may be prepared for any type of project if uncertainty exists about the magnitude or extent of the impacts. Experience has shown that most of the EA's prepared for transit projects require an assessment of noise impacts.

1.3 NOISE AND VIBRATION ANALYSIS IN PLANNING AND PROJECT DEVELOPMENT

Major capital investment projects are developed initially from a comprehensive transportation planning process conducted in metropolitan areas (see 23 CFR 450.300). The metropolitan planning process includes the consideration of social, economic, and environmental effects of proposed major infrastructure improvements. However, at this stage, environmental effects are usually considered on a broad scale, for example, overall development patterns, impact on greenspace, and regional air quality. Noise and vibration assessments are not typically done at the systems planning stage since the proposed infrastructure improvements lack the necessary detail.

Once the need for a major capital investment in a corridor is established in the metropolitan transportation plan, the task then becomes identifying the transit mode and alignment best suited for the corridor. If FTA capital investment funds will be pursued, the project sponsor must perform an "alternatives analysis."[(2)] Often combined with a Draft EIS, the alternatives analysis presents information on benefits, costs, and impacts of alternative strategies for meeting the need for new capacity. Usually, several alternatives ranging in cost will be evaluated. If environmental impacts of the alternatives will be assessed, noise and, to a lesser extent, vibration are primary issues. The screening and general assessment procedures described in this manual are well-suited to compare and contrast noise/vibration effects among different modes and alignments. In fact, the general assessment procedures were developed partly to respond to this need. In addition, they can be used for any specific project where the screening procedure indicates potential for impact and the project sponsor wants a relatively quick assessment of the level of impact.

If the results of the alternatives analysis justify further development of a major capital investment, FTA will approve entry of the proposed project into preliminary engineering. During preliminary engineering, the environmental review process is completed. With the mode and alignment determined, the impact assessment at this stage focuses on the locally preferred alternative for a major capital investment. The detailed analysis procedures for noise can be used to produce the most accurate estimates of noise impact for the proposed project. The detailed procedures should be used as the basis for reaching any decisions on the need for noise reduction measures and the types of measures that are appropriate for the project.

After the NEPA process is completed for a major project, federal funding for final design may be granted. If vibration impacts were identified during preliminary engineering, a detailed analysis of vibration impact may be conducted during final design. Final design activities will produce the geotechnical information needed to refine the impact assessment and allow the most detailed consideration of vibration control measures, if needed. Even for smaller transit projects, if vibration impact is predicted in a general assessment, vibration mitigation measures should only be specified after a detailed analysis has been done. Detailed vibration analysis is best accomplished during final design of the project.

Once the project enters construction, there may still be a need for noise or vibration analysis in some circumstances. Large construction projects in densely populated residential areas may require noise monitoring to make sure that agreed-upon noise limits are not exceeded. Vibration testing may be needed in the final stages of construction to determine whether vibration control measures are having the predicted effect.

Considering that transit projects must be located amid or very close to concentrations of people, noise and vibration impacts can be a concern throughout the planning and project development phases. This manual offers the flexibility to address noise and vibration at different stages in the development of a project and in different levels of detail depending on the types of decisions that need to be made.

There are three levels of analysis which may be employed, depending on the type and scale of the project, the stage of project development, and the environmental setting. The technical content of each of the three levels is specified in the body of this document, but a summary of each level is given in the following paragraphs:

- **Screening Procedure:** Identifies noise- and vibration-sensitive land uses in the vicinity of a project and whether there is likely to be impact. It also serves to determine the noise and vibration study areas for further analysis when sensitive locations are present. The screening process may be all that is required for many of the smaller transit projects which qualify as categorical exclusions. When noise/vibration-sensitive receivers are found to be present, there are two levels of quantitative analysis available to predict impact and assess the need for mitigation measures.

- **General Assessment:** Identifies location and estimated severity of noise and vibration impacts in the noise and vibration study areas identified in the screening procedure. For major capital investments, the General Assessment provides the appropriate level of detail to compare alternative modes and alignments in alternatives analysis. It can be used in conjunction with established highway noise prediction procedures to compare and contrast highway, transit and multimodal alternatives. Before basic decisions have been reached on mode and alignment in a corridor, it is not prudent to conduct the most detailed level of noise and vibration analysis. For smaller transit projects, this level is used for a closer examination of projects which show possible impacts as a result of screening. For many smaller projects, this level may be sufficient to define impacts and determine whether mitigation is necessary.

- **Detailed Analysis:** Quantifies impacts through an in-depth analysis usually only performed for a single alternative. Delineates site-specific impacts and mitigation measures for the preferred alternative in major investment projects during preliminary engineering. For other smaller projects, Detailed Analysis may be warranted as part of the initial environmental assessment if there are potentially severe impacts due to close proximity of sensitive land uses.

The three levels of noise and vibration assessment are described in the chapters which follow.

1.4 ORGANIZATION OF THE MANUAL

The guidance manual is divided into two parts, noise and vibration. Each part has parallel organization according to the following subjects:

Noise/Vibration

- Basic Concepts
- Criteria
- Screening Procedure
- General Assessment
- Detailed Analysis

Construction Noise/Vibration

Documentation

Appendices

- Glossary
- Background for Transit Noise Impact Criteria
- Receiver Selection
- Existing Noise Determination
- Noise Source Level Determination
- Maximum Noise Level Computation

REFERENCES

1. U.S. Department of Transportation, Federal Transit Administration and Federal Highway Administration, "Environmental Impact and Related Procedures," Final Rule, 52 Federal Register 32646 -32669; August 28, 1987 (23 Code of Federal Regulations 771).

2. U.S. Department of Transportation, Federal Transit Administration, “Major Capital Investment Projects,” Final Rule, 65 Federal Register 76863-76884; December 7, 2000 (49 CFR Part 611).

2. BASIC NOISE CONCEPTS

This chapter discusses the basic concepts of transit noise which provide background for Chapters 3 through 6, where transit noise is computed and assessed. The Source-Path-Receiver framework sketched in Figure 2-1 is central to all environmental noise studies. Each transit **source** generates close-by noise levels which depend upon the type of source and its operating characteristics. Then, along the propagation **path** between all sources and receivers, noise levels are reduced (attenuated) by distance, intervening obstacles and other factors. And finally at each **receiver**, noise combines from all sources to interfere, perhaps, with receiver activities. This chapter contains an overview of this Source-Path-Receiver framework. Following this overview is a primer on the fundamentals of noise characteristics.

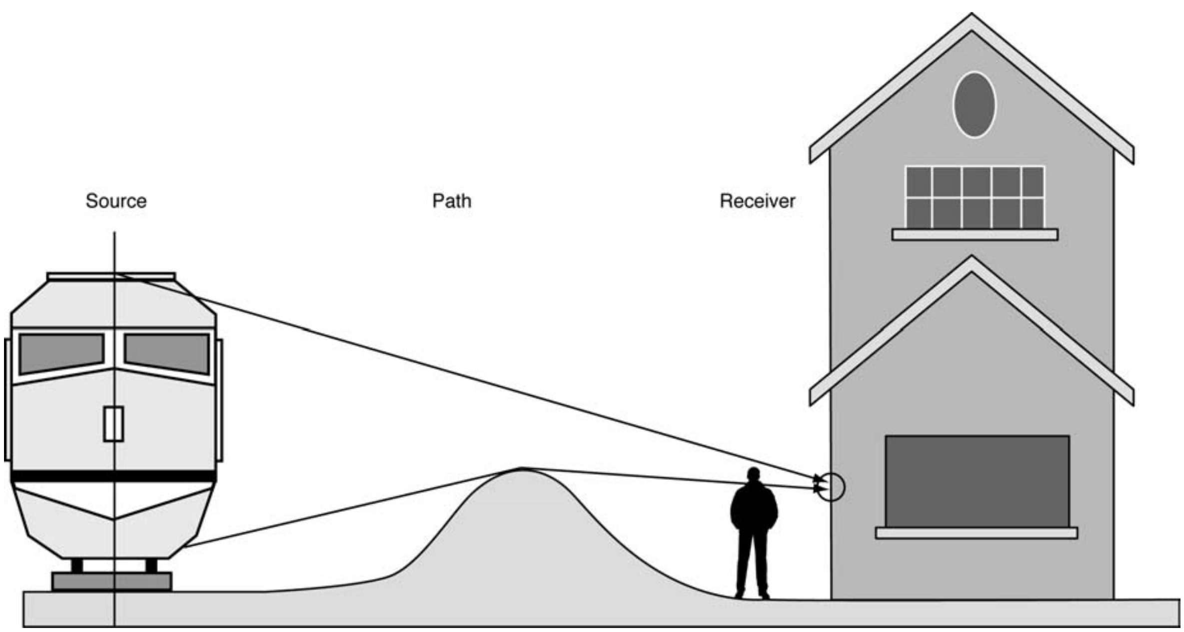

Figure 2-1. The Source-Path-Receiver Framework

In brief, this chapter contains:

- A primer on the fundamentals of noise characteristics (Section 2.1)
- An overview of transit **sources**: a listing of major sources, plus some discussion of noise-generation mechanisms (Section 2.2)
- An overview of noise **paths**: a discussion of the various attenuating mechanisms on the path between source and receiver (Section 2.3)
- An overview of **receiver** response to transit noise: a discussion of the technical background for transit-noise criteria and the distinction between absolute and relative noise impact (Section 2.4)
- A discussion of the **noise descriptors** used in this manual for transit noise (Section 2.5)

2.1 FUNDAMENTALS OF NOISE

Noise is generally considered to be unwanted sound. Sound is what we hear when our ears are exposed to small pressure fluctuations in the air. There are many ways in which pressure fluctuations are generated, but typically they are caused by vibrating movement of a solid object. This manual uses the terms ‘noise’ and ‘sound’ interchangeably since there is no physical difference between them. Noise can be described in terms of three variables: amplitude (loud or soft); frequency (pitch); and time pattern (variability).

Amplitude. Loudness of a sound depends on the amplitude of the fluctuations above and below atmospheric pressure associated with a particular sound wave. The mean value of the alternating positive and negative pressure fluctuations is the static atmospheric pressure, not a useful descriptor of sound. However, the effective magnitude of the sound pressure in a sound wave can be expressed by the “root-mean-square” (rms) of the oscillating pressure measured in Pascals, a unit named after Blaise Pascal a 17th century French mathematician. In calculation of the ‘rms’, the values of sound pressure are squared to make them all positive and time-averaged to smooth out variations. The ‘rms’ pressure is the square root of this time-averaged value.

The quietest sound that can be heard by most humans, the “threshold of hearing," is a sound pressure of about 20 microPascals, and the loudest sounds typically found in our environment range up to 20 million microPascals. Because of the difficulty in dealing with such an extreme range of numbers, acousticians use a compressed scale based on logarithms of the ratios of the sound energy contained in the wave related to the square of sound pressures instead of the sound pressures themselves, resulting in the “sound pressure level” in decibels (dB). The ‘B’ in dB is always capitalized because the unit is named after Alexander Graham Bell, a leading 19th century innovator in communication. Sound pressure level (L_p) is defined as:

$$L_p = 10 \log_{10} (p^2_{rms} / p^2_{ref}) = 20 \log_{10} (p_{rms} / p_{ref}) \text{ dB, where } p_{ref} = 20 \text{ microPascals.}$$

Inserting the range of sound pressure values mentioned above results in the threshold of hearing at 20 microPascals at 0 dB and a typical loudest sound of 20 million microPascals is 120 dB.

Decibel Addition. The combination of two or more sound pressure levels at a single location involves 'decibel addition' or the addition of logarithmic quantities. The quantities that are added are the sound energies (p^2_{rms}). For example, a doubling of identical sound sources results in a 3 dB increase, since:

$$10 \log_{10} (2\, p^2_{rms} / p^2_{ref}) = 10 \log_{10} (p^2_{rms} / p^2_{ref}) + 10 \log_{10} (2) = 10 \log_{10} (p^2_{rms} / p^2_{ref}) + 3.$$

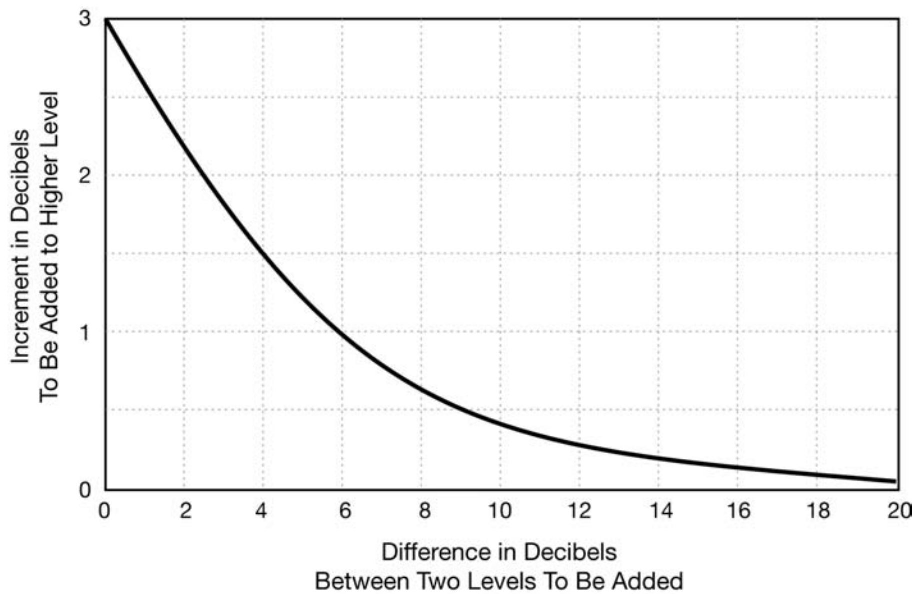

Figure 2-2. Graph for Approximate Decibel Addition

For example, if the noise from one bus resulted in a sound pressure level of 70 dB, the noise from two buses would be 73 dB. Figure 2.2 provides a handy graph that can be used to add sound levels in decibels. For example, if two sound levels of 64 dB and 60 dB are to be added, the difference in decibels between the two levels to be added is 4 dB. The curve intersects the "4" where the increment to be added to the higher level is "1.5." Therefore the sum of the two levels is 65.5 dB.

Frequency. Sound is a fluctuation of air pressure. The number of times the fluctuation occurs in one second is called its frequency. In acoustics, frequency is quantified in cycles per second, or Hertz (abbreviated Hz), named after Heinrich Hertz, a famous 19th century German physicist. Some sounds, like whistles, are associated with a single frequency; this type of sound is called a "pure tone." Most often, however, noise is made up of many frequencies, all blended together in a spectrum. Human hearing covers the frequency range of 20 Hz to 20,000 Hz. If the spectrum is dominated by many low frequency components, the noise will have a characteristic like the rumble of thunder. The spectrum in Figure 2-3 illustrates the full range of acoustical frequencies that can occur near a transit system. In this example, the noise spectrum was measured near a train on a steel elevated structure with a sharp curve. This spectrum has a major low frequency peak centered around 80 Hz. Although not dominant in this example, frequencies in the range of 500 Hz to 2000 Hz are associated with the roar of wheel /rail noise. However a strong peak above 2000 Hz is associated with the wheel squeal of the train on the curve.

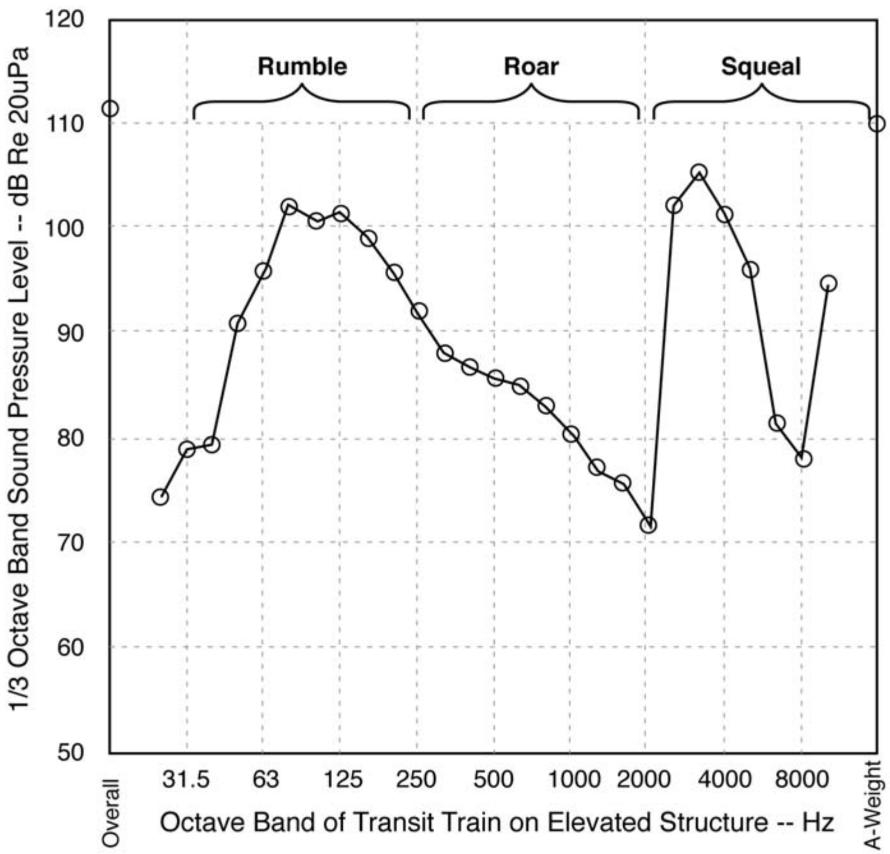

Figure 2-3. Noise Spectrum of Transit Train on Curve on Elevated Structure

Our human hearing system does not respond equally to all frequencies of sound. For sounds normally heard in our environment, low frequencies below 250 Hz and very high frequencies above 10,000 Hz are less audible than the frequencies in between. Acoustical scientists measured and developed frequency response functions that characterize the way people respond to different frequencies. These are the so-called A-, B- and C-weighted curves, representing the way people respond to sounds of normal, very loud and extremely loud sounds, respectively. Environmental noise generally falls into the “normal” category so that the A-weighted sound level is considered best to represent the human response. The A-weighted curve is shown in

Figure 2-4. This curve shows that sounds at 50 Hz would have to be amplified by 30 dB to be perceived equally as loud as a sound at 1000 Hz at normal sound levels.

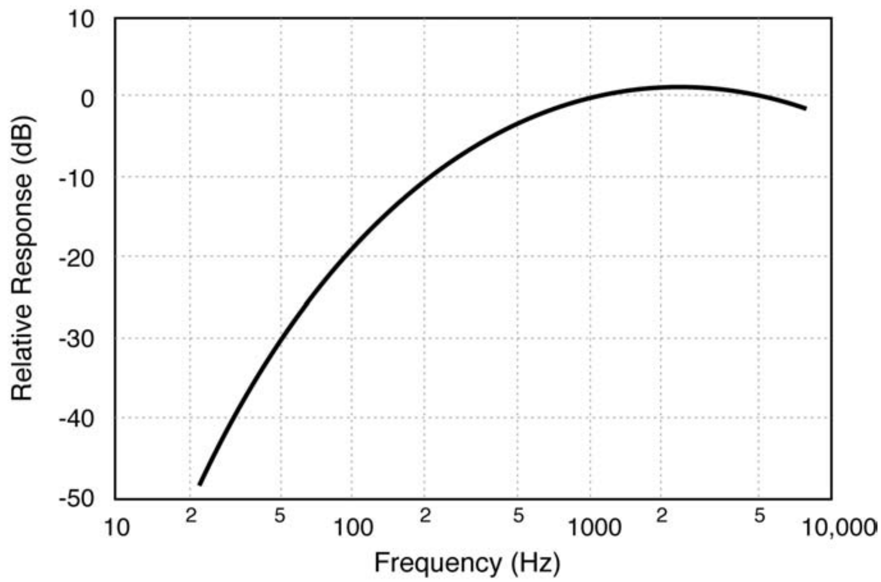

Figure 2-4. A-weighting Curve

Low frequencies are associated with long wavelengths of sound. Conversely, high frequencies are the result of short wavelengths. The way in which frequency and wavelength of sound waves are related is the speed of sound. The relationship is:

$$f\lambda = c, \text{ where}$$

f = frequency in cycles per second (Hz)
λ = wavelength in feet, and
c = speed of sound in feet per second.

The speed of sound in air varies with temperature, but at standard conditions is approximately 1000 feet per second. Therefore, according to the equation, a frequency of 1000 Hz has a wavelength of 1 foot and a frequency of 50 Hz has a wavelength of 20 feet.

The scale of these waves explains in part the reason humans perceive sounds of 1000 Hz better than those of 50 Hz – the wavelengths are similar to the size of the receiver’s head. Waves of 20 feet in length at 50 Hz are house-sized, which is why low-frequency sounds, such as those from idling locomotives, are not deterred by walls and windows of a home. These sounds transmit indoors with relatively little reduction in strength.

Time pattern. The third important characteristic of noise is its variation in time. Environmental noise generally derives, in part, from a conglomeration of distant noise sources. Such sources may include distant traffic, wind in trees, and distant industrial or farming activities, all part of our daily lives. These distant sources create a low-level "background noise" in which no particular individual source is identifiable. Background noise is often relatively constant from moment to moment, but varies slowly from hour to hour as natural forces change or as human activity follows its daily cycle. Superimposed on this low-level, slowly varying background noise is a succession of identifiable noisy events of relatively brief duration. These events may include single-vehicle passbys, aircraft flyovers, screeching of brakes, and other short-term events, all causing the noise level to fluctuate significantly from moment to moment.

It is possible to describe these fluctuating noises in the environment using single-number descriptors. To do this allows manageable measurements, computations, and impact assessment. The search for adequate single-number noise descriptors has encompassed hundreds of attitudinal surveys and laboratory experiments, plus decades of practical experience with many alternative descriptors.

2.2 SOURCES OF TRANSIT VEHICLE NOISE

This section discusses major characteristics of the sources of transit noise. Transit noise is generated by transit vehicles in motion. Vehicle propulsion units generate: (1) whine from electric control systems and traction motors that propel rapid transit cars, (2) diesel-engine exhaust noise, from both diesel-electric locomotives and transit buses, (3) air-turbulence noise generated by cooling fans, and (4) gear noise. Additional noise of motion is generated by the interaction of wheels/tires with their running surfaces. Tire noise from rubber-tired vehicles is significant at normal operating speeds. The interaction of steel wheels and rails generates three types of noise: (1) rolling noise due to continuous rolling contact, (2) impact noise when a wheel encounters a discontinuity in the running surface, such as a rail joint, turnout or crossover, and (3) squeal generated by friction on tight curves.

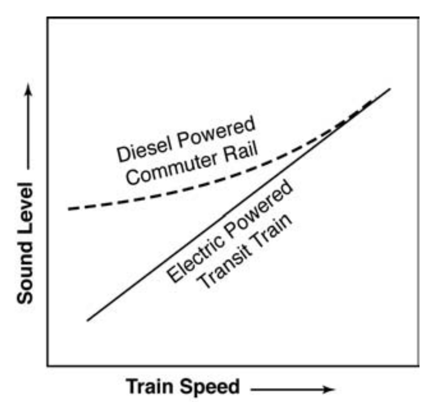

Figure 2-5. Example Sound Level Dependence on Speed

Figure 2-5 illustrates typical dependence of source strength on vehicle speed for two types of transit vehicles. Plotted vertically in this figure is a qualitative indication of the maximum sound level during a passby. In the figure, speed dependence is strong for electric-powered transit trains because wheel/rail noise dominates, and noise from this source increases strongly with increasing speed. On the other hand, speed dependence is less for diesel-powered commuter rail trains, particularly at low speeds where the locomotive exhaust noise dominates. As speed increases, wheel-rail noise becomes the dominant noise source and diesel- and electric-powered trains will generate similar noise levels. Similarly, but not shown, speed dependence is also strong for automobiles, city buses (two-axle) and non-accelerating highway buses (three-axle), because tire/pavement noise dominates for these vehicles; but it is not significant for accelerating highway buses where exhaust noise is dominant. For transit vehicles in motion, close-by sound levels also depend upon other parameters, such as vehicle acceleration and vehicle length, plus the type/condition of the running surfaces. For very high-speed rail vehicles, air turbulence can also be a significant source of noise. In addition, the guideway structure can also radiate noise as it vibrates in response to the dynamic loading of the moving vehicle.

Transit vehicles are equipped with horns and bells for use in emergency situations and as a general audible warning to track workers and trespassers within the right-of-way as well as to pedestrians and motor vehicles at highway grade crossings. Horns and bells on the moving transit vehicle, combined with stationary bells at grade crossings can generate noise levels considered to be extremely annoying to nearby residents.

Noise is generated by transit vehicles even when they are stationary. For example, auxiliary equipment often continues to run even when vehicles are stationary – equipment such as cooling fans on motors, radiator fans, plus hydraulic, pneumatic and air-conditioning pumps. Also, transit buses are often left idling in stations or storage yards. Noise is also generated by sources at fixed-transit facilities. Such sources include ventilation fans in transit stations, in subway tunnels, and in power substations, equipment in chiller plants, and many activities within maintenance facilities and shops.

Table 2-1 summarizes sources of transit noise separately by vehicle type and/or type of facility. Procedures for computing close-by noise levels for major sources as a function of operating parameters such as vehicle speed are given in Chapters 5 and 6.

Table 2-1. Sources of Transit Noise

Vehicle or Facility	Dominant Components	Comments
Rail Rapid Transit (RRT), or Light Rail Transit (LRT) on exclusive right-of-way	Wheel/rail interaction and guideway amplification	Depends on condition of wheels and rails.
	Propulsion system	When accelerating and at higher speeds.
	Brakes	When stopping.
	Auxiliary equipment	When stopped.
	Wheel squeal	On tight curves.
	In general	Noise increases with speed and train length.
Light Rail Transit (LRT) in mixed traffic	Wheel squeal	On tight curves.
	Auxiliary equipment	When stopped.
	Horns and crossing bells	At grade crossings.
	In general	Lower speeds mean less noise than for RRT and LRT on exclusive right-of-way.
Commuter Rail	Diesel exhaust	On diesel-hauled trains.
	Cooling fans	On both diesel and electric-powered trains.
	Wheel/rail interaction	Depends on condition of wheels and rails.
	Horns and crossing gate bells	At grade crossings.
	In general	Noise is usually dominated by locomotives and horns at grade crossings.
Low and Intermediate Capacity Transit	Propulsion systems, including speed controllers	At low speeds.
	Ventilation systems	At low speeds.
	Tire/guideway interaction	For rubber-tired vehicles, including monorails.
	Wheel/rail interaction	Depends on condition of wheels and rails.
	In general	Wide range of vehicles: monorail, rubber-tired, steel wheeled, linear induction. Noise characteristics depend upon type.
Diesel Buses	Cooling fans	While idling.
	Engine casing	While idling.
	Diesel exhaust	At low speeds and while accelerating.
	Tire/roadway interaction	At moderate and high speeds.
	In general	Includes city buses (generally two axle) and commuter buses (generally three axle).
Electric Buses and Trackless Trolleys	Tire/roadway interaction	At moderate speeds.
	Electric traction motors	At moderate speeds.
	In general	Much quieter than diesel buses.

Table 2-1. Sources of Transit Noise (continued)

Vehicle or Facility	Dominant Components	Comments
Bus Storage Yards	Buses starting up	Usually in early morning.
	Buses accelerating	Usually near entrances/exits.
	Buses idling	Warm-up areas
	In general	Site specific. Often peak periods with significant noise.
Rail Transit Storage Yards	Wheel squeal	On tight curves.
	Wheel impacts	On joints and switches.
	Wheel rolling noise	On tangent track
	Auxiliary equipment	Throughout day and night. Includes air-release noise.
	Coupling/uncoupling	On storage tracks
	Signal horns	Throughout yard site
	In general	Site specific. Often early morning and peak periods with significant noise.
Maintenance Facilities	Signal horns	Throughout facility
	PA systems	Throughout facility
	Impact tools	Shop buildings
	Car/bus washers/driers	Wash facility
	Vehicle activity	Throughout facility
	In general	Site specific. Considerable activity throughout day and night, some outside.
Stations	Automobiles	Patron arrival/departure, especially in early morning.
	Buses idling	Bus loading zone
	P.A. systems	Platform area
	Locomotive idling	At commuter rail terminal stations.
	Auxiliary systems	At terminal stations and layover facilities.
	In general	Site specific, with peak activity periods.
Subways	Fans	Noise through vent shafts.
	Buses/trains in tunnels	Noise through vent shafts.
	In general	Noise is not a problem.

2.3 PATHS OF TRANSIT NOISE, FROM SOURCE TO RECEIVER

This section contains a qualitative overview of noise-path characteristics from source to receiver, including attenuation along these paths. Equations for specific noise-level attenuations along source-receiver paths appear in Chapters 5 and 6.

Sound paths from source to receiver are predominantly through the air. Along these paths, sound reduces with distance due to (1) divergence, (2) absorption/diffusion and (3) shielding. These mechanisms of sound attenuation are discussed below.

Divergence. Sound levels naturally attenuate due to distance, as shown in Figure 2-6. Plotted vertically is the attenuation at the receiver, relative to the sound level 50 feet from the source. As shown, the sound level attenuates with increasing distance. Such attenuation, technically called "divergence," depends upon source configuration and source-emission characteristics. For sources grouped closely together (called point sources), attenuation with distance is large: 6 decibels per doubling of distance. Point sources include crossing signals along rail corridors, PA systems in maintenance yards and other closely grouped sources of noise. For vehicles passing along a track or roadway (called line sources), divergence with distance is less: 3 decibels per doubling of distance for L_{eq} and L_{dn}, and 3 to 6 decibels per doubling of distance for L_{max}. In Figure 2-6, the line source curve separates into three separate lines for L_{max}, with the point of departure depending on the length of the line source. These three noise descriptors – L_{eq} , L_{dn} and L_{max} – are discussed in Section 2.5. Equations for the curves in Figure 2-6 appear in Chapter 6.

Absorption/Diffusion. In addition to distance alone, sound levels are further attenuated when sound paths lie close to freshly-plowed or vegetation-covered ground. Plotted vertically in Figure 2-7 is this additional attenuation, which can be as large as 5 decibels as close in as several hundred feet. At very large distances, wind and temperature gradients sometimes modify the ground attenuation shown here; such variable atmospheric effects are not included in this manual because they generally occur beyond the range of typical transit-noise impact. Equations for the curves in this figure appear in Chapter 6.

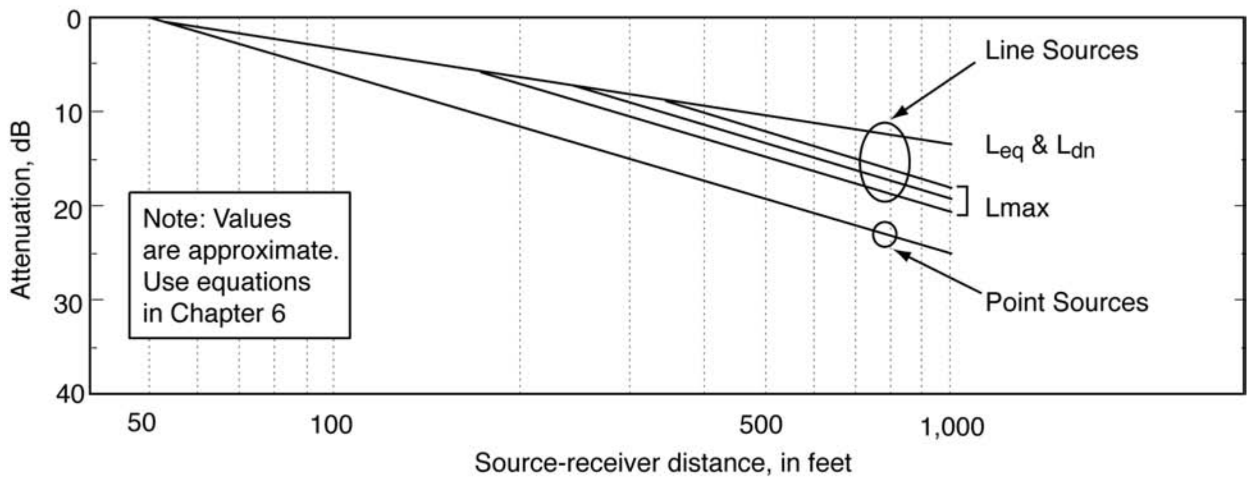

Figure 2-6. Attenuation due to Distance (divergence)

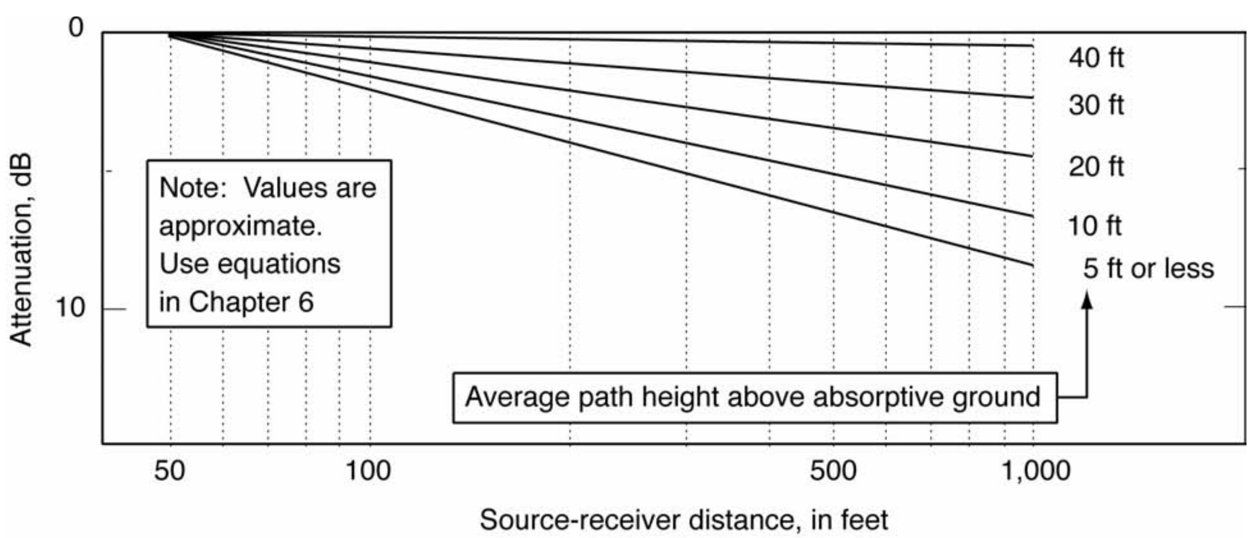

Figure 2-7. Attenuation due to Soft Ground

Shielding. Sound paths are sometimes interrupted by man-made noise barriers, by terrain, by rows of buildings, or by vegetation. Most important of these path interruptions are noise barriers, one of the best means of mitigating noise in sensitive areas. A noise barrier reduces sound levels at a receiver by breaking the direct line-of-sight between source and receiver with a solid wall (in contrast to vegetation, which hides the source but does not reduce sound levels significantly). Sound energy reaches the receiver only by bending (diffracting) over the top of the barrier, as shown in Figure 2-8, and this diffraction reduces the sound level at the receiver.

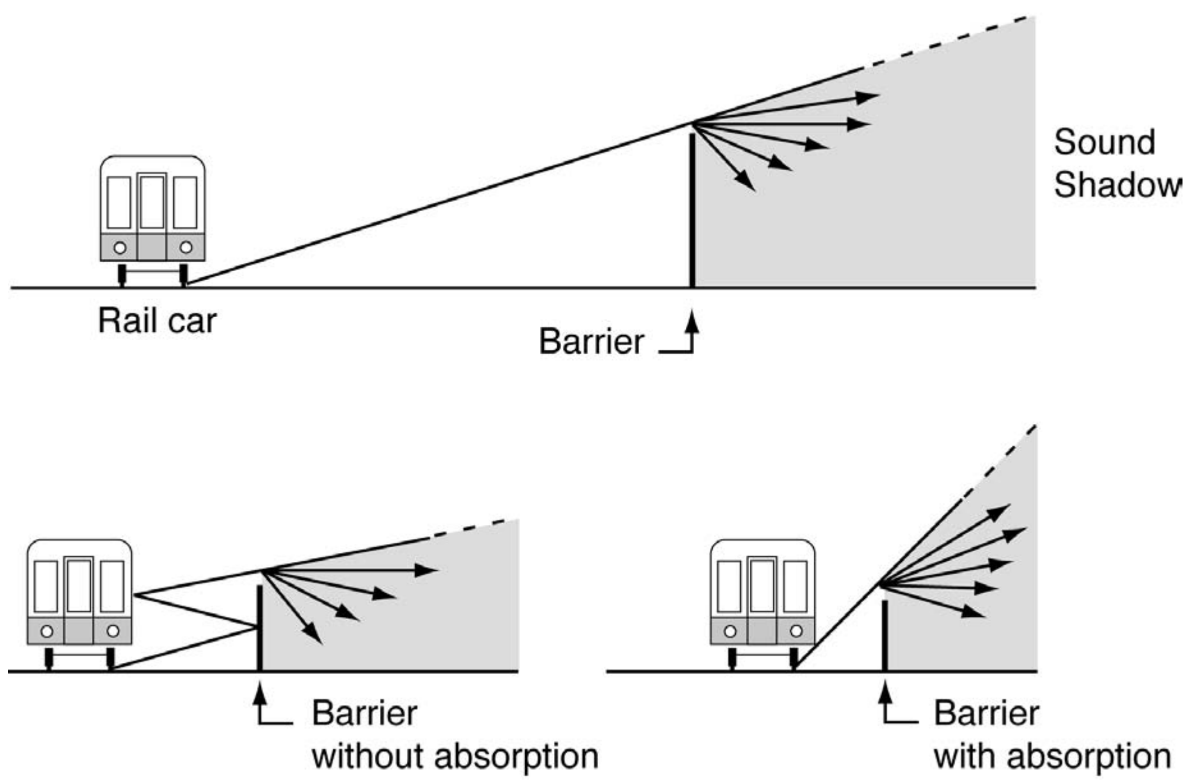

Figure 2-8. Noise Barrier Geometry

Sound barriers for transportation systems are typically used to attenuate noise at the receiver by 5 to 15 decibels, depending upon barrier height, length, and distance from both source and receiver. Barriers on structure, very close-in to the source, sometimes provide less attenuation than do barriers slightly more distant from the source, due to reverberation (multiple reflections) between the barrier and the body of the vehicle. However, this reverberation is often offset by increased barrier height, which is easy to obtain for such close-in barriers, and/or acoustical absorption on the source side of the barrier. Acoustical absorption is included as a mitigation option in Chapter 6. Equations for barrier attenuation, plus equations for other sound-path interruptions, also appear in Chapter 6.

Sometimes a portion of the source-to-receiver path is not through the air, but rather through the ground or through structural components of the receiver's building. Discussion of such ground-borne and structure-borne propagation is included in Chapter 7.

2.4 RECEIVER RESPONSE TO TRANSIT NOISE

This section contains an overview of receiver response to noise. It serves as background information for the noise impact criteria in Chapter 3.

Noise can interrupt ongoing activities and can result in community annoyance, especially in residential areas. In general, most residents become highly annoyed when noise interferes significantly with activities such as sleeping, talking, noise-sensitive work, and listening to radio or TV or music. In addition, some land uses, such as outdoor concert pavilions, are inherently incompatible with high noise levels.

Annoyance to noise has been investigated and approximate dose-response relationships have been quantified by the Environmental Protection Agency (EPA).[(1)] The selection of noise descriptors in this manual is largely based upon this EPA work. Beginning in the 1970s, the EPA undertook a number of research and synthesis studies relating to community noise of all types. Results of these studies have been widely published, and discussed and refereed by many professionals in acoustics. Basic conclusions of these studies have been adopted by the Federal Interagency Committee on Noise, the Department of Housing and Urban Development (HUD), the American National Standards Institute, and even internationally.[(2)(3)(4)(5)] Conclusions from this seminal EPA work remain scientifically valid to this day.

Figure 2-9 contains a synthesis of actual case studies of community reaction to newly introduced sources of noise in a residential urban neighborhood.[(6)] Plotted horizontally in the figure is the new noise's excess above existing noise levels. Both the new and existing noise levels are expressed as Day-Night Sound Levels, L_{dn}, discussed in Section 2.5. Plotted vertically is the community reaction to this newly introduced noise. As shown in the figure, community reaction varies from "No Reaction" to "Vigorous Action," for newly introduced noises averaging from "10 decibels below existing" to "25 decibels above existing." Note that these data points apply only when the stated assumptions are true. For other conditions, the points shift to the right or left somewhat.

In a large number of community attitudinal surveys, transportation noise has been ranked among the most significant causes of community dissatisfaction. A synthesis of many such surveys on annoyance appears in Figure 2-10.[(7)(8)] Plotted horizontally are different neighborhood noise exposures. Plotted vertically is the percentage of people who are *highly annoyed* by their particular level of neighborhood noise. As shown in the figure, the percentage of high annoyance is approximately 0 percent at 45 decibels, 10 percent around 60 decibels and increases quite rapidly to approximately 70 percent around 85 decibels. The scatter about the synthesis line is due to variation from community to community and to some wording differences in the various surveys. A recent update of the original research, containing several additional railroad, transit and street traffic noise surveys, has not significantly changed the shape of the original Schultz curve.[(8)(9)]

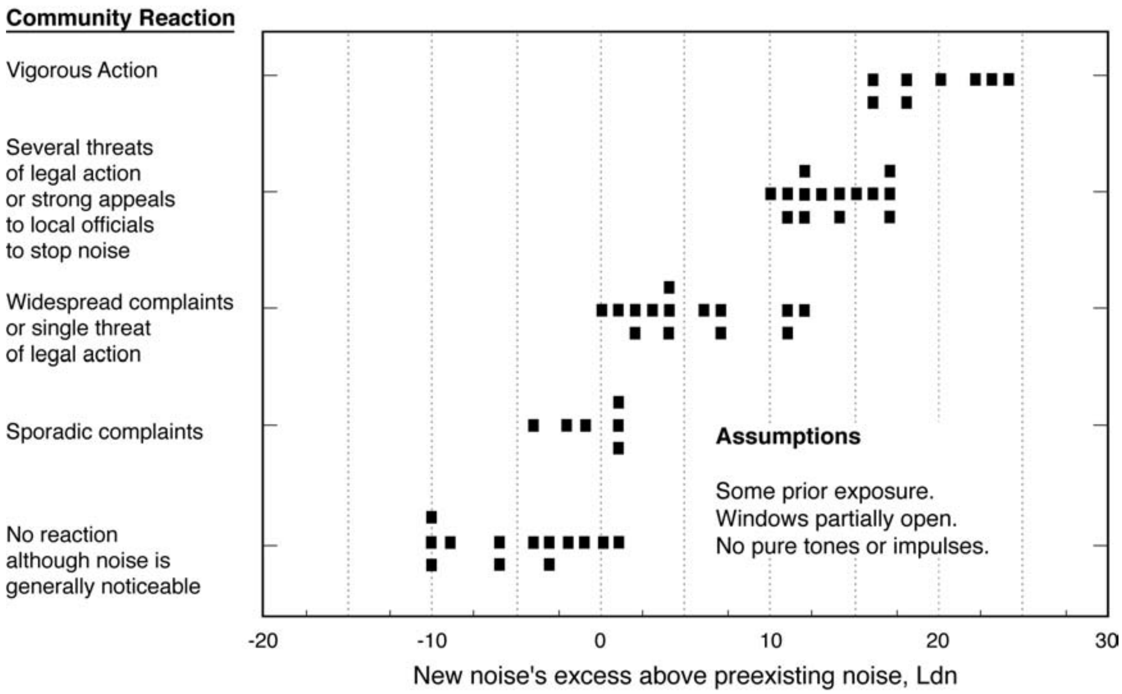

Figure 2-9. Community Reaction to New Noise, Relative to Existing Noise In a Residential Urban Environment

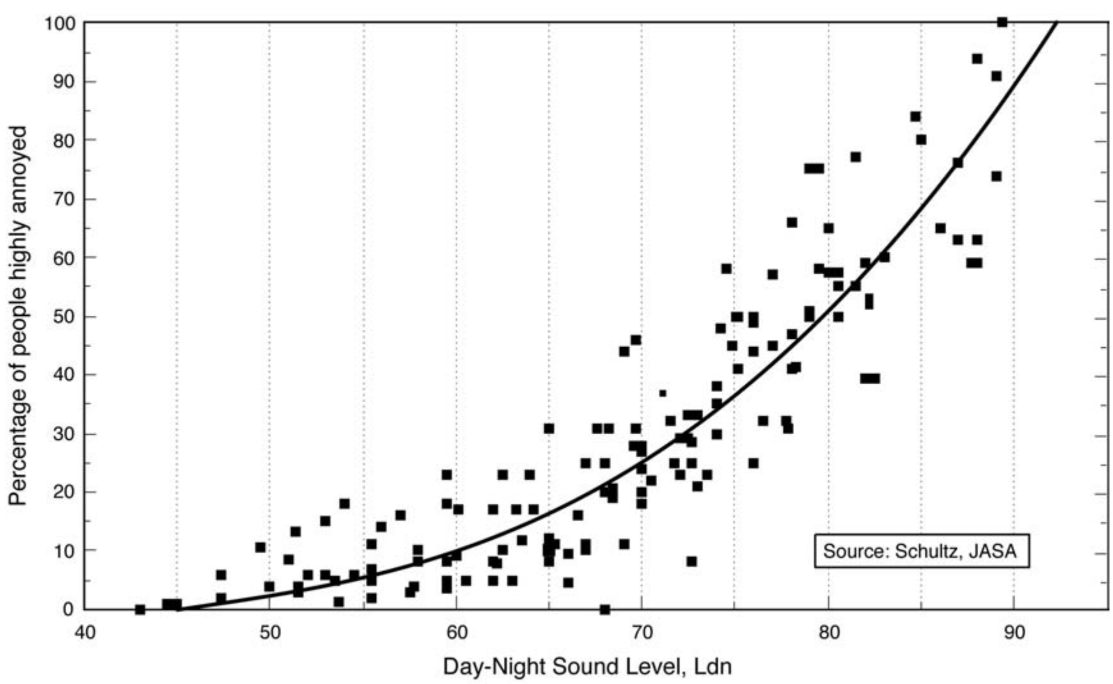

Figure 2-10. Community Annoyance Due to Noise

As indicated by these two figures, introduction of transit noise into a community may have two undesirable effects. First, it may significantly increase existing noise levels in the community, levels to which residents have mostly become accustomed. This effect is called "relative" noise impact. Evaluation of this effect is "relative" to existing noise levels; relative criteria are based upon noise increases above existing levels. Second, newly introduced transit noise may interfere with community activities, independent of existing noise levels; it may be simply too loud to converse or to sleep. This effect is called "absolute" noise impact, because it is expressed as a fixed level not to be exceeded and is independent of existing noise levels. Both these effects, relative and absolute, enter the assessment of transit noise impact in Chapters 4, 5 and 6. These two types of impact, relative and absolute, are merged into the transit noise criteria of Chapter 3.

2.5 DESCRIPTORS FOR TRANSIT NOISE

This manual uses the following single-number descriptors for transit-noise measurements, computations, and assessment. The terminology is consistent with common usage in the United States. For comparison with national standard terminology, see Appendix A.

The *A-weighted Sound Level,* which describes a receiver's noise at any moment in time.

The *Maximum Sound Level* (L_{max}) during a single noise event.

The *Sound Exposure Level (SEL)*, which describes a receiver's cumulative noise exposure from a single noise event.

The *Hourly Equivalent Sound Level* ($L_{eq}(h)$), which describes a receiver's cumulative noise exposure from all events over a one-hour period.

The *Day-Night Average Sound Level* (L_{dn}), which describes a receiver's cumulative noise exposure from all events over a full 24 hours, with events between 10pm and 7am increased by 10 decibels to account for greater nighttime sensitivity to noise.

This section illustrates all of these noise descriptors, in turn, and describes their particular application in this manual. Emphasized here are graphic illustrations rather than mathematical definitions to help the reader gain understanding and to see the interrelationships among descriptors.

2.5.1 A-weighted Sound Level: The Basic Noise Unit

The basic noise unit for transit noise is the A-weighted Sound Level. It describes a receiver's noise at any moment in time and is read directly from noise-monitoring equipment, with the "weighting switch" set on "A." Figure 2-11 shows some typical A-weighted Sound Levels for both transit and non-transit sources.

As is apparent from Figure 2-11, typical A-weighted Sound Levels range from the 30s to the 90s, where 30 is very quiet and 90 is very loud. The scale in the figure is labeled "dBA" to denote the way A-weighted Sound Levels are typically written, for example, 80 dBA. The letter "A" indicates that the sound has been filtered to reduce the strength of very low and very high-frequency sounds, as described in Section 2.1. Without this A-weighting, noise-monitoring equipment would respond to events people cannot hear, events such as high-frequency dog whistles and low-frequency seismic disturbances. On the average, each A-weighted sound level increase of 10 decibels corresponds to an approximate doubling of subjective loudness. Other frequency weighting such as B, C, and linear weights have been used to filter sound for specific applications.

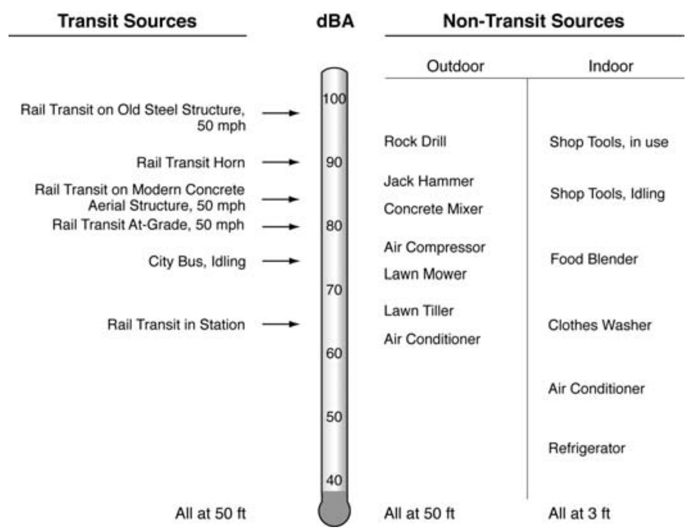

Figure 2-11. Typical A-weighted Sound Levels

A-weighted sound levels are adopted here as the basic noise unit because: (1) they can be easily measured, (2) they approximate our ear's sensitivity to sounds of different frequencies, (3) they match attitudinal-survey tests of annoyance better than do other basic units, (4) they have been in use since the early 1930s, and (5) they are endorsed as the proper basic unit for environmental noise by nearly every agency concerned with community noise throughout the world.

2.5.2 Maximum Sound Level (L_{max}) During a Single Noise Event

As a transit vehicle approaches, passes by, and then recedes into the distance, the A-weighted sound level rises, reaches a maximum, and then fades into the background noise. The maximum A-weighted sound level reached during this passby is called the Maximum Sound Level, abbreviated here as "L_{max}." For noise compliance tests of transient sources, such as moving transit vehicles under controlled conditions with smooth wheel and rail conditions, L_{max} is typically measured with the sound level meter's switch set on "fast." However, for tests of continuous or stationary transit sources, and for the general assessment of transit noise impact, it is usually more appropriate to use the "slow" setting. When set on "slow," sound level meters ignore some of the very transient fluctuations, which are unimportant to people's overall assessment of the noise. L_{max} is illustrated in Figure 2-12, where time is plotted horizontally and A-weighted sound level is plotted vertically.

Because L_{max} is commonly used in vehicle-noise specifications and because it is commonly measured for individual vehicles, equations are included in Appendices E and F to convert between L_{max} and the cumulative descriptors discussed below. However, L_{max} is not used as the descriptor for transit environmental noise impact assessment for several reasons. L_{max} ignores the number and duration of transit events, which are important to people's reaction to noise, and cannot be totalled into a one-hour or a 24-hour cumulative measure of impact. Moreover, the L_{max} is not conducive to comparison among different transportation modes. For example, noise descriptors used in highway noise assessments are L_{eq} and L_{10}, the noise level exceeded for 10 percent of the peak hour.

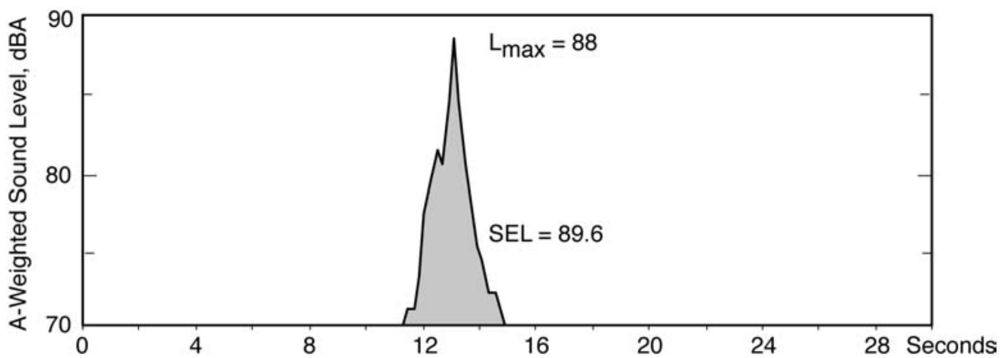

Figure 2-12. Typical Transit-Vehicle Passby

2.5.3 Sound Exposure Level (SEL): The Cumulative Exposure from a Single Noise Event

Shaded in Figure 2-12 is the noise "exposure" during a transit-vehicle passby. This exposure represents the total amount of sound energy that enters the receiver's ears (or the measurement microphone) during the vehicle passby. Figure 2-13 shows another noise event – this one within a fixed-transit facility as a transit bus is started, warmed up, and then driven away. For this event, the noise exposure is large due to *duration*.

The quantitative measure of the noise exposure for single noise events is the Sound Exposure Level, abbreviated here as "SEL" and shaded in both these figures. The fact that SEL is a cumulative measure means that (1) louder events have greater SELs than do quieter ones, and (2) events that last longer in time have greater SELs than do shorter ones. People react to the duration of noise events, judging longer events to be more annoying than shorter ones, assuming equal maximum A-Levels. Mathematically, the Sound Exposure Level is computed as:

$$\text{SEL} = 10\log_{10}\begin{bmatrix}\text{Total sound energy}\\ \text{during the event}\end{bmatrix}$$

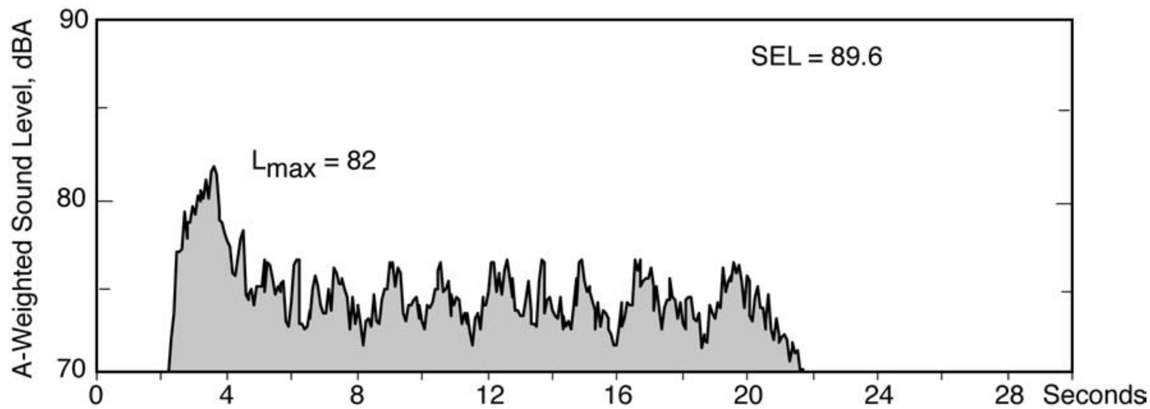

Figure 2-13. Typical Fixed-Facility Noise Event

Figure 2-14 repeats the previous time histories, but with a stretched vertical scale. The stretched scale corresponds to sound "energy" at any moment in time. Mathematically, sound energy is proportional to 10 raised to the (L/10) power, that is, $10^{(L/10)}$. The vertical scale has been stretched in this way because noise is "energy" exposure. Only in this way do the shaded zones properly correspond to the noise exposures that underlie the SEL. Note that the shaded zones in the two frames have equal numerical areas, corresponding to equal SELs for these two very different noise events.

Each frame of the figure also contains a tall, thin shaded zone of one-second duration. This tall zone is another way to envision SELs. Think of the original shaded zone being squeezed shorter and shorter in time, while retaining the same numerical area. As its duration is squeezed, its height must increase to keep the area constant. If an SEL shading is squeezed to a duration of one second, its height will then equal its SEL value; mathematically, its area is now $10^{(L/10)}$ times one second. Note that the resulting height of the squeezed zone depends both upon the L_{max} and the duration of the event -- that is, upon the total area under the original, time-varying A-Level. Often this type of "squeezing" helps communicate the meaning of SELs and noise doses to the reader.

SEL is used in this manual as the cumulative measure of each single transit-noise event because unlike L_{max}: (1) SEL increases with the duration of a noise event, which is important to people's reaction, (2) SEL, therefore, allows a uniform assessment method for both transit-vehicle passbys and fixed-facility noise events, and (3) SEL can be used to calculate the one-hour and 24-hour cumulative descriptors discussed below.

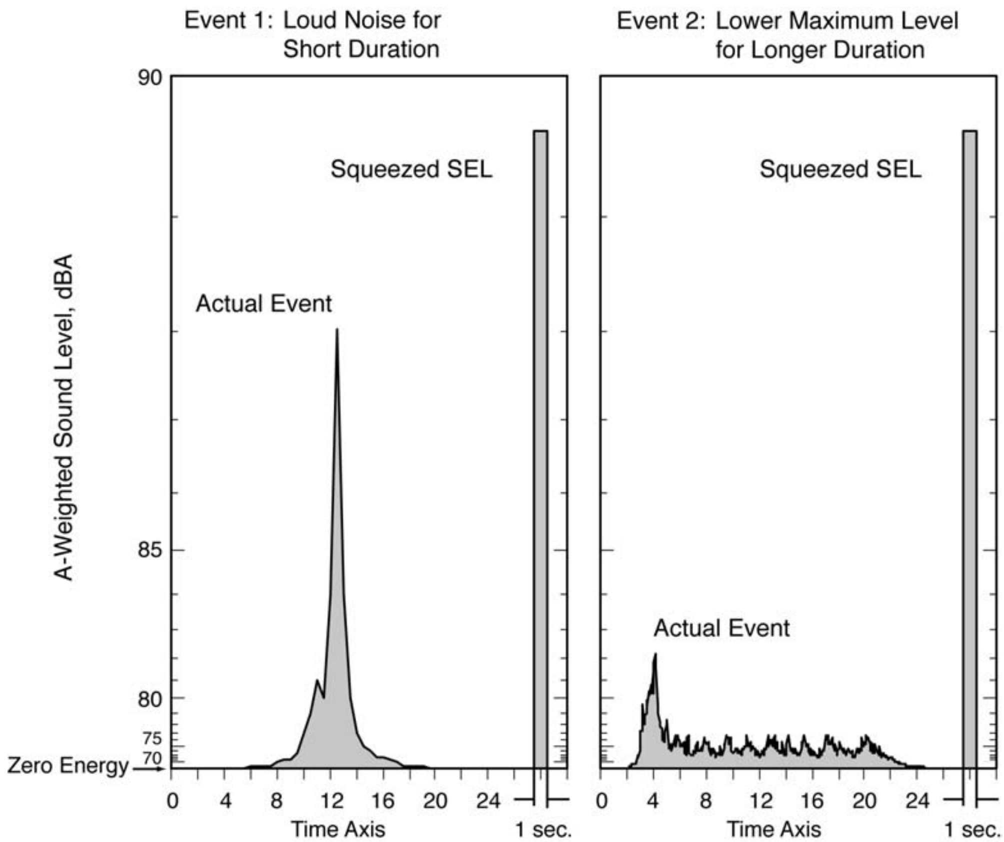

Figure 2-14. An "Energy" View of Noise Events

2.5.4 Hourly Equivalent Sound Level ($L_{eq}(h)$)

The descriptor for cumulative one-hour exposure is the Hourly Equivalent Sound Level, abbreviated here as "L_{eq}(h)." It is an hourly measure that accounts for the moment-to-moment fluctuations in A-weighted sound levels due to all sound sources during that hour, combined. Sound fluctuation is illustrated in the upper frame of Figure 2-15 for a single noise event such as a train passing on nearby tracks. As the train approaches, passes by, and then recedes into the distance, the A-weighted Sound Level rises, reaches a maximum, and then fades into the background noise. The area under the curve in this upper frame is the receiver's noise dose over this five-minute period.

The center frame of the figure shows sound level fluctuations over the one-hour period that includes the five-minute period from the upper frame. Now the area under the curve represents the noise exposure for one hour. Mathematically, the Hourly Equivalent Sound Level is computed as:

$$L_{eq}(hour) = 10\ \log_{10}\begin{bmatrix}\text{Total sound energy}\\ \text{during one hour}\end{bmatrix} - 35.6$$

Sound energy is totaled here over a full hour; it accumulates from all noise events during that hour. Subtraction of 35.6 from this one-hour sound exposure converts it into a time average, as explained in Section 2.5.6. In brief, if the actual fluctuating noise were replaced by a constant noise equal to this average value, the same total sound energy would enter the receiver's ears. This type of average value is "equivalent" in that sense to the actual fluctuating noise.

A useful, alternative way of computing L_{eq} due to a series of transit-noise events is:

$$L_{eq}(hour) = 10\ \log_{10}\begin{bmatrix}\text{Energy Sum of}\\ \text{all SELs}\end{bmatrix} - 35.6$$

This equation concentrates on the cumulative contribution of individual noise events, and is the fundamental equation incorporated into Chapters 5 and 6.

The bottom frame of Figure 2-15 shows the sound level fluctuations over a full 24-hour period. It is discussed in Section 2.5.5.

Figure 2-16 shows some typical hourly L_{eq}'s, both for transit and non-transit sources. As is apparent from the figure, typical hourly L_{eq}'s range from the 40s to the 80s. Note that these L_{eq}'s depend upon the number of events during the hour and also upon each event's duration, which is affected by vehicle speed. Doubling the number of events during the hour will increase the L_{eq} by 3 decibels, as will doubling the duration of each individual event.

Hourly L_{eq} is adopted here as the measure of cumulative noise impact for non-residential land uses (those not involving sleep) because: (1) L_{eq}'s correlate well with speech interference in conversation and on the telephone – as well as interruption of TV, radio and music enjoyment, (2) L_{eq}'s increase with the duration of transit events, which is important to people's reaction, (3) L_{eq}'s take into account the number of transit events over the hour, which is also important to people's reaction, and (4) L_{eq}'s are used by the Federal Highway Administration in assessing highway-traffic noise impact. Thus, this noise descriptor can be used for comparing and contrasting highway, transit and multi-modal alternatives. L_{eq} is computed for the loudest facility hour during noise-sensitive activity at each particular non-residential land use. Section 2.5.6 contains more detail in support of L_{eq} as the adopted descriptor for cumulative noise impact for non-residential land uses.

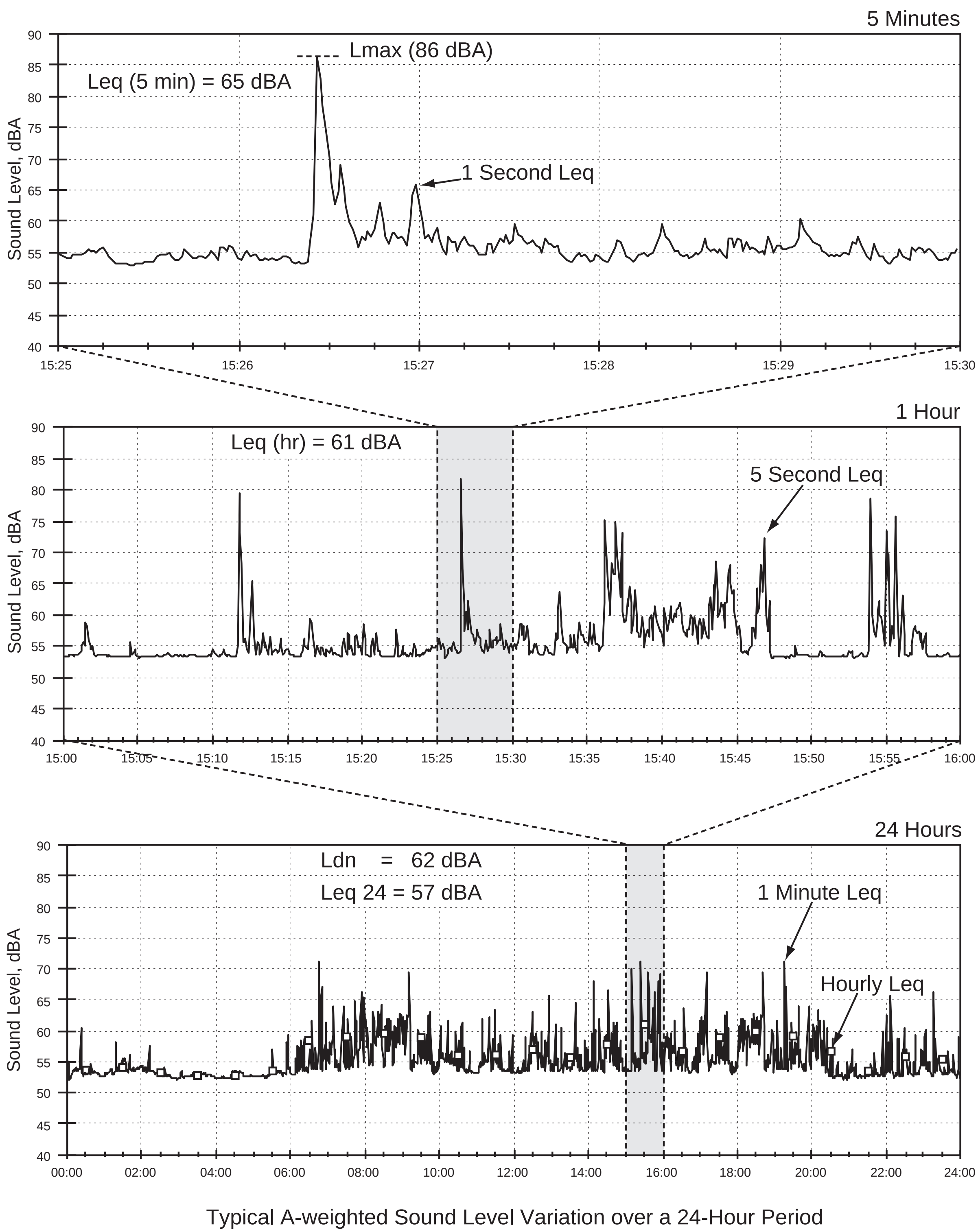

Figure 2-15. Example A-weighted Sound Level Time Histories

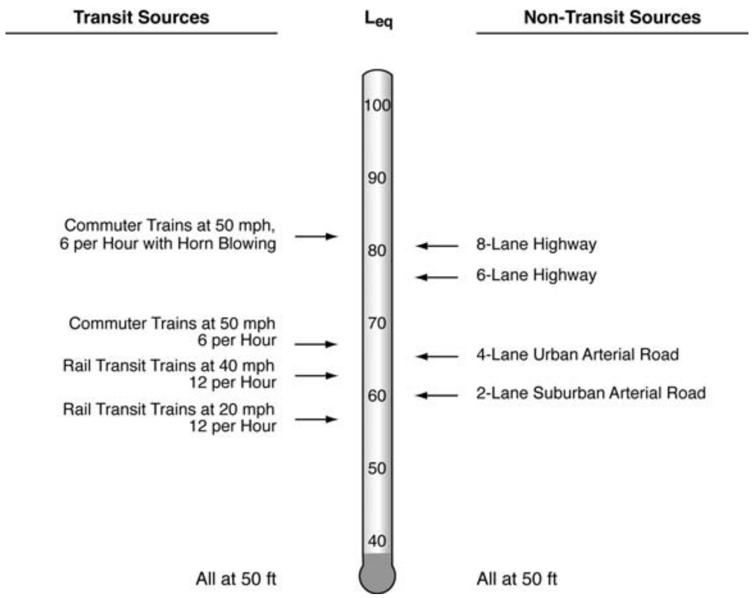

Figure 2-16. Typical Hourly L_{eq}'s

2.5.5 Day-Night Sound Level (L_{dn}): The Cumulative 24-Hour Exposure from All Events

The descriptor for cumulative 24-hour exposure is the Day-Night Sound Level, abbreviated here as "L_{dn}." It is a 24-hour measure that accounts for the moment-to-moment fluctuations in A-Levels due to all sound sources during 24 hours, combined. Such fluctuations are illustrated in the bottom frame of Figure 2-15. Here the area under the curve represents the receiver's noise dose over a full 24 hours. Note that some vehicle passbys occur at night in the figure, when the background noise is less. Mathematically, the Day-Night Level is computed as:

$$L_{dn} = 10\log_{10}\left[\begin{matrix}\text{Total sound energy}\\ \text{during 24 hours}\end{matrix}\right] - 49.4$$

where nighttime noise (10pm to 7am) is increased by 10 decibels before totaling.

Sound energy is totaled over a full 24 hours; it accumulates from all noise events during that 24 hours. Subtraction of 49.4 from this 24-hour dose converts it into a type of "average," as explained in Section 2.5.6. In brief, if the actual fluctuating noise were replaced by a constant noise equal to this average value, the same total sound energy would enter the receiver's ears.

An alternative way of computing L_{dn} from twenty-four hourly L_{eq}'s is:

$$L_{dn} = 10\log_{10}\left[\begin{matrix}\text{Energy sum of}\\ \text{24 hourly } L_{eq}\text{s}\end{matrix}\right] - 13.8$$

where nighttime L_{eq}'s are increased by 10 decibels before totaling, as in the previous equation. L_{dn} due to a series of transit-noise events can also be computed as:

$$L_{dn} = 10 \log_{10} \begin{bmatrix} \text{Energy sum of} \\ \text{all SELs} \end{bmatrix} - 49.4$$

assuming that transit noise dominates the 24-hour noise environment. Here again, nighttime SELs are increased by 10 decibels before totaling. This last equation concentrates upon individual noise events, and is the equation incorporated into Chapters 5 and 6.

Figure 2-17 shows some typical L_{dn}'s, both for transit and non-transit sources. As is apparent from the figure, typical L_{dn}'s range from the 50s to the 70s – where 50 is a quiet 24-hour period and 70 is an extremely loud one. Note that these L_{dn}'s depend upon the number of events during day and night separately – and also upon each event's duration, which is affected by vehicle speed.

L_{dn} is adopted here as the measure of cumulative noise impact for residential land uses (those involving sleep), because: (1) L_{dn} correlates well with the results of attitudinal surveys of residential noise impact, (2) L_{dn}'s increase with the duration of transit events, which is important to people's reaction, (3) L_{dn}'s take into account the number of transit events over the full twenty-four hours, which is also important to people's reaction, (4) L_{dn}'s take into account the increased sensitivity to noise at night, when most people are asleep, (5) L_{dn}'s allow composite measurements to capture all sources of community noise combined, (6) L_{dn}'s allow quantitative comparison of transit noise with all other community noises, (7) L_{dn} is the designated metric of choice of other Federal agencies (Department of Housing and Urban Development (HUD), Federal Aviation Administration (FAA), Environmental Protection Agency (EPA)) and also has wide acceptance internationally. Section 2.4.6 contains more detail in support of L_{dn} as the adopted descriptor for cumulative noise impact for residential land uses.

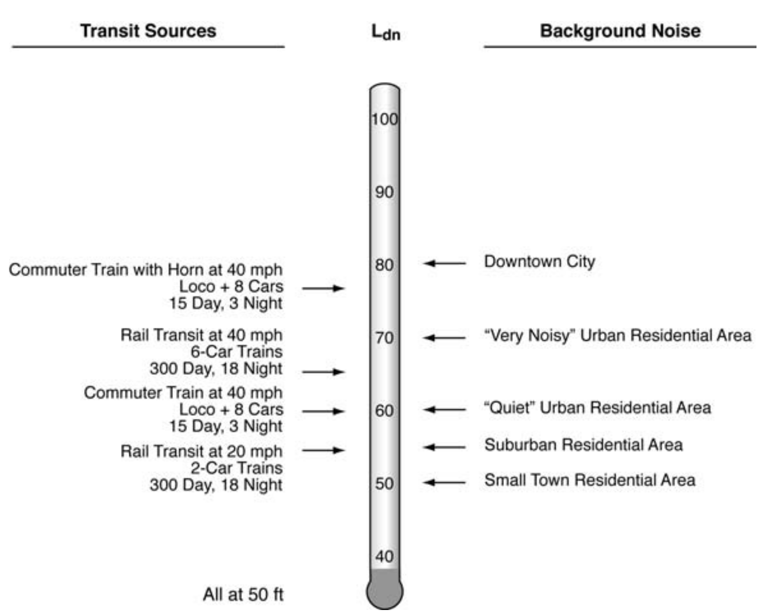

Figure 2-17. Typical L_{dn}'s

2.5.6 A Noise-Exposure Analogy for L_{eq} and L_{dn}

In Figure 2-15, the area under the curves represents noise exposure. An analogy between rainfall and noise is sometimes helpful to further explain these noise exposures.

The one-hour noise time history in the middle frame of the figure is analogous to one hour of rainfall, that is, the total accumulation of rain over this one-hour period. Note that every rain shower increases the one-hour accumulation. Also, note that heavier showers increase the amount more than do lighter ones, and longer showers increase the amount more than shorter ones. The same is true for noise: (1) every transit event increases the one-hour noise exposure; (2) loud events increase the noise exposure more than do quieter ones; and (3) events that stretch out longer in time increase the noise exposure more than shorter ones.

Unfortunately, the word "average" leaves many people with the impression that the maximum levels which attract their attention are being devalued or ignored. They are not. Just as all the rain that falls in the rain gauge in one hour counts toward the total, all sounds are included in the one-hour noise exposure that underlies L_{eq} and in the 24-hour noise exposure that underlies L_{dn}. None of the noise is being ignored, even though the L_{eq} and L_{dn} are often numerically lower than many maximum A-weighted Sound Levels. Noise exposure includes all transit events, all noise levels that occur during their time periods -- without exception. Every added event, even the quiet ones, will increase the noise exposure, and therefore increase L_{eq} and L_{dn}.

Neither the L_{eq} nor the L_{dn} is an "average" in the normal sense of the word, where introduction of a quiet event would pull down the average. Furthermore, similar to the effect of rainfall in watering a field or garden, scientific evidence strongly indicates that total noise exposure is the truest measure of noise impact. Neither the moment-to-moment rain rate nor the moment-to-moment A-level is a good measure of long-term effects.

Why not just compute transit noise impact on the basis of the highest L_{max} of the day, for example, as "loudest L_{max} equals 90 dBA?" If that were done, then there would be no difference in noise impact between a main trunk line and a suburban branch line; one passby per day would be no better than 100 per day, if the loudest level remained unchanged. Clearly such a reduction in number-of-passbys is a true benefit, so it should reduce the numerical measure of impact. It does with L_{eq} and L_{dn}, but not with L_{max}. In addition, if assessments were made just on the loudest passby, then one passby at 90 dBA would be worse than 100 passbys at 89 dBA. Clearly this is not true. Both L_{eq} and L_{dn} increase with the number of passbys, while L_{max} does not. Both the L_{eq} and the L_{dn} combine the number of passbys with each passby's L_{max} and duration, all into a cumulative noise exposure, with mathematics that make sense from an annoyance point of view. L_{eq} and L_{dn} mathematics produce results that correlate well with independent tests of noise annoyance from all types of noise sources.

In terms of individual passbys, here are some characteristics of both the L_{eq} and the L_{dn}:

When passby L_{max}'s increase:	→	Both L_{eq} and L_{dn} increase
When passby durations increase:	→	Both L_{eq} and L_{dn} increase
When the number of passbys increases:	→	Both L_{eq} and L_{dn} increase
When some operations shift to louder vehicles:	→	Both L_{eq} and L_{dn} increase
When passbys shift from day to night:	→	L_{dn} increases

All of these increases in L_{eq} and L_{dn} correlate to increases in community annoyance.

2.5.7 Summary of Noise Descriptors

In summary, the following noise descriptors are adopted in this manual for the computation and assessment of transit noise:

The **A-weighted Sound Level,** which describes a receiver's noise at any moment in time. It is adopted here as the basic noise unit, and underlies all the noise descriptors below.

The **Maximum Level (L_{max})** during a single noise event. The L_{max} descriptor is not recommended for transit noise impact assessment, but because it is commonly used in vehicle noise specifications and because it is commonly measured for individual vehicles, equations are included in Appendices E and F to convert between L_{max} and the cumulative descriptors adopted here.

The **Sound Exposure Level (SEL),** which describes a receiver's cumulative noise exposure from a single noise event. It is adopted here as the primary descriptor for the measurement of transit vehicle noise emissions, and as an intermediate descriptor in the measurement and calculation of both L_{eq} and L_{dn}.

The **Hourly Equivalent Sound Level (L_{eq}(h)),** which describes a receiver's cumulative noise exposure from all events over a one-hour period. It is adopted here to assess transit noise for non-residential land uses. For assessment, L_{eq} is computed for the loudest transit facility hour during the hours of noise-sensitive activity.

The **Day-Night Sound Level (L_{dn}),** which describes a receiver's cumulative noise exposure from all events over a full 24 hours. It may be thought of as a noise dose, totaled after increasing all nighttime A-Levels (between 10pm and 7am) by 10 decibels. Every noise event during the 24-hour period increases this dose, louder ones more than quieter ones, and ones that stretch out in time more than shorter ones. L_{dn} is adopted here to assess transit noise for residential land uses.

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3. NOISE IMPACT CRITERIA

This chapter presents the criteria to be used in evaluating noise impact from mass transit projects. Different approaches are taken depending on the type of project and the agencies involved. In general terms, these criteria describe the noise environment considered acceptable for a given situation. Because some projects are strictly transit projects while other projects are basically highway projects that include a transit component, two different sets of criteria are required as follows:

- **Rail and Bus Facilities:** This category includes all rail projects (e.g., rail rapid transit, light rail transit, commuter rail, and automated guideway transit), as well as fixed facilities such as storage and maintenance yards, passenger stations and terminals, parking facilities, substations, etc. Also included are rail transit projects built within a highway or railroad corridor. Certain bus facilities are included in this category, such as bus rapid transit (BRT) on separate roadways and bus operations on local streets and highways where the project does not include roadway construction or modification that significantly changes roadway capacity. The distinguishing feature in all these cases is that the existing noise levels generated by roadway traffic and other sources will not change as a result of the project; therefore the project noise is exclusively due to the new transit sources. For projects like these, FTA is generally the lead agency and the methodology from this manual is the appropriate approach.

- **Highway/Transit Projects:** Projects in this category involve transit as part of new highway construction or modifications to existing highways to increase carrying capacity. For these multi-modal projects, the Federal Highway Administration (FHWA) may be a joint lead agency with FTA, and the state department of transportation (DOT) would probably also be participating in the environmental impact assessment. Projects would involve traffic lanes with preferential treatment for buses or high-occupancy vehicles (HOVs). The distinguishing feature here is that the *project* noise includes a combination of highway and transit sources. Examples are: new highway construction providing general-purpose lanes as well as dedicated bus/HOV lanes and lane additions or reconfigurations on existing highways or arterials to accommodate buses/HOVs. These multi-modal projects fall into two sub-categories and the appropriate method to use for noise prediction and impact assessment depends on whether the highway noise dominates throughout day and night or the transit noise dominates during off-peak and late night hours.

If sufficient evidence shows that highway noise dominates, the methods of FHWA, including the latest authorized version of the Traffic Noise Model (TNM), should be used. Otherwise both FHWA and FTA prediction and impact assessment procedures should be used to determine whether neither, one or each mode causes impact and where mitigation is best applied.

Factors to consider when deciding which sub-category is appropriate for a given project are as follows:

- **Volume of traffic:** Major freeways and interstate highways often carry significant volumes of traffic throughout the day and night, such that the highway noise dominates at all times. Transit noise in this case may be insignificant in comparison, and the FHWA prediction method and noise abatement criteria would be used.
- **Traffic patterns:** Some highways and arterials serve primarily as commuter routes such that nighttime traffic diminishes considerably, while transit systems continue to operate well into the late hours. Here the dominant noise source at times of maximum sensitivity may be transit. Consequently, both FHWA and FTA prediction methods would be used.
- **Type of traffic:** Some highways and arterials may serve commuters during the daytime hours, but provide access to business centers by trucks at night. In this case, the roadway noise would likely continue to dominate and the FHWA methods would be appropriate.
- **Alignment configuration:** Elevation of the transit mode in the median or beside a busy highway may result in transit noise contributing more noise to nearby neighborhoods than a highway that may be partially shielded by rows of buildings adjacent to the right-of-way. In this case, both the FHWA and FTA methods should be used.

The noise impact criteria for rail and bus facilities are presented in Section 3.1. These criteria were developed specifically for transit noise sources operating on fixed guideways or at fixed facilities in urban areas. The criterion for the onset of Moderate Impact varies according to the existing noise level and the predicted project noise level, and is determined by the threshold at which the percentage of people highly annoyed by the project noise starts to become measurable. The corresponding criterion for Severe Impact similarly varies according to the existing noise level as well as the project noise level, but is determined by a higher, more significant percentage of people highly annoyed by project noise. Guidelines for the application of the criteria are included in Section 3.2, and background materials on the development of the criteria are included in Appendix B.

3.1 NOISE IMPACT CRITERIA FOR TRANSIT PROJECTS

The noise impact criteria for mass transit projects involving rail or bus facilities are shown graphically in Figure 3-1 and are tabulated in Table 3-1. The equations used to define these criteria are included in Appendix B. The criteria apply to all rail projects (e.g., rail rapid transit, light rail transit, commuter rail, and automated guideway transit) as well as fixed facilities such as storage and maintenance yards, passenger stations and terminals, parking facilities, and substations. They may also be used for bus projects operating on local streets and separate roadways built exclusively for buses. In contrast, for busways and HOV lanes which are to be integrated in existing highways (e.g., the addition of new lanes or the redesignation of existing lanes on a highway), FHWA's noise abatement criteria are the appropriate noise criteria to use. Likewise, if the project is a new highway involving both general-purpose and dedicated bus/HOV lanes, the FHWA approach is followed. The FHWA criteria are briefly summarized in Section 3.3.

3.1.1 Basis of Noise Impact Criteria

The noise impact criteria in Figure 3-1 and Table 3-1 are based on comparison of the existing outdoor noise levels and the future outdoor noise levels from the proposed project. They incorporate both absolute criteria, which consider activity interference caused by the transit project alone, and relative criteria, which consider annoyance due to the change in the noise environment caused by the transit project.

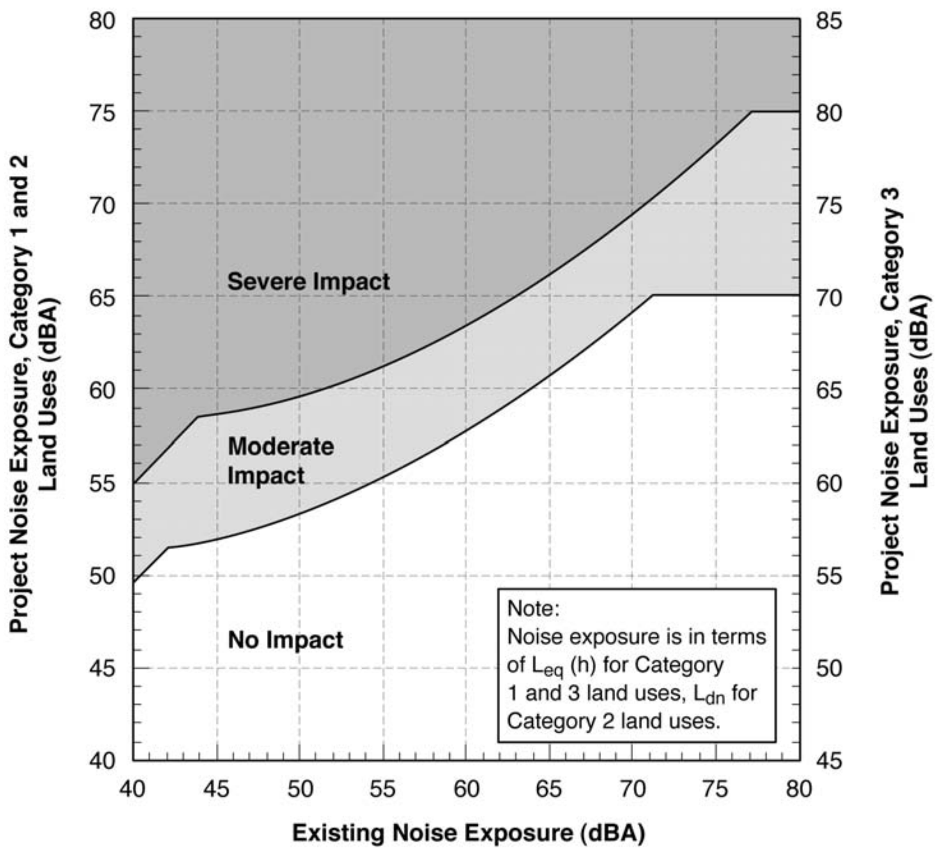

Figure 3-1. Noise Impact Criteria for Transit Projects

The noise criteria and descriptors depend on land use, as defined in Table 3-2. Further guidance on the definition of land use, the selection of the appropriate noise metric and the application of the criteria is given in Section 3.2 of this chapter, with more detailed guidelines given in Chapters 5 and 6.

Table 3-1. Noise Levels Defining Impact for Transit Projects

Existing Noise Exposure* $L_{eq}(h)$ or L_{dn} (dBA)	**Project Noise Impact Exposure,*** $L_{eq}(h)$ or L_{dn} (dBA)					
	Category 1 or 2 Sites			**Category 3 Sites**		
	No Impact	Moderate Impact	Severe Impact	No Impact	Moderate Impact	Severe Impact
<43	< Ambient+10	Ambient + 10 to 15	>Ambient+15	<Ambient+15	Ambient + 15 to 20	>Ambient+20
43	<52	52-58	>58	<57	57-63	>63
44	<52	52-58	>58	<57	57-63	>63
45	<52	52-58	>58	<57	57-63	>63
46	<53	53-59	>59	<58	58-64	>64
47	<53	53-59	>59	<58	58-64	>64
48	<53	53-59	>59	<58	58-64	>64
49	<54	54-59	>59	<59	59-64	>64
50	<54	54-59	>59	<59	59-64	>64
51	<54	54-60	>60	<59	59-65	>65
52	<55	55-60	>60	<60	60-65	>65
53	<55	55-60	>60	<60	60-65	>65
54	<55	55-61	>61	<60	60-66	>66
55	<56	56-61	>61	<61	61-66	>66
56	<56	56-62	>62	<61	61-67	>67
57	<57	57-62	>62	<62	62-67	>67
58	<57	57-62	>62	<62	62-67	>67
59	<58	58-63	>63	<63	63-68	>68
60	<58	58-63	>63	<63	63-68	>68
61	<59	59-64	>64	<64	64-69	>69
62	<59	59-64	>64	<64	64-69	>69
63	<60	60-65	>65	<65	65-70	>70
64	<61	61-65	>65	<66	66-70	>70
65	<61	61-66	>66	<66	66-71	>71
66	<62	62-67	>67	<67	67-72	>72
67	<63	63-67	>67	<68	68-72	>72
68	<63	63-68	>68	<68	68-73	>73
69	<64	64-69	>69	<69	69-74	>74
70	<65	65-69	>69	<70	70-74	>74
71	<66	66-70	>70	<71	71-75	>75
72	<66	66-71	>71	<71	71-76	>76
73	<66	66-71	>71	<71	71-76	>76
74	<66	66-72	>72	<71	71-77	>77
75	<66	66-73	>73	<71	71-78	>78
76	<66	66-74	>74	<71	71-79	>79
77	<66	66-74	>74	<71	71-79	>79
>77	<66	66-75	>75	<71	71-80	>80

* L_{dn} is used for land use where nighttime sensitivity is a factor; L_{eq} during the hour of maximum transit noise exposure is used for land use involving only daytime activities.

Table 3-2. Land Use Categories and Metrics for Transit Noise Impact Criteria

Land Use Category	Noise Metric (dBA)	Description of Land Use Category
1	Outdoor $L_{eq}(h)^*$	Tracts of land where quiet is an essential element in their intended purpose. This category includes lands set aside for serenity and quiet, and such land uses as outdoor amphitheaters and concert pavilions, as well as National Historic Landmarks with significant outdoor use. Also included are recording studios and concert halls.
2	Outdoor L_{dn}	Residences and buildings where people normally sleep. This category includes homes, hospitals and hotels where a nighttime sensitivity to noise is assumed to be of utmost importance.
3	Outdoor $L_{eq}(h)^*$	Institutional land uses with primarily daytime and evening use. This category includes schools, libraries, theaters, and churches where it is important to avoid interference with such activities as speech, meditation and concentration on reading material. Places for meditation or study associated with cemeteries, monuments, museums, campgrounds and recreational facilities can also be considered to be in this category. Certain historical sites and parks are also included.

* L_{eq} for the noisiest hour of transit-related activity during hours of noise sensitivity.

3.1.2 Defining the Levels of Impact

The noise impact criteria are defined by two curves which allow increasing project noise levels as existing noise increases up to a point, beyond which impact is determined based on project noise alone. Below the lower curve in Figure 3-1, a proposed project is considered to have no noise impact since, on the average, the introduction of the project will result in an insignificant increase in the number of people highly annoyed by the new noise. The curve defining the onset of noise impact stops increasing at 65 dB for Category 1 and 2 land use, a standard limit for an acceptable living environment defined by a number of Federal agencies. Project noise above the upper curve is considered to cause Severe Impact since a significant percentage of people would be highly annoyed by the new noise. This curve flattens out at 75 dB for Category 1 and 2 land use, a level associated with an unacceptable living environment. As indicated by the right-hand scale on Figure 3-1, the project noise criteria are 5 decibels higher for Category 3 land uses since these types of land use are considered to be slightly less sensitive to noise than the types of land use in categories 1 and 2.

Between the two curves the proposed project is judged to have Moderate Impact. The change in the cumulative noise level is noticeable to most people, but may not be sufficient to cause strong, adverse reactions from the community. In this transitional area, other project-specific factors must be considered to determine the magnitude of the impact and the need for mitigation, such as the existing level, predicted level of increase over existing noise levels and the types and numbers of noise-sensitive land uses affected.

Although the curves in Figure 3-1 are defined in terms of the project noise exposure and the existing noise exposure, it is important to emphasize that it is the increase in the cumulative noise – when project is added to existing – that is the basis for the criteria. The complex shapes of the curves are based on the considerations of cumulative noise increase described in Appendix B. To illustrate this point, Figure 3-2 shows the noise impact criteria for Category 1 and 2 land use in terms of the allowable increase in the cumulative noise exposure. The horizontal axis is the existing noise exposure and the vertical axis is the increase in cumulative noise level due to the transit project. The measure of noise exposure is L_{dn} for residential areas and L_{eq} for land uses that do not have nighttime noise sensitivity. Since L_{dn} and L_{eq} are measures of total acoustic energy, any new noise source in a community will cause an increase, even if the new source level is less than the existing level. Referring to Figure 3-2, it can be seen that the criterion for Moderate Impact allows a noise exposure increase of 10 dBA if the existing noise exposure is 42 dBA or less but only a 1 dBA increase when the existing noise exposure is 70 dBA

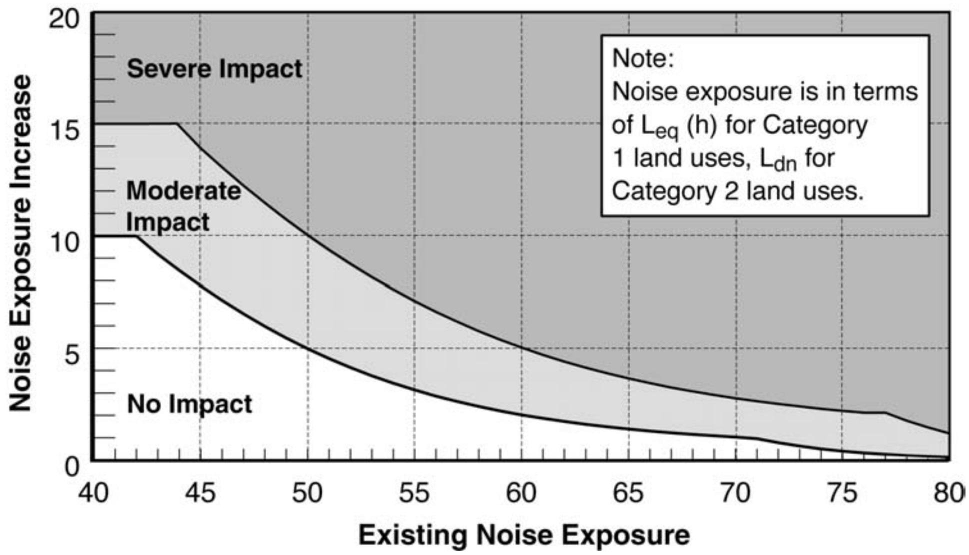

Figure 3-2. Increase in Cumulative Noise Levels Allowed by Criteria (Land Use Cat. 1 &2)

As the existing level of ambient noise increases, the allowable level of transit noise increases, but the total amount that community noise exposure is allowed to increase is reduced. This accounts for the unexpected result that a project noise exposure which is less than the existing noise exposure can still cause impact. This is clearer from the examples given in Table 3-3 which indicate the level of transit noise allowed for different existing levels of exposure.

Table 3-3. Noise Impact Criteria: Effect on Cumulative Noise Exposure

L_{dn} or L_{eq} in dBA (rounded to nearest whole decibel)			
Existing Noise Exposure	**Allowable Project Noise Exposure**	**Allowable Combined Total Noise Exposure**	**Allowable Noise Exposure Increase**
45	51	52	7
50	53	55	5
55	55	58	3
60	57	62	2
65	60	66	1
70	64	71	1
75	65	75	0

Any increase greater than shown above in Table 3-3 will cause Moderate Impact. This table shows that as the existing noise exposure increases from 45 dBA to 75 dBA, the allowed transit noise exposure increases from 51 dBA to 65 dBA. However, the allowed increase in the cumulative noise level decreases from 7 dBA to 0 dBA (rounded to the nearest whole decibel). The justification for this is that people already exposed to high levels of noise should be expected to tolerate only a small increase in the amount of noise in their community. In contrast, if the existing noise levels are quite low, it is reasonable to allow a greater change in the community noise for the equivalent difference in annoyance. It should be noted that these criteria are based on general community reactions to noise at varying levels which have been documented in scientific literature and do not account for specific community attitudinal factors which may exist.

3.2 APPLICATION OF NOISE IMPACT CRITERIA

3.2.1 Noise-Sensitive Land Uses

As indicated in Section 3.1.1, the noise impact criteria and descriptors depend on land use, designated either Category 1, Category 2 or Category 3. Category 1 includes uses where quiet is an essential element in their intended purpose, such as indoor concert halls or outdoor concert pavilions or National Historic Landmarks where outdoor interpretation routinely takes place. Category 2 includes residences and buildings where people sleep, while Category 3 includes institutional land uses with primarily daytime and evening use such as schools, places of worship and libraries.

The criteria do not apply to most commercial or industrial uses because, in general, the activities within these buildings are compatible with higher noise levels. They do apply to business uses which depend on quiet as an important part of operations, such as sound and motion picture recording studios.

Historically significant sites are treated as noise-sensitive depending on the land use activities. Sites of national significance with considerable outdoor use required for site interpretation would be in Category 1. Historical sites that are currently used as residences will be in Category 2. Historic buildings with indoor use of an interpretive nature involving meditation and study fall into Category 3. These include museums, significant birthplaces and buildings in which significant historical events occurred.

Most busy downtown areas have buildings which are historically significant because they represent a particular architectural style or are prime examples of the work of an historically significant designer. If the buildings or structures are used for commercial or industrial purposes and are located in busy commercial areas, they are not considered noise-sensitive and the noise impact criteria do not apply. Similarly, historical transportation structures, such as terminals and railroad stations, are not considered noise-sensitive land uses themselves. These buildings or structures are, of course, afforded special protection under Section 4(f) of the DOT Act and Section 106 of the National Historic Preservation Act. However, based strictly on how they are used and the settings in which they are located, these types of historical buildings are not considered noise-sensitive sites.

Parks are a special case. Whether a park is noise-sensitive depends on how it is used. Most parks used primarily for active recreation would not be considered noise-sensitive. However, some parks---even some in dense urban areas-–are used for passive recreation like reading, conversation, meditation, etc. These places are valued as havens from the noise and rapid pace of everyday city life and they should be treated as noise-sensitive. The noise sensitivity of parks should be determined on a case-by-case basis after carefully considering how each facility is used. The state or local agency with jurisdiction over the park should be consulted on questions about how the park is used and how much use it gets.

3.2.2 Noise Metrics

The basis for the development of the noise impact criteria (see Appendix B) has been the relationship between the percentage of highly annoyed people and the noise levels of their residential environment. Consequently, the criteria are centered around residential land use with the use of L_{dn} as the noise descriptor sensitive to noise intrusion at night. The noise criteria use L_{dn} for other land uses where nighttime sensitivity is a factor. The criteria are also to be applied to non-residential land uses that are sensitive to noise during daytime hours. Because the L_{dn} and the maximum daytime hourly L_{eq} have similar values for a typical noise environment, the daytime or early evening L_{eq} can be used for evaluating noise impact at locations where nighttime sensitivity is not a factor. For land use involving only daytime activities (e.g. churches, schools, libraries, parks) the impact is evaluated in terms of L_{eq}(h), defined as the L_{eq} for the noisiest hour of transit-related activity during which human activities occur at the noise-sensitive location.

However, due to the types of land use included in Category 3, the criteria allow the project noise for Category 3 sites to be 5 decibels greater than for Category 1 and Category 2 sites. With the exception of recreational facilities, which are clearly less sensitive to noise than Category 1 and 2 sites, Category 3 sites include primarily indoor activities and thus the criteria account for the noise reduction provided by the building structure.

Although the maximum noise level (L_{max}) is not used in this manual as the basis for the noise impact criteria for transit projects, it is a useful metric for providing a fuller understanding of the noise impact from some transit operations. Specifically, rail transit characteristically produces high intermittent noise levels which may be objectionable depending on the distance from the alignment. Thus, it is recommended that L_{max} information be provided in environmental documents to supplement the noise impact assessment and to help satisfy the "full disclosure" requirements of NEPA. Procedures for computing the L_{max} for a single train passby are provided in Appendix F.

3.2.3 Considerations in Applying the Noise Impact Criteria

The procedure for assessing impact is to determine the existing noise exposure and the predicted project noise exposure at a given site, in terms of either L_{dn} or L_{eq}(h) as appropriate, and to plot these levels on Figure 3-1. The location of the plotted point in the three impact ranges is an indication of the magnitude of the impact. For simplicity, noise impact can also be determined by using Table 3-1, rounding all noise level values to the nearest whole decibel before using the table. This level of precision is sufficient for determining the degree of noise impact at specific locations and should be adequate for most applications. However, a more precise determination of noise impact may be appropriate in some situations, such as when estimating the distance from the project to which noise impact extends. In such cases, more precise noise limits can be determined using the criteria equations provided in Appendix B.

In certain cases, the cumulative form of the noise criteria shown in Figure 3-2 must be used. These cases involve projects where changes are proposed to an existing transit system, as opposed to a new project in an area previously without transit. Such changes might include operations of a new type of vehicle, modifications of track alignments within existing transit corridors, or changes in facilities that dominate existing noise levels. In these cases, the existing noise sources change as a result of the project, and so it is not possible to define project noise separately from existing noise. An example would be a commuter rail corridor where the existing noise along the alignment is dominated by diesel locomotive-hauled trains, and where the project involves electrification with the resulting replacement of some of the diesel-powered locomotives with electric trains operating at increased frequency of service and higher speeds on the same tracks. In this case, the existing noise can be determined and a new future noise can be calculated, but it is not possible to describe what constitutes the “project noise.” For example, if the existing noise dominated by trains was measured to be an Ldn of 63 dBA at a particular location, and the new combination of diesel and electric trains is projected to be an Ldn of 65 dBA, the change in the noise exposure due to the project would be 2 dB. Referring to Figure 3-2, a 2 dB increase with an existing noise exposure of 63 dBA would be rated as a Moderate Impact. Normally the project noise is added to the existing noise to come up with a new cumulative noise, but in this case, the existing noise was dominated by a source that changed due to the project so it would be incorrect to add the project noise to the existing noise. Consequently, the existing noise determined by measurement is compared with a new calculated future noise, but a description of what constitutes the actual project is complex.

Another example would be a rail corridor where a track is added and grade crossings are closed, potentially resulting in a change in train location and horn operation. Here the “project noise” results from moving some trains closer to some receivers, away from others, and elimination of horns. In this case, the change in noise level is more readily determined than the noise from the actual project elements. In all cases, Figure 3-2 for changes in a transit system results in the same assessment of impact as Figure 3-1 for development of transit facilities in a new area.

For residential land use, the noise criteria are to be applied outside the *building locations* at noise-sensitive areas with frequent human use including outdoor patios, decks, pools, and play areas . If none, the criteria should be applied near building doors and windows. For parks and other significant outdoor use, apply criteria at the *property line*. However, for locations where land use activity is solely indoors, noise impact may be less significant if the outdoor-to-indoor reduction is greater than for typical buildings (about 25 dB with windows closed). Thus, if the project sponsor can demonstrate indoor activity only, mitigation may not be needed.

It is important to note that the criteria specify a comparison of future project noise with existing noise and *not* with projections of future "no-build" noise exposure (i.e. without the project). Furthermore, it should be emphasized that it is not necessary nor recommended that existing noise exposure be determined by measuring at every noise-sensitive location in the project area. Rather, the recommended approach is to characterize the noise environment for "clusters" of sites based on measurements or estimates at representative locations in the community. In view of the sensitivity of the noise criteria to the existing noise exposure, careful characterization of pre-project ambient noise is important. Guidelines for selecting representative receiver locations and determining ambient noise are provided in Appendix C and Appendix D, respectively.

3.2.4 Mitigation Policy Considerations

The following statutes and implementing regulations concerning environmental protection guide the Federal Transit Administration’s decisions on the need for noise mitigation. While the environmental impact statement requirement in the National Environmental Policy Act (NEPA) is widely known, the statute also establishes a broad mandate for Federal agencies to incorporate environmental protection and enhancement measures into the programs and projects they help finance.(1) In conjunction with FHWA, FTA has issued a regulation implementing NEPA which sets out the agencies' general policy on environmental mitigation. It states that measures necessary to mitigate adverse impacts are to be incorporated into the project and, further, that such measures are eligible for Federal funding when FTA determines that ". . . the proposed mitigation represents a reasonable public expenditure after considering the impacts of the action and the benefits of the proposed mitigation measures."(2)

While NEPA establishes broad policy, a more explicit statutory mandate for mitigating adverse noise impacts is set forth in the Federal Transit Laws.(3) Before approving a construction grant, FTA must make a finding that ". . . (ii) the preservation and enhancement of the environment, and the interest of the community in which a project is located, were considered; and (iii) no adverse environmental effect is likely to result from the project, or no feasible and prudent alternative to the effect exists and all reasonable steps have been taken to minimize the effect." (49 U.S.C. 5324(b)(3)(A)).

3.2.5 Determining the Need for Noise Mitigation

Because intrusive noise is frequently among the most significant environmental concerns of planned mass transit projects, FTA, working with the project sponsor, makes every reasonable effort to reduce predicted noise to levels deemed acceptable for affected noise-sensitive land uses. The noise impact criteria in Chapter 3 provide the framework for identifying the magnitude of the impact. Then, the need for noise mitigation is determined based on the magnitude and consideration of factors specifically related to the proposed project and affected land uses.

Project-generated noise in the “No Impact” range is not likely to be found annoying. Noise projections in this range are considered acceptable by FTA and mitigation is not required. At the other extreme, noise projections in the “Severe” range represent the most compelling need for mitigation. However, before mitigation measures are considered, the project sponsor should first evaluate alternative locations/alignments to determine whether it is feasible to avoid Severe impacts altogether. In densely populated urban areas, this evaluation of alternative locations may reveal a trade-off of one group of impacted noise-sensitive sites for another – especially for surface rail alignments passing through built-up areas. However, this is not always the case; projects which are characterized more as point sources of noise than line sources often present a greater opportunity for selecting alternative sites. Note that this guidance manual and FTA's environmental impact regulation both attempt to encourage project sites which are compatible with surrounding development. The regulation designates certain projects as categorical exclusions when located in areas with compatible land use (e.g., bus terminals and maintenance facilities located in areas with mostly commercial or industrial use). In this manual, the list of noise-sensitive land uses in Chapter 3 does not include most commercial and industrial land uses, thus obviating the need to consider noise mitigation in areas with predominantly commercial or industrial use.

If it is not practical to avoid Severe impacts by changing the location of the project, mitigation measures must be considered. Impacts in this range have the greatest adverse impact on the community; thus there is a presumption by FTA that mitigation will be incorporated in the project unless there are truly extenuating circumstances which prevent it. The goal is to gain substantial noise reduction through the use of mitigation measures, not simply to reduce the predicted levels to just below the Severe Impact threshold. Since FTA has to determine whether the mitigation is feasible and prudent, the evaluation of specific measures should include the noise reduction potential, the cost, the effect on transit operations and maintenance, and any other relevant factors, for example, any new environmental impacts which may be caused by the measure. A thorough evaluation enables FTA to make the findings required by section 5324(b) of the Federal Transit Laws and possibly other statutes, such as Section 4(f) of the DOT Act or Section 106 of the National Historic Preservation Act.

Projected noise levels in the Moderate Impact range will also require consideration and adoption of mitigation measures when it is considered reasonable. The range of Moderate Impact delineates an area where project planners are alerted to the potential for adverse impacts and complaints from the community and must then carefully consider project specifics as well as details concerning the affected properties in determining the need for mitigation. While impacts in this range are not of the same magnitude as Severe impacts, there can be circumstances regarding the factors outlined below which make a compelling argument for mitigation.

The following considerations will help project planners and FTA staff in reaching these determinations:

- The number of noise-sensitive sites affected at this level. A row or cluster of residences adjacent to a rail transit line establishes a greater need for mitigation than one or several isolated residences in a mixed-use area.
- The increase over existing noise levels. Since the noise impact criteria are delineated as bands or ranges, project noise can vary 5-7 decibels within the band of Moderate Impact at any specific ambient noise level. If the project and ambient noise plot falls just below the Severe range (in Figure 3-1), the need for mitigation is strongest. Similarly, if the plot falls just above the No Impact threshold, there is less need.
- The noise sensitivity of the property. Table 3-2 gives a comprehensive list of noise-sensitive land uses; yet there can be differences in noise sensitivity depending on individual circumstances. For example, parks and recreational areas vary in their sensitivity depending on the type of use they experience (active vs. passive recreation) and the settings in which they are located.
- Effectiveness of the mitigation measure(s). What is the magnitude of the noise reduction that can be achieved? Are there conditions which limit effectiveness, for example, noise barrier effectiveness for a multi-story apartment building?
- Neighborhoods with ambient noise levels already heavily influenced by transportation noise, especially the same type of noise source as the project. Ambient levels above 65 dB (Ldn) are considered “normally unsatisfactory” for residential land use by the Department of Housing and Urban Development. Thus there is a stronger need for mitigation if a project is proposed in an area currently experiencing high noise levels from surface transportation. An example would be a project where additional commuter tracks are added to a very busy rail corridor. If this project were placed in a less noisy environment, the impact assessment might show a Severe Impact, but when the project is overlaid on an existing noisy environment, the result could be Moderate Impact or, possibly, No Impact. However, in this situation the new cumulative noise environment may be very objectionable because people will not be compartmentalizing the existing noise versus the new noise and reacting only to the new noise. In this circumstance impacts predicted in the Moderate range should be treated as if they were Severe.
- Community views. This manual provides the methodology to make an objective assessment of the need for noise mitigation. However, the views of the community cannot be overlooked. The NEPA compliance process provides the framework for hearing the community's concerns about a proposed project and then making a good-faith effort to address those concerns. Many projects can be expected to have projected noise levels within the Moderate Impact range and decisions regarding mitigation should be made only after considering input from the affected public, relevant government agencies and community organizations. There have been cases where the solution to the noise problem – a sound barrier – was rejected by community members because of perceived adverse visual effects.
- Special protection provided by law. Section 4(f) of the DOT Act and Section 106 of the National Historic Preservation Act come into play frequently during the environmental review of transit projects. Section 4(f) protects historic sites and publicly-owned parks, recreation areas and wildlife refuges. Section 106

protects historic and archeological resources. In general, noise in the Moderate Impact range would not substantially impair the use of a property afforded protection under Section 4(f). Thus it would not constitute a "constructive use" as this term is defined in Section 4(f) regulations.   In the Section 106 process protecting historic and cultural properties, Moderate Impact may or may not be considered an "adverse effect" depending on the individual circumstances. Historic properties are only noise-sensitive based on how they are used. As previously noted, some historic properties are not noise-sensitive at all. It is possible, though, that a historic building housing sensitive uses like a library or museum could be adversely affected by noise in the Moderate range. The regulatory processes stemming from these statutes require coordination and consultation with agencies and organizations having jurisdiction over these resources. Their views on the project's impact on protected resources are given careful consideration by FTA and the project sponsor, and their recommendations may influence the decision to adopt noise reduction measures.

Cost is an important consideration in reaching decisions about noise mitigation measures. One guideline for gauging the reasonableness of the cost of mitigation is the state DOT's procedures on the subject. Each state has established its own cost threshold for determining whether installation of sound barriers for noise reduction is a reasonable expenditure. The states' cost thresholds range from $15,000 to $50,000 per benefited residence, with a cost-weighted average of $24,000 per residence. Several airport authorities have placed limits on the costs they will incur for sound insulation per residence for homes that are impacted according to Federal Aviation Administration criteria. These costs range from $20,000 to $35,000 per residence (2002 dollars). As a starting point, FTA considers the midpoints of these ranges--$25,000 to $30,000 per benefited residence--to be reasonable from the standpoint of cost. It should be noted, though, that higher costs may be justified depending on the specific set of circumstances applying to a project.

The decision to include noise mitigation in a project is made by FTA after public review of the environmental document. This decision is reached in consultation with the project sponsor. If mitigation measures are deemed necessary to satisfy the statutory requirements, they will be incorporated as an integral part of the project, and subsequent grant documents will reference these measures as contractual obligations on the part of the project sponsor. FTA is required by law to ensure that the project sponsor complies with all design and mitigation commitments contained in the environmental document (23 U.S.C. 139 (c) (4)). There are some differences as to how noise mitigation and vibration mitigation are handled in EISs. The different approaches are discussed in Chapter 13.

3.3 NOISE IMPACT CRITERIA FOR HIGHWAY/TRANSIT PROJECTS

Under specific circumstances, noise impact from a mass transit project should be determined using FHWA's assessment procedures and noise abatement criteria, instead of the FTA procedures and guidelines. General guidance is given at the beginning of this chapter. FHWA methods are required for highway/transit projects (or portions of projects) that meet the following conditions:

- The project is jointly funded with FHWA and the state DOT is assisting with the impact assessment.

- The mass transit portions of the project are directly adjacent to (or within) FHWA-funded portions of the project.
- The project is located where highway noise predominates throughout the day and night.

In contrast, FTA methods should be used for other portions of the project that do not meet these requirements—for example, portions where the transit right-of-way diverges from the highway, or associated bus terminals and other transit facilities off the highway right-of-way.

In some cases, both FHWA and FTA methods should be used, such as when both highway and transit cause significant noise, but at different times of day. An example would be a transit alignment that shares the right-of-way with an arterial road with heavy traffic. Traffic noise may dominate during the peak commuting hours but not during off-peak periods when transit continues to operate. In this case, both sets of criteria would be used to determine whether impact occurs from neither, one or each mode.

In following the FHWA procedures, only loudest-hour noise levels are computed and assessed. These noise levels may be computed either with (1) the hourly calculation method in Chapter 6 of this manual or (2) the FHWA Traffic Noise Model (TNM). Often this choice of computation methods will depend upon the assistance provided by the FHWA-funded staff on the project. Even if methods in Chapter 6 are used for computation, however, the resulting noise levels must be assessed with FHWA methods under these circumstances.

FHWA criteria appear in the Code of Federal Regulations,[4, 5] which is supplemented by a separate FHWA policy and guidance document.[6] All three documents are available at: www.fhwa.dot.gov/environment/noise. The following sections summarize these FHWA criteria and their use.

3.3.1 FHWA Impact Criteria

FHWA requires assessment at affected existing activities, developed lands, and undeveloped lands for which development is planned, designed and programmed. At these locations, traffic noise is computed for the project's design year, which is often 20 years from the onset of environmental studies. This computation uses the traffic for the hour with the worst impact "on a regular basis." In practice, traffic engineers often predict traffic volumes and speeds at several times during an average design-year day, and then noise computations decide the "worst" hour. Because assessment is for a single hour rather than for a 24-hour period, the noise metric is an hourly one, $L_{eq}(h)$.

FHWA requires two assessments of noise impact: one related to land-use type and the other to existing noise level.

First, noise impact occurs when predicted traffic noise levels "approach or exceed" the applicable Noise Abatement Criteria (NAC) in Table 3-4. FHWA allows individual state highway agencies to define "approach or exceed." As a result, the actual impact criteria are all 1 to 3 decibels lower than the values in this table. Contact specific state highway agencies to learn their definition of "approach or exceed." In addition, FHWA requires that primary consideration be given to exterior areas (Activity Categories A, B and C). The table's interior NAC (Category E) is used only where either (1) there are no affected exterior activities or (2) exterior activities are not impacted because they are far from or are physically shielded from the roadway.

Table 3-4. FHWA Noise Abatement Criteria

Activity Category	Hourly A-weighted Sound Level (dBA)		Description of Activity Category
	$L_{eq}(h)$	$L_{10}(h)$	
A	57 Exterior	60 Exterior	Lands on which serenity and quiet are of extraordinary significance and serve an important public need and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose.
B	67 Exterior	70 Exterior	Picnic areas, recreation areas, playgrounds, active sports areas, parks, residences, motels, hotels, schools, churches, libraries, and hospitals.
C	72 Exterior	75 Exterior	Developed lands, properties, or activities not included in Categories A or B above.
D	--	--	Undeveloped lands.
E	52 Interior	55 Interior	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals, and auditoriums.

Note: Noise mitigation must be studied where predicted traffic noise levels approach or exceed the values in this table. Individual state highway agencies define "approach or exceed" within their states. As a result, the actual criteria that trigger mitigation studies are all 1 to 3 decibels lower than the values in this table. Contact specific state highway agencies to learn their definition of "approach or exceed."

Second, noise impact occurs when predicted traffic noise levels substantially exceed existing noise levels (future no-build noise levels are not used here). FHWA allows individual state highway agencies to define "substantially exceed." Contact specific state highway agencies to learn their definition of "substantially exceed" (a criterion of 10 decibels above existing levels is the most common).

3.3.2 Use of Impact Criteria

When impact occurs by either method of assessment, NAC or substantial increase, FHWA requires study of the following noise abatement measures: traffic management, alteration of horizontal and vertical alignments, noise barriers whether within or outside the right-of-way, acquisition of buffer zones, noise insulation of public-use or nonprofit institutional structures. Measures that are both feasible and reasonable must be incorporated into the project.

Feasibility. Feasibility deals with engineering considerations. To be feasible, an abatement measure must first meet all safety, maintenance and other accepted design requirements. After safety/maintenance issues are resolved, FHWA considers a noise-abatement measure to be feasible if that measure can technically achieve a noise reduction of 5 decibels or more, given its physical aspects and those of its surroundings. Such acoustical feasibility is objective, not subjective. It is a matter of acoustical computation, depending upon such factors as topography, location of other nearby sound sources, and location of driveways, ramps, and cross streets.

Reasonableness. In the context of FHWA regulations, reasonableness is a more subjective matter. Reasonableness implies that common sense and good judgment were applied in arriving at a decision concerning the abatement measure. FHWA requires that: (1) the views of the impacted residents be a major consideration, and (2) the overall noise abatement benefits outweigh the overall adverse social, economic, and environmental effects, as well as the abatement cost.

Reasonableness also depends upon community wishes, aesthetics, community desires for their surrounding view, projected noise-level increase above existing levels, projected noise-level increase above future no-build levels, amount of development that occurred before and after the initial construction of the highway, type of protected development, effectiveness of land-use controls by the local jurisdiction, construction effects of the abatement measure on the natural environment, and the potential ability of the abatement measure to reduce noise during project construction, as well. Many state highway agencies restrict or expand this list of factors.

Reasonableness also depends upon cost effectiveness. FHWA requires state highway agencies to develop quantitative cost-effectiveness guidelines, which generally consider abatement cost and the number of people protected by the abatement measure—and sometimes also the amount of noise reduction provided by the abatement measure.

REFERENCES

1. United States Congress, National Environmental Policy Act of 1969; P.L. 91-190, January 1, 1970.

2. U.S. Department of Transportation, Federal Transit Administration and Federal Highway Administration, "Environmental Impact and Related Procedures." Final Rule, 52 Federal Register 32646-32669; August 28, 1987 (23 Code of Federal Regulations 771.105(d)).

3. The Federal Transit Laws, 49 U.S.C. 5301 et seq.

4. Federal Highway Administration. *23 CFR Part 772: Procedures for Abatement of Highway Traffic Noise and Construction Noise -- Final rule*. Federal Register, Vol. 62, No. 154, 11 August 1997.

5. Federal Highway Administration. *23 CFR Part 772: Procedures for Abatement of Highway Traffic Noise and Construction Noise*. Federal Register, Vol. 67, No. 58, 26 March 2002 (provides further background).

6. Federal Highway Administration. *Highway Traffic Noise Analysis and Abatement Policy and Guidance.* Office of Environment and Planning, Noise and Air Quality Branch, Washington DC, June 1995 (71 pages).

4. NOISE SCREENING PROCEDURE

The noise screening procedure is designed to identify locations where a project may cause noise impact. If no noise-sensitive land uses are present within a defined area of project noise influence, then no further noise assessment is necessary. This approach allows the focusing of further noise analysis on locations where impacts are likely. The screening procedure takes account of the noise impact criteria, the type of project and noise-sensitive land uses. For screening purposes, all noise-sensitive land uses are considered to be in a single category.

4.1 SCREENING DISTANCES

The distances given in Table 4-1 delineate a project's noise study area. The areas defined by the screening distances are meant to be sufficiently large to encompass all potentially impacted locations. They were determined using relatively high-capacity scenarios for a given project type. Data used in the calculations are listed in Table 4-2 as assumptions based on operations of a given project type and using the lowest threshold of impact, 50 dB, from the criteria curves in Figure 3-1. These distances can be scaled up or down for different sized projects by use of the methodology in Chapter 5, General Noise Assessment. FTA provides an Excel spreadsheet program to assist in these adjustments. The Federal Railroad Administration horn noise model is used to develop the screening distance at commuter rail grade crossings where horns and warning bells are used.(1)

The noise screening procedure is applicable to all types of transit projects. The types of projects listed in Table 4-1 cover nearly all of the kinds of projects expected to undergo environmental assessment. Clarification can be obtained from FTA on any special cases that are not represented in the table.

4.2 STEPS IN SCREENING PROCEDURE

The screening method works as follows:

- Determine the type of project and locate on Table 4-1.

- Review assumptions in Table 4-2. Make adjustments in screening distances to suit the project through the use of the methodology in Chapter 5, or the FTA spreadsheet model. The appropriate screening distance is where the project noise reaches 50 dBA for the descriptor shown.

- Determine the appropriate column under Screening Distance in Table 4-1. If buildings occur in the sound paths, then use the distances under Intervening Buildings. Otherwise use the distances under "Unobstructed”.

- Note the distance in feet for that project in Table 4-1, or in the adjusted values obtained from Step 2. Apply this distance from the guideway centerline or nearest right-of-way line on both sides of a highway or access road. For small fixed facilities apply the distance from the center of the noise-generating activity. In the case of a fixed facility spread out over a large area, apply the distance from the outer boundary of the proposed project site.

- Within the distance noted above, locate any of the noise-sensitive land uses listed in Table 3-2.

- If it is determined that none of the listed land uses are within the distances noted in Table 4-1, then no further noise analysis is needed. On the other hand, if one or more of the noise-sensitive land uses are within the screening distances noted in Table 4-1, as adjusted, then further analysis is needed and the procedure described in Chapter 5 is followed.

Table 4-1. Screening Distances for Noise Assessments

Type of Project		Screening Distance* (ft) Unobstructed	Intervening Buildings
Fixed Guideway Systems:			
Commuter Rail Mainline		750	375
Commuter Rail Station	With Horn Blowing	1,600	1,200
	Without Horn Blowing	250	200
Commuter Rail-Highway Crossing with Horns and Bells		1,600	1,200
Rail Rapid Transit		700	350
Rail Rapid Transit Station		200	100
Light Rail Transit		350	175
Access Roads		100	50
Low- and Intermediate-Capacity Transit	Steel Wheel	125	50
	Rubber Tire	90	40
	Monorail	175	70
Yards and Shops		1000	650
Parking Facilities		125	75
Access Roads		100	50
Ancillary Facilities			
Ventilation Shafts		200	100
Power Substations		250	125
Bus Systems:			
Busway		500	250
BRT on exclusive roadway		200	100
Bus Facilities	Access Roads	100	50
	Transit Mall	225	150
	Transit Center	225	150
	Storage & Maintenance	350	225
	Park & Ride Lots w/Buses	225	150
Ferry Boat Terminals:		300	150

*Measured from centerline of guideway/roadway for mobile sources; from center of noise-generating activity for stationary sources.

Table 4-2. Assumptions for Screening Distances for Noise Assessments				
Type of Project		**Operations**	**Speeds**	**Descriptor**
Fixed Guideway Systems:				
Commuter Rail Mainline		66 day /12 night; 1 loco, 6 cars	55 mph	Ldn
Commuter Rail Station	With Horn Blowing	22 day / 4 night	N/A	Ldn
	W/O Horn Blowing	22 day / 4 night	N/A	Ldn
Commuter Rail-Highway Crossing with Horns and Bells		22 day / 4 night	55 mph	Ldn
Rail Rapid Transit		220 day / 24 night; 6-car trains	50 mph	Ldn
Rail Rapid Transit Station		220 day / 24 night	20 mph	Ldn
Light Rail Transit		150 day / 18 night; 2 artic veh.	35 mph	Ldn
Access Roads to Stations		1000 cars, 12 buses	35 mph	PH Leq*
Low- and Intermediate-Capacity Transit	Steel Wheel	220 day / 24 night	30 mph	Ldn
	Rubber Tire	220 day / 24 night	30 mph	Ldn
	Monorail	220 day / 24 night	30 mph	Ldn
Yards and Shops		20 train movements	N/A	PH Leq
Parking Facilities		1000 cars	N/A	PH Leq
Access Roads to Parking		1000 cars	35 mph	PH Leq
Ancillary Facilities				
Ventilation Shafts		Rapid Transit in Subway	50 mph	Ldn
Power Substations		Sealed shed, air conditioned	N / A	Ldn
Bus Systems:				
Busway		30 buses, 120 automobiles	50 mph	PH Leq
BRT on exclusive roadway		30 buses	35 mph	PH Leq
Bus Facilities	Access Roads	1000 cars	35 mph	PH Leq
	Transit Mall	20 buses	N/A	PH Leq
	Transit Center	20 buses	N/A	PH Leq
	Storage & Maintenance	30 buses	N/A	PH Leq
	Park & Ride Lots w/Buses	1000 cars, 12 buses	N/A	PH Leq
Ferry Boat Terminals:		8 boats with horns used in normal docking cycle	N/A	PH Leq

* PH Leq = hour of maximum transit activity

REFERENCES

1. U.S. Department of Transportation, Federal Railroad Administration. "Final Environmental Impact Statement: Interim Final Rule for the Use of Locomotive Horns at Highway-Rail Grade Crossings; Technical Supplement to DEIS and Chapter 3.4," Office of Railroad Development, Washington, D.C., December 5, 2003. Also see: http://www.fra.dot.gov/downloads/RRDev/hornmodel.xls.

5. GENERAL NOISE ASSESSMENT

This chapter contains procedures for the computation of both project and existing ambient noise levels for use in noise assessments required beyond the stage of the screening procedure of Chapter 4.

The **Screening Procedure** described in Chapter 4 is used to determine whether any noise-sensitive receivers are within a distance where impact is likely to occur. The distance given in the table defines the study area of any subsequent noise impact assessment. Where there is potential for noise impact, the procedures of Chapters 5 and 6 will be used to determine the extent and severity of impact. In some cases, a General Assessment may be all that is needed. On the other hand, if the proposed project is in close proximity to noise-sensitive land uses and it appears at the outset that the impact would be substantial, it is prudent to conduct a Detailed Analysis.

The **General Assessment** is used for a wide range of projects which show potential noise impact from the screening procedure. For a variety of smaller transit projects, a General Assessment may be all that is needed to evaluate noise impact and propose mitigation measures where necessary. It is also used to compare alternatives, such as locations of facilities or alignments, or even candidate transportation modes in a corridor. A General Assessment can provide the appropriate level of detail about noise impacts when an Alternatives Analysis/Draft EIS is being prepared to evaluate alternatives for a major capital investment. The procedure involves noise predictions commensurate with the level of design of the alternatives in the early stages of major investment planning. Estimates are made of project noise levels and of existing noise conditions to estimate the location of a noise impact contour which defines the outer limit of an impact corridor or area. An inventory of noise impacts within the area identifies locations where noise mitigation is likely and is used in comparing noise impact among alternatives. Noise mitigation policy considerations are discussed in Section 3.2.4 and the application of noise mitigation measures is described in Section 6.8.

Detailed Analysis is undertaken when the greatest accuracy is needed to assess impacts and the effectiveness of mitigation measures on a site-specific basis. In order to do this, the project must be defined to the extent that location, alignment, mode and operating characteristics are determined.

Detailed Analysis is often accomplished during the preliminary engineering phase. The results of the Detailed Analysis would be used in predicting the effectiveness of noise mitigation measures on particular noise-sensitive receivers. The procedures for performing a Detailed Analysis are described in Chapter 6.

This chapter describes the procedure for performing a General Noise Assessment. The General Assessment is based on noise source and land use information likely to be available at an early stage in the project development process. Sections of this chapter cover the key elements of the prediction procedure:

- Section 5.2 describes how to predict noise source levels with preliminary estimations of the effect of mitigation.
- Section 5.3 covers a simplified procedure for estimating noise propagation characteristics assuming flat terrain, with approximate shielding by rows of buildings or other barriers.
- Section 5.4 includes a simplified procedure for estimating existing noise.
- Section 5.5 shows how to estimate the noise impact contour that defines the approximate outer limit of noise impact.
- Section 5.6 describes how to conduct the noise impact inventory and how to present the information in an environmental document or a technical noise report.
- Four examples of General Assessments are given at the end of this chapter.

5.1 OVERVIEW

The steps in the General Noise Assessment are shown in Figure 5-1 and are described below. When several alternatives are evaluated in an environmental document, this approach can be applied to each alternative and the results compared.

Project Alternatives. Place the alternative under study into one of three categories: fixed-guideway transit, highway/transit, or stationary facility. Determine the Source Reference Level from the tables in Section 5.2. Each Source Reference Level pertains to a typical operation for one hour for a stationary source or one vehicle passby under reference operating conditions. Each utilizes the SEL noise descriptor, as discussed in Chapter 2.

Operational Characteristics. Convert the Source Reference Level to noise exposure in terms of L_{eq}(h) or L_{dn} under approximate project operating conditions, using the appropriate equations depending upon the type of source. The noise exposure is determined at the reference distance of 50 feet.

Propagation Characteristics. Draw noise exposure-vs.-distance curve for this source, using the graphic in Section 5.3. This curve will show the source's noise exposure as a function of distance, ignoring shielding. To account for shielding attenuation from rows of buildings, use a general rule for estimating the reduction in noise level and draw an adjusted exposure-vs-distance curve.

Study Area Characteristics. Estimate the existing noise exposure for areas surrounding the project from Table 5-7 in Section 5.4.

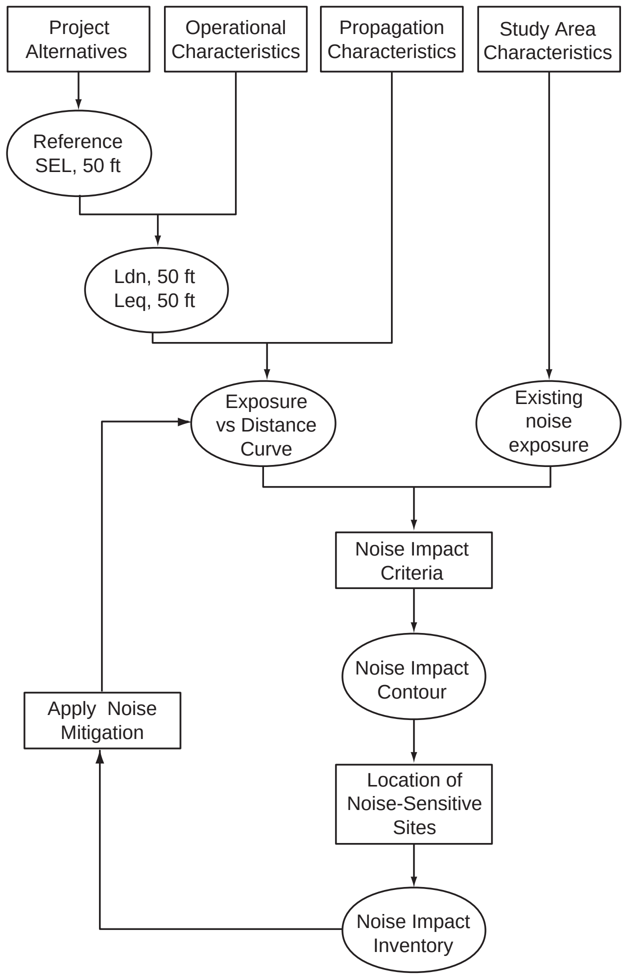

Figure 5-1. Procedure for General Noise Assessment

Noise Impact Contour Estimation. On a point-by-point basis, locate the project noise exposure and existing noise exposure combination that results in Moderate Impact according to the impact criteria from Chapter 3. Connect the points to obtain a contour line around the project which signifies the outer limits of Moderate Impact.

Alternatively, in the case where it is desired to make a comparison among different modal alternatives, specific decibel-level noise contours can be determined from the exposure-vs-distance curves (for example, 60dB, 65dB, 70dB contours).

Noise Impact Inventory. Tabulate noise-sensitive land uses within the specific contours using general assumptions for shielding attenuation from rows of buildings.

Noise Mitigation. Apply estimates of the noise reduction from mitigation in the community areas where potential impact has been identified and repeat the tabulation of noise impacts.

5.2 NOISE SOURCE LEVELS FOR GENERAL ASSESSMENT

The General Noise Assessment procedure begins by determining the project noise exposure at a reference distance for the various project alternatives. The reference noise exposure estimation procedures differ depending on the type of project (fixed-guideway, highway/transit, or stationary facility) as described in the following sections.

5.2.1 Fixed-Guideway Transit Sources

Fixed-guideway transit sources include commuter rail, rail rapid transit, light rail transit, automated guideway transit (AGT), monorail, and magnetically levitated vehicles (maglev). The noise characteristics of each depend on the system characteristics described in Chapter 2. For commuter railroads and light rail transit systems, the crossing of streets and highways at grade is likely, in which case the noise assessment of warning devices will have to be taken into account. At an early project stage, the information available includes:

- Candidate transit mode
- Guideway options
- Time of operation
- Operational headways
- Design speed
- Alternative alignments

This information is not sufficient to predict noise levels at all locations along the right-of-way, but by using conservative estimates (for example, maximum design speeds and operations at design capacities) it is sufficient to estimate worst-case noise impact contours.

Reference Levels in SEL. The procedure starts with predicting the source noise levels, expressed in terms of SEL at a reference distance and a reference speed. These are given in Table 5-1.

The reference SEL's are used in the equations of Table 5-2 to predict the noise exposure at 50 feet. Also shown in Table 5-2 are rough estimates of the noise reduction available from wayside noise barriers, the most common noise mitigation measure. See Chapter 6 for a complete description of the benefits resulting from noise mitigation. The approximate noise barrier lengths and locations developed in a General Assessment provide a preliminary basis for evaluating the costs and benefits of impact mitigation.

Table 5-1. Reference SEL's at 50 feet from Track and 50 mph

Source / Type		Reference Conditions	Reference SEL (SEL_{ref}), dBA
Commuter Rail, At-Grade	Locomotives	Diesel-electric, 3000 hp, throttle 5	92
		Electric	90
	Diesel Multiple Unit (DMU)	Diesel-powered, 1200 hp	85
	Horns	Within ¼ mile of grade crossing	110
	Cars	Ballast, welded rail	82
Rail Transit		At-grade, ballast, welded rail	82
Transit whistles / warning devices		Within 1/8 mile of grade crossing	93
AGT	Steel wheel	Aerial, concrete, welded rail	80
	Rubber Tire	Aerial, concrete guideway	78
Monorail		Aerial straddle beam	82
Maglev		Aerial, open guideway	72

Noise Exposure at 50 feet. After determining the reference levels for each of the noise sources, the next step is to determine the noise exposure at 50 feet expressed in terms of $L_{eq}(h)$ and L_{dn}. The additional data needed include:

- Number of train passbys during the day (defined as 7am to 10 pm) and night (defined as 10 pm to 7 am).
- Maximum number of train passbys during hours that Category 1 or Category 3 land uses are normally in use. This is usually the peak hour train volume.
- Number of vehicles per train (if this number varies during the day, take the average).
- Speed (maximum expected).
- Guideway configuration.
- Noise barrier location (if noise mitigation is determined necessary at the end of the first pass on the General Assessment).
- Location of highway and street grade crossings, if any.

These data are used in the equations in Table 5-2 to obtain adjustment factors to calculate L_{dn} and $L_{eq}(h)$ at 50 feet.

Table 5-2. Computation of Noise Exposure at 50 feet for Fixed-Guideway General Assessment	
LOCOMOTIVES[†] Hourly L_{eq} at 50 ft:	$L_{eqL}(h) = SEL_{ref} + 10\log(N_{locos}) + K\log\left(\frac{S}{50}\right) + 10\log(V) - 35.6$ Where K = -10 for passenger diesel; = 0 for DMU; = +10 for electric
LOCOMOTIVE WARNING HORNS[†††] Hourly L_{eq} at 50 ft:	$L_{eqH}(h) = SEL_{ref} + 10\log(V) - 35.6$
RAIL VEHICLES[††] Hourly L_{eq} at 50 ft:	$L_{eqC}(h) = SEL_{ref} + 10\log(N_{cars}) + 20\log\left(\frac{S}{50}\right) + 10\log(V) - 35.6$ use the following adjustments as applicable: + 5 → JOINTED TRACK + 3 → EMBEDDED TRACK ON GRADE + 4 → AERIAL STRUCTURE WITH SLAB TRACK (except AGT & monorail) - 5 → if a NOISE BARRIER blocks the line of sight
TRANSIT WARNING HORNS[†††] Hourly L_{eq} at 50 ft:	$L_{eqH}(h) = SEL_{ref} - 10\log\left(\frac{S}{50}\right) + 10\log(V) - 35.6$
COMBINED Hourly L_{eq} at 50 ft:	$L_{eq}(h) = 10\log\left[10^{\left(L_{eqL}/10\right)} + 10^{\left(L_{eqC}/10\right)}\right]$
Daytime L_{eq} at 50 ft:	$L_{eq}(day) = L_{eq}(h)\Big\vert\ v = v_d$
Nighttime L_{eq} at 50 ft:	$L_{eq}(night) = L_{eq}(h)\Big\vert\ v = v_n$
L_{dn} at 50 ft:	$L_{dn} = 10\log\left[(15)\times 10^{\left(L_{eq}(day)/10\right)} + (9)\times 10^{\left((L_{eq}(night)+10)/10\right)}\right] - 13.8$

N_{locos} = average number of locomotives per train

N_{cars} = average number of cars per train

S = train speed, in miles per hour

V = average hourly volume of train traffic, in trains per hour

V_d = average hourly daytime volume of train traffic, in trains per hour

$= \frac{number\ of\ trains, 7am\ to 10pm}{15}$

V_n = average hourly nighttime volumes of train traffic, in trains per hour

$= \frac{number\ of\ trains, 10pm\ to 7am}{9}$

[†] Assumes a passenger diesel locomotive power rating at approximately 3000 hp
[††] Includes all commuter rail cars, transit cars, AGT and monorail
[†††] Based on FRA's horn noise model (www.fra.dot.gov/downloads/RRDev/hornmodel.xls)

5.2.2 Highway/Transit Sources

The highway/transit type sources include most transit modes that do not require a fixed-guideway. Examples are high-occupancy vehicles, such as buses, commuter vanpools and carpools. As noted in Chapter 3, some highway/transit projects are best analyzed with FHWA's noise prediction and impact assessment procedures. However, the procedures in this manual can be used for all types of projects involving highway vehicles. The noise characteristics of the vehicles depend on the system characteristics described in Chapter 2. Recent research has shown there is no statistically significant difference in the reference noise levels from various types of buses, so all buses are placed in a single category. At an early project development stage, the information available is as follows:

- Vehicle type
- Transitway design options
- Time of operation
- Typical headways
- Design speed
- Alternative alignments

This information is not sufficient to predict noise levels at all locations along the right-of-way, but is sufficient to estimate worst-case noise impact contours. The procedure is consistent with FHWA's highway noise prediction method (see Section 6.7.2 for an overview of the computation methods), with buses and vans corresponding to user-defined source emission levels and speed coefficients for buses and automobiles, respectively[1].

Reference Levels in SEL. Projections of noise from highway/transit sources begin by defining the source SEL at a reference distance of 50 feet and a reference speed. These are given in Table 5-3. The reference distance SEL's are used in the equations of Table 5-4 to predict the noise exposure at 50 feet. Also shown in Table 5-4 is a rough estimate of the minimum noise reduction available with wayside sound barriers. See Chapter 6 for descriptions of other mitigation measures and procedures for developing more accurate estimates of noise reduction from mitigation measures. The approximate noise barrier lengths and locations developed in a General Assessment allow preliminary estimates of the costs and benefits of impact mitigation.

Noise Exposure at 50 feet. After determining the reference levels for each of the noise sources, the next step is to determine the noise exposure at 50 feet. The additional data needed include:

- Number of vehicle passbys during the day (7am to 10 pm) and night (10 pm to 7 am).
- Number of vehicle passbys during hours that Category 1 or Category 3 land uses are normally in use.
- Speed (maximum expected).
- Transitway configuration (with or without noise barrier).

These data are used in the equations in Table 5-4 with the reference SEL's to calculate L_{eq}(h) and L_{dn} at 50 feet.

Table 5-3. Source Reference Levels at 50 feet from Roadway, 50 mph

Source†	Reference SEL (dBA)
Automobiles and Vans	74
Buses (diesel-powered)	82
Buses (electric)	80
Buses (hybrid)	83**

† Assumes normal roadway surface conditions

** For hybrid buses, Reference SEL should be determined on a case-by-case basis.

Table 5-4. Computation of L_{eq} and L_{dn} at 50 feet for Highway/Transit General Assessment

Hourly L_{eq} at 50 ft:	$L_{eq}(h) = SEL_{ref} + 10\log(V) + C_s \log\left(\frac{S}{50}\right) - 35.6$	
Daytime L_{eq} at 50 ft:	$L_{eq}(day) = L_{eq}(h)\vert v = v_d$	
Nighttime L_{eq} at 50 ft:	$L_{eq}(night) = L_{eq}(h)\vert v = v_n$	
L_{dn} at 50 ft:	$L_{dn} = 10\log\left[(15)\times 10^{\left(L_{eq}(day)/10\right)} + (9)\times 10^{\left(L_{eq}(night)+10/10\right)}\right] - 13.8$	
Speed Constant:	C_s = 15 = 28 = 30,	Diesel Buses Electric Buses Automobile and van pools
Adjustment:	- 5	Noise Barrier

V	= hourly volume of vehicles of this type, in vehicles per hour.
V_d	= average hourly daytime volume of vehicles of this type, in vehicles per hour
	$= \frac{total vehicle volume, 7 am to 10 pm}{15}$
V_n	= average hourly nighttime volume of vehicles of this type, in vehicles per hour
	$= \frac{total vehicle volume, 10 pm to 7 am}{9}$
S	= average vehicle speed, in miles per hour

5.2.3 Stationary Sources

This section covers the general approach to assessment of noise from fixed transit system facilities. New transit facilities undergo a site review for best location which includes consideration of the noise sensitivity of surrounding land uses. Although many facilities, such as bus maintenance garages, are usually located in industrial and commercial areas, some facilities such as bus terminals, ferry terminals, train stations and park-and-ride lots may be placed near residential neighborhoods where noise impact may occur. Access roads to some of these facilities may also pass through noise-sensitive areas. In a General Assessment, only the salient features of each fixed facility are considered in the noise analysis.

Reference Levels in SEL. The source reference levels given in Table 5-5 are determined based on measurements for the peak hour of operation of a typical stationary source of the type and size noted. A large facility, such as a rail yard, is spread out over considerable area with various noise levels depending on the layout of the facility. Specifying the reference SEL at a distance of 50 feet from the property line would be misleading in this case. Consequently, the reference distance is described as "the equivalent distance of 50 feet," which is determined by estimating the noise levels at a greater distance and projecting back to 50 feet, assuming the noise sources are concentrated at the center of the site. If the location of noise sources is known, then the distance should be taken from the point of the noisiest activity on the site (e.g. the dock in the case of ferry boat operations). The reference SEL's are used in the equations of Table 5-6 to predict noise exposure at an equivalent distance of 50 feet from the center of the site. Noise from access roads is treated according to the procedures described in Section 5.2.2.

Table 5-6 also includes an estimate of the minimum noise reduction available with wayside noise barriers. Only approximate locations and lengths for barrier or other noise mitigation measures are developed during a General Assessment to provide a preliminary indication of the costs and benefits of mitigation.

Noise Exposure at Equivalent Distance of 50 feet. After determining the reference SEL's for each of the noise sources, the next step is to determine the noise exposure expressed in terms of L_{eq} and L_{dn} at an equivalent distance of 50 feet. The additional data needed include:

- Number of layover tracks and hours of use.
- Number of buses, if different from assumed reference conditions (if this number varies during the day, take the average).
- Number of ferry boat landings, if different from assumed reference conditions (if this number varies during the day, take the average).
- Actual capacity of parking garage or lot.

These data are used in the equations in Table 5-6 with the reference SEL's to calculate $L_{eq}(h)$ and L_{dn} at an equivalent distance of 50 feet.

Table 5-5. Source Reference Levels at 50 feet from Center of Site, Stationary Sources		
Source	**Reference SEL (dBA)**	**Reference Conditions**
Rail System:		
Yards and Shops	118	20 train movements in peak activity hour
Layover Tracks (commuter rail)	109	One train with diesel locomotive idling for one hour
Crossovers	100	One train
Crossing signals	109	3600 seconds duration
Bus System:		
Storage Yard	111	100 buses accessing facility in peak activity hour
Operating Facility	114	100 buses accessing facility, 30 buses serviced and cleaned in peak activity hour
Transit Center	101	20 buses in peak activity hour
Ferry Terminal:		
Ferry Boat (no fog horn sounded)	97	4 ferry boats landings in one hour
Ferry Boat (fog horn sounded)	100	
Parking Garage	92	1000 cars in peak activity hour
Park & Ride Lot	101	12 buses, 1000 cars in peak activity hour

Table 5-6. Computation of L_{eq} and L_{dn} at 50 feet for Stationary Source General Assessment

Hourly L_{eq} at 50 ft:	$L_{eq}(h) = SEL_{ref} + C_N - 35.6$	
Daytime L_{eq} at 50 ft:	$L_{eq}(day) = 10\log\left[\left(\frac{1}{15}\right)\sum_{7am-10pm} 10^{L_{eq}(h)/10}\right]$	
Nighttime L_{eq} at 50 ft:	$L_{eq}(night) = 10\log\left[\left(\frac{1}{9}\right)\sum_{10pm-7am} 10^{L_{eq}(h)/10}\right]$	
L_{dn} at 50 ft:	$L_{dn} = 10\log\left[(15)\times 10^{\left(L_{eq}(day)/10\right)} + (9)\times 10^{\left(L_{eq}(night)+10/10\right)}\right] - 13.8$	
Volume Adjustment:	$C_N = 10\log\left(\frac{N_T}{20}\right)$,	Rail Yards and Shops
	$= 10\log(N_T)$,	Layover Tracks
	$= 10\log(N_T)$,	Crossovers
	$= 10\log\left(\frac{N_B}{100}\right)$,	Bus Storage Yard
	$= 10\log\left(\frac{N_B}{200} + \frac{N_S}{60}\right)$,	Bus Operating Facility
	$= 10\log\left(\frac{N_B}{20}\right)$,	Bus Transit Center
	$= 10\log\left(\frac{N_F}{4}\right)$,	Ferry Terminal
	$= 10\log\left(\frac{N_A}{1000}\right)$,	Parking Garage
	$= 10\log\left(\frac{N_A}{2000} + \frac{N_B}{24}\right)$,	Park & Ride Lot
Duration Adjustment:	$= 10\log(E/3600)$,	Crossing Signals
Other Adjustment:	-5	Noise Barrier at Property Line

N_T = Number of trains per hour
N_B = Number of buses per hour
N_F = Number of ferry boat landings per hour
N_S = Number of buses serviced and cleaned per hour
N_A = Number of automobiles per hour

E = average hourly duration of one event in seconds

Note: If any of these numbers is zero, then omit that term

5.3 COMPUTATION OF NOISE EXPOSURE-VS.-DISTANCE CURVES

The previous section results in estimates of noise exposure at 50 feet for each type of project. The following procedure is used to estimate the project noise exposure at other distances, resulting in a noise exposure-vs.-distance curve sufficient for use in a General Assessment. The procedure is as follows:

1. Determine the L_{dn} or L_{eq} at 50 feet for one of the three project types in Section 5.2.

2. Select the appropriate distance correction curve from Figure 5-2.

3. Apply the Distance Corrections ($C_{distance}$) to the noise exposure at 50 feet using:

$$L_{dn}(or L_{eq})\Big|_{at\,new\,distance} = L_{dn}(or L_{eq})\Big|_{at\,50\,feet} - C_{distance}$$

4. Plot the noise exposure curve as a function of distance. This curve will be used to determine the noise impact contour for the first row of unobstructed buildings. This plot can be used to display noise from both unmitigated and mitigated conditions in order to assess the benefits from mitigation measures.

5. For second row receivers and beyond, it is necessary to account for shielding attenuation from rows of intervening buildings. Without accounting for shielding, impact may be substantially over-estimated. Use the following general rules of thumb to determine the effect of shielding from intervening rows of buildings:

   - Assign -4.5 dB of shielding attenuation for the *first* row of intervening buildings only.
   - Assign -1.5 dB of shielding attenuation for each subsequent row, up to a maximum total attenuation of 10 dB.

   Figure 5-2 can then be used to develop a curve of noise exposure vs. distance when there is shielding. The curve of noise exposure as a function of this distance will be used to determine the location of the noise impact contours.

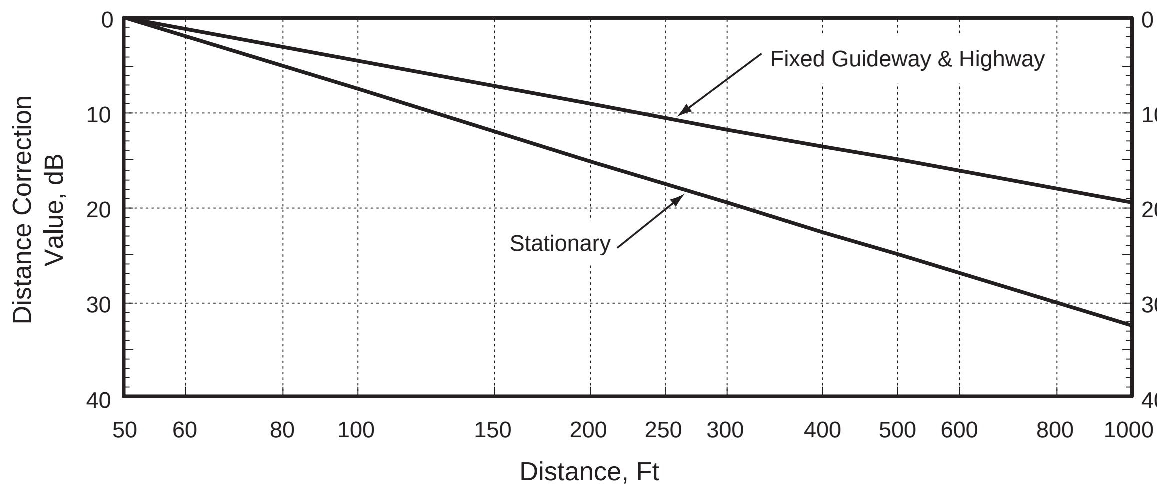

Figure 5-2. Curves for Estimating Exposure vs. Distance in General Noise Assessment

5.4 ESTIMATING EXISTING NOISE EXPOSURE

The existing noise in the vicinity of the project is required to determine the noise impact according to the criteria described in Chapter 3. Recall that impact is assessed based on a combination of the existing ambient noise exposure and the additional noise exposure that will be caused by the project. In the Detailed Analysis, the existing noise exposure is based on noise measurements at representative locations in the community. It is generally a good idea to base all estimates of existing noise on measurements, especially at locations known to be noise-sensitive. However, measurements are not always available at the General Assessment stage. This section describes how to estimate the existing noise in the project study area from general data available early in project planning. The procedure uses Table 5-7, where a neighborhood's existing noise exposure is based on proximity to nearby major roadways or railroads or on population density. For areas near major airports, published aircraft noise contours can also be used to estimate the existing noise exposure. The process is as follows:

1. Mapping: Obtain scaled mapping and aerial photographs showing the project location and alternatives. A scale of 1" = 200' or 400' is convenient for the accuracy needed in the noise assessment. The size of the base map should be sufficient to show distances of at least 1000' from the center of the alignment or property center, depending on whether the project is a guideway/roadway or a stationary facility.

2. Identify Sensitive Receivers: Review the maps, together with the most current land use information, to determine the proximity of noise-sensitive land uses to the project and to the nearest major roadways and railroad lines. When necessary, windshield surveys or more detailed land use maps may be used to confirm the location of sensitive receivers. For land uses more than

1000 feet from major roadways or railroad mainlines (see definitions in Table 5-7), obtain an estimate of the population density in the immediate area, expressed in people per square mile.

3. Use Table 5-7 to Estimate Existing Noise Exposure: Existing noise exposure is estimated by first looking at a site's proximity to major roads and railroad lines. If these noise sources are far enough away that ambient noise is dominated by local streets and community activities, then the estimate is made based on population density. The decision of which to use is made by comparing the noise levels from each of the three categories, roadways, railroads and population density, and selecting the highest level. In case of a lightly used railroad, one train per day or less, select the population density category.

   Major roadways are separated into two categories: "Interstates," or roadways with four or more lanes that allow trucks; and "Others," parkways without trucks and city streets with the equivalent of 75 or more heavy trucks per hour or 300 or more medium trucks per hour. The estimated roadway noise levels are based on data for light to moderate traffic on typical highways and parkways using FHWA highway noise prediction procedures. Where a range of distances is given, the predictions are made at the outer limit, thereby underestimating the traffic noise at the inner distance. For highway noise, distances are measured from the centerline of the near lane for roadways with two lanes, while for roadways with more than two lanes the distance is measured from the geometric mean of the roadway. This distance is computed as follows:

$$D_{GM} = \sqrt{(D_{NL})(D_{FL})}$$

   where D_{GM} is the distance to the geometric mean, D_{NL} and D_{FL} are distances to the nearest lane and farthest lane centerlines, respectively.

   For railroads, the estimated noise levels are based on an average train traffic volume of 5-10 trains per day at 30-40 mph for main line railroad corridors, and the noise levels are provided in terms of L_{dn} only. Distances are referenced to the track centerline, or in the case of multiple tracks, to the centerline of the rail corridor. Because of the intermittent nature of train operations, train noise will affect the L_{eq} only during certain hours of the day, and these hours may vary from day to day. Therefore, to avoid underestimating noise impact when using the one-hour L_{eq} descriptor, it is recommended that the L_{eq} at sites near rail lines be estimated based on nearby roadways or population density unless very specific train information is available.

   In areas away from major roadways, noise from local streets or in neighborhoods is estimated using a relationship determined during a research program by the U.S. EPA.[(2)] EPA determined that ambient noise can be related to population density in locations away from transportation corridors, such as airports, major roads and railroad tracks, according to the following relation:

$$L_{dn} = 22 + 10\log(p) \qquad \text{(in dBA)}$$

   where p = population density in people per square mile.

Table 5-7. Estimating Existing Noise Exposure for General Assessment

Distance from Major Noise Source[1] (feet)			Population Density (people per sq mile)	Noise Exposure Estimates			
Interstate Highways[2]	Other Roadways[3]	Railroad Lines[4]		L_{eq} Day	L_{eq} Evening	L_{eq} Night	L_{dn}
10 - 50				75	70	65	75
50 - 100				70	65	60	70
100 - 200				65	60	55	65
200 - 400				60	55	50	60
400 - 800				55	50	45	55
800 and up				50	45	40	50
	10 - 50			70	65	60	70
	50 - 100			65	60	55	65
	100 - 200			60	55	50	60
	200 - 400			55	50	45	55
	400 and up			50	45	40	50
		10 - 30		--	--	--	75
		30 - 60		--	--	--	70
		60 - 120		--	--	--	65
		120 - 240		--	--	--	60
		240 - 500		--	--	--	55
		500 - 800		--	--	--	50
		800 and up		--	--	--	45
			1 - 100	35	30	25	35
			100 - 300	40	35	30	40
			300 - 1000	45	40	35	45
			1000 - 3000	50	45	40	50
			3000 - 10000	55	50	45	55
			10000 - 30000	60	55	50	60
			30000 and up	65	60	55	65

NOTES:

[1] Distances do not include shielding from intervening rows of buildings. General rule for estimating shielding attenuation in populated areas: Assume 1 row of buildings every 100 ft; -4.5 dB for the first row, -1.5 dB for every subsequent row up to a maximum of -10 dB attenuation.

[2] Roadways with 4 or more lanes that permit trucks, with traffic at 60 mph.

[3] Parkways with traffic at 55 mph, but without trucks, and city streets with the equivalent of 75 or more heavy trucks per hour and 300 or more medium trucks per hour at 30 mph.

[4] Main line railroad corridors typically carrying 5-10 trains per day at speeds of 30-40 mph.

In areas near major airports, published noise contours can be used to estimate the existing noise exposure. The L_{dn} from such contours should be applied if greater than the estimates of existing noise from other sources at a given location.

5.5 DETERMINING NOISE IMPACT CONTOURS

It is often desirable to draw noise impact contours on the land use map mentioned in the previous section to aid the impact inventory. Once the contours are on the map, the potential noise impacts can be estimated by counting the buildings inside the contours.

The first step is to identify the noise-sensitive neighborhoods and buildings and estimate existing noise exposure following the procedures described in Section 5.4. The estimate of existing noise exposure is used along with the noise impact criteria in Figure 3-1 to determine how much additional noise exposure would need to be created by the project before there would be Moderate Impact or Severe Impact.

The next step is to determine the distances from the project boundary to the two impact levels using the noise exposure-vs.-distance curves from Section 5.3. Plot points on the map corresponding to those distances in the neighborhood under study. Continue this process for all areas surrounding the project. The plotted points are connected by lines to represent the noise impact contours.

Alternatively, if it is desired to plot specific decibel-level noise contours, for example, 65 dBA, the distances can also be determined directly from the approach described in Section 5.3. Again, the points associated with a given decibel level are plotted on the map and connected by lines to represent that contour.

Locations of points will change with respect to the project boundary as the existing ambient exposure changes, as project source levels change, and as shielding effects change. In general, the points should be placed close enough to allow a smooth curve to be drawn. For a General Assessment, the contours may be drawn through buildings and salient terrain features as if they were not present. This practice is acceptable considering the level of detail associated with a project in its early stages of development. Examples 5-1 and 5-4 describe the development of noise contours, with illustrations in Figures 5-3 and 5-4.

5.6 INVENTORY NOISE IMPACT

The final step in the General Assessment is to develop an inventory of noise-impacted land uses. Using the land-use information and noise impact contours from Sections 5.4 and 5.5, it should be possible to locate which buildings are within the impact contours. In some cases it may be necessary to supplement the land-use information or determine the number of dwelling units within a multi-family building with a visual survey. If the objective is to compare and contrast major alignment or modal alternatives on the basis of noise impact, as in an Alternatives Analysis/Draft EIS, it may not be necessary to identify every different type of noise-sensitive land use. The inventory might be limited to only a few types, for example, residential and public institutional uses.

The steps for developing the inventory are:

1. Construct tables for all the noise-sensitive land uses identified in the three land-use categories from Section 5.4.

2. Tabulate buildings and sites that lie between the impact contours and the project boundary. For residential buildings, an estimate of the number of dwelling units is satisfactory. This is done for each alternative being considered.

3. Prepare summary tables showing the number of buildings (and estimated dwelling units, if available) within each impact zone for each alternative. Various alternatives can be compared in this way, including those with and without noise mitigation measures.

4. Determine the need for mitigation based on the policy considerations discussed in Section 3.2.4 and the application guidelines provided in Section 6.8.

Example 5-1. General Noise Assessment for a Commuter Rail System in an Existing Abandoned Railroad Right of Way

The following example illustrates the General Noise Assessment procedure for a new fixed-guideway project. The hypothetical project is a commuter rail system to be built within the abandoned right-of-way of a railroad. The example covers a segment of the corridor that passes through a densely developed area with population density of 25,000 people per square mile in mixed single-family and multi-family residential land use as shown in Figure 5-3. The example is presented in two parts: first, a segment where the rail line is grade-separated and a horn is not sounded; and second, an at-grade street-rail crossing where the horn is sounded.

Assumptions for Example

The assumptions for the project are as follows:

- **Project Corridor:** Existing population density is 25,000 people per square mile.

- **Commuter Rail System:** Commuter train with one locomotive and a three car consist on a double-track at-grade system with welded rail. Trains operate with 20-minute headways during peak hours, and 1-hour headways during off-peak. Speeds are approximately 40 mph along the corridor.

- **Operating Schedule:**

	Period	Headway (minutes)		Trains per hour		
		Inbound	Outbound	Inbound	Outbound	Total
Daytime	7am - 8am	20	20	3	3	6
	8am – 4pm	60	60	1	1	2
	4pm - 6pm	20	20	3	3	6
	6pm - 10pm	60	60	1	1	2
Nighttime	10pm – 11pm	60	60	1	1	2
	11pm – 5am	--	--	--	--	--
	5am - 6am	60	60	1	1	2
	6am - 7am	20	20	1	1	2

Procedure

The Screening Procedure calls for additional analysis for noise-sensitive land use within 375 feet of a commuter rail mainline. Figure 5-3 shows that the closest residences are about 100 ft from the Commuter Rail corridor centerline, thereby requiring further noise analysis. The procedure is summarized as follows:

Part 1. Grade-Separated Street Crossing

Determination of Noise Exposure at 50 feet

1. Determine average hourly daytime and nighttime volumes of train traffic.

   Daytime (7am - 10pm):
   V_d = 42 trains/15 hours = 2.8 trains/hour

   Nighttime (10pm - 7am):
   V_n = 6 trains/9 hours = 0.7 trains/hour

2. Calculate L_{eq}(day), and L_{eq}(night) 50 ft.

   From Table 5-1 and 5-2 these levels are determined as follows:

$$L_{eqL}(day) = SEL_{ref} + 10\log(N_{locos}) - 10\log(S/50) + 10\log(V_d) - 35.6$$
$$= 92 + 10 \log (1) - 10 \log (40/50) + 10 \log (2.8) - 35.6$$
$$= 61.8 \text{ dB}$$

$$L_{eqC}(day) = SEL_{ref} + 10 \log (N_{cars}) + 20 \log (S/50) + 10 \log (V_n) - 35.6$$
$$= 82 + 10 \log (3) + 20 \log (40/50) + 10 \log (2.8) - 35.6$$
$$= 53.7 \text{ dB}$$

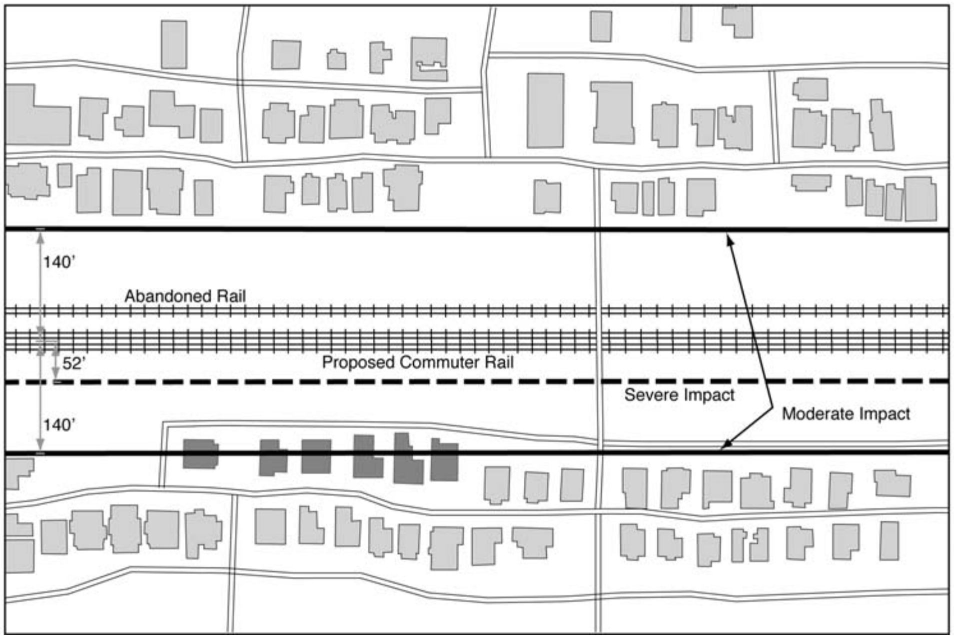

Figure 5-3. Noise Impacts of Commuter Rail

Calculate the total daytime L_{eq} for the locomotive and rail cars.

$$L_{eqT}(day) = 10*\log(10^{(LeqL/10)} + 10^{(LeqC/10)})$$
$$= 10*\log(10^{(62.2/10)}+10^{(54.1/10)})$$
$$= 62.4 \text{ dB}$$

Calculate the nighttime L_{eq} for the locomotive and rail cars.

$$L_{eqL}(night) = SEL_{ref} + 10\log(N_{locos}) - 10\log(S/50) + 10\log(V_n) - 35.6$$
$$= 92 + 10 \log (1) - 10 \log (40/50) + 10 \log (0.7) - 35.6$$
$$= 55.8 \text{ dB}$$

$$L_{eqC}(night) = SEL_{ref} + 10 \log (N_{cars}) + 20 \log (S/50) + 10 \log (V_n) - 35.6$$
$$= 82 + 10 \log (3) + 20 \log (40/50) + 10 \log (0.7) - 35.6$$
$$= 47.7 \text{ dB}$$

Calculate the total nighttime L_{eq} for the locomotive and rail cars.

$$L_{eqT}(night) = 10*\log(10^{(LeqL/10)} + 10^{(LeqC/10)})$$
$$= 10*\log(10^{(55.6/10)}+10^{(47.5/10)})$$
$$= 56.4 \text{ dB}$$

3. Calculate project L_{dn} at 50 ft.

   From Table 5-2 this level is determined as follows:

   $$L_{dn} = 10\log\left[(15)10^{Leq(day)/10} + (9)10^{(Leq(night)+10)/10}\right] - 13.8$$

   which gives:

   $$L_{dn} = 78.2 - 13.8$$

   or

   $$L_{dn} = 64.4 \text{ dB}$$

Estimate Existing Noise Exposure

4. Estimate existing noise at noise-sensitive sites. Since the existing alignment is on an abandoned railroad, the dominant existing noise source can be described by a "generalized" noise level to characterize a large area. An estimate of the existing noise environment is obtained from Table 5-7 with population density of 25,000 people per square mile, giving an Ldn = 60 dBA.

   From Figure 5-3, unobstructed residences range from 100 to 200 ft from the rail line. Based on Table 5-7 the L_{dn} is 60 dB for the area.

Noise Impact Contours

5. The following table is constructed using the impact criteria curves.
   Note: The project criteria for L_{eq} is not shown since L_{eq} only applies to the non-residential receptors.

Existing Noise, L_{dn} or L_{eq}(day)	Onset of Moderate Impact	Onset of Severe Impact
	L_{dn}	L_{dn}
60 dB	58 dB	64 dB

6. Distance to impact contours are determined using the curve in Figure 5-2 for "Fixed-Guideway" and the project impact thresholds obtained above. The results are summarized as follows for the residences:

Existing Noise, L_{dn} or L_{eq}(h)	Distance to Noise Impact Threshold, feet	
	Moderate Impact	Severe Impact
60 dB	140	52

7. Draw contours for each affected land use, based on the above table and its distance from the rail line. Note that the impact distances listed are in terms of distance to the *centerline of the Commuter Rail corridor*.

8. Within the contours defining "Moderate Impact" are six residential buildings (shaded in Figure 5-3).

Noise Mitigation

9. The procedure is repeated assuming a noise barrier to be placed at the railroad right-of-way line. The barrier serves to reduce project noise from the Commuter Rail by at least 5 dB. This, however, does not affect the project criteria to be used in determining impact. That is, the same existing noise levels (as the case without a barrier) are used to determine these thresholds.

   The net effect of the noise barrier is to decrease the Moderate Impact distance from 140 to 60 ft. Hence, the noise barrier eliminates all residential noise impact for this segment of the project area.

Part 2. Crossing At-Grade with Horn Blowing

Now consider the case of an active street crossing of the commuter railroad tracks. The General Assessment method includes source reference levels for horns on moving trains and warning bells (crossing signals) at the street crossing. According to Table 5-1, the horn noise applies to track segments within ¼ mile of the grade crossing. Using the train volumes from Part 1 and the information in Tables 5-1 and 5-2, the day- and nighttime Leqs from sounding the horns are determined at 50 feet as follows:

$$
\begin{aligned}
L_{eqL}(day)_{horns} &= SEL_{ref} + 10\log(V_d) - 35.6 \\
&= 113 + + 10 \log (3.1) - 35.6 \\
&= 82.3 \text{ dB}
\end{aligned}
$$

$$
\begin{aligned}
L_{eqC}(night)_{horns} &= SEL_{ref} + 10 \log (V_n) - 35.6 \\
&= 113 + 10 \log (0.7) - 35.6 \\
&= 75.9 \text{ dB}
\end{aligned}
$$

The L_{dn} at 50 ft. from train horns is the next calculation:

From Table 5-2 this level is determined as follows:

$$L_{dn} = 10\log\left[(15)10^{Leq(day)/10} + (9)10^{(Leq(night)+10)/10}\right] - 13.8$$

which gives:

$$L_{dn} = 84 \text{ dB}$$

At-grade street crossings will have warning bells, typically sounding for 20 seconds for every train pass-by. The total day- and nighttime durations are as follows:

E_d = average daytime hourly duration
= 20 seconds x 3.1 trains/hour = 62 seconds/hour

E_n = average nighttime hourly duration
= 20 seconds x 0.7 trains/hour = 14 seconds/hour.

From Table 5-6 for stationary sources:

$L_{eqL}(day)_{cs}$ = SEL_{ref} + 10log(E_d/3600) - 35.6
= 109 + + 10 log (62/3600) - 35.6
= 55.8 dB

$L_{eqC}(night)_{cs}$ = SEL_{ref} + 10 log (E_n/3600) - 35.6
= 109 + 10 log (14/3600) - 35.6
= 49.3 dB

Applying the L_{dn} equation from Table 5-6, $L_{dn,\ cs}$ = 57.5 dB.

Compared to horn blowing, the crossing signal noise is negligible.

Noise impact distances are found in the same way as in Part 1, with a new noise level, L_{dn} = 84 dB.

Again, the existing noise level is used to determine the onset of Moderate and Severe Impacts:

Existing Noise, L_{dn} or L_{eq}(day)	Onset of Moderate Impact	Onset of Severe Impact
	L_{dn}	L_{dn}
60 dB	58 dB	64 dB

Distance to impact contours is determined using the curve in Figure 5-2 for "Fixed-Guideway" and the project impact thresholds obtained above. The results are summarized as follows for the residences:

Existing Noise, L_{dn} or L_{eq}(h)	Distance to Noise Impact Threshold, feet	
	Moderate Impact	Severe Impact
60 dB	1000	500

Contours are drawn as in Part 1, extending to the distances above for ¼ mile on either side of the grade crossing.

End of Example 5-1

Example 5-2. Example of Highway/Transit Corridor Projects

This example illustrates two cases of highway/transit projects, one where the highway noise dominates and the FHWA procedures should be used and another where the FTA methodology is appropriate.

Case 1: Highway dominates

A new LRT system is planned for the median of a major freeway that carries heavy traffic both day and night. The noise levels at the first row of houses along the freeway were measured during peak hour, mid-day and late evening with hourly Leq readings of 65 dBA, 63 dBA and 60 dBA, respectively. The LRT tracks will be 125 feet from the first row of houses. The LRT operations during peak hour will be 4-car trains at 45 mph, with 5-minute headways in both directions. Late evening service decreases to 2-car trains and 20 minute headways. Referring to Table 5-2, "Rail Vehicles," the applicable terms for determining the peak hour Leq in this case are: SEL_{REF} = 82 dBA; N = 4 cars per train; S = 45 mph; and V = 24 trains per hour. Inserting these parameters into the equation in Table 5-2, the LRT peak-hour noise level is determined to be 65 dBA at 50 feet, and from Figure 5-2, the level at 125 feet is 60 dBA. The corresponding calculation for late evening hourly Leq results in 51 dBA.

FTA is providing a share of the funding for the LRT project, but the State DOT and the FHWA are co-lead agencies because the median requires considerable preparation for the tracks, including replacing bridge piers of street crossings and moving some highway lanes. In this case, the freeway dominates the noise environment in the area both day and night, by 5 dB during peak hour and 9 dB at night. According to Chapter 3, the FHWA procedures are to be used when sufficient evidence shows that highway noise dominates. Consequently TNM is used to calculate the future noise levels at the first row of houses, with a result of peak-hour Leq of 66 dBA. The State has a policy of implementing noise abatement measures if the FHWA Noise Abatement Criteria (NAC) are approached and the increase over existing noise levels is 5 dB or more at residential land use.

Combining the freeway noise and LRT noise during the peak traffic hour by decibel addition results in a combined noise level of 67 dBA.

In this case, no mitigation is proposed because although the combined level reaches the FHWA NAC of 67 dBA for residential land use, the increase in noise over existing conditions is only 2 dB, thereby failing this State's policy requirement of at least a 5 dB increase over existing levels to justify noise mitigation measures.

Case 2: LRT dominates at night

A new LRT is planned for the median of a major arterial highway used by commuters primarily during rush hours. Traffic volume on the arterial drops considerably during off-peak and nighttime hours. Currently the arterial has signalized intersections, but in the future the cross streets will be grade-separated, but commercial businesses and residential developments will continue to be accessible with "right-turn-off / right-turn-on". The existing noise at the nearest homes adjacent to the arterial has been measured, resulting in a peak-hour Leq of 63 dBA and an Ldn of 60 dBA.

The future traffic noise after improvements to the arterial is projected to be 65 dBA for the two-hour morning peak period and the same for the two-hour evening peak period, falling to hourly Leq's of 60 dBA during the remaining daytime hours and 50 dBA after 10 p.m. Accordingly, Ldn is calculated to be 61 dBA from the arterial at the homes.

The LRT is proposed to be on elevated structure in the median of the arterial, located 125 feet from the nearest homes in the development. The proposed operations at this location are:

- Peak hours (7:00 a.m. to 9:00 a.m. and 5:00 p.m. to 7:00 p.m.): 4-car trains, with 5 minute headways, at 50 mph.
- Off-peak hours (9:00 a.m. to 5:00 p.m. and 7:00 p.m. to 10:00 p.m.): 3-car trains, with 10 minute headways, at 50 mph.
- Night hours (10:00 p.m. to 1:00 a.m.): 2-car trains, with 15 minute headways, at 40 mph.

This train schedule results in an average hourly volume of 15.2 trains per hour, with an average of 3.42 cars per train in both directions during the daytime, and 2-car trains with an average hourly volume of 2.67 trains per hour during the nighttime. According to the equations in Table 5-2 and the propagation curve in Figure 5-2, the Ldn = 63 dBA at these homes. The combined arterial and LRT noise is projected to be Ldn = 64.7 dBA by decibel addition.

FTA procedures are appropriate in this case, since the LRT continues to operate into the nighttime hours and actually dominates the noise environment because the arterial noise diminishes in those hours. Here is a case where the cumulative noise impact curve (Figure 3-2) is applicable because the project included changes to the arterial as well as addition of a new transportation source. With an existing Ldn of 60 dB and a future Ldn of 64.7 dBA, Figure 3-2 indicates the increase of 4.7 dB would cause Moderate Impact.

End of Example 5-2

Example 5-3. General Noise Assessment for a BRT System in an Existing Railroad Right of Way

This example for an uncomplicated Bus Rapid Transit (BRT) project is meant to illustrate the approach for a highway/transit type project using the FTA procedures.

A new BRT corridor is planned in an existing abandoned railroad right-of-way. For this project source,

SEL_{ref} = 82 for buses
S = 25 mph
V_d = (344 buses)/(15 hours) = 22.9 buses per hour
V_n = (116 buses)/(9 hours) = 12.9 buses per hour

In addition, from Table 5-4,

C_s = 15 for buses

Using the equations in Table 5-4 the resulting L_{eq}'s at 50 feet are:

L_{eq}(day) = 55.5
L_{eq}(night) = 53

This total day and night traffic results in:

L_{dn} = 60 at 50 ft

The surrounding area is residential with 2,500 people per square mile starting approximately 100 feet away from the proposed alignment. Using Table 5-7 the existing noise in the area is 50 dBA.

From Figure 3-1 the impacts thresholds are:

Background Level	Moderate Impact	Severe Impact
50	54	59

Therefore, from Figure 5-2:

Project Level	Onset of Moderate Impact	Onset of Severe Impact
60	125 feet	60 feet

This results in impacts to the residences. A barrier is proposed for mitigation, resulting in a predicted new level of 55 and:

Mitigated Project Level	Onset of Moderate Impact	Onset of Severe Impact
55	60 feet	N/A

The onset of Severe Impact is listed as N/A because the Severe Impact criterion is not exceeded by the project. Mitigation is accomplished by a barrier because the Moderate Impact contour has been moved in to a distance of 60 feet, whereas the residential area lies beyond 100 feet.

End of Example 5-3

Example 5-4. General Noise Assessment for a Transit Center

The following example illustrates the procedure for performing a General Noise Assessment for a stationary source. The example represents a typical FTA-assisted project in an urban area, the siting of a busy transit center in a mixed commercial and residential area, as shown in Figure 5-4.

Assumptions for Example

The assumptions for the Transit Center and its environs are as follows:

- **Main Street Traffic:** Peak hour traffic of 1200 autos, 20 heavy trucks, 300 medium trucks.

- **Population Density:** 12 houses per block; single family homes; 3 people per family.

  Block area = 78,750 square feet.
  Population density = 9,750 people/square mile.

- **Bus Traffic:**

Period	Hours	Buses per Hour
Peak, Morning	7am - 9am	30
Peak, Afternoon	4pm - 6pm	30
Mid-day	9am - 4pm	15
Evening	6pm - 10pm	12
Early Morning (Night)	6am - 7am	15
Late Night	10pm - 1am	4

Procedure

Before beginning the General Assessment, note that the Screening Procedure calls for additional analysis if any residential or other noise-sensitive land use is within 150 feet of a Transit Center when there are intervening buildings. According to Figure 5-4 the nearest residence is about 140 feet from the center of the proposed Transit Center, thereby calling for further analysis. The General Assessment proceeds as follows:

Determination of Noise Exposure at 50 feet

1. Determine the average number of buses per hour during day and night.

   Day (7am - 10pm):
   N_B *(avg day)* = 273 buses/15 hours = 18.2 buses/hour average

   Night (10pm - 7am):
   N_B *(avg night)* = 27 buses/9 hours = 3 buses/hour average

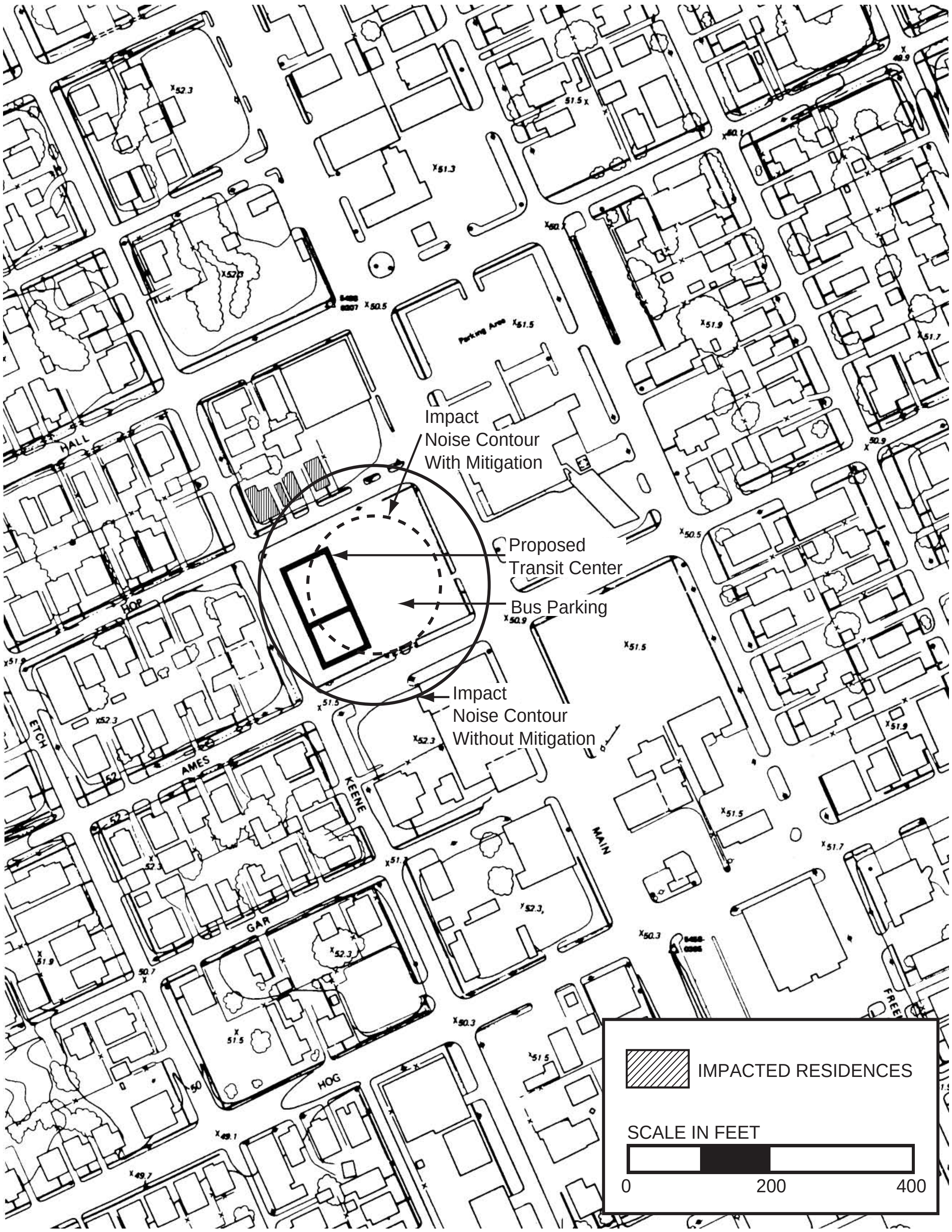

Figure 5-4. Example of Project for General Assessment: Siting of Transit Center in Mixed Commercial/Residential Area

2. Calculate $L_{eq}(day)$ and $L_{eq}(night)$ at 50 feet, assuming no noise barrier.

From Table 5-5 and Table 5-6 the levels are determined as follows:

$$L_{eq}(day) = SEL_{ref} + C_N - 35.6$$
$$= 101 + 10 \log (18.2/20) - 35.6$$
$$= 65 \text{ dB}$$

$$L_{eq}(night) = SEL_{ref} + C_N - 35.6$$
$$= 101 + 10 \log (3/20) - 35.6$$
$$= 57 \text{ dB}$$

3. Calculate L_{dn} at 50 ft for the project.

From Table 5-6 the level at 50 feet is determined as follows:

$$L_{dn} = 10\log\left[(15)10^{Leq(day)/10} + (9)10^{(Leq(night)+10)/10}\right] - 13.8$$

which gives:

$$L_{dn} = 79.7 - 13.8$$

or L_{dn} = 66 dB

Estimate Existing Noise Exposure

4. Estimate existing noise at noise-sensitive sites from the dominant noise source, either major roadways or local streets (population density).

Roadway Noise Estimate: The traffic on Main Street qualifies this street for the "Other Major Roadway" category in Table 5-7. According to the map, the nearest residence is 275 feet from the edge of Main Street. The table shows existing L_{dn} = 55 dB at this distance for representative busy city street traffic.

Population Density Noise Estimate: As a check on which ambient noise category to use, noise from local streets is estimated from the population density of 9,750 people/square mile. Table 5-7 indicates the L_{dn} should be approximately 55 dB.

The existing noise level associated with the residential neighborhood is therefore taken to be L_{dn} = 55 dB. In case the two estimates are different, use the lower L_{dn} value.

Noise Impact Contours

5. Distance to Impact Contours: For an existing noise exposure of 55 dB, the noise impact criteria indicate that the onset of Moderate Impact will occur at a project noise level of 56 dB, and onset of Severe Impact will occur at 62 dB. The next step is to determine the distances from the center of the property at which these levels are reached. This is accomplished by use of Figure 5-2, the exposure-vs-distance curve. With the project noise level at 50 feet given as 66 dB and the two

impact levels at 56 dB and 62 dB, the differences are 10 dB and 4 dB, respectively. Using the curve in Figure 5-2 labeled "Stationary" source, the distance to where the project level drops 10 dB is approximately 160 feet, and 4 dB attenuation occurs at about 80 feet. Consequently, the Moderate Impact contour occurs about 140 feet from the center of the property and the Severe Impact contour occurs at 80 feet.

6. Draw Contours: Lines are drawn at 80 feet and 140 feet from the center of the property of the proposed Transit Center. These lines represent the noise impact contours. (Note in Figure 5-4 the Severe Impact contour is left out for clarity: it is just within the dashed line representing the Moderate Impact contour after mitigation.)

7. Assessment: Within, or touching, the contour defining "Moderate Impact" are three residential buildings (shaded in Figure 5-4). No residences are within the "Severe Impact contour."

Noise Mitigation

8. Noise Barrier: The process is repeated with a hypothetical noise barrier at the property line on the residential side of the Transit Center. This would consist of a wall approximately 15 feet high partially enclosing the transit center, sufficient to screen the residences but not the commercial block facing Main Street. According to Table 5-6, the approximate noise barrier effect is -5 dB. Repeating the procedure above, the effect of the noise barrier is to shrink the Moderate Impact contour to 90 feet and the Severe Impact contour to 45 feet, which in this example eliminates all adverse effect on the residences.

End of Example 5-4

REFERENCES

1. U.S. Department of Transportation, Federal Highway Administration, *FHWA Traffic Noise Model User's Guide*, Report FHWA-PD-96-009, Washington, DC, January 1998. In addition, *FHWA Traffic Noise Model User's Guide (Version 2.5 Addendum)*, April 2004.

2. U.S. Environmental Protection Agency, "Population Distribution of the United States as a Function of Outdoor Noise Level," Report 550/9-74-009, June 1974.

6. DETAILED NOISE ANALYSIS

This chapter describes the detailed computation of both project and existing noise levels for a comprehensive assessment of project noise impact. The main purpose of this chapter is to provide a procedure that allows prediction of impact and assessment of the effectiveness of mitigation with greater precision than can be achieved with the General Assessment. In some cases, decisions on appropriate mitigation measures can be made based on the results of the General Assessment. When a more detailed evaluation of mitigation measures is needed, the procedures in this chapter should be followed.

It is important to recognize that use of the Detailed Analysis methods will not provide more accurate results than the General Assessment unless more detailed and specific input data are used. In the case of a transit center, for example, the General Assessment provides a source level at a reference distance from the center of the site based on the number of buses at the facility during each hour. Thus, the only information needed for a General Assessment of the transit center is the site location and hourly bus volumes. However, a Detailed Analysis would require specific information on the locations, reference levels, traffic volumes and duration of operations for individual sources that contribute to the total noise output of the transit center. Such information would include a detailed design plan for the facility, the locations of idling buses and the idling durations, as well as the bus and automobile traffic patterns and volumes. A Detailed Analysis cannot be done until such information is available.

Detailed Noise Analysis is appropriate in two main circumstances: first, for a major fixed-guideway project after the preferred mode and alignment have been selected; and second, for any other transit project where potentially severe impacts are identified at an early stage. For fixed-guideway projects, once the preferred mode and alignment are established, the project sponsor begins preliminary engineering and works to complete the environmental impact assessment, usually with a Final EIS. Information required for the Detailed Noise Analysis is generally available at the preliminary engineering stage; such information includes hourly operational schedules during day and night, speed profiles, plan and profiles of guideways, locations of access roads, and landform topography including terrain and building features.

Even for relatively minor transit projects, noise impacts are likely to occur whenever the project is in close proximity to noise-sensitive sites, particularly residences. Some examples are: (1) a terminal or station sited adjacent to a residential neighborhood; (2) a maintenance facility located near a school; (3) a storage yard adjacent to residences; and (4) an electric substation located adjacent to a hospital. As with the larger fixed-guideway projects mentioned above, a Detailed Noise Analysis for these projects will require information normally developed at the preliminary design stage.

The procedures of this chapter include everything needed for a fully detailed transit noise analysis. They are aimed at major transit projects that have enough lead time for thorough environmental analysis. They need not be followed to the letter; they can be tempered by competent engineering judgment and adapted somewhat to specific project constraints.

This chapter employs equations as the primary mode of computation, rather than graphs or tables of numbers, in order to facilitate the use of spreadsheets and/or programmable calculators. Moreover, these equations and their supporting text have been streamlined to provide as concise a view of the Detailed Noise Analysis as possible. As a result, basic noise concepts are not repeated in this chapter.

The steps in the procedure appear in Figure 6-1 and are described below. They parallel the steps for the General Noise Assessment, though they are more refined in the prediction of project noise and subsequent evaluation of mitigation measures.

1. Receivers of Interest. Select receivers of interest, guided by Section 6.1. The number of receivers will depend upon the land use in the vicinity of the proposed project and the extent of the study area defined by the Screening Procedure. If a General Assessment has been done, this will give a good indication of the extent of potential impacts.

2. Project Noise. Determine whether the project is primarily a fixed-guideway transit, highway/transit, or stationary facility. Note that a major fixed-guideway system will have stationary facilities associated with it, and that a stationary facility may have highway/transit elements associated with it. Identify the project noise sources that are in the vicinity of receivers of interest. For these sources, determine the source reference noise in terms of SEL from the tables in Section 6.2. Each reference SEL pertains to reference operating conditions for stationary sources or to one vehicle passby under reference operating conditions for fixed-guideway and highway/transit sources. These reference levels should incorporate source-noise mitigation only if such mitigation will be incorporated into the system specifications. For example, if the specifications include vehicle noise limits which may not be exceeded, these limits should be used to determine the reference level, and this level should be used in the analysis rather than the standard, tabulated reference level. Convert each source SEL to noise exposure (L_{dn} or L_{eq} (h)) at 50 feet, for the appropriate project operating parameters, using additional equations in Section 6.2.

3. Propagation and Summation of Project Noise at Receivers of Interest. Draw a noise exposure-vs.-distance curve for each relevant source, using the equations in Section 6.3. This curve will show source noise as a function of distance, accounting for shielding along the path, as well as any

propagation-path mitigation that will be included in the project. From these curves, determine the total project noise exposure at all receivers of interest by combining the levels from all relevant sources (Section 6.4).

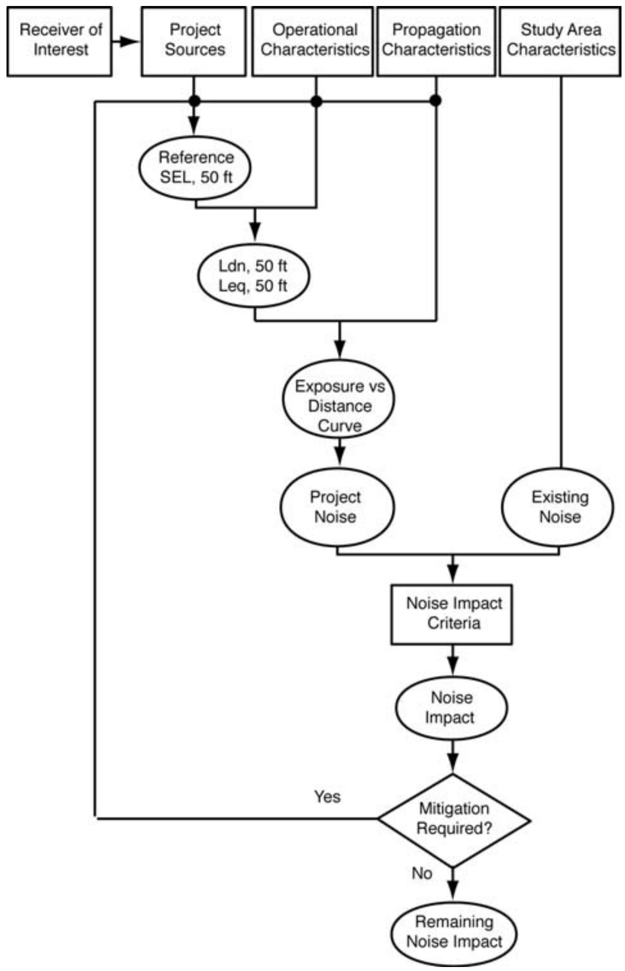

Figure 6-1. Procedure for Detailed Analysis

4. Existing Noise in the Study Area. Estimate the existing noise exposure at each receiver of interest, using the methods in Section 6.6.

5. Noise Impact Assessment. Assess noise impact at each receiver of interest using the procedures in Section 6.7 which incorporate the noise impact criteria of Chapter 3.

6. Mitigation of Noise Impact. Where the assessment shows either Severe Impact or Moderate Impact, evaluate alternative mitigation measures referring to Section 6.8. Then loop back to modify

the project-noise computations, thereby accounting for the adopted mitigation, and reassess the remaining noise impact.

6.1 RECEIVERS OF INTEREST

The steps in identifying the receivers of interest, both the number of receivers needed and their locations, are shown in Figure 6-2. Later sections discuss the measurement/computation of ambient noise, the computation of project noise, and the resulting assessment of noise impact that is done for each receiver. The basic steps, which are discussed in the following subsections, are:

1. Identify all noise-sensitive land uses.
2. Find individual receivers of interest. Examples are isolated residences and institutional resources such as schools.
3. Cluster residential neighborhoods and other relatively large noise-sensitive areas.

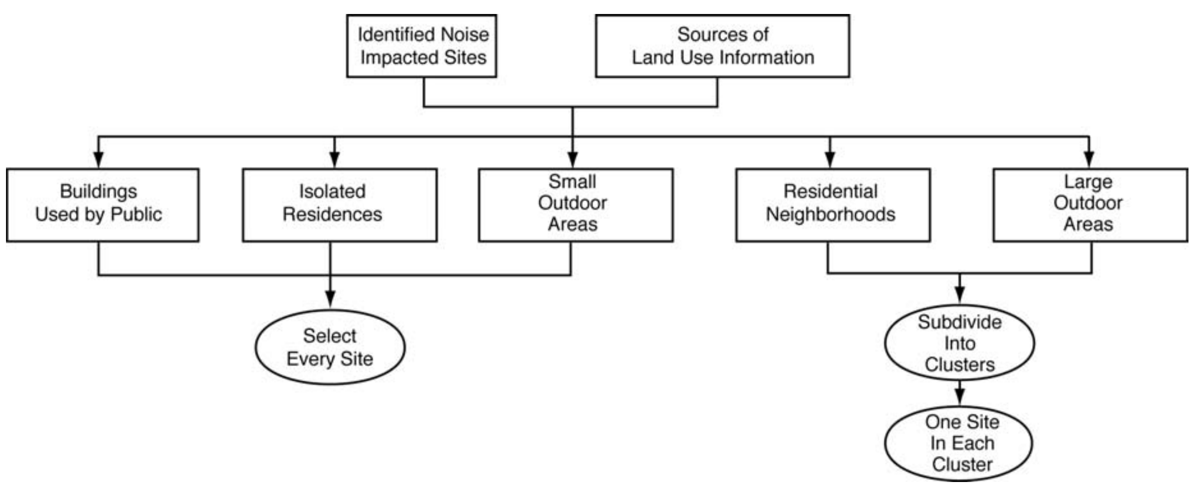

Figure 6-2. Guide to Selecting Receivers of Interest

6.1.1 Identifying Noise-Sensitive Land Uses

A Detailed Noise Analysis should usually be performed on all noise-sensitive land uses where impact is identified by the General Noise Assessment. If a General Noise Assessment has not been done, but there appears to be potential for noise impacts, all noise-sensitive sites within the area defined by the noise screening procedure should be included. In areas where ambient noise is low, the assessment will include land uses that are farther from the proposed project than for areas with higher ambient levels.

Some of the land-use materials and methods that can be helpful in locating noise-sensitive land uses in the vicinity of the proposed project include:

- **Land-use maps**, prepared by regional or local planning agencies or by the project staff. Area-wide maps often do not have sufficient detail to be of much use. However, they can provide broad guidance and may suggest residential pockets hidden within otherwise commercial zones. Of more use are project-specific maps which provide building-by-building detail on the land nearest the proposed project.
- **USGS maps,** prepared by the United States Geological Survey generally at 2000-foot scale. These maps contain details of house placement, except in highly urbanized areas, and generally show the location of all schools and places of worship, plus many other public-use buildings. In addition, the topographic contours on these maps may be useful later during noise computation.
- **Road and town maps**. These can supplement the USGS maps, are generally more up-to-date, and may be of larger scale.
- **Aerial photographs,** especially those of 400-foot scale or better. When current, aerial photos are valuable in locating all potential noise-sensitive land uses close to the proposed project. In addition, they can be useful in determining the distances between receivers and the project.
- **Windshield survey** of the corridor. Definitive identification of noise-sensitive sites is accomplished by a windshield survey in which the corridor is driven and land uses are annotated on base maps. The windshield survey, supplemented by footwork where needed, is especially useful in identifying newly-constructed sites and in confirming land uses very close to the proposed project.
- **Geographic Information Systems (GIS).** Mapping needed for identifying noise-sensitive land uses is often available in electronic GIS format. GIS data may include land parcels, building structures, aerial photography and project-specific information. These data may be obtained during the project study or from local or regional agencies that store and maintain GIS data. Using electronic GIS data has advantages over paper mapping in being able to automate the process of identifying noise-sensitive land use and accurately being able to determine their distances to the project alignment.

Table 6-1 contains the types of land use of most interest in the impact assessment, separated into three types of land use. If noise impact was identified at other types of buildings/areas with noise-sensitive use by the General Noise Assessment, these should be selected also.

6.1.2 Selecting Individual Receivers of Interest

Select as an individual receiver of interest: (1) every major noise-sensitive building used by the public; (2) every isolated residence; and (3) every relatively small outdoor noise-sensitive area. Use judgment here to avoid analyzing noise where such analysis is obviously not needed. For example, many roadside motels are not particularly sensitive to noise from outdoors. On the other hand, be careful to include buildings used by the public or outdoor areas which are considered to be particularly noise-sensitive by the community. Isolated residences that are particularly close to the project should certainly be included, while those at some distance may often be omitted or "clustered" together with other land uses, as described in the next section. Use judgment also concerning relatively small outdoor noise-sensitive areas. For example, playgrounds can often be omitted unless they directly abut the proposed project, since noise sensitivity in playgrounds is generally low.

Table 6-1. Land Uses of Interest

Land Uses	Specific Use	Selecting Receivers
Outdoor noise-sensitive areas	Certain parks Historic sites used for interpretation Amphitheaters Passive recreation areas Cemeteries Other outdoor noise-sensitive areas	For relatively small noise-sensitive areas: same as indoor noise-sensitive sites. For relatively large areas: same as for residential areas.
Residences	Single family residences Multi-family residences (apartment buildings, duplexes, etc.)	Select each isolated residence as a receiver of interest. For residential areas, cluster by proximity to project sources, proximity to ambient-noise sources, and location along project line. Choose one receiver of interest in each cluster.
Indoor noise-sensitive sites	Places of worship Schools Hospitals/nursing homes Libraries Public meeting halls Concert halls/auditoriums/theaters Recording/broadcast studios Museums and certain historic buildings Hotels and motels Other public buildings with noise-sensitive indoor use	Select noise-sensitive buildings as separate receivers of interest.

6.1.3 Clustering Residential Neighborhoods and Outdoor Noise-Sensitive Areas

Residential neighborhoods and relatively large outdoor noise-sensitive areas can often be clustered, simplifying the analysis that is required without compromising the accuracy of the analysis. The goal is to subdivide all such neighborhoods/areas into clusters of approximately uniform noise, each containing a collection of noise-sensitive sites. Attempt to obtain uniformity of both project noise and ambient noise, guided by these considerations:

1. In general, project noise drops off with distance from the project. For this reason, project noise uniformity requires nearly equal distances between the project noise source and all points within the cluster. Such clusters will usually be shaped as long narrow strips parallel to the transit corridor and/or circling project point sources such as a maintenance facility. Suggested are clusters within which the project noise will vary over a range of 5 decibels or less. Be guided here by the fact that project noise will drop off approximately 3 decibels per doubling of distance for line sources and 6 decibels per doubling of distance for point sources over open terrain. Drop-off with distance will be faster in areas containing obstacles to sound propagation, such as rows of buildings.

2. Ambient noise usually drops off from non-project sources in the same manner as does noise from project sources. For this reason, clustering for uniform ambient noise will usually result in long narrow strips parallel to major roadways or circling major point sources of ambient noise, such as a manufacturing facility. Suggested are clusters within which the ambient noise will vary over a range

of 5 decibels or less, though this may be hard to judge without measurements. In areas without predominant sources of noise, like highways, ambient noise varies with population density, which is generally uniform along the corridor. In situations where ambient noise tends to be uniform, the clusters can encompass relatively large areas.

After defining the cluster, select one receiver as representative in each cluster. Generally choose the receiver closest to the project and at an intermediate distance from the predominant sources of existing noise. Detailed procedures for clustering appear in Appendix C along with an example of clustering for a segment of rail line. This method will generally result in an adequate selection of receivers along the corridor or surrounding the site.

6.2 PROJECT NOISE

Once receivers have been selected, projections of noise from the project must be developed for each receiver. This section describes the first step, calculating the noise exposure at an equivalent distance of 50 feet from each project noise source. As shown in Figure 6-3, the basic procedures for the computation are: (1) Separate nearby sources into these source-type categories: fixed-guideway sources, highway/transit sources, and stationary sources; (2) Determine the reference SEL for each source; and (3) Use the projected source operating parameters to convert each reference SEL to noise exposure (either L_{dn} or $L_{eq}(h)$) at 50 feet.

Table 6-2 lists many of the noise sources that are involved in transit projects. The right-hand column of the table indicates whether or not each source is a major contributor to overall noise impact. Note that some noise sources, such as track maintenance equipment, create high noise levels but are not indicated as "major." Although such sources are loud, they rarely stay in a neighborhood for more than a day or two; therefore, the overall noise exposure is relatively minor. Computations are required for all major noise sources in this table. The computations for the three basic groups – fixed-guideway sources, highway/transit sources, and stationary sources – appear in separate sections below.

6.2.1 Fixed-Guideway Sources

This section describes the computation of project noise at 50 feet from fixed-guideway sources of transit noise, identified in the second column of Table 6-2.

Step 1: Source SELs at 50 feet

For each major fixed-guideway noise source, first determine the reference SEL at 50 feet, either by measurement or by table look-up. Table 6-3 provides guidance on which method is preferred for each source type. A "NO" implies that the source levels are based on a solid and consistent data base; a "YES" means that a solid data base is not available. In general, measurements are preferred for source types that vary significantly from project to project, including any emerging technology sources. Table look-up is adequate for source types that do not vary significantly from project to project. In general, table look-up is adequate for fewer source types during Detailed Noise Analysis than during General Noise Assessment where less precision is acceptable.

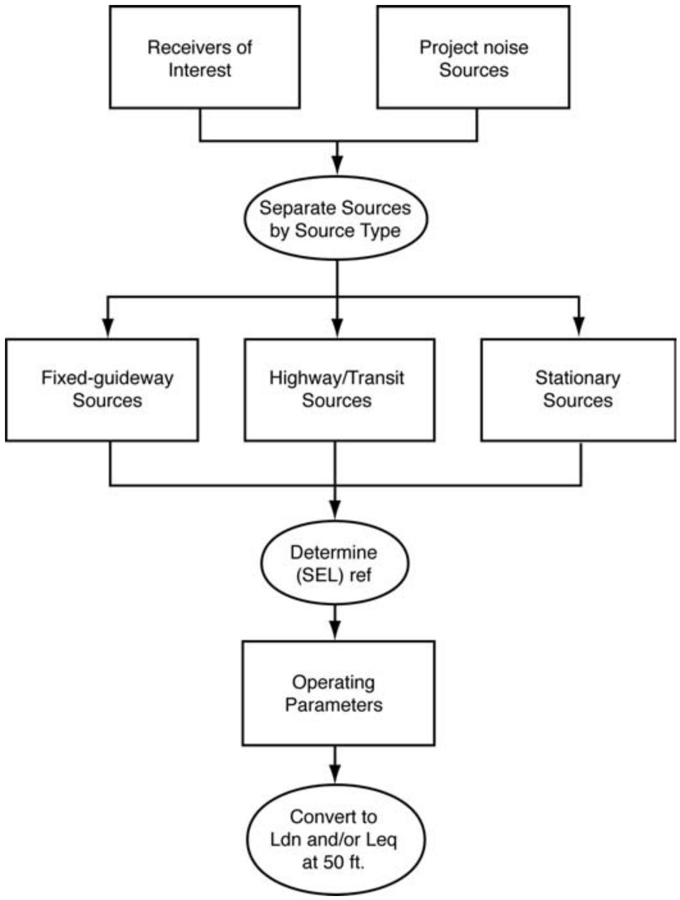

Figure 6-3. Flow Diagram for Determining Project Noise at 50 ft

For sources where measurements are indicated in Table 6-3, Appendix E discusses measurement procedures and conversion of these measurements to the reference conditions of Table 6-3. These procedures have been placed in an appendix because of their relative complexity. For projects where source-noise specifications have been defined (e.g., noise limits are usually included in the specifications for purchase of new transit vehicles), these specifications may be used instead of measurements, after conversion to reference conditions with the equations of Appendix E. This would only be appropriate where there is a firm commitment to adopt the noise specifications in the vehicle procurement documents during final design and adhere to the specifications throughout the procurement, delivery and testing of the vehicles.

For sources where table look-up is indicated in Table 6-3, the table provides appropriate Source Reference SELs. Approximate L_{max} values also appear in the table for general user information and for comparison with factors such as the noise limits that are included in transit vehicle specifications. As discussed in Chapter 2, L_{max} is not used directly in the evaluation of noise impact.

Table 6-2. Sources of Transit Noise

Project Type	Source Type	Actual Source	Major?
Commuter Rail Light Rail Rail Rapid Transit	Fixed-Guideway	Locomotive and rail car passbys	YES
		Horns and whistles	YES
		Crossing signals	YES
		Crossovers/switches	YES
		Squeal on tight curves	YES
		Track-maintenance equipment	NO
	Stationary	Substations	YES
		Chiller plants	NO
Busways Bus Transit Malls	Highway/Transit	Bus passbys	YES
		Buses parking	NO
	Stationary	Buses idling	YES
Automated Guideway Transit Monorail	Fixed-Guideway	Vehicle passbys	YES
	Miscellaneous	Line equipment	NO
Terminals Stations Transit Centers	Fixed-Guideway	Locomotive and rail car passbys	YES
		Crossovers/switches	YES
		Squeal on tight curves	YES
	Highway/Transit	Bus passbys	YES
		Buses parking	NO
		Automobile passbys	NO
	Stationary	Locomotives idling	YES
		Buses idling	YES
		Ferry boats landing, idling and departing at dock	YES
		HVAC equipment	NO
		Cooling towers	NO
		P/A systems	NO
Park-and-Ride Lots	Highway/Transit	Bus passbys	YES
		Buses idling	YES
		Automobile passbys	NO
	Stationary	P/A systems	NO
Traffic Diversion Projects	Highway/Transit	Highway vehicle passbys	YES
Storage Facilities Maintenance Facilities	Fixed-Guideway	Locomotive and rail car passbys	YES
		Locomotives idling	YES
		Squeal on tight curves	YES
		Horns, warning signals, coupling/ uncoupling, auxiliary equipment, crossovers/ switches, brake squeal and air release	YES
	Highway/Transit	Bus passbys	YES
	Stationary	Buses idling	YES
		Yard/shop activities	NO
		Car washes	NO
		HVAC Equipment	NO
		P/A Systems	NO

Table 6-3. Source Reference SELs at 50 Feet: Fixed-Guideway Sources @ 50 mph			
Source	**Reference SEL (dBA)**	**Approximate L_{max} (dBA)**	**Prefer Measurements?**
Rail Cars	82	80	NO
Locomotives – Diesel	92	88	NO
Locomotives – Electric	90	86	NO
Diesel Multiple Unit (DMU)	85	81	YES
AGT - Steel Wheel	80	78	YES
AGT - Rubber Tire	78	75	YES
Monorail	82	80	YES
Maglev	72	70	YES
Transit Car Horns (Emergency)	93	90	NO
Transit Car Whistles	81	78	NO
Locomotive Horns			
At Grade Crossing	113	110	NO
From Crossing to 1/8 mile	113-3*(D_p/660)	110	
From 1/8 mile to ¼ mile	110	110	
D_p = distance from grade crossing parallel to tracks			

Step 2: Conversion to Noise Exposure at 50 feet

Step 1 results in reference SELs at 50 feet. Step 2 is to convert from these reference SELs to noise exposure based on operating conditions and parameters such as train consists, speed, and number of trains per hour. The steps are:

1. Identify operating conditions. Trains with different consists require separate conversion since they will produce different noise exposure. The same is true for trains at different speeds, or under different operating conditions. As guidance here, the following percentage changes in operating conditions will produce an approximate 2-decibel change in noise exposure:

   - 40 percent change in number of locomotives or cars per train
   - 40 percent change in number of trains per hour
   - 40 percent change in number of trains per day, or per night (for computation of L_{dn})
   - 15 percent change in train speed
   - Change of one notch in diesel locomotive throttle setting (e.g. from notch 5 to notch 6)

   In general, where operating conditions change by these amounts, separate calculations should be made. Without separate conversions, the risk is that the results may not be accurate enough.

2. Establish relevant time periods. For each of these source types/conditions, decide what are the relevant time periods for all receivers that may be affected by this source. For residential receivers, the two time periods of interest for computation of L_{dn} are: daytime (7 am to 10 pm) and nighttime

(10 pm to 7 am). If the source will affect non-residential receivers, choose the loudest project hour during noise-sensitive activity. Several different hours may be of interest for non-residential receivers depending on the hours the facility is used.

3. Collect input data.
   - Source reference SELs for locomotives, rail cars, and warning horns.
   - N_{cars}, the number of rail cars in the train.
   - N_{locos}, the number of locomotives in the train, if any.
   - *S*, the train speed, in miles per hour.
   - *T*, the average throttle setting of the train's locomotive(s), if it is diesel-electric.[1] If this input is not available, assume a throttle setting of 8.
   - For residential receivers of interest:

     V_d, the average hourly train volume during daytime hours (equals the total number of train passbys between 7 am and 10 pm, divided by 15), and

     V_n, the average hourly train volume during nighttime hours (equals the total number of train passbys between 10 pm and 7 am, divided by 9).
   - For non-residential receivers: *V*, the hourly train volume for each hour of interest.
   - Track type (continuously welded or jointed) and profile (at-grade or elevated).

4. Calculate L_{eq} at 50 ft for each hour of interest.
   - Compute $L_{eqL}(h)$ for the locomotive(s) using the first equation in Table 6-4.
   - Compute $L_{eqC}(h)$ for the rail car(s) using the second equation in Table 6-4. Use the adjustments indicated in the table, as needed.
   - Compute $L_{eqH}(h)$ for the train horn using the third equation in Table 6-4.
   - Compute the total $L_{eq}(h)$ using the fourth equation in Table 6-4. Two totals may be necessary: one with the warning horn and one without it. These will pertain to different neighborhoods along the corridor, depending upon whether the horn is sounded in that neighborhood or not.

5. Compute L_{dn} at 50 ft. If the project noise will affect any residential receivers, compute the total train L_{dn} from the fifth equation in Table 6-4. Again two totals may be necessary: one with the warning horn and one without it, as explained above.

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1 Otherwise, this term is not applicable and should be omitted from the equation in Table 6-4.

Table 6-4. Computation of L_{eq} and L_{dn} at 50 feet: Fixed-Guideway Sources	
LOCOMOTIVES† Hourly L_{eq} at 50 ft:	$L_{eqL}(h) = SEL_{ref} + 10\log(N_{locos}) + C_T + K\log\left(\frac{S}{50}\right) + 10\log(V) - 35.6$ $where C_T = \begin{cases} 0 & for T < 6 \\ 2(T-5) & for T \geq 6 \end{cases}$ $and\ K = -10\ for\ passenger\ diesel; = 0\ for\ DMU; = +10\ for\ electric$
AIL VEHICLES†† Hourly L_{eq} at 50 ft:	$L_{eqC}(h) = SEL_{ref} + 10\log(N_{cars}) + 20\log\left(\frac{S}{50}\right) + 10\log(V) - 35.6$ use the following adjustments as applicable: + 5 $\rightarrow$ JOINTED TRACK + 3 $\rightarrow$ EMBEDDED TRACK ON GRADE + 4 $\rightarrow$ AERIAL STRUCTURE WITH SLAB TRACK
LOCOMOTIVE WARNING HORNS††† Hourly L_{eq} at 50 ft:	$L_{eqH}(h) = SEL_{ref} + 10\log(V) - 35.6$
TRANSIT WARNING HORNS††† Hourly L_{eq} at 50 ft:	$L_{eqH}(h) = SEL_{ref} - 10\log\left(\frac{S}{50}\right) + 10\log(V) - 35.6$
COMBINED Hourly L_{eq} at 50 ft:	$L_{eq}(h) = 10\log\left[10^{\left(L_{eqL}/10\right)} + 10^{\left(L_{eqC}/10\right)} + 10^{\left(L_{eqH}/10\right)}\right]$
Daytime L_{eq} at 50 ft:	$L_{eq}(day) = L_{eq}(h)\big\|_{v=v_d}$
Nighttime L_{eq} at 50 ft:	$L_{eq}(night) = L_{eq}(h)\big\|_{v=v_n}$
L_{dn} at 50 ft:	$L_{dn} = 10\log\left[(15)\cdot 10^{\left(L_{eq}(day)/10\right)} + (9)\cdot 10^{\left(L_{eq}(night)+10/10\right)}\right] - 13.8$

N_{locos} = average number of locomotives per train
N_{cars} = average number of cars per train
T = average throttle setting of diesel-powered locomotives and DMU's
S = train speed, in miles per hour
V = average hourly volume of train traffic, in trains per hour
V_d = average hourly daytime volume of traffic, in trains per hour

$$= \frac{number\ of\ trains, 7am\ to\ 10pm}{15}$$

V_n = average hourly nighttime volume of train traffic, in trains per hour

$$= \frac{number\ of\ trains, 10pm\ to 7am}{9}$$

† Assumes a passenger diesel locomotive power rating of approximately 3000 hp
†† Includes all commuter rail cars, transit cars, AGT and monorail
††† Based on FRA's horn noise model (www.fra.dot.gov/downloads/RRDev/hornmodel.xls)

Example 6-1. Computation of L_{eq} and L_{dn} at 50 feet for Fixed-Guideway Source

A commuter train with 1 diesel locomotive and 6 cars will pass close to a residential area at a grade crossing. For this project source,

SEL_{ref}	=	92 for locomotives,
	=	82 for rail cars,
	=	113 for locomotive warning horns at grade crossing

In addition,

N_{cars}	=	6
N_{locos}	=	1
S	=	43 mph
T	=	8
V_d	=	(40 trains)/(15 hours)= 2.667 trains per hour, and
V_n	=	(2 trains)/(9 hours) = 0.222 trains per hour.

The track is also jointed in this vicinity. Using Table 6-4, the resulting daytime L_{eq}'s at 50 feet are as follows:

L_{eqL}(day)	=	67.3 for locomotives,
L_{eqC}(day)	=	62.1 for cars, and
L_{eqH}(day)	=	81.7 for horns.
Total L_{eq}(day)	=	81.9 in neighborhoods where the horn is sounded, and
	=	69.3 in neighborhoods where it is not.

Using Table 6-4, the resulting nighttime L_{eq}'s at 50 feet are as follows:

L_{eqL}(night)	=	56.5 for locomotives,
L_{eqC}(night)	=	51.3 for cars, and
L_{eqH}(night)	=	70.9 for horns,
Total L_{eq}(night)	=	71.1 with horns, and
	=	57.6 without horns.

Finally, this total day and night traffic results in:

L_{dn}	=	81.6 at 50 ft in neighborhoods where horns are sounded, and
	=	68.7 at 50 ft in neighborhoods where they are not.

(Note: Computation results should always be rounded to the nearest decibel at the end of the computation. In all examples of this chapter, however, the first decimal place is retained in case readers wish to precisely match their own computations against the example computations.)

End of Example 6-1

6.2.2 Highway/Transit Sources

This section describes the computation of project noise at 50 feet for highway/transit sources, identified in the second column of Table 6-2. This method is based on the original FHWA highway noise prediction model, with updated noise emission levels.(1) This model can be used because the vehicle equations are applicable to speeds typical of freely-flowing traffic on city streets and access roads. In Chapter 3 there is a discussion of specific types of projects and conditions for which the FHWA procedures should be used, including TNM, the currently approved highway noise prediction model.

Step 1: Source SELs at 50 feet

Determine the source reference SEL at 50 feet for each "major" highway/transit source near a receiver of interest. As indicated in the fourth column of Table 6-5, it is usually adequate to use the standard Reference SELs of Table 6-5 for highway/transit sources. If measurements are chosen, however, Appendix E discusses the measurement procedures, plus procedures for the conversion of these measurements to reference conditions of Table 6-5. These measurement/conversion procedures have been placed in an appendix because of their relative complexity.

Table 6-5. Source Reference SELs at 50 Feet: Highway/Transit Sources @ 50 mph.

Source	Reference SEL (dBA)	Approximate L_{max} (dBA)	Prefer Measurements?
Automobiles	74	70	No
Buses (diesel)	82	79	No
Buses (electric trolleybus)	80	77	No
Buses (hybrid)[i]	83	80	Yes

[i] Hybrid bus with full-time diesel engine and electric drive motors.

Step 2: Conversion to Noise Exposure

Convert the source reference SELs at 50 feet to actual operating conditions such as actual vehicle speed and number of vehicles per hour. Next convert to noise exposure using the following steps:

1. Identify actual source operating conditions. Noise emission from most transit buses does not depend significantly upon whether the buses are accelerating or cruising. On the other hand, accelerating suburban buses are significantly louder than are cruising suburban buses. For this reason, suburban buses require separate conversion along roadway stretches where they are accelerating. Separate conversion is also needed for all highway/transit vehicles at different speeds, since speed affects noise emissions. As guidance here, the following percentage changes in operating conditions will produce an approximate 2-decibel change in noise exposure:

    - 40 percent change in number of vehicles per hour
    - 40 percent change in number of vehicles per day, or per night (for computation of L_{dn})
    - 15 percent change in vehicle speed.

    In general, where operating conditions change by these amounts, separate conversions should be made.

2. Establish relevant time periods. For each of these source types/conditions, decide what are the relevant time periods for all receivers that may be affected by this source. If the source will affect residential receivers, two time periods are of interest to compute L_{dn}: daytime (7 am to 10 pm) and nighttime (10 pm to 7 am). In addition, if the source will affect non-residential receivers, choose the loudest facility hour during noise-sensitive activity. Several different hours may be of interest for non-residential receivers, depending on the hours the facility is used.

3. Collect input data. Gather the following information:
    - Source reference SELs for the vehicle types of concern.
    - *S*, the average running speed in miles per hour.
    - For residential receivers of interest:

      V_d, the average hourly vehicle volume during daytime hours (equals the total number of vehicle passbys between 7 am and 10 pm, divided by 15), and

      V_n, the average hourly vehicle volume during nighttime hours (equals the total number of vehicle passbys between 10 pm and 7 am the next day, divided by 9).
    - For non-residential receivers of interest: *V*, the hourly vehicle volume for each hour of interest, in vehicles per hour.

4. Calculate L_{eq} at 50 ft for each hour of interest. Compute $L_{eq}(h)$ for the vehicle type using the first equation in Table 6-6.

5. Compute L_{dn} at 50 ft. If this vehicle type will affect any residential receivers, compute the total L_{dn} for the vehicle type using the fourth equation in Table 6-6.

Table 6-6. Computation of L_{eq} and L_{dn} at 50 feet: Highway/Transit Sources

Hourly L_{eq} at 50 ft:	$L_{eq}(h) = SEL_{ref} + 10\log(V) + C_{emissions} - 10\log\left(\frac{S}{50}\right) - 35.6$
Daytime L_{eq} at 50 ft:	$L_{eq}(day) = L_{eq}(h)\big\|_{v=v_d}$
Nighttime L_{eq} at 50 ft:	$L_{eq}(night) = L_{eq}(h)\big\|_{v=v_n}$
L_{dn} at 50 ft:	$L_{dn} = 10\log\left[(15)\times 10^{\left(L_{eq}(day)/10\right)} + (9)\times 10^{\left(L_{eq}(night)+10/10\right)}\right] - 13.8$
Noise Emissions	$C_{emissions}$ $= 25\times\log\left(\frac{S}{50}\right)$ → buses $= 1.6$ → accelerating 3-axle commuter buses $= 40\times\log\left(\frac{S}{50}\right)$ → automobiles
Other adjustments	-3 → automobiles, open-graded asphalt +3 → automobiles, grooved pavement

V = hourly volume of vehicles of this type, in vehicles per hour

V_d = average hourly daytime volume of vehicles of this type, in vehicles per hour

$$= \frac{total vehicle volume, 7 am to 10 pm}{15}$$

V_n = average hourly nighttime volume of vehicles of this type, in vehicles per hour

$$= \frac{total vehicle volume, 10 pm to 7 am}{9}$$

S = average vehicle speed in miles per hour (distance divided by time, excluding stop time at red lights)

Note: Idling buses appear under Stationary Sources.

Example 6-2. Computation of L_{eq} and L_{dn} at 50 feet for Highway/Transit Source

A bus route with city buses will pass close to a school that is in session from 8 am to 4 pm on weekdays. Within this time period, the hour of greatest activity for this bus route is 8 am to 9 am. For this project source,

SEL_{ref} = 82 dB
S = 40 mph, and
V = 30 buses per hour

Using Table 6-6, the resulting hourly L_{eq} at 50 ft = 59.7 dB.
(Note: Computation results should always be rounded to the nearest decibel at the end of the computation.)

Continuing the example, this same bus also passes close to a residential area. For this project source, SEL_{ref} is the same as above, as is S. In addition,

V_d = (200 buses)/(15 hours) = 13.33 buses per hour, and
V_n = (20 buses)/(9 hours) = 2.22 buses per hour.

Using Table 6-6, the resulting L_{eq}'s at 50 ft are as follows:

L_{eq}(day) = 56.2 dB and
L_{eq}(night) = 48.4 dB.

Finally, the total day and night traffic results in L_{dn} at 50 ft = 57.2 dB.

End of Example 6-2

6.2.3 Stationary Sources

This section describes the computation of project noise at 50 feet for stationary sources of transit noise, identified in the second column of Table 6-2.

Step 1: Source SELs at 50 feet

Determine the reference SEL at 50 feet for each major source, either by measurement or by table look-up. Table 6-7 provides guidance on which method is preferred for each source type. In general, measurements are preferred for source types that vary significantly from project to project. For example, curve squeal is highly variable depending on weather conditions, curve radius, and train speed. In general, a standard steel wheel on steel rail system will tend to initiate curve squeal at curves with radii less than 100 time the truck wheelbase. Table look-up is adequate for source types that do not vary significantly from project to project (crossing signals, for example). Ferry boat landings are included in the stationary source category because the noise from the landing remains in one area even though the boats move in and out.

Table 6-7. Source Reference SELs at 50 Feet: Stationary Sources

Source	Reference SEL (dBA)	Approximate L_{max} (dBA)	Prefer Measurements?
Auxiliary Equipment	101	65	YES
Locomotive Idling	109	73	NO
Rail Transit Idling	106	70	NO
Buses Idling	111	75	NO
Ferry Boat Landing, Idling and Departing	91	78	NO
Ferry Boat Fog Horn	90	84	NO
Track Crossover	100	90	NO
Track Curve Squeal	136	100	YES
Car Washes	111	75	YES
Crossing Signals	109	73	NO
Substations	99	63	NO

For sources where measurements are indicated in Table 6-7, Appendix E discusses the measurement procedures, plus procedures for the conversion of these measurements to the reference conditions of Table 6-7.

For most sources where table look-up is indicated in Table 6-7, the table provides appropriate reference SELs for one typical noise event at 50 feet and of 1-hour duration (3600 seconds). For ferry boats and fog horns, the reference SELs are for one typical noise event at 50 feet. Approximate L_{max} values are also given in the table for general user information.

Layover facilities and transit centers can be the sources of low-frequency noise from idling diesel engines. Sounds with considerable low-frequency components can cause greater annoyance than would be expected based on their A-weighted levels. Low-frequency sounds often cause windows and walls to vibrate resulting in secondary effects in buildings such as rattling of dishes in cupboards and wall-mounted pictures. The SEL's in Table 6-7 are adjusted to include a factor to take increased annoyance into account. However, for a detailed analysis at locations where such idling takes place for an extended period, the method described in ANSI Standard S12.9-Part 4, Annex D, should be used.(2)

Step 2: Conversion to Noise Exposure at 50 feet

Step 1 results in reference SELs at 50 feet. Step 2 is to convert from these reference SELs to actual operating conditions, such as actual event durations and numbers of events, and calculate noise exposure at 50 ft. The steps are:

1. Identify actual source durations and numbers of events. The following percentage changes in durations/numbers will produce an approximate 2-decibel change in noise exposure:

    - 40 percent change in event duration (e.g. from 30 to 42 minutes)
    - 40 percent change in number of events per hour (e.g. from 10 to 14 events per hour).

    In general, where durations/numbers change by these amounts, separate conversions should be made.

2. Establish relevant time periods. For each source, determine the relevant time periods for all receivers that may be affected by the source. For residential receivers, the two time periods of interest to compute L_{dn} are: daytime (7 am to 10 pm) and nighttime (10 pm to 7 am). If the source will affect non-residential receivers, choose the loudest facility hour during noise-sensitive activity.

3. Collect input data. Gather the following input information:
    - Source reference SELs for each relevant source.
    - E, the average duration of one event, in seconds.
    - For residential receivers of interest:

        N_d, the average number of events per hour that occur during the daytime (equals the total number of events between 7 am and 10 pm, divided by 15), and

        N_n, the average number of events per hour that occur during the nighttime (equals the total number of events between 10 pm and 7 am, divided by 9).

    - For non-residential receivers of interest: N, the number of events that occur during each hour of interest, in events per hour.

4. Compute L_{eq} at 50 ft. For each hour of interest, compute the L_{eq} for the source using the first equation in Table 6-8.

5. Compute L_{dn} at 50 ft. If this source will affect any residential receivers of interest, compute the total L_{dn} for the source using the fourth equation in Table 6-8.

Table 6-8. Computation of L_{eq} and L_{dn} at 50 feet: Stationary Sources	
Hourly L_{eq} at 50 ft:	$L_{eq}(h) = SEL_{ref} + 10\log(N) + 10\log\left(\frac{E}{3600}\right) - 35.6$
Daytime Leq at 50 ft:	$L_{eq}(day) = L_{eq}(h)\Big\vert_{N=N_d}$
Nighttime Leq at 50 ft:	$L_{eq}(night) = L_{eq}(h)\Big\vert_{N=N_n}$
Ldn at 50 ft:	$L_{dn} = 10\log\left[(15)\times 10^{\left(L_{eq}(day)/10\right)} + (9)\times 10^{\left(L_{eq}(night)+10/10\right)}\right] - 13.8$

E† = duration of one event, in seconds
N = number of events of this type that occur during one hour
N_d = hourly average number of events of this type that occur during daytime (7am to 10pm)
$= \frac{number that occur between 7 am and 10 pm}{15}$
N_n = hourly average number of events of this type that occur during nighttime (10pm to 7am)
$= \frac{number that occur between 10 pm and 7 am}{9}$
† Omit the term containing E for ferry boat and fog horn and crossover noise sources

Example 6-3. Computation of L_{eq} and L_{dn} at 50 feet for Stationary Source

A signal crossing lies close to a school that is in session from 8 am to 4 pm on weekdays. Within this time period, the hour of greatest activity for the signal crossing is 8am to 9am. For this project source,

SEL_{ref}	=	109 dB
E	=	25 seconds (counting both cycles of the signal), and
N	=	22

Using Table 6-8 the resulting $L_{eq}(h)$ = 65.2 from 8 to 9 am. (Computation results should always be rounded to the nearest decibel at the end of the computation.)

This same signal crossing lies close to a residential area. For this project source, SEL_{ref} is the same as above, as is E. In addition,

N_d	=	(200)/(15 hours) = 13.3 events per hour, and
N_n	=	(12)/(9 hours) = 1.33 events per hour.

Using Table 6-8, the resulting daytime and nighttime L_{eq}'s are:

$L_{eq}(day)$	=	63.0 and
$L_{eq}(night)$	=	53.0.

Finally, using the fourth equation in Table 6-8, the resulting L_{dn} at 50 feet = 63.0 dB.

End of Example 6-3

6.3 PROPAGATION CHARACTERISTICS

Once estimates of noise exposure at 50 feet from each source are available, then propagation characteristics must be taken into account to compute the noise exposure at receivers of interest. The steps, shown in Figure 6-4, for this are: 1) determine the propagation characteristics between each source and the receiver of interest; then, 2) draw a noise exposure-vs.-distance curve outward from each relevant source as a function of distance; and 3) add a final adjustment using the appropriate shielding term based on intervening barriers between source and receiver.

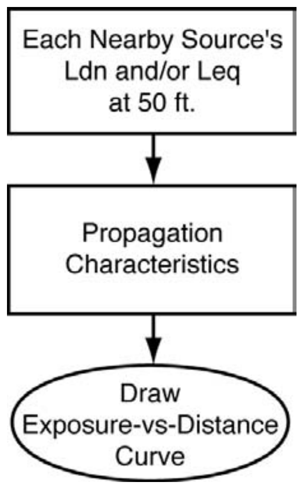


Figure 6-4. Flow Diagram for Determining Project Noise at Receiver Location

6.3.1 Noise Exposure vs. Distance

The following steps result in a noise exposure-vs.-distance curve for each project source:

1. Draw several approximate topographic sections, each perpendicular to the path of moving sources or outward from point sources, similar to those shown in Figure 6-5. Draw separate sections, if necessary, to account for significant changes in topography. Use judgment here to prevent an extreme number of different topographic sections. Often, several typical sections will suffice throughout the transit corridor.

2. For each topographic section, use the relationship illustrated in Figure 6-5 to determine the effective path height, H_{eff}, and from it the Ground Factor, G. Larger Ground Factors mean larger amounts of ground attenuation with increasing distance from the source. As shown in the figure, the effective path height depends upon source heights, which are standardized at the bottom of the figure, and upon receiver heights, which can often be taken as 5 feet for both outdoor receivers and first-floor receivers. With these standard heights, only one H_{eff} (and therefore one Ground Factor)

results from each cross section. For acoustically "hard" (i.e. non-absorptive) ground conditions, G should be taken to be zero.

3. Then for each L_{dn} and each L_{eq} at 50 feet developed earlier in the analysis, plot a noise exposure-vs.-distance curve with L_{dn} or L_{eq} represented on the vertical axis and distance on the horizontal axis using one of the following equations:

L_{dn} or L_{eq}

$$= (L_{dn} or L_{eq})\Big|_{at\,50\,ft} - 20\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{50}\right)$$

for stationary sources

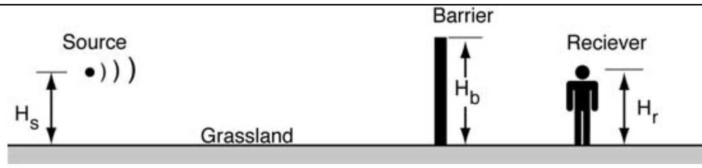
$$= (L_{dn} or L_{eq})\Big|_{at\,50\,ft} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{42}\right)$$

for fixed-guideway rail car passbys

$$= (L_{dn} or L_{eq})\Big|_{at\,50\,ft} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{29}\right)$$

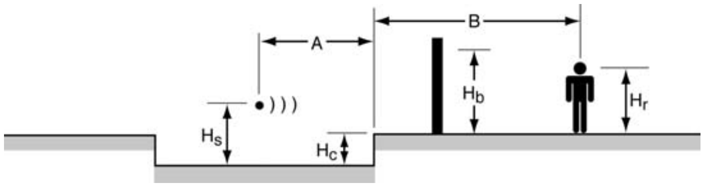
For fixed-guideway locomotive and rubber-tired vehicle passbys, highway vehicle passbys and horns

IN GENERAL: H_{eff} = sum of average path heights on either side of barrier



$$H_{eff} = \frac{H_s + 2H_b + H_r}{2} \qquad (1)$$

Example 1: Source in shallow cut

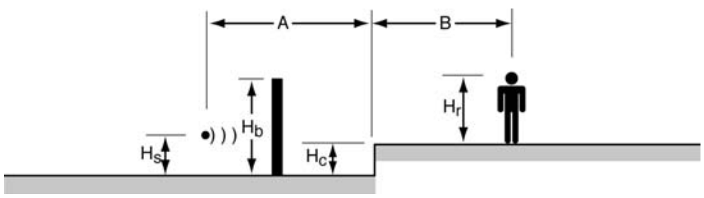


$For B \le A/2,$

$$H_{eff} = \frac{H_S + 2H_b + H_c + H_r}{2}$$

* Otherwise use Equation (1)

Example 2: Receiver elevated



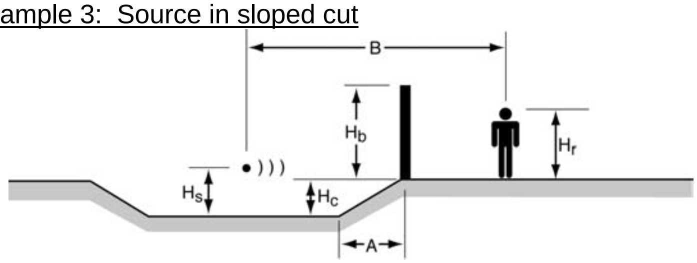
$For H_b \ge H_c,$

$$H_{eff} = \frac{H_s + 2H_b - H_c + H_r}{2}$$

$For H_b \le H_c,$

$$H_{eff} = \frac{H_s + H_c + H_r}{2}$$

Example 3: Source in sloped cut



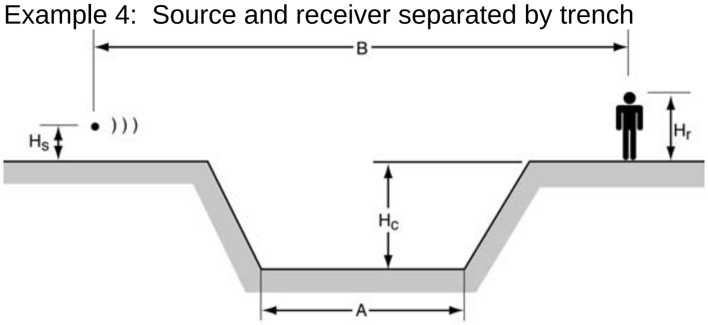
$For A \le B/2,$

use equation (1)

$For A \ge B/2,$

$$H_{eff} = \frac{H_s + 2H_b + H_c + H_r}{2}$$

Example 4: Source and receiver separated by trench



$For A \ge B/2,$

$$H_{eff} = \frac{H_s + 2H_c + H_r}{2}$$

$For A \le B/2,$

$$H_{eff} = \frac{H_s + H_r}{2}$$

Source Heights:

H_s = 8 ft, trains **with** diesel-electric locomotives

2 ft, trains **without** diesel-electric locomotives

0 ft, automobiles

3 ft, 2-axle city buses

8 ft, 3-axle commuter buses

Note: Equations for H_{eff} remain valid even when H_b = 0.

Ground Factor

For soft ground:

$$G = \begin{cases} 0.66 & H_{eff} \le 5 \\ 0.75\left(1 - \frac{H_{eff}}{42}\right) & 5 \le H_{eff} \le 42 \\ 0 & H_{eff} \ge 42 \end{cases}$$

For hard ground:

G=0

Figure 6-5. Computation of Ground Factor G for Ground Attenuation

Example 6-4. Computing Exposure-vs.-Distance Curve for Fixed-Guideway Source

A commuter train will produce the following levels without horn blowing at 50 feet:

L_{eq}(8-9am)	=	72 decibels
L_{dn}	=	68 decibels.

For sound propagation over grassland with a flat cross-sectional geometry without a noise barrier, and H_R = 5 feet:

H_{eff}	=	6.5 feet

and from Figure 6-5 the resulting Ground Factor is:

G	=	0.63

Hence the relevant equations from above become:

L_{eq}(8-9am)	=	72 _ 10 log(D/50) _ 6.3 log(D/42)
L_{dn}	=	68 _ 10 log(D/50) _ 6.3 log(D/42)

Plots of these two equations appear in Figure 6-6. From these curves, the noise levels due to this train operation can be determined for a receiver of interest at any distance. The only factor not accounted for is the effect of shielding between source and receiver, which is the subject of the next section.

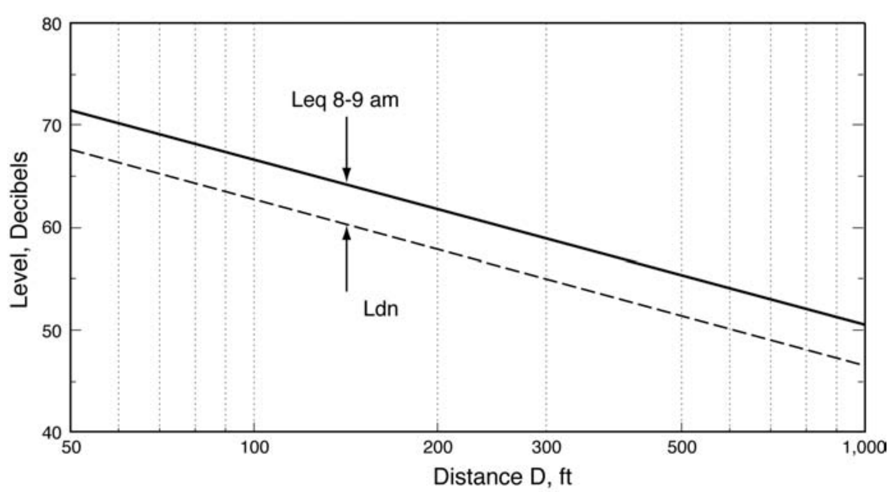


Figure 6-6. Example Exposure-vs.-Distance Curves

End of Example 6-4

6.3.2 Shielding at each Receiver

The resulting L_{eq}'s and L_{dn}'s from the previous section do not include shielding between source and receiver. Such shielding can be due to intervening noise barriers, terrain features, rows of buildings, and dense tree zones. The individual attenuations are computed using the equations from Table 6-9 for barriers and terrain, or from Table 6-10 for rows of buildings and dense tree zones.

The results are attenuation values which are applied to the previously determined project noise at receiver locations (Figure 6-4).

Table 6-9. Computation of Shielding: Barriers and Terrain

Condition	Equation[†]
For ***non-absorptive*** transit barriers within 5 feet of the track:	$A_{barrier} = \min\{12 or [5.3\times\log(P)+6.7]\}$
For ***absorptive*** transit barriers within 5 feet of the track:	$A_{barrier} = \min\{15 or [5.3\times\log(P)+9.7]\}$
For all other barriers, and for protrusion of terrain above the line of sight:	$A_{barrier} = \min\left\{15 or \left[20\times\log\left(\frac{2.51\sqrt{P}}{\tanh\left[4.46\sqrt{P}\right]}\right)+5\right]\right\}$
Barrier Insertion Loss	$IL_{barrier} = \max\left\{0 or \left[A_{barrier} - 10(G_{NB}-G_B)\log\left(\frac{D}{50}\right)\right]\right\}$

D = <u>closest</u> distance between the receiver and the source, in feet
P = path length difference, in feet (see figure below)
G_{NB} = Ground factor G computed *without barrier* (see Figure 6-5)
G_B = Ground factor G computed *with barrier* (see Figure 6-5)

† The term "tanh(variable)" stands for hyperbolic tangent, available on many scientific calculators. If "tanh" is not available, then compute E = exp(variable), and set tanh(variable) = (E - 1/E) / (E + 1/E), where exp(variable) is the "exponential" function, also written as e^x on calculator keypads.

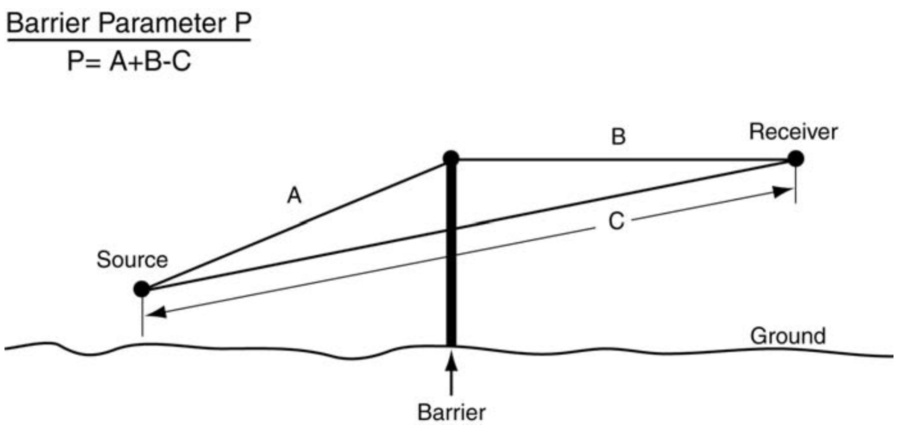


Figure 6-7. Sketch Showing Noise Barrier Parameter "P"

Table 6-10. Computation of Shielding: Rows of Buildings and Dense Tree Zones	
Condition	**Equation**
If gaps in the row of buildings constitute less than 35 percent of the length of the row:	$A_{buildings} = \min\{10 or [1.5(R-1)+5]\}$
If gaps in the row of buildings constitute between 35 and 65 percent of the length of the row:	$= \min\{10 or [1.5(R-1)+3]\}$
If gaps in the row of buildings constitute more than 65 percent of the length of the row:	= 0
Where at least 100 feet of trees intervene between source and receiver, *and* if no clear line-of-sight exists between source and receiver, *and* if the trees extend 15 feet or more above the line-of-sight:	$A_{trees} = \min\left\{10 or \frac{W}{20}\right\}$
If above conditions do not occur:	= 0
R = number of rows of houses that intervene between source and receiver W = width of the tree zone along the line-of-site between source and receiver, in feet	
NET ATTENUATION	$A_{shielding} = \max\{IL_{barrier} or A_{buildings} or A_{trees}\}$

Example 6-5. Computation of Shielding

Intervening between the rail corridor and a receiver of interest is the following shielding:

(1) a 15-foot high noise barrier, 40 feet from the closest track and 130 feet from the 5-foot-high receiver, and
(2) a dense tree zone 100 feet thick. The source height H_S = 8 feet, per Figure 6-5.

For the barrier: A = 40.61 feet, B = 130.38 feet, C = 170.03 feet, and therefore P = 0.96 feet, according to Table 6-9.

From Figure 6-5,

H_{eff} (no barrier) = 6.5 feet and
H_{eff} (with barrier) = 21.5 feet,

which results in

G_{NB} = 0.63, and
G_B = 0.37.

From Table 6-9, the resulting barrier attenuation is

$$\begin{aligned} A_{barrier} &= \min\{15 \textit{ or } 20x\log[2.45/\tanh(4.37)]+5\} \\ &= \min\{15 \textit{ or } 12.8\} \\ &= 12.8 \text{ dB} \end{aligned}$$

and the resulting barrier Insertion Loss is

$$\begin{aligned} IL_{barrier} &= 12.8 - 10(0.63-0.37)x\log(170/50) \\ &= 12.8 - 1.4 \\ &= 11.4 \text{ decibels.} \end{aligned}$$

For the tree zone: The attenuation is estimated to be 5 decibels using Table 6-10. The total shielding is the maximum of the barrier and tree zone shielding, i.e. 11.4 decibels. (Computation results should always be rounded to the nearest decibel at the end of the calculation.)

End of Example 6-5

6.3.3 Combined Propagation Characteristics

The result of combining shielding with geometrical spreading and ground effects involves subtracting the attenuation values obtained from Tables 6-9 and 6-10 from the noise exposure values obtained in Section 6.3.1 at the receiver location.

	$= (L_{dn} or L_{eq})\Big\vert_{at\,50\,ft} - 20\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{50}\right) - A_{shielding}$	$\rightarrow$ for stationary sources
L_{dn} or L_{eq}	$= (L_{dn} or L_{eq})\Big\vert_{at\,50\,ft} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{42}\right) - A_{shielding}$	$\rightarrow$ for fixed-guideway rail car passbys
	$= (L_{dn} or L_{eq})\Big\vert_{at\,50\,ft} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{29}\right) - A_{shielding}$	$\rightarrow$ for fixed-guideway locomotive and rubber-tired vehicle passbys, highway vehicle passbys and horns

6.4 COMBINED NOISE EXPOSURE FROM ALL SOURCES

Once propagation adjustments have been made for the noise exposure from each source separately, then the sources must be combined to predict the total project noise at the receivers. Table 6-11 contains the equations for combining sources. Total noise exposure is used in Section 6.7 to assess the transit noise at each receiver of interest.

Table 6-11. Computing Total Noise Exposure	
Total L_{eq} from All Sources Combined, for the hour of interest:	$L_{eq}(total) = 10\log\left(\sum_{allsources} 10^{L_{eq}/10}\right)$
Total L_{dn} from All sources Combined:	$L_{dn}(total) = 10\log\left(\sum_{allsources} 10^{L_{dn}/10}\right)$

Example 6-6. Computation of Total Exposure from Combined Sources

A commuter train operation produces the following levels at a certain receiver of interest:

L_{eq}(8-9am) = 72 decibels, and
L_{dn} = 68 decibels.

At this same receiver, a light rail system produces the following levels:

L_{eq}(8-9am) = 69 decibels, and
L_{dn} = 70 decibels.

No other project sources affect this receiver. Using Table 6-11, the receiver's total noise exposures are therefore:

L_{eq}(8-9am, total) = 73.8 decibels, and
L_{dn}(total) = 72.1 decibels.

(Computation results should always be rounded to the nearest decibel at the end of the calculation.)

End of Example 6-6

6.5 MAXIMUM NOISE LEVEL FOR FIXED-GUIDEWAY SOURCES

The assessment of noise impact in this manual utilizes either the L_{dn} or the L_{eq} descriptor. As such, in determining impact it is not necessary to determine and tabulate the maximum levels (L_{max}). However, it is often desirable to include computations of L_{max} in environmental documents, particularly for rail projects, because the noise from an individual train passby is quite distinguishable from the existing background noise. The L_{max} is also the descriptor used in vehicle specifications. Because L_{max} represents the sound level heard during a transportation vehicle passby, people can relate this metric with other noise experienced in the environment. Particularly with rail transit projects, it is representative of what people hear at any particular instant and can be measured with a sound level meter. A comparison of L_{max} with other sources can be made by referring to Figure 2-11. Thus, although L_{max} is not used in this manual as a basis for assessing noise impact, it can provide people with a more complete description of the noise effects of a proposed project and should be reported in environmental documents. Equations for computing L_{max} from SEL are given in Appendix F.

6.6 STUDY AREA CHARACTERISTICS

This section contains procedures to estimate existing noise exposure at each receiver of interest identified previously for use in assessing noise impact. Figure 6-8 shows the flow diagram for estimating ambient noise. First decide whether to measure noise exposure, to compute it from partial measurements, or to estimate it from the table provided in this chapter. Different methods may be used at different receivers along the project. Finally, make the measurements, computations or estimates of the ambient noise at each receiver of interest.

6.6.1 Deciding Whether to Measure, Compute, or Estimate

In general, it is better to measure existing noise than to compute or estimate it. Measurements are more precise than computations and estimates and therefore lead to more precise conclusions concerning noise impact. However, measurements are expensive, are often thwarted by weather, and take significant time in the field. So the choice between measurements and computations/estimates is a choice between the precision of measurements and the convenience of computations/estimates. A mixture of these is generally selected, relying on measurements where the greatest precision is needed.

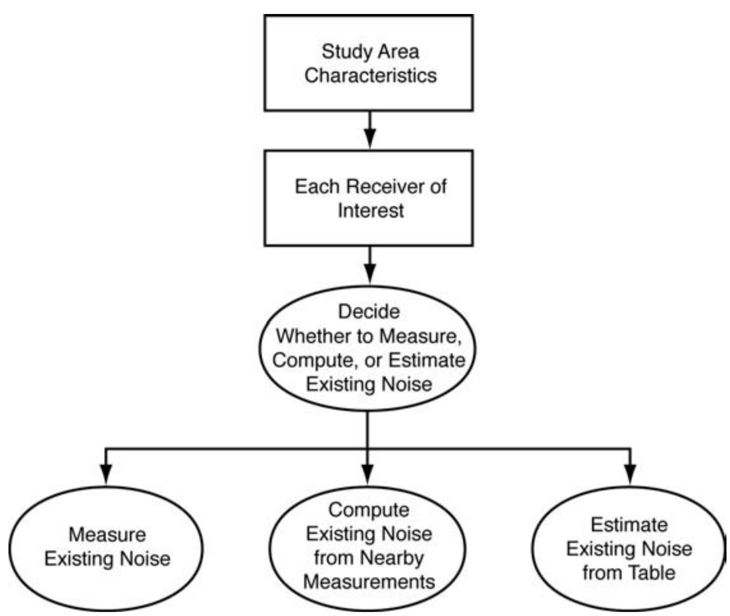


Figure 6-8. Flow Diagram for Determining Existing Noise

A penalty comes along with the convenience of computations and especially of tabular estimates. Because computations/estimates are less precise than measurements, the procedures for them (in Appendix D) are purposely conservative and consequently are inappropriate for the accuracy needed in a Detailed Noise Analysis. When more precise impact projections are desired, measurements must be chosen instead.

The combination of measurements, computations, and estimates depends partly upon the type of land use. For non-residential land uses with daytime use only, it is usually adequate to measure only one hour's ambient L_{eq}, preferably during the hour when project activity is likely to cause the greatest impact. This is relatively easy to measure. On the other hand, in residential areas that are not near major roadways, a full day's ambient L_{dn} is usually required. The following sections describe the approaches to be taken in each case and how to combine the results to characterize the existing ambient conditions.

6.6.2 Noise Exposure Measurements

Full one-hour measurements are the most precise way to determine ambient noise exposure for non-residential receivers. For residential receivers, full 24-hour measurements are most precise. Such full-duration measurements are preferred over other options, where time and study funds allow. The following procedures apply to full-duration measurements:

- For non-residential land uses, measure a full hour's L_{eq} at the receiver of interest, on at least two non-successive weekdays (generally between noon Monday and noon Friday). Select the hour of the day when the maximum project activity is expected to occur.
- For residential land uses, measure a full 24-hours' L_{dn} at the receiver of interest, for a single weekday (generally between noon Monday and noon Friday).
- Use judgment in positioning the measurement microphone. Location of the microphone at the receiver depends upon the proposed location of the transit noise source. If, for example, a new rail line will be in front of the house, do not locate the microphone in the back yard. Figure 6-9 illustrates recommended measurement positions for various locations of the project, with respect to the house and the existing source of ambient noise.
- Undertake all measurements in accordance with good engineering practice following guidelines given in ASTM and ANSI standards.[3,4]

6.6.3 Noise Exposure Computations from Partial Measurements

Often measurements can be made at some of the receivers of interest and then these measurements can be used to estimate noise exposure at nearby receivers. In other situations, several hourly L_{eq}'s can be measured at a receiver and then the L_{dn} computed from these. Both of these options require experience and knowledge of acoustics to select representative measurement sites.

Measurements at one receiver can be used to represent the noise environment at other sites, but only when proximity to major noise sources is similar among the sites. For example, a residential neighborhood with otherwise similar homes may have greatly varying noise environments: one part of the neighborhood may be located where the ambient noise is clearly due to highway traffic; a second part, toward the interior of the neighborhood, may have highway noise as a factor but also a significant contribution from other community noise; and a third part located deep into the residential area will have local street traffic and other community activities dominate the ambient noise. In this example, three or more measurement sites would be required to represent the varying ambient noise conditions in a single neighborhood.

Typical situations where representative measurement sites can be used to estimate noise levels at other sites occur when both share the following characteristics:

- proximity to the same major transportation noise sources, such as highways, rail lines and aircraft flight patterns;

- proximity to the same major stationary noise sources, such as power plants, industrial facilities, rail yards and airports;
- similar type and density of housing, such as single-family homes on quarter-acre lots and multi-family housing in apartment complexes.

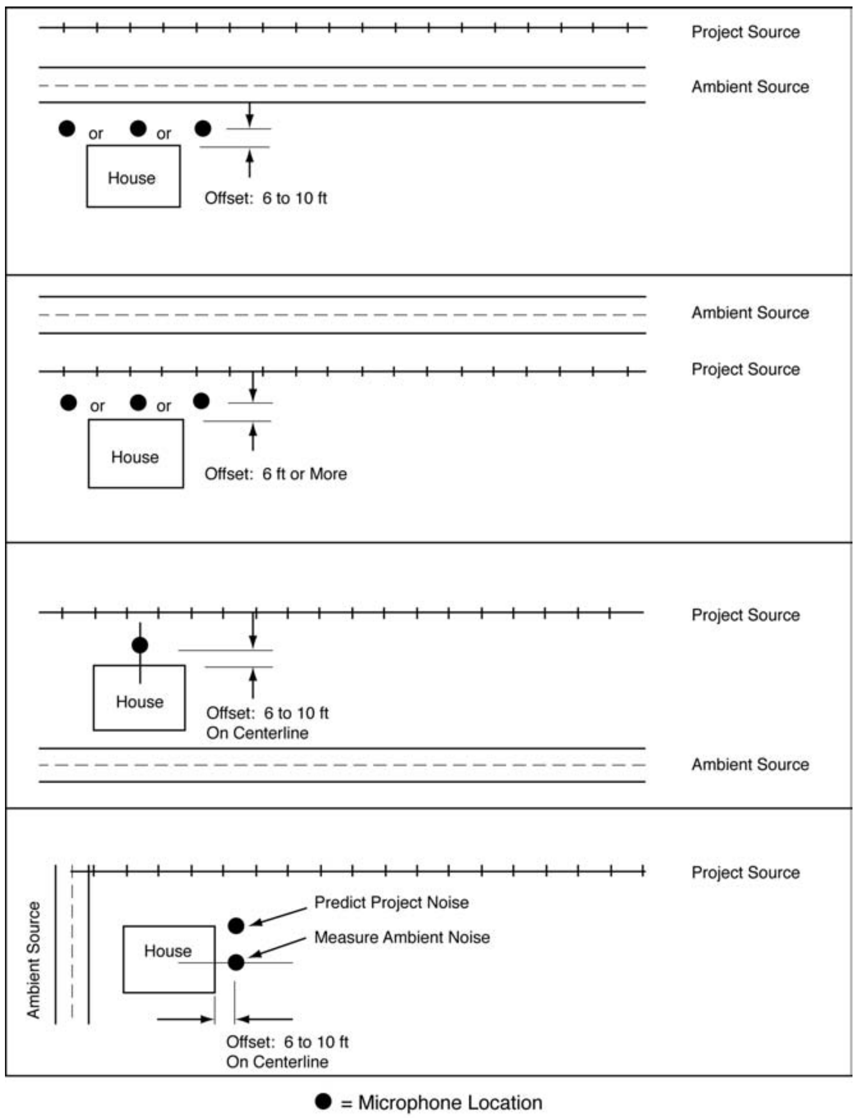


Figure 6-9. Recommended Microphone Locations for Existing Noise Measurements

Acoustical professionals are often adept at such computations from partial data and are encouraged here to use their experience and judgment in fully utilizing the measurements in their computations. Required here is an attempt to somewhat underestimate ambient noise in the process, to account for reduced precision compared to full noise measurements.

On the other hand, people lacking the background in acoustics are encouraged to use the procedures in Appendix D to accomplish this same aim. These procedures are an attempt to systematize such computations from partial measurements. The methods in Appendix D are designed with a safety factor to underestimate ambient noise to account for reduced precision compared to full noise measurements.

6.6.4 Estimating Existing Noise Exposure

The least precise way to determine noise exposure is to estimate it from a table. This method can be used for the General Noise Assessment, but it is not recommended for a Detailed Noise Analysis. However, it can be used in the absence of better data for locations where roadways or railroads are the predominant ambient noise source. Table 5-7 presents these ambient levels. In general, the tabulated values of noise exposure are underestimates. As explained above, underestimates here are intended to compensate for the reduced precision of the estimated ambient levels compared to the options that incorporate full or partial measurements.

Notwithstanding the guidance above, there is one situation where it may be more accurate to estimate rather than measure the existing noise exposure, namely in areas near major airports where aircraft noise is dominant. Because airport noise is highly variable based on weather conditions and corresponding runway usage, it is preferable in such cases to base the existing noise exposure on published aircraft noise contours in terms of Annual Average L_{dn}.

6.7 NOISE IMPACT ASSESSMENT

This section contains procedures for the assessment of project noise impact, utilizing the ambient noise and project noise results from the previous analysis. Two assessment methods are included:

- Rail and Bus Facilities: This category includes all rail projects (e.g., rail rapid transit, light rail transit, commuter rail, and automated guideway transit), as well as fixed facilities such as storage and maintenance yards, passenger stations and terminals, parking facilities, substations, etc. Also included are rail transit projects built within a highway or railroad corridor. Certain bus facilities are included in this category, such as bus rapid transit (BRT) on separate roadways and bus operations on local streets and highways where the project does not include roadway construction or modification that significantly changes roadway capacity. The distinguishing feature in all these cases is that the existing noise levels generated by roadway traffic and other sources will not change as a result of the project; therefore the project noise is exclusively due to the new transit sources. For projects like these, FTA is generally the lead agency and the methodology from this manual is the appropriate approach.
- Highway/Transit Projects: Projects in this category involve transit as part of new highway construction or modifications to existing highways to increase carrying capacity. For these multi-

modal projects, the Federal Highway Administration (FHWA) may be a joint lead agency with FTA, and the State department of transportation (DOT) would probably also be participating in the environmental impact assessment. Projects would involve traffic lanes with preferential treatment for buses or high-occupancy vehicles (HOVs). The distinguishing feature here is that the *project* noise includes a combination of highway and transit sources. Examples are: new highway construction providing general-purpose lanes as well as dedicated bus/HOV lanes and lane additions or reconfigurations on existing highways or arterials to accommodate buses/HOVs. These multi-modal projects fall into two sub-categories and the appropriate method to use for noise prediction and impact assessment depends on whether the highway noise dominates throughout day and night or the transit noise dominates during off-peak and late night hours. If sufficient evidence shows that highway noise dominates, the methods of FHWA, including the latest authorized version of the Traffic Noise Model (TNM), should be used. Otherwise both FHWA and FTA prediction procedures should be used along with both sets of impact assessment criteria since the transit mode's greatest impact will likely not occur during the worst traffic hours.

The factors to consider when deciding which sub-category is appropriate for a given project are given in the beginning of Chapter 3.

6.7.1 Assessment for Rail and Bus Facilities

For these types of projects, noise impact is assessed at each receiver of interest using the criteria for transit projects described in Chapter 3. The assessment procedure is as follows:

1. Tabulate existing ambient noise exposure (rounded to the nearest whole decibel) at all receivers of interest from earlier in the analysis. In cases where large residential buildings are exposed to noise on one side only, the receivers on that side are included in the analysis.

2. Tabulate project noise exposure at these receivers from the analytical procedures described in this chapter.

3. Determine the level of noise impact (No Impact, Moderate Impact or Severe Impact) following the procedures in Chapter 3.

4. Document the results in noise-assessment inventory tables. These tables should include the following types of information:

   - Receiver identification and location
   - Land-use description
   - Number of noise-sensitive sites represented (number of dwelling units in residences or acres of outdoor noise-sensitive land)
   - Closest distance to the project

- Existing noise exposure
- Project noise exposure
- Level of noise impact (No Impact, Moderate Impact, or Severe Impact)

These tables should provide a sum of the total number of receivers, especially numbers of dwelling units, predicted to experience Moderate Impact or Severe Impact.

5. Illustrate the areas of Moderate Impact and Severe Impact on maps or aerial photographs. Two methods of impact display are labeling and contouring. In a Detailed Analysis, the most accurate indication of impact is a label attached to each impacted building or cluster identified in the inventory table. A less precise illustration of impacted areas is a plot of project noise contours on the maps or aerial photographs, along with shaded impact areas. This is done by delineating two impact lines: one between the areas of No Impact and Moderate Impact and the second between Moderate Impact and Severe Impact. Such impact contours would be similar to those estimated in the General Assessment of Chapter 5, but with greater precision. As a cautionary note, it is difficult to position noise contours in urban areas due to shielding, terrain features and other propagation anomalies. If noise contours are used, they should be considered illustrative rather than definitive. If desired to conform with the practices of another agency, the contouring may perhaps include several contour lines of constant project noise, such as L_{dn} 65, L_{dn} 70 and L_{dn} 75.

6. Discussion of the magnitude of the impacts is an essential part of the assessment. The magnitude of noise impact is defined by the two threshold curves delineating onset of Moderate Impact and Severe Impact. Interpretation of the two impact regimes is discussed in Chapter 3.

6.7.2 Assessment for Highway/Transit Projects

For most highway/transit projects where highway noise dominates, the FHWA Noise Abatement Criteria should be used, with the exceptions noted in Chapter 3.(5) In general the appropriate calculation method is the current version of FHWA's Traffic Noise Model (TNM). The TNM was first released by FHWA in April 1998 for use on Federal-aid highway projects.(6) TNM is a state of the art computer program used for predicting noise impacts in the vicinity of highways. TNM Version 2.5 was released in April 2004, which includes updates to the User's Guide and Technical Manual.(7)

The program allows for a detailed assessment at each receiver of interest by separately calculating the noise contribution of each roadway segment. For each roadway segment, the noise from each vehicle type is computed from reference energy-mean emission levels, adjusted for:

- Vehicle volume,
- Vehicle speed,
- Grade,
- Roadway segment length, and

- Source-to-receiver distance.

Further adjustments needed to accurately model the sound propagation from source to receiver include:

- Shielding provided by rows of buildings,
- Effects of different ground types,
- Source and receiver elevations, and
- Effect of any intervening noise barriers.

The program sums the noise contributions of each vehicle type for a given roadway segment at the receiver. TNM then repeats this process for all roadway segments, summing their contributions to generate the predicted noise level at each receiver.

6.8 MITIGATION OF NOISE IMPACT

6.8.1 Noise Mitigation Measures

Where the noise impact assessment shows either Severe Impact or Moderate Impact, this section provides guidance on considering and implementing noise reduction measures. In general, mitigation options are chosen from those below, and then portions of the project noise are recomputed and reassessed to account for this mitigation. This allows an accurate prediction of the level of noise reduction. It is important to emphasize that the source levels used in this manual are typical of systems designed according to current engineering practice, but they do not include special noise control features that could be incorporated in the specifications at extra cost. This approach provides a reasonable analysis of conditions without mitigation measures. If special features that result in noise reductions are included in any of the predictions, then the Federal environmental document must include a commitment by the project sponsor to adopt such treatments before the project is approved for construction. Since cost considerations often play into decisions before committing to mitigation, this manual provides general cost information based on data presented in a Transit Cooperative Research Program (TCRP) report.[8] A detailed discussion of mitigation costs is presented in Chapter 5 of the TCRP report, especially the tables included in Chapter 5.

Mitigation of noise impact from transit projects may involve treatments at the three fundamental components of the noise problem: (1) at the noise source, (2) along the source-to-receiver propagation path or (3) at the receiver. Generally, the transit property has authority to treat the source and some elements of the propagation path, but may have little or no authority to modify anything at the receiver.

A list of practical noise mitigation measures that should be considered by project sponsors is summarized in Table 6-12 and discussion of the measures follows. This table is organized according to whether the treatment applies to the source, path or receiver, and includes estimates of the acoustical effectiveness of each treatment.

6.8.2 Source Treatments

Vehicle Noise Specifications (Rail and Bus)

Among the most effective noise mitigation treatments is noise control at the outset, during the specification and design of the transit vehicle. Such source treatments apply to all transit modes. By developing and enforcing stringent but achievable noise specifications, the transit property takes a major step in controlling noise everywhere on the system. It is important to ensure that the noise levels quoted in the specifications are achievable with the application of best available technology during the development of the vehicle and reasonable in light of the noise reduction benefits and costs.

Effective enforcement includes significant penalties for non-compliance with the specifications. The noise mitigation achieved by source treatment depends on the quality of installation and maintenance. In the past, transit vehicles have been delivered that did not meet a noise specification, causing complaints from the public and requiring additional noise mitigation measures applied to the wayside.

Table 6-12. Transit Noise Mitigation Measures

Application	Mitigation Measure		Effectiveness
SOURCE	Stringent Vehicle & Equipment Noise Specifications		Varied
	Operational Restrictions		Varied
	Resilient or Damped Wheels*	For Rolling Noise on Tangent Track:	2 dB
		For Wheel Squeal on Curved Track:	10-20 dB
	Vehicle Skirts*		6-10 dB
	Undercar Absorption*		5 dB
	Spin-slide control (prevents flats)*		**
	Wheel Truing (eliminates wheel flats)*		**
	Rail Grinding (eliminates corrugations)*		**
	Turn Radii greater than 1000 ft*		(Avoids Squeal)
	Rail Lubrication on Sharp Curves*		(Reduces Squeal)
	Movable-Point Frogs (reduce rail gaps at crossovers)*		(Reduces Impact Noise)
	Engine Compartment Treatments (Buses)		6-10 dB
PATH	Sound Barriers close to Vehicles		6-15 dB
	Sound Barriers at ROW Line		3-10 dB
	Alteration of Horiz. & Vert. Alignments		Varied
	Acquisition of Buffer Zones		Varied
	Ballast on At-Grade Guideway*		3 dB
	Ballast on Aerial Guideway*		5 dB
	Resilient Track Support on Aerial Guideway		Varied
RECEIVER	Acquisition of Property Rights for Construction of Sound Barriers		5-10 dB
	Building Noise Insulation		5-20 dB

* Applies to rail projects only

** These mitigation measures work to maintain a rail system in its as-new condition. Without incorporating them into the system, noise levels could increase up to 10 dB.

Stationary Source Noise Specifications

Stringent but achievable noise specifications also represent an effective approach for mitigating noise impact from stationary sources associated with a transit system. Such equipment includes fixed plant equipment (for example, transformers and mechanical equipment) as well as grade-crossing signals. For example, noise impact from grade-crossing signals can be mitigated by specifying equipment that sets the level of the warning signal lower where ambient noise is lower, that minimizes the signal duration, and that minimizes signal noise in the direction of noise-sensitive receivers.

Wheel Treatments (Rail)

A major source of noise from steel-wheel/steel-rail systems is the wheel/rail interaction which has three components: roar, impact and squeal. Roar is the rolling noise caused by small-scale roughness on the wheel tread and rail running surface. Impacts are caused by discontinuities in the running surface of the rail or by a flat spot on the wheels. Squeal occurs when a steel-wheel tread or its flange rubs across the rail, setting up resonant vibrations in the wheel which cause it to radiate a screeching sound. Various wheel designs and other mitigation measures exist to reduce the noise from each of these three mechanisms.

- **Resilient wheels** serve to reduce rolling noise, but only slightly. A typical reduction is 2 decibels on tangent track. This treatment is more effective in eliminating wheel squeal on tight turns; reductions of 10 to 20 decibels for high-frequency squeal noise are typical. The costs for resilient wheels are approximately $3000 per wheel, in comparison to about $700 for standard steel wheels.
- **Damped wheels,** like resilient wheels, serve to reduce rolling noise, but only slightly. A typical reduction is 2 decibels on tangent track. This treatment involves attaching vibration absorbers to standard steel wheels. Damping is effective in eliminating wheel squeal on tight turns; reductions of 5 to 15 decibels for high-frequency squeal noise are typical. The costs for damped wheels add approximately $500 to $1000 to the normal $700 for each steel wheel.
- **Spin-slide control systems,** similar to anti-locking brake systems (ABS) on automobiles, reduce the incidence of wheel flats, a major contributor of impact noise. Trains with smooth wheel treads can be up to 20 decibels quieter than those with wheel flats. To be effective, the anti-locking feature should be in operation during all braking phases, including emergency braking. Wheel flats are more likely to occur during emergency braking than during dynamic braking. The cost of slip-slide control may be incorporated in the new vehicle costs, but may be between $5,000 and $10,000 per vehicle.
- **Maintenance** of wheels by truing eliminates wheel flats from the treads and restores the wheel profile. As discussed above, wheel flats are a major source of impact noise. A good maintenance program includes the installation of equipment to detect and correct wheel flats on a continuing basis. Costs vary according to transit property practices, but the TCRP report identifies a cost for truing wheels at $60 per wheelset.

Vehicle Treatments (Rail and Bus)

Vehicle noise mitigation measures are applied to the various mechanical systems associated with propulsion, ventilation and passenger comfort.

- **Propulsion systems** of transit vehicles include diesel engines, electric motors and diesel-electric combinations. Noise from the propulsion system depends on the type of unit and how much noise mitigation is built into the design. Mufflers on diesel engines are generally required to meet noise specifications; however, mufflers are generally practical only on buses, not on locomotives. Control of noise from engine casings may require shielding the engine by body panels without louvers, dictating other means of cooling and ventilation.
- **Ventilation** requirements for vehicle systems are related to the noise generated by a vehicle. Fan noise often remains a major noise source after other mitigation measures have been instituted because of the need to have direct access to cooling air. This applies to heat exchangers for electric traction motors, diesel engines and air-conditioning systems. Fan-quieting can be accomplished by installation of one of several new designs of quiet, efficient fans. Forced-air cooling on electric traction motors can be quieter than self-cooled motors at operating speeds. Placement of fans on the vehicle can make a significant difference in the noise radiated to the wayside or to patrons on the station platforms.
- The **vehicle body** design can provide shielding and absorption of the noise generated by the vehicle components. Acoustical absorption under the car has been demonstrated to provide up to 5 decibels of mitigation for wheel/rail noise and propulsion-system noise on rapid transit trains. Similarly, vehicle skirts over the wheels can provide more than 5 decibels of mitigation. By carrying their own noise barriers, vehicles with these features can provide cost-effective noise reduction.

Use of Locomotive Horns at Grade Crossings

In cases where commuter rail operations share tracks or rights-of-way with freight or intercity passenger trains that are part of the "general railroad system," the safety rules of the Federal Railroad Administration (FRA) apply. In particular, the rule for the use of locomotive horns at highway-rail grade crossings is in effect.[9] This rule requires generally that horns be sounded at public road crossings, although some exceptions are allowed in carefully defined circumstances. One exception enables the establishment of a "quiet zone" in which certain supplemental safety measures (SSM's) are used in place of the locomotive horn to provide an equivalent level of safety at grade crossings. By adopting an approved SSM at each public grade crossing, a quiet zone of at least a half-mile long can be established. These measures are in addition to the standard safety devices required at most public grade crossings (e.g., stop signs, reflectorized crossbucks, flashing lights with gates that do not completely block travel over the tracks). Below are four SSM's which have been predetermined by the FRA to fully compensate for the lack of a locomotive horn:

- Temporary closure of a public highway-rail grade crossing. This measure requires closure of the grade crossing one period for each 24 hours, and must be closed the same time each day.

- Four-quadrant gate system. This measure involves the installation of at least one gate for each direction of traffic to fully block vehicles from entering the crossing.
- Gates with medians or channelization devices. This measure keeps traffic in the proper travel lanes as it approaches the crossing. This denies the driver the option of circumventing the gates by traveling in the opposing lane.
- One-way street with gates. This measure consists of one-way streets with gates installed so that all approaching travel lanes are completely blocked.

In addition to the pre-approved SSM's, the FRA rule also identifies a range of other measures that may be used in establishing a quiet zone. These could be modified SSM's or non-engineering types of measures, such as increased monitoring by law enforcement for grade crossing violations or instituting public education and awareness programs that emphasize the risks associated with grade crossings and applicable requirements. These alternative safety measures (ASMs) require approval by FRA based on a demonstration that public safety would not be compromised by eliminating the horn.

Locomotive horns are quite loud, and horn noise is often the major contributor in projections of adverse noise impact in the community from proposed commuter rail projects. Since sound barriers are not feasible at highway-rail grade crossings, the establishment of quiet zones may be an attractive option. The lead agency in designating a quiet zone is the local public authority responsible for traffic control and law enforcement on the roads crossing the tracks. In order to satisfy the FRA regulatory requirements, the public transit agency must work closely with this agency while also coordinating with any freight or passenger railroad operator sharing the right-of-way. Depending on the circumstances, establishment of a quiet zone would probably not be completed in the time frame of the environmental review process. However, as with other types of mitigation, the final environmental document should discuss the main considerations in adopting the quiet zone, for example, engineering feasibility, receptiveness of the local public authority, consultation with the railroad, preliminary cost estimates, etc., and show evidence of the planning and interagency coordination that has occurred to date. If a quiet zone will be relied on as a mitigation measure, the final environmental document should provide reasonable assurance that any remaining issues can and will be resolved.

The cost of establishing a quiet zone varies considerably, depending on the number of intersections that must be treated and the specific SSM's, ASM's, or combination of measures that are used. The FRA gives a cost estimate of $15,000 per crossing for installing two 100-foot-long non-traversable medians that prevent motorists from driving around closed gates. A typical installation of a four-quadrant gate system is in the range of $175,000-$300,000 per crossing. Who pays for the installation of modifications can become a major consideration in a decision to pursue a quiet zone designation, especially in cases where noise from preexisting railroad operations has been a sore point in the community. In cases where a quiet zone would mitigate a Severe Impact situation brought about by the proposed transit project, the costs would be borne by the local transit agency and FTA in the same proportion as the overall cost-sharing for the project.

Guideway Support (Bus and Rail)

The smoothness of the running surface is critical in the mitigation of noise from a moving vehicle. Smooth roadways for buses and smooth rail running surfaces for rail systems are required. In either case, roughness of the street, roadway and rail surfaces can be eliminated by resurfacing roads or grinding rails, thereby reducing noise levels by up to 10 decibels. Bridge expansion joints are also a source of noise for rubber-tire vehicles. This source of noise can be reduced by placing expansion joints on an angle or by specifying the serrated type rather than joints with right-angle edges.

In the case of steel-wheel/steel-rail systems with non-steerable trucks and sharp turns, squeal can be mitigated by installation of rail lubricators. Squeal in such systems can usually be eliminated altogether by designing all turn radii to be greater than 1000 feet, or 100 times the truck wheelbase, whichever is less.

Operational Restrictions (Rail and Bus)

Two changes in operations that can mitigate noise are the lowering of speed and the reduction of nighttime (10 pm to 7 am) operations. Because noise from most transit vehicles depends on speed, a reduction of speed results in lower noise levels. The effect can be considerable. For example, the speed dependency of steel-wheel/steel-rail systems for L_{eq} and L_{dn} (see Table 6-4) results in a 6 dB reduction for a halving of the speed. Complete elimination of nighttime operations has a strong effect on reducing the L_{dn}, because nighttime noise is increased by 10 decibels when calculating L_{dn}. Restrictions on operations are usually not feasible because of service demands, and FTA does not pursue restrictions on operations as a noise reduction measure. However, if early morning idling can be curtailed to the minimum necessary, this can have a measurable effect on L_{dn}.

Other operational restrictions that can reduce noise impact for light rail and commuter rail systems include minimizing or eliminating horn blowing and other types of warning signals at grade crossings. While these mitigation options are limited by safety considerations, they can be effective in the right circumstances and they are discussed elsewhere in this section (e.g., wayside horns).

6.8.3 Path Treatments

Sound Barriers

Sound barriers are effective in mitigating noise when they break the line-of-sight between source and receiver. The mechanism of sound shielding is described in Chapter 2. The necessary height of a barrier depends on such factors as the source height and the distance from the source to the barrier. For example, if a barrier is located very close to a rapid transit train, it need only be 3 to 4 feet above the top of rail to be effective. Barriers close to vehicles can provide noise reductions of 6 to 10 decibels. For barriers further away, such as on the right-of-way line or for trains on the far track, the height must be increased to provide equivalent effectiveness. Otherwise, the effectiveness can drop to 5 decibels or less, even if the barrier breaks the line-of-sight. Where the barrier is very close to the transit vehicle or where the vehicles travel between sets of parallel barriers, barrier effectiveness can be increased by as much as 5 decibels by applying sound-absorbing material to the inner surface of the barrier.

Similarly, the length of the barrier wall is important to its effectiveness. The barrier must be long enough to screen out a moving train along most of its visible path. This is necessary so that train noise from beyond the ends of the barrier will not severely compromise noise-barrier performance at sensitive locations.

Noise barriers can be made of any outdoor weather-resistant solid material that meets a minimum sound transmission loss requirement. The sound requirements are not particularly strict; they can be met by many commonly available materials, such as 16-gauge steel, 1-inch thick plywood, and any reasonable thickness of concrete. The normal minimum requirement is a surface density of 4 pounds per square foot. To hold up under wind loads, structural requirements are more stringent. Achieving the maximum possible noise reduction requires careful sealing of gaps between barrier panels and between the barrier and the ground or elevated guideway deck.

Costs for noise barriers, based on highway installations, range from $25 to $35 per square foot of installed noise barrier at-grade, not counting design and inspection costs(10). Installation on aerial structure may be a factor of two greater, especially if the structure has to be strengthened to accommodate the added weight and wind load.

Location of a transit alignment in cut, as part of grade separation, can accomplish the same result as installation of a noise barrier at-grade or on aerial structure. The walls of the cut serve the same function as barrier walls in breaking the line-of-sight between source and receiver.

Wayside Horns

The sounding of a locomotive horn as the train approaches an at-grade intersection produces a very wide noise “footprint” in the community. Using wayside horns at the intersection instead of the locomotive horn has been shown to substantially reduce the noise footprint without compromising safety at the grade crossing. A wayside horn does not need to be as loud as a locomotive horn, but the real advantage is the focusing of the warning sound only on the area where it is needed. These are pole-mounted horns used in conjunction with flashing lights and gates at the intersection, with a separate horn oriented toward each direction of oncoming vehicle traffic. Field tests have shown that noise levels in nearby residential and business areas can be reduced significantly with wayside horns, depending on the location with respect to the grade crossing.

A plan to use wayside horns in place of the locomotive horn at public grade crossings must be coordinated with several public and private entities, notably the local agency having responsibility for traffic control and law enforcement on the road crossings, the state agency responsible for railroad safety, any railroads that share the right-of-way, and FRA. Public notification must also be given.

Preliminary cost information from testing programs indicates a wayside horn system at a railroad/ highway grade crossing costs approximately $50,000.

Noise Buffers

Because noise levels attenuate with distance, one noise mitigation measure is to increase the distance between noise sources and the closest sensitive receivers. This can be accomplished by locating alignments away from sensitive sites. Acquisition of land or purchasing easements for noise buffer zones is an option that may be considered if impacts due to the project are severe enough.

Ground Absorption

Propagation of noise over ground is affected by whether the ground surface is absorptive or reflective. Noise from vehicles on the surface is strongly affected by the character of the ground in the immediate vicinity of the vehicle. Roads and streets for buses are hard and reflective, but the ground at the side of a road has a significant effect on the propagation of noise to greater distance. This effect is described in Chapter 2 and taken into account in the computations of this chapter. Guideways for rail systems can be either reflective or absorptive, depending on whether they are concrete or ballast. Ballast on a guideway can reduce train noise 3 decibels at-grade and up to 5 decibels on aerial structure.

6.8.4 Receiver Treatments

Sound Barriers

In certain cases it may be possible to acquire limited property rights for the construction of sound barriers at the receiver. As discussed above, barriers need to break the line-of-sight between the noise source and the receiver to be effective and are most effective when they are closest to either the source or the receiver. Computational procedures for estimating barrier effectiveness are given earlier in this chapter.

Building Insulation

In cases where sound barriers are not feasible, such as multi-story buildings, buildings very close to the rights-of-way, or grade crossings, the only practical noise mitigation measure may be to provide sound insulation for the buildings. Effective treatments include caulking and sealing gaps in the building façade, and installation of new doors and windows that are specially designed to meet acoustical transmission-loss requirements. Exterior doors facing the noise source should be replaced with well-gasketed, solid-core wood doors and well-gasketed storm doors. Acoustical windows are usually made of multiple layers of glass with air spaces between to provide noise reduction. Acoustical performance ratings are published in terms of “Sound Transmission Class” (STC) for these special windows. A minimum STC rating of 39 should be used on any window exposed to the noise source. These treatments are beneficial for heat insulation as well as for sound insulation. As an added consideration for costs, however, acoustical windows are usually non-operable so that central ventilation or air conditioning is needed.

Additional building sound insulation, if needed, can be provided by sealing vents and ventilation openings and relocating them to a side of the building away from the noise source. In cases where low frequency noise from diesel locomotives is the problem, it may be necessary to increase the mass of the building façade of wood frame houses by adding a layer of sheathing to the exterior walls.

Criteria for Interior Noise Levels. Depending on the quality of the original building façade, especially windows and doors, sound insulation treatments can improve the noise reductions from transit noise by 5 to 20 dBA. In order to be considered cost-effective, a treatment should provide a minimum of 5 dBA reduction in the interior of the building and provide an interior noise level of 65 dBA or less from transit sources. In homes where noise impact from train horns is identified, the sound insulation should provide sufficient noise reduction such that horn noise inside the building is 70 dBA or less.

Examples of residential sound insulation for rail or highway projects are limited. However, much practical experience with sound insulation of buildings has been gained through grants for noise mitigation to local airport authorities by the Federal Aviation Administration (FAA). Based on FAA experience, a typical single-family home can be fitted for sound insulation for costs ranging from $25,000 to $50,000.

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7. BASIC GROUND-BORNE VIBRATION CONCEPTS

Ground-borne vibration can be a serious concern for nearby neighbors of a transit system route or maintenance facility, causing buildings to shake and rumbling sounds to be heard. In contrast to airborne noise, ground-borne vibration is not a common environmental problem. It is unusual for vibration from sources such as buses and trucks to be perceptible, even in locations close to major roads. Some common sources of ground-borne vibration are trains, buses on rough roads, and construction activities such as blasting, pile-driving and operating heavy earth-moving equipment.

The effects of ground-borne vibration include feelable movement of the building floors, rattling of windows, shaking of items on shelves or hanging on walls, and rumbling sounds. In extreme cases, the vibration can cause damage to buildings. Building damage is not a factor for normal transportation projects, with the occasional exception of blasting and pile-driving during construction. Annoyance from vibration often occurs when the vibration exceeds the threshold of perception by only a small margin. A vibration level that causes annoyance will be well below the damage threshold for normal buildings.

The basic concepts of ground-borne vibration are illustrated for a rail system in Figure 7-1. The train wheels rolling on the rails create vibration energy that is transmitted through the track support system into the transit structure. The amount of energy that is transmitted into the transit structure is strongly dependent on factors such as how smooth the wheels and rails are and the resonance frequencies of the vehicle suspension system and the track support system. These systems, like all mechanical systems, have resonances which result in increased vibration response at certain frequencies, called natural frequencies.

The vibration of the transit structure excites the adjacent ground, creating vibration waves that propagate through the various soil and rock strata to the foundations of nearby buildings. The vibration propagates from the foundation throughout the remainder of the building structure. The maximum vibration amplitudes of the floors and walls of a building often will be at the resonance frequencies of various components of the building.

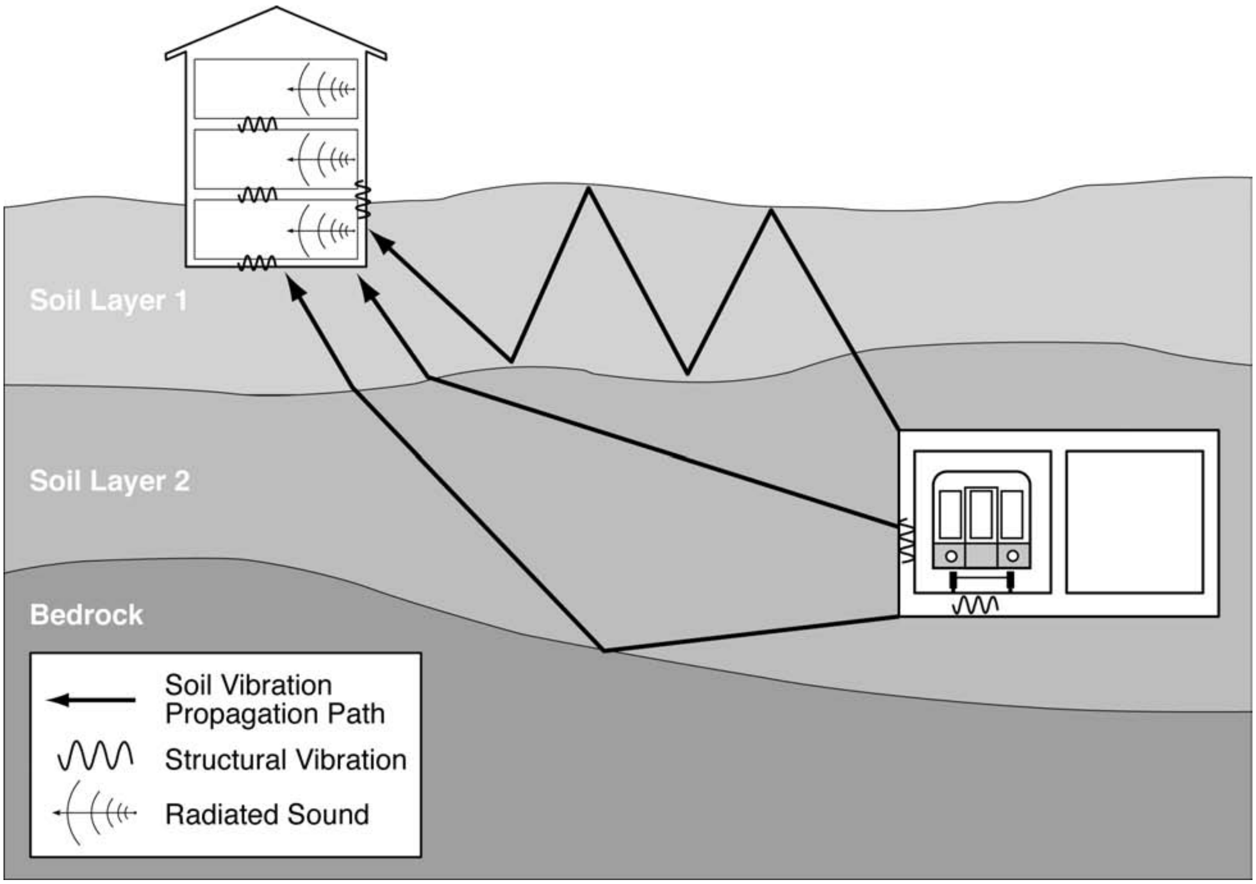

Figure 7-1. Propagation of Ground-Borne Vibration into Buildings

The vibration of floors and walls may cause perceptible vibration, rattling of items such as windows or dishes on shelves, or a rumble noise. The rumble is the noise radiated from the motion of the room surfaces. In essence, the room surfaces act like a giant loudspeaker causing what is called ground-borne noise.

Ground-borne vibration is almost never annoying to people who are outdoors. Although the motion of the ground may be perceived, without the effects associated with the shaking of a building, the motion does not provoke the same adverse human reaction. In addition, the rumble noise that usually accompanies the building vibration is perceptible only inside buildings.

7.1 DESCRIPTORS OF GROUND-BORNE VIBRATION AND NOISE

7.1.1 Vibratory Motion

Vibration is an oscillatory motion which can be described in terms of the displacement, velocity, or acceleration. Because the motion is oscillatory, there is no net movement of the vibration element and the average of any of the motion descriptors is zero. Displacement is the easiest descriptor to understand. For a vibrating floor, the displacement is simply the distance that a point on the floor moves away from its static position. The velocity represents the instantaneous speed of the floor movement and acceleration is the rate of change of the speed.

Although displacement is easier to understand than velocity or acceleration, it is rarely used for describing ground-borne vibration. Most transducers used for measuring ground-borne vibration use either velocity or acceleration. Furthermore, the response of humans, buildings, and equipment to vibration is more accurately described using velocity or acceleration.

7.1.2 Amplitude Descriptors

Vibration consists of rapidly fluctuating motions with an average motion of zero. Several descriptors can be used to quantify vibration amplitude, three of which are shown in Figure 7-2. The raw signal is the lighter-weight curve in the top graph. This curve shows the instantaneous vibration velocity which fluctuates positive and negative about the zero point. The peak particle velocity (PPV) is defined as the maximum instantaneous positive or negative peak of the vibration signal. PPV is often used in monitoring of blasting vibration since it is related to the stresses that are experienced by buildings.

Although peak particle velocity is appropriate for evaluating the potential of building damage, it is not suitable for evaluating human response. It takes some time for the human body to respond to vibration signals. In a sense, the human body responds to an average vibration amplitude. Because the net average of a vibration signal is zero, the root mean square (rms) amplitude is used to describe the "smoothed" vibration amplitude. The root mean square of a signal is the square root of the average of the squared amplitude of the signal. The average is typically calculated over a one-second period. The rms amplitude is shown superimposed

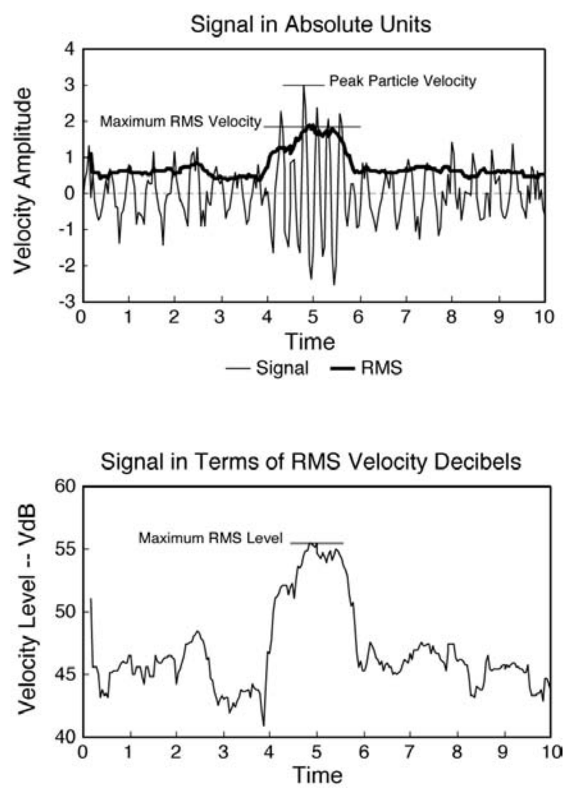

Figure 7-2. Different Methods of Describing a Vibration Signal

on the vibration signal in Figure 7-2. The rms amplitude is always less than the PPV* and is always positive.

The PPV and rms velocity are normally described in inches per second in the USA and meters per second in the rest of the world. Although it is not universally accepted, decibel notation is in common use for vibration.

Decibel notation acts to compress the range of numbers required to describe vibration. The bottom graph in Figure 7-2 shows the rms curve of the top graph expressed in decibels. Vibration velocity level in decibels is defined as:

$$L_v = 20 \times \log_{10}\left(\frac{v}{v_{ref}}\right)$$

where "L_v" is the velocity level in decibels, "v" is the rms velocity amplitude, and "v_{ref}" is the reference velocity amplitude. A reference must always be specified whenever a quantity is expressed in terms of decibels. The accepted reference quantities for vibration velocity are 1×10^{-6} inches/second in the USA and either 1×10^{-8} meters/second or 5×10^{-8} meters/second in the rest of the world. Because of the variations in the reference quantities, it is important to be clear about what reference quantity is being used whenever velocity levels are specified. ***All** vibration levels in this manual are referenced to 1×10^{-6} in./sec.* Although not a universally accepted notation, the abbreviation "VdB" is used in this document for vibration decibels to reduce the potential for confusion with sound decibels.

7.1.3 Ground-Borne Noise

As discussed above, the rumbling sound caused by the vibration of room surfaces is called ground-borne noise. The annoyance potential of ground-borne noise is usually characterized with the A-weighted sound level. Although the A-weighted level is almost the only metric used to characterize community noise, there are potential problems when characterizing low-frequency noise using A-weighting. This is because of the non-linearity of human hearing which causes sounds dominated by low-frequency components to seem louder than broadband sounds that have the same A-weighted level. The result is that ground-borne noise with a level of 40 dBA sounds louder than 40 dBA broadband noise. This is accounted for by setting the limits for ground-borne noise lower than would be the case for broadband noise.

*The ratio of PPV to maximum rms amplitude is defined as the **crest factor** for the signal. The crest factor is always greater than 1.71, although a crest factor of 8 or more is not unusual for impulsive signals. For ground-borne vibration from trains, the crest factor is usually 4 to 5.

7.2 HUMAN PERCEPTION OF GROUND-BORNE VIBRATION AND NOISE

This section gives some general background on human response to different levels of building vibration, laying the groundwork for the criteria for ground-borne vibration and noise that are presented in Chapter 8.

7.2.1 Typical Levels of Ground-Borne Vibration and Noise

In contrast to airborne noise, ground-borne vibration is not a phenomenon that most people experience every day. The background vibration velocity level in residential areas is usually 50 VdB or lower, well below the threshold of perception for humans which is around 65 VdB. Most perceptible indoor vibration is caused by sources within buildings such as operation of mechanical equipment, movement of people or slamming of doors. Typical outdoor sources of perceptible ground-borne vibration are construction equipment, steel-wheeled trains, and traffic on rough roads. If the roadway is smooth, the vibration from traffic is rarely perceptible.

Figure 7-3 illustrates common vibration sources and the human and structural response to ground-borne vibration. The range of interest is from approximately 50 VdB to 100 VdB. Background vibration is usually well below the threshold of human perception and is of concern only when the vibration affects very sensitive manufacturing or research equipment. Electron microscopes and high-resolution lithography equipment are typical of equipment that is highly sensitive to vibration.

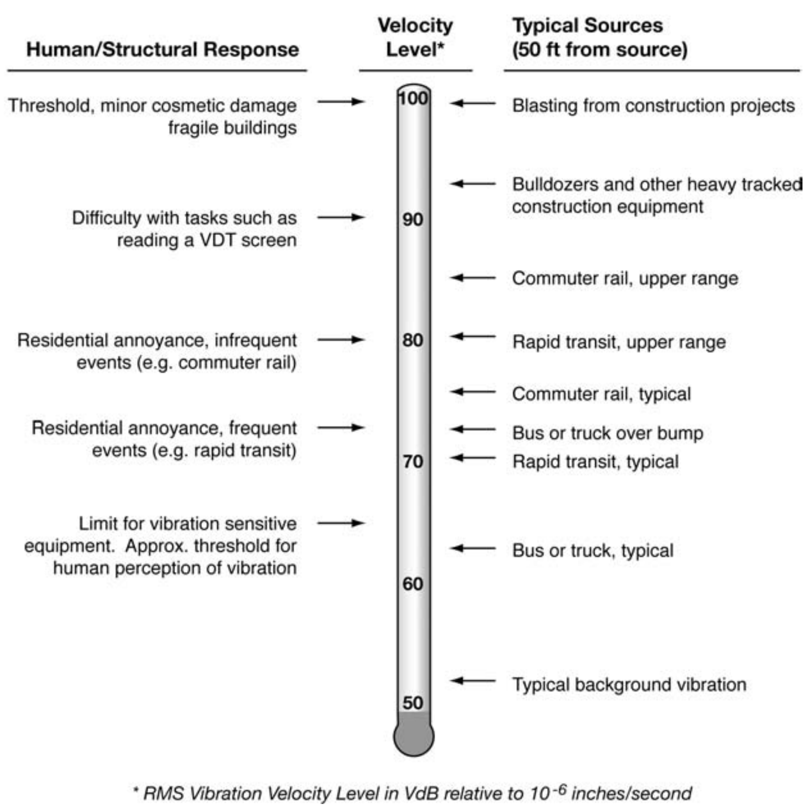

Figure 7-3. Typical Levels of Ground-Borne Vibration

Although the perceptibility threshold is about 65 VdB, human response to vibration is not usually significant unless the vibration exceeds 70 VdB. Rapid transit or light rail systems typically generate vibration levels of 70 VdB or more near their tracks. On the other hand, buses and trucks rarely create vibration that exceeds 70 VdB unless there are bumps in the road. Because of the heavy locomotives on diesel commuter rail systems, the vibration levels average about 5 to 10 decibels higher than rail transit vehicles. If there is unusually rough road or track, wheel flats, geologic conditions that promote efficient propagation of vibration, or vehicles with very stiff suspension systems, the vibration levels from any source can be 10 decibels higher than typical. Hence, at 50 feet, the upper range for rapid transit vibration is around 80 VdB and the high range for commuter rail vibration is 85 VdB. If the vibration level in a residence reaches 85 VdB, most people will be strongly annoyed by the vibration.

The relationship between ground-borne vibration and ground-borne noise depends on the frequency content of the vibration and the acoustical absorption of the receiving room. The more acoustical absorption in the room, the lower will be the noise level. For a room with average acoustical absorption, the unweighted sound pressure level is approximately equal to the average vibration velocity level of the room surfaces.[*] Hence, the A-weighted level of ground-borne noise can be estimated by applying A-weighting to the vibration velocity spectrum. Since the A-weighting at 31.5 Hz is -39.4 dB, if the vibration spectrum peaks at 30 Hz, the A-weighted sound level will be approximately 40 decibels lower than the velocity level. Correspondingly, if the vibration spectrum peaks at 60 Hz, the A-weighted sound level will be about 25 decibels lower than the velocity level.

7.2.2 Quantifying Human Response to Ground-Borne Vibration and Noise

One of the major problems in developing suitable criteria for ground-borne vibration is that there has been relatively little research into human response to vibration, in particular, human annoyance with building vibration. The American National Standards Institute (ANSI) developed criteria for evaluation of human exposure to vibration in buildings in 1983[(1)] and the International Organization for Standardization (ISO) adopted similar criteria in 1989[(2)] and revised them in 2003 [(3)]. The 2003 version of ISO 2361-2 acknowledges that "human response to vibration in buildings is very complex." It further indicates that the degree of annoyance can not always be explained by the magnitude of the vibration alone. In some cases the complaints are associated with measured vibration that is lower than the perception threshold. Other phenomena such as ground-borne noise, rattling, visual effects such as movement of hanging objects, and time of day (e.g., late at night) all play some role in the response of individuals. To understand and evaluate human response, which is often measured by complaints, all of these related effects need to be considered. The available data documenting real world experience with these phenomena is still relatively sparse. Experience with U.S. rapid transit projects represents a good foundation for developing suitable limits for residential exposure to ground-borne vibration and noise from transit operations.

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[*]The sound level approximately equals the average vibration velocity level *only* when the velocity level is referenced to 1 micro-inch/second. When velocity level is expressed using the international standard of 1×10^{-8} m/sec, the sound level is approximately 8 decibels lower than the average velocity level.

Figure 7-4 illustrates the relationship between the vibration velocity level measured in 22 homes and the general response of the occupants to the vibration. The data shown were assembled from measurements performed for several transit systems along with subjective ratings by the researchers and residents. These data were previously published in the "State-of-the-Art Review of Ground-borne Noise and Vibration."[4] Both the occupants and the people who performed the measurements agreed that floor vibration in the "Distinctly Perceptible" category was unacceptable for a residence. The data in Figure 7-4 indicate that residential vibration exceeding 75 VdB is unacceptable for a repetitive vibration source such as rapid transit trains that pass every 5 to 15 minutes. Also shown in Figure 7-4 is a curve showing the percent of people annoyed by vibration from high-speed trains in Japan.[5] The scale for the percent annoyed is on the right-hand axis of the graph. The results of the Japanese study confirm the conclusion that at a vibration velocity level of 75 to 80 VdB, many people will find the vibration annoying.

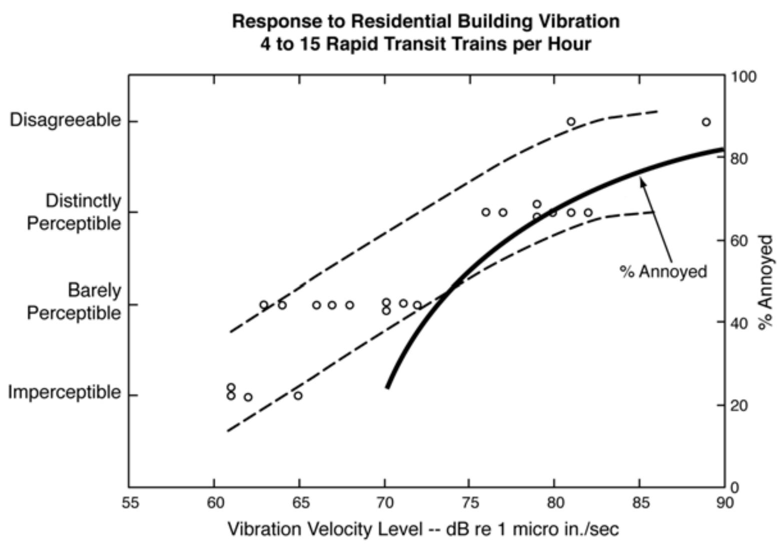

Figure 7-4. Response to Transit-induced Residential Vibration

Table 7-1 describes the human response to different levels of ground-borne noise and vibration. The first column is the vibration velocity level, and the next two columns are for the corresponding noise level assuming that the vibration spectrum peaks at 30 Hz or 60 Hz. As discussed above, the A-weighted noise level will be approximately 40 dB less than the vibration velocity level if the spectrum peak is around 30 Hz, and 25 dB lower if the spectrum peak is around 60 Hz. Table 7-1 illustrates that achieving either the acceptable vibration or acceptable noise levels does not guarantee that the other will be acceptable. For example, the noise caused by vibrating structural components may be very annoying even though the vibration cannot be felt. Alternatively, a low-frequency vibration could be annoying while the ground-borne noise level it generates is acceptable.

Table 7-1. Human Response to Different Levels of Ground-Borne Noise and Vibration

Vib. Velocity Level	Noise Level		Human Response
	Low Freq1	Mid Freq2	
65 VdB	25 dBA	40 dBA	Approximate threshold of perception for many humans. Low-frequency sound usually inaudible, mid-frequency sound excessive for quiet sleeping areas.
75 VdB	35 dBA	50 dBA	Approximate dividing line between barely perceptible and distinctly perceptible. Many people find transit vibration at this level annoying. Low-frequency noise acceptable for sleeping areas, mid-frequency noise annoying in most quiet occupied areas.
85 VdB	45 dBA	60 dBA	Vibration acceptable only if there are an infrequent number of events per day. Low-frequency noise annoying for sleeping areas, mid-frequency noise annoying even for infrequent events with institutional land uses such as schools and churches.

Notes:
1. Approximate noise level when vibration spectrum peak is near 30 Hz.
2. Approximate noise level when vibration spectrum peak is near 60 Hz.

7.3 GROUND-BORNE VIBRATION FOR DIFFERENT TRANSIT MODES

This section provides a brief discussion of typical problems with ground-borne vibration and noise for different modes of transit.

- **Steel-Wheel Urban Rail Transit:** This category includes both heavy rail transit and light rail transit. Heavy rail is generally defined as electrified rapid transit trains with dedicated guideway, and light rail as electrified transit trains that do not require dedicated guideway. The ground-borne vibration characteristics of heavy and light rail vehicles are very similar since they have similar suspension systems and axle loads. Most of the studies of ground-borne vibration in this country have focused on urban rail transit. Problems with ground-borne vibration and noise are common when there is less than 50 feet between a subway structure and building foundations. Whether the problem will be perceptible vibration or audible noise is strongly dependent on local geology and the structural details of the building. Complaints about ground-borne vibration from surface track are more common than complaints about ground-borne noise. A significant percentage of complaints about both ground-borne vibration and noise can be attributed to the proximity of special trackwork, rough or corrugated track, or wheel flats.

- **Commuter and Intercity Passenger Trains:** This category includes passenger trains powered by either diesel or electric locomotives. In terms of vibration effects at a single location, the major difference between commuter and intercity passenger trains is that the latter are on a less frequent schedule. Both often share track with freight trains, which have quite different vibration characteristics as discussed below. The locomotives usually create the highest vibration levels. There is the potential of vibration-related problems anytime that new commuter or intercity rail passenger service is introduced in an urban or suburban area.
- **High-Speed Passenger Trains:** High-speed passenger trains have the potential of creating high levels of ground-borne vibration. Ground-borne vibration should be anticipated as one of the major environmental impacts of any high-speed train located in an urban or suburban area. The Amtrak trains on the Northeast Corridor between Boston and Washington, D.C., which attain moderate to high speeds in some sections with improved track, fit into this category.
- **Freight Trains:** Local and long-distance freight trains are similar in that they both are diesel-powered and have the same types of cars. They differ in their overall length, number and size of locomotives, and number of heavily loaded cars. Locomotives and rail cars with wheel flats are the sources of the highest vibration levels. Because locomotive suspensions are similar, the maximum vibration levels of local and long-distance freights are similar. It is not uncommon for freight trains to be the source of intrusive ground-borne vibration. Most railroad tracks used for freight lines were in existence for many years before the affected residential areas were developed. Vibration from freight trains can be a consideration for FTA-assisted projects when a new transit line will share an existing freight train right-of-way. Relocating the freight tracks within the right-of-way to make room for the transit tracks must be considered a direct impact of the transit system which must be evaluated as part of the proposed project. However, vibration mitigation is very difficult to implement on tracks where trains with heavy axle loads will be operating.
- **Automated Guideway Transit Systems (AGT):** This transit mode encompasses a wide range of transportation vehicles providing local circulation in downtown areas, airports and theme parks. In general, ground-borne vibration can be expected to be generated by steel-wheel/steel-rail systems even when limited in size. Because AGT systems normally operate at low speeds, have lightweight vehicles, and rarely operate in vibration-sensitive areas, ground-borne vibration problems are very rare.
- **Bus Projects:** Because the rubber tires and suspension systems of buses provide vibration isolation, it is unusual for buses to cause ground-borne noise or vibration problems. When buses cause effects such as rattling of windows, the source is almost always airborne noise. Most problems with bus-related vibration can be directly related to a pothole, bump, expansion joint, or other discontinuity in the road surface. Smoothing the bump or filling the pothole will usually solve the problem. Problems are likely when buses will be operating inside buildings. Intrusive building vibration can be caused by sudden loading of a building slab by a heavy moving vehicle or by vehicles running over lane divider bumps. A bus transfer station with commercial office space in the same building may have annoying vibration within the office space caused by bus operations.

7.4 FACTORS THAT INFLUENCE GROUND-BORNE VIBRATION AND NOISE

One of the major problems in developing accurate estimates of ground-borne vibration is the large number of factors that can influence the levels at the receiver position. This section gives a general appreciation of which factors have significant effects on the levels of ground-borne vibration. Table 7-2 is a summary of some of the many factors that are known to have, or are suspected of having, a significant influence on the levels of ground-borne vibration and noise. As indicated, the physical parameters of the transit facility, the geology, and the receiving building all influence the vibration levels. The important physical parameters can be divided into the following four categories:

- **Operational and Vehicle Factors:** This category includes all of the parameters that relate to the vehicle and operation of the trains. Factors such as high speed, stiff primary suspensions on the vehicle, and flat or worn wheels will increase the possibility of problems from ground-borne vibration.
- **Guideway:** The type and condition of the rails, the type of guideway, the rail support system, and the mass and stiffness of the guideway structure will all have an influence on the level of ground-borne vibration. Jointed rail, worn rail, and wheel impacts at special trackwork can all cause substantial increases in ground-borne vibration. A rail system guideway will be either subway, at-grade, or elevated. It is rare for ground-borne vibration to be a problem with elevated railways except when guideway supports are located within 50 feet of buildings. For guideways at-grade, directly radiated noise is usually the dominant problem, although vibration can be a problem. For subways, ground-borne vibration is often one of the most important environmental problems. For rubber-tired systems, the smoothness of the roadway/guideway is the critical factor; if the surface is smooth, vibration problems are unlikely.
- **Geology:** Soil and subsurface conditions are known to have a strong influence on the levels of ground-borne vibration. Among the most important factors are the stiffness and internal damping of the soil and the depth to bedrock. Experience with ground-borne vibration is that vibration propagation is more efficient in stiff clay soils, and shallow rock seems to concentrate the vibration energy close to the surface and can result in ground-borne vibration problems at large distances from the track. Factors such as layering of the soil and depth to water table can have significant effects on the propagation of ground-borne vibration.
- **Receiving Building:** The receiving building is a key component in the evaluation of ground-borne vibration since ground-borne vibration problems occur almost exclusively inside buildings. The train vibration may be perceptible to people who are outdoors, but it is very rare for outdoor vibration to cause complaints. The vibration levels inside a building are dependent on the vibration energy that reaches the building foundation, the coupling of the building foundation to the soil, and the propagation of the vibration through the building. The general guideline is that the heavier a building is, the lower the response will be to the incident vibration energy.

Table 7-2. Factors that Influence Levels of Ground-Borne Vibration and Noise

Factors	Influence
Factors Related to Vibration Source	
Factors	**Influence**
Vehicle Suspension	If the suspension is stiff in the vertical direction, the effective vibration forces will be higher. On transit cars, only the primary suspension affects the vibration levels, the secondary suspension that supports the car body has no apparent effect.
Wheel Type and Condition	Use of pneumatic tires is one of the best methods of controlling ground-borne vibration. Normal resilient wheels on rail transit systems are usually too stiff to provide significant vibration reduction. Wheel flats and general wheel roughness are the major cause of vibration from steel wheel/steel rail systems.
Track/Roadway Surface	Rough track or rough roads are often the cause of vibration problems. Maintaining a smooth surface will reduce vibration levels.
Track Support System	On rail systems, the track support system is one of the major components in determining the levels of ground-borne vibration. The highest vibration levels are created by track that is rigidly attached to a concrete trackbed (e.g. track on wood half-ties embedded in the concrete). The vibration levels are much lower when special vibration control track systems such as resilient fasteners, ballast mats and floating slabs are used.
Speed	As intuitively expected, higher speeds result in higher vibration levels. Doubling speed usually results in a vibration level increase of 4 to 6 decibels.
Transit Structure	The general rule-of-thumb is that the heavier the transit structure, the lower the vibration levels. The vibration levels from a lightweight bored tunnel will usually be higher than from a poured concrete box subway.
Depth of Vibration Source	There are significant differences in the vibration characteristics when the source is underground compared to surface level.
Factors Related to Vibration Path	
Factor	**Influence**
Soil Type	Vibration levels are generally higher in stiff clay-type soils than in loose sandy soils.
Rock Layers	Vibration levels are usually high near at-grade track when the depth to bedrock is 30 feet or less. Subways founded in rock will result in lower vibration amplitudes close to the subway. Because of efficient propagation, the vibration level does not attenuate as rapidly in rock as it does in soil.
Soil Layering	Soil layering will have a substantial, but unpredictable, effect on the vibration levels since each stratum can have significantly different dynamic characteristics.
Depth to Water Table	The presence of the water table may have a significant effect on ground-borne vibration, but a definite relationship has not been established.
Factors Related to Vibration Receiver	
Factor	**Influence**
Foundation Type	The general rule-of-thumb is that the heavier the building foundation, the greater the coupling loss as the vibration propagates from the ground into the building.
Building Construction	Since ground-borne vibration and noise are almost always evaluated in terms of indoor receivers, the propagation of the vibration through the building must be considered. Each building has different characteristics relative to structureborne vibration, although the general rule-of-thumb is the more massive the building, the lower the levels of ground-borne vibration.
Acoustical Absorption	The amount of acoustical absorption in the receiver room affects the levels of ground-borne noise.

REFERENCES

1. American National Standards Institute, Guide to the Evaluation of Human Exposure to Vibration in Buildings. ANSI S3.29-1983

2. International Organization for Standardization, "Evaluation of Human exposure to whole body vibration: Part 2 – Continuous and shock-induced vibration in buildings (1 – 80 Hz), ISO 2361-2-1989

3. International Organization for Standardization, "Mechanical Vibration and Shock : Evaluation of human exposure to whole body vibration: Part 2 – Vibration in buildings (1 to 80 Hz), ISO 2631-2-2003.

4. J. T. Nelson, H. J. Saurenman, "State-of-the-Art Review: Prediction and Control of Groundborne Noise and Vibration from Rail Transit Trains," U.S. Department of Transportation, Urban Mass Transportation Administration, Report Number UMTA-MA-06-0049-83-4, DOT-TSC-UMTA-83-3, December 1983.

5. Y. Tokita, "Vibration Pollution Problems in Japan," In Inter-Noise 75, Sendai, Japan, pp. 465-472, 1975.

8. VIBRATION IMPACT CRITERIA

Because of the relatively rare occurrence of annoyance due to ground-borne vibration and noise, there has been only limited sponsored research of human response to building vibration and structure-borne noise. However, with the construction of new rail rapid transit systems in the past 30 years, considerable experience has been gained as to how people react to various levels of building vibration. This experience, combined with the available national and international standards,[1,2,3] represents a good foundation for predicting annoyance from ground-borne noise and vibration in residential areas as well as interference with vibration-sensitive activities.

The criteria for environmental impact from ground-borne vibration and noise are based on the maximum root-mean-square (rms) vibration levels for repeated events of the same source. The criteria presented in Table 8-1 account for variation in project types as well as the frequency of events, which differ widely among transit projects. Most experience is with the community response to ground-borne vibration from rail rapid transit systems with typical headways in the range of 3 to 10 minutes and each vibration event lasting less than 10 seconds. It is intuitive that when there will be many fewer events each day, as is typical for commuter rail projects, it should take higher vibration levels to evoke the same community response. This is accounted for in the criteria by distinguishing between projects with varying numbers of events, where *Frequent Events* are defined as more than 70 events per day, *Occasional Events* range between 30 and 70 events per day, and *Infrequent Events* are fewer than 30 events per day. Most commuter rail branch lines will fall into the infrequent events category, although the trunk lines of some commuter rail lines serving major cities are in the occasional events category.

The criteria are primarily based on experience with passenger train operations with only limited experience from freight train operations. The difference is that passenger train operations, whether rapid transit, commuter rail, or intercity passenger railroad, create vibration events that last less than about 10 seconds. A typical line-haul freight train is about 5000 feet long. At a speed of 30 mph, it will take a 5000-foot freight train approximately two minutes to pass. Even though the criteria are primarily based on experience with shorter vibration events and this manual is oriented to transit projects, there will be situations where potential impacts from freight train ground-borne vibration will need to be evaluated. The prime example is when freight train tracks must be relocated to provide space for a transit project within a railroad right-of-way. Some guidelines for applying these criteria to freight train operations are given later in this chapter.

8.1 VIBRATION IMPACT CRITERIA FOR GENERAL ASSESSMENT

8.1.1 Sensitive-Use Categories

The criteria for acceptable ground-borne vibration are expressed in terms of rms velocity levels in decibels and the criteria for acceptable ground-borne noise are expressed in terms of A-weighted sound levels. The limits are specified for the three land-use categories defined below:

- **Vibration Category 1 - High Sensitivity:** Included in Category 1 are buildings where vibration would interfere with operations within the building, including levels that may be well below those associated with human annoyance. Concert halls and other special-use facilities are covered separately in Table 8-2. Typical land uses covered by Category 1 are: vibration-sensitive research and manufacturing, hospitals with vibration-sensitive equipment, and university research operations. The degree of sensitivity to vibration will depend on the specific equipment that will be affected by the vibration. Equipment such as electron microscopes and high resolution lithographic equipment can be very sensitive to vibration, and even normal optical microscopes will sometimes be difficult to use when vibration is well below the human annoyance level. Manufacturing of computer chips is an example of a vibration-sensitive process.

  The vibration limits for Vibration Category 1 are based on acceptable vibration for moderately vibration-sensitive equipment such as optical microscopes and electron microscopes with vibration isolation systems. Defining limits for equipment that is even more sensitive requires a detailed review of the specific equipment involved. This type of review is usually performed during the Detailed Analysis associated with the final design phase and not as part of the environmental impact assessment. Mitigation of transit vibration that affects sensitive equipment typically involves modification of the equipment mounting system or relocation of the equipment rather than applying vibration control measures to the transit project.

  Note that this category does not include most computer installations or telephone switching equipment. Although the owners of this type of equipment often are very concerned about the potential of ground-borne vibration interrupting smooth operation of their equipment, it is rare for computer or other electronic equipment to be particularly sensitive to vibration. Most such equipment is designed to operate in typical building environments where the equipment may experience occasional shock from bumping and continuous background vibration caused by other equipment.

- **Vibration Category 2 - Residential:** This category covers all residential land uses and any buildings where people sleep, such as hotels and hospitals. No differentiation is made between different types of residential areas. This is primarily because ground-borne vibration and noise are experienced indoors and building occupants have practically no means to reduce their exposure. Even in a noisy urban area, the bedrooms often will be quiet in buildings that have effective noise insulation and tightly closed windows. Moreover, street traffic often abates at night when transit continues to operate. Hence, an occupant of a bedroom in a noisy urban area is likely to be just as exposed to ground-borne noise and vibration as someone in a quiet suburban area. The criteria apply to the transit-generated ground-borne vibration and noise whether the source is subway or surface running trains.

- **Vibration Category 3 - Institutional:** Vibration Category 3 includes schools, churches, other institutions, and quiet offices that do not have vibration-sensitive equipment, but still have the potential for activity interference. Although it is generally appropriate to include office buildings in this category, it is not appropriate to include all buildings that have any office space. For example, most industrial buildings have office space, but it is not intended that buildings primarily for industrial use be included in this category.

Table 8-1. Ground-Borne Vibration (GBV) and Ground-Borne Noise (GBN) Impact Criteria for General Assessment

Land Use Category	GBV Impact Levels (VdB re 1 micro-inch /sec)			GBN Impact Levels (dB re 20 micro Pascals)		
	Frequent Events[1]	Occasional Events[2]	Infrequent Events[3]	Frequent Events[1]	Occasional Events[2]	Infrequent Events[3]
Category 1: Buildings where vibration would interfere with interior operations.	65 VdB[4]	65 VdB[4]	65 VdB[4]	N/A[4]	N/A[4]	N/A[4]
Category 2: Residences and buildings where people normally sleep.	72 VdB	75 VdB	80 VdB	35 dBA	38 dBA	43 dBA
Category 3: Institutional land uses with primarily daytime use.	75 VdB	78 VdB	83 VdB	40 dBA	43 dBA	48 dBA

Notes:
1. "Frequent Events" is defined as more than 70 vibration events of the same source per day. Most rapid transit projects fall into this category.
2. "Occasional Events" is defined as between 30 and 70 vibration events of the same source per day. Most commuter trunk lines have this many operations.
3. "Infrequent Events" is defined as fewer than 30 vibration events of the same kind per day. This category includes most commuter rail branch lines.
4. This criterion limit is based on levels that are acceptable for most moderately sensitive equipment such as optical microscopes. Vibration-sensitive manufacturing or research will require detailed evaluation to define the acceptable vibration levels. Ensuring lower vibration levels in a building often requires special design of the HVAC systems and stiffened floors.
5. Vibration-sensitive equipment is generally not sensitive to ground-borne noise.

There are some buildings, such as concert halls, TV and recording studios, and theaters, that can be very sensitive to vibration and noise but do not fit into any of the three categories. Because of the sensitivity of these buildings, they usually warrant special attention during the environmental assessment of a transit project. Table 8-2 gives criteria for acceptable levels of ground-borne vibration and noise for various types of special buildings.

Table 8-2. Ground-Borne Vibration and Noise Impact Criteria for Special Buildings

Type of Building or Room	**Ground-Borne Vibration Impact Levels (VdB re 1 micro-inch/sec)**		**Ground-Borne Noise Impact Levels (dB re 20 micro-Pascals)**	
	Frequent [1] Events	**Occasional or Infrequent[2] Events**	**Frequent[1] Events**	**Occasional or Infrequent[2] Events**
Concert Halls	65 VdB	65 VdB	25 dBA	25 dBA
TV Studios	65 VdB	65 VdB	25 dBA	25 dBA
Recording Studios	65 VdB	65 VdB	25 dBA	25 dBA
Auditoriums	72 VdB	80 VdB	30 dBA	38 dBA
Theaters	72 VdB	80 VdB	35 dBA	43 dBA

Notes:
1."Frequent Events" is defined as more than 70 vibration events per day. Most rapid transit projects fall into this category.
2."Occasional or Infrequent Events" is defined as fewer than 70 vibration events per day. This category includes most commuter rail systems.
3.If the building will rarely be occupied when the trains are operating, there is no need to consider impact. As an example, consider locating a commuter rail line next to a concert hall. If no commuter trains will operate after 7 pm, it should be rare that the trains interfere with the use of the hall.

The criteria in Tables 8-1 and 8-2 are related to ground-borne vibration causing human annoyance or interfering with use of vibration-sensitive equipment. It is extremely rare for vibration from train operations to cause any sort of building damage, even minor cosmetic damage. However, there is sometimes concern about damage to fragile historic buildings located near the right-of-way. Even in these cases, damage is unlikely except when the track will be very close to the structure. Damage thresholds that apply to these structures are discussed in Section 12.2.2.

8.1.2 Existing Vibration Conditions

One factor not incorporated in the criteria is how to account for existing vibration. In most cases, the existing environment does not include a significant number of perceptible ground-borne vibration or noise events. The most common example of needing to account for the pre-existing vibration is when the project will be located in an existing rail corridor. When the project will cause vibration more than 5 VdB greater than the existing source, the existing source can be ignored and the standard vibration criteria applied to the project. Following are methods of handling representative scenarios:

1. *Infrequently-used rail corridor (fewer than 5 trains per day):* Use the general vibration criteria, Tables 8-1 and 8-2.

2. *Moderately-used rail corridor (5 to 12 trains per day):* If the existing train vibration exceeds the impact criteria given in Tables 8-1 and 8-2, there will be no impact from the project vibration if the levels estimated using the procedures outlined in either Chapter 10 or 11 are at least 5VdB less than the existing train vibration. Otherwise, vibration criteria in Tables 8-1 and 8-2 apply to the project. The existing train vibration can be either measured or estimated using the General Assessment procedures in Chapter 10. It is usually preferable to measure vibration from existing train traffic.

3. *Heavily-used rail corridor (more than 12 trains per day):* If the existing train vibration exceeds the impact criteria given in Tables 8-1 and 8-2, the project will cause additional impact if the project significantly increases the number of vibration events. Approximately doubling the number of events is required for a significant increase.

   If there is not a significant increase in vibration events, there will be additional impact only if the project vibration, estimated using the procedures of Chapters 10 or 11, will be 3 VdB or more higher than the existing vibration. An example of a case with no additional impact would be an automated people mover system planned for a corridor with an existing rapid transit service with 220 trains per day. On the other hand, there could be impact if it is a new commuter rail line planned to share a corridor with the rapid transit system. In this latter case, the project vibrations are likely to be higher than the existing vibrations by 3 VdB or more.

4. *Moving existing tracks:* Another scenario where existing vibration can be significant is when a new transit project will use an existing railroad right-of-way and result in shifting the location of existing railroad tracks. The track relocation and reconstruction can result in lower vibration levels, in which case this aspect of the project represents a benefit, not an adverse impact. If the track relocation will cause higher vibration levels at sensitive receptors, then the projected vibration levels must be compared to the appropriate impact criterion to determine if there will be new impacts. If impact is judged to have existed prior to moving the tracks, new impact will be assessed only if the relocation results in more than a 3 VdB increase in vibration level.

8.1.3 Application to Freight Trains

The impact thresholds given in Tables 8-1 and 8-2 are based on experience with vibration from rail transit systems. They have been used to assess vibration from freight trains since no specific impact criteria exist for freight railroads. However, the significantly greater length, weight and axle loads of freight trains make it problematic to use these impact criteria for freight rail. Nevertheless, in shared right-of-way situations where the proposed transit alignment causes the freight tracks to be moved closer to sensitive sites, these impact criteria will have to be used. In assessing the freight train vibration, a dual approach is recommended with separate consideration of the locomotive and rail car vibration. Because the locomotive vibration only lasts for a very short time, the few-event criterion is appropriate for fewer than 30 events per day. However, for a typical line-haul freight train where the rail car vibration lasts for several minutes, the many-event limits should be applied to the rail car vibration. Some judgment must be exercised to make sure that the approach is reasonable. For example, some spur rail lines carry very little rail traffic (sometimes only one train per week) or have short trains, in which case the criteria may be disregarded altogether.

Finally, it should be pointed out that the vibration control measures developed for rail transit systems are not effective for freight trains. Consequently, any decision to relocate freight tracks closer to sensitive sites should be made with the understanding that the increased vibration impact due to freight rail will be very difficult, if not impossible, to mitigate.

8.2 VIBRATION IMPACT CRITERIA FOR DETAILED ANALYSIS

8.2.1 Ground-Borne Vibration

Specification of mitigation measures requires more detailed information and more refined impact criteria than what were used in the General Assessment. A frequency distribution, or spectrum, of the vibration energy determines whether the vibrations are likely to generate a significant response in a receiving building or structure. The Detailed Analysis method in this manual provides an estimate of building response in terms of a one-third octave band frequency spectrum. This section provides criteria for assessing the potential for interference or annoyance from building response and for determining the performance of vibration reduction methods.

International standards have been developed for the effects of vibration on people in buildings with ratings related to annoyance and interference with activities based on frequency distribution of acceptable vibrations.(2) These criteria have been supplemented by industry standards for vibration-sensitive equipment.(3) Both sets of criteria are expressed in terms of one-third octave band velocity spectra, with transient events like train passbys described in terms of the maximum rms vibration velocity level with a one-second averaging time. The measurement point is specified as the floor of the receiving building at the location of the prescribed activity.

The vibration impact criteria are shown in Figure 8-1 where the international standard curves and the industry standards are plotted on the same figure. Interpretations of the various levels are presented in Table 8-3. Detailed Analysis results in one-third octave band spectra levels that are plotted over the curves shown in Figure 8-1. Band levels that exceed a particular criterion curve indicate the need for mitigation and the frequency range within which the treatment needs to be effective.

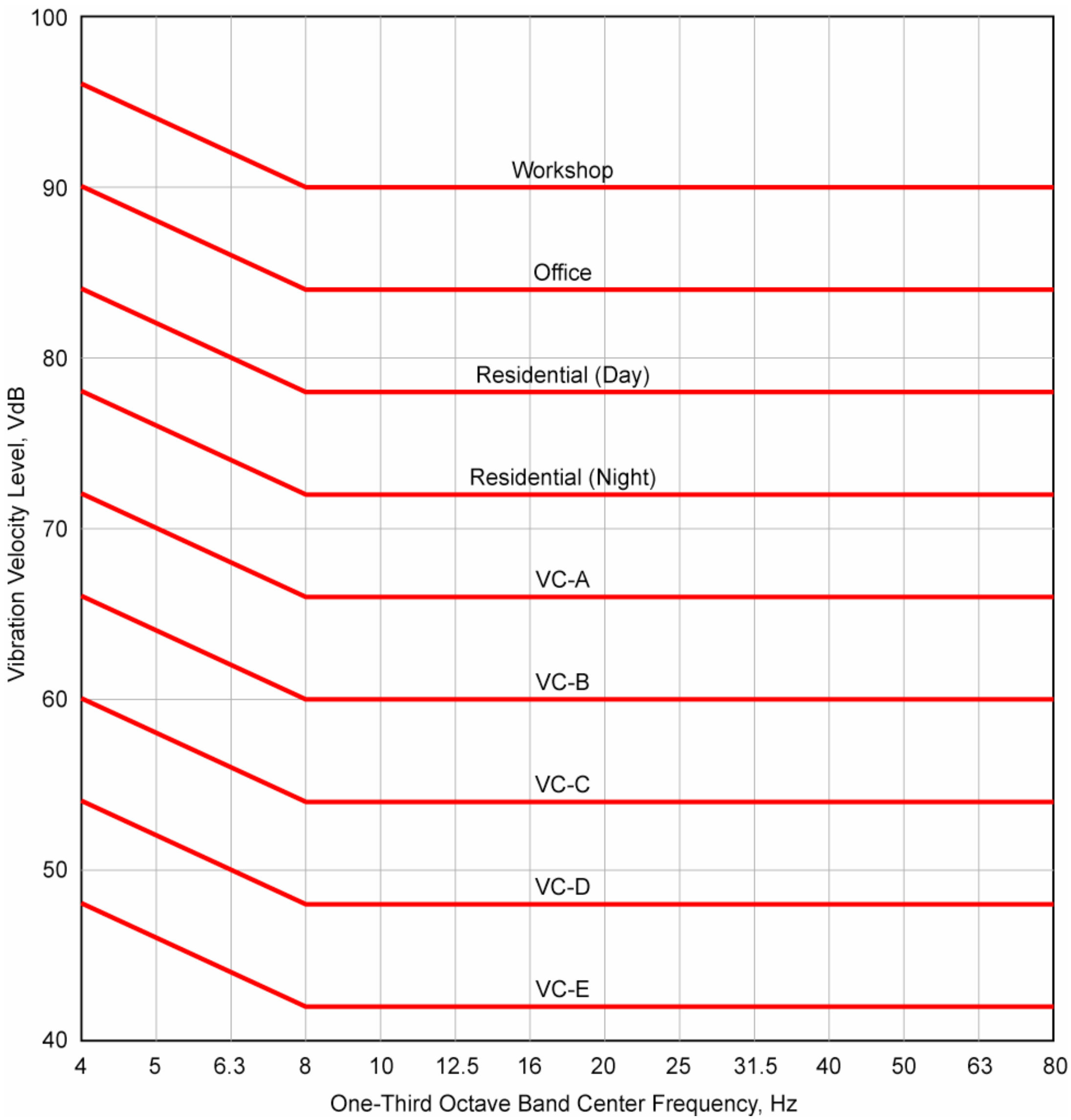

Figure 8-1. Criteria for Detailed Vibration Analysis

Table 8-3. Interpretation of Vibration Criteria for Detailed Analysis

Criterion Curve[1] (See Figure 8-1)	Max L_v (VdB)[2]	Description of Use
Workshop	90	Distinctly feelable vibration. Appropriate to workshops and non-sensitive areas.
Office	84	Feelable vibration. Appropriate to offices and non-sensitive areas.
Residential Day	78	Barely feelable vibration. Adequate for computer equipment and low-power optical microscopes (up to 20X).
Residential Night, Operating Rooms	72	Vibration not feelable, but ground-borne noise may be audible inside quiet rooms. Suitable for medium-power optical microscopes (100X) and other equipment of low sensitivity.
VC-A	66	Adequate for medium- to high-power optical microscopes (400X), microbalances, optical balances, and similar specialized equipment.
VC-B	60	Adequate for high-power optical microscopes (1000X), inspection and lithography equipment to 3 micron line widths.
VC-C	54	Appropriate for most lithography and inspection equipment to 1 micron detail size.
VC-D	48	Suitable in most instances for the most demanding equipment, including electron microscopes operating to the limits of their capability.
VC-E	42	The most demanding criterion for extremely vibration-sensitive equipment.

[1]Descriptors on curves are those provided by References 2 and 3.
[2]As measured in 1/3-octave bands of frequency over the frequency range 8 to 80 Hz.

These criteria use a frequency spectrum because vibration-related problems generally occur due to resonances of the structural components of a building or vibration-sensitive equipment. Resonant response is frequency-dependent. A Detailed Analysis can provide an assessment that identifies potential problems resulting from resonances.

The detailed vibration criteria are based on generic cases when people are standing or equipment is mounted on the floor in a conventional manner. Consequently, the criteria are less stringent at very low frequencies below 8 Hz. Where special vibration isolation has been provided in the form of pneumatic isolators, the resonant frequency of the isolation system is very low. Consequently, in this special case, the curves may be extended flat at lower frequencies.

8.2.2 Ground-Borne Noise

Ground-borne noise impacts are assessed based on criteria for human annoyance and activity interference. The results of the Detailed Analysis provide vibration spectra inside a building. These vibration spectra can be converted to sound pressure level spectra in the occupied spaces using the method described in Section 11.2.2. For residential buildings, the criteria for acceptability are given in terms of the A-weighted sound pressure level in Table 8-1. For special buildings listed in Table 8-2, a single-valued level may not be sufficient to assess activity interference at the Detailed Analysis stage. Each special building may have a unique specification for acceptable noise levels. For example, a recording studio may have stringent requirements for allowable noise in each frequency band. Therefore, the ground-borne noise criteria for each sensitive building in this category will have to be determined on a case-by-case basis.

REFERENCES

1. Acoustical Society of America, "American National Standard: Guide to Evaluation of Human Exposure to Vibration in Buildings," ANSI S3.29-1983 (ASA 48-1983).

2. International Organization for Standardization, "Evaluation of Human Exposure to Whole-Body Vibration, Part 2: Continuous and Shock-Induced Vibrations in Buildings (1-80Hz)," ISO-2361-2, 1989.

3. Institute of Environmental Sciences and Technology, “Considerations in Clean Room Design,” RR-CC012.1, 1993.

9. VIBRATION SCREENING PROCEDURE

The vibration screening procedure is designed to identify projects that have little possibility of creating significant adverse impact. If the screening procedure does not identify any potential problem areas, it is usually safe to eliminate further consideration of vibration impact from the environmental analysis.

9.1 STEPS IN SCREENING PROCEDURE

The steps in the vibration screening procedure are summarized in Figure 9-1 in a flow chart format. Following is a summary of the steps:

Initial Decision: If the project includes any type of steel-wheeled/steel-rail vehicle, there is potential for vibration impact. Proceed directly to the evaluation of screening distances. Transit projects that do not involve vehicles, such as a station rehabilitation, do not have potential for vibration impact unless the track system will be modified (e.g., tracks moved or switches modified). Rail systems include urban rapid transit, light rail transit, commuter rail, and steel-wheel intermediate capacity transit systems. For projects that involve rubber-tire vehicles, vibration impact is unlikely except in unusual situations. Three specific factors shown in Figure 9-1 should be checked to determine if there is potential vibration impact from bus projects or any other projects that involve rubber-tire vehicles:

1. Will there be expansion joints, speed bumps, or other design features that result in unevenness in the road surface near vibration-sensitive buildings? Such irregularities can result in perceptible ground-borne vibration at distances up to 75 feet away.
2. Will buses, trucks or other heavy vehicles be operating close to a sensitive building? Research using electron microscopes and manufacturing of computer chips are examples of vibration-sensitive activities.

3. Does the project include operation of vehicles inside or directly underneath buildings that are vibration-sensitive? Special considerations are often required for shared-use facilities such as a bus station located inside an office building complex.

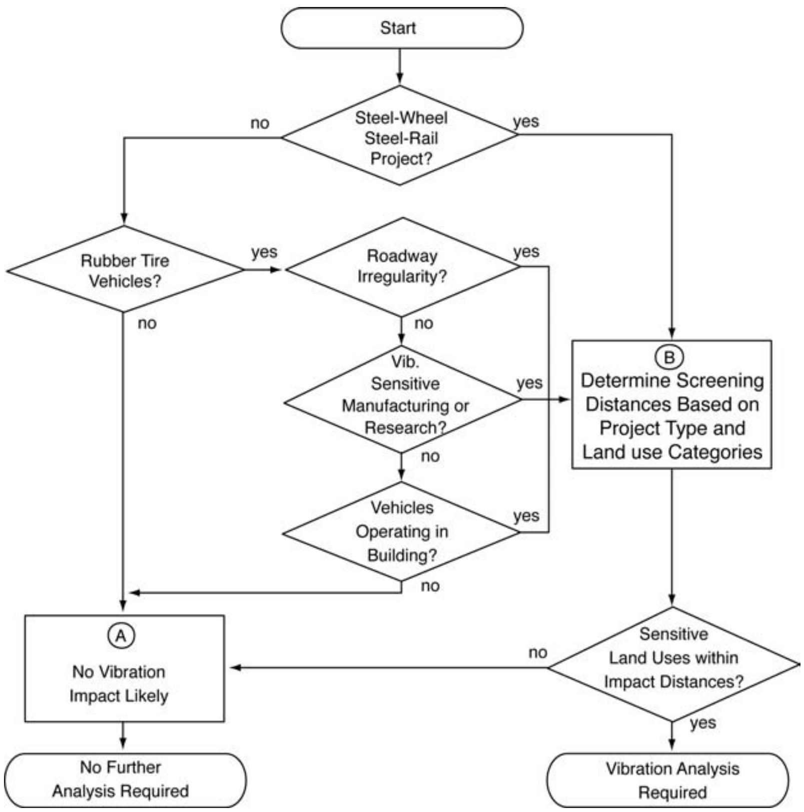

Figure 9-1. Flow Chart of Vibration Screening Process

No Impact (Box A): The decisions in step 1 lead to either box A, "No vibration impact likely," or box B. Reaching box A indicates that further analysis is not required. The majority of smaller FTA-assisted projects, such as bus terminals and park-and-ride lots, will be eliminated from further consideration of ground-borne vibration impact in the first step.

Screening Distances (Box B): If the result of the first step is that there is potential for vibration impact, determine if any vibration-sensitive land uses are within the screening zones. Vibration-sensitive land uses are identified in Chapter 8. Tables 9-1 and 9-2 are used to determine the applicable vibration screening distances for the project.

Impact: If there are any vibration-sensitive land uses within the screening distances, there is the potential for vibration impact. The result of the screening procedure is that a General Vibration Assessment should be done as part of the environmental analysis.

9.2 SCREENING DISTANCES

9.2.1 Project Categories

The vibration screening procedure is applicable to all types of FTA-assisted projects. The project categories for the vibration screening procedure are summarized in Table 9-1 for four types of rail transit. The fifth category includes all bus projects. Any project that does not include some type of vehicle is not likely to cause vibration impact.

With respect to Project Type 5, the rubber-tire vehicle category, most complaints about vibration caused by buses and trucks are related to rattling of windows or items hung on the walls. These vibrations are usually the result of airborne noise and not ground-borne vibration. In the case where ground-borne vibration is the source of the problem, the vibration can usually be related to potholes, some sort of bump in the road, or other irregularities.

Table 9-1. Project Types for Vibration Screening Procedure

Project Type	Description
1. Conventional Commuter Railroad	Both the locomotives and the passenger vehicles create significant vibration. The highest vibration levels are usually created by the locomotives. Electric commuter rail vehicles create levels of ground-borne vibration that are comparable to electric rapid transit vehicles.
2. Rail Rapid Transit	Ground-borne vibration impact from rapid transit trains is one of the major environmental issues for new systems. For operation in subway, the ground-borne vibration is usually a significant environmental impact. It is less common for at-grade and elevated rapid transit lines to create intrusive ground-borne vibration.
3. Light Rail Transit	The ground-borne vibration characteristics of light rail systems are very similar to those of rapid transit systems. Because the speeds of light rail systems are usually lower, the typical vibration levels usually are lower. Steel-wheel/steel-rail Automated Guideway Transit (AGT) will fall into either this category or the Intermediate Capacity Transit category depending on the level of service and train speeds.
4. Intermediate Capacity Transit	Because of the low operating speeds of most ICT systems, significant vibration problems are not common. However, steel-wheel ICT systems that operate close to vibration-sensitive buildings have the potential of causing intrusive vibration. With a stiff suspension system, an ICT system could create intrusive vibration.
5. Bus and Rubber-Tire Transit Projects	This category encompasses most projects that do not include steel-wheel trains of some type. Examples are diesel buses, electric trolley buses, and rubber-tired people movers. Most projects that do not include steel-wheel trains do not cause significant vibration impact.

9.2.2 Distances

The screening distances are given in Table 9-2. These distances are based on the criteria presented in Chapter 8, with a 5-decibel factor of safety included. The distances have been determined using vibration prediction procedures that are summarized in Chapter 10 assuming "normal" vibration propagation. As discussed in Chapter 10, efficient vibration propagation can result in substantially higher vibration levels.

Because of the 5-decibel safety factor, even with efficient propagation, the screening distances will identify most of the potentially impacted areas. By not specifically accounting for the possibility of efficient vibration propagation, there is some possibility that some potential impact areas will not be identified in the screening process. When there is evidence of efficient propagation, such as previous complaints about existing transit facilities or a history of problems with construction vibration, the distances in Table 9-2 should be increased by a factor of 1.5.

Table 9-2. Screening Distances for Vibration Assessment

Type of Project	Critical Distance for Land Use Categories* Distance from Right-of-Way or Property Line		
	Cat. 1	Cat. 2	Cat. 3
Conventional Commuter Railroad	600	200	120
Rail Rapid Transit	600	200	120
Light Rail Transit	450	150	100
Intermediate Capacity Transit	200	100	50
Bus Projects (if not previously screened out)	100	50	--

* The land-use categories are defined in Chapter 8. Some vibration-sensitive land uses are not included in these categories. Examples are: concert halls and TV studios which, for the screening procedure, should be evaluated as Category 1; and theaters and auditoriums which should be evaluated as Category 2.

10. GENERAL VIBRATION ASSESSMENT

This chapter outlines procedures that can be used to develop generalized predictions of ground-borne vibration and noise. This manual includes three different levels of detail for projecting ground-borne vibration:

- **Screening:** The screening procedure is discussed in Chapter 9. A standard table of impact distances is used to determine if ground-borne vibration from the project may affect sensitive land uses. More detailed analysis is required if any sensitive land uses are within the screening distances. The screening procedure does not require any specific knowledge about the vibration characteristics of the system or the geology of the area. If different propagation conditions are known to be present, a simple adjustment is provided.

- **General Assessment:** The general level of assessment, as described in this chapter, is an extension of the screening procedure. It uses generalized data to develop a curve of vibration level as a function of distance from the track. The vibration levels at specific buildings are estimated by reading values from the curve and applying adjustments to account for factors such as track support system, vehicle speed, type of building, and track and wheel condition. The general level deals only with the overall vibration velocity level and the A-weighted sound level. It does not consider the frequency spectrum of the vibration or noise.

- **Detailed Analysis:** Discussed in Chapter 11, the Detailed Analysis involves applying all of the available tools for accurately projecting the vibration impact at specific sites. The procedure outlined in this manual includes a test of the vehicle (or similar vehicle) to define the forces generated by the vibration source and tests at the site in question to define how the local geology affects vibration propagation. It is considerably more complex to develop detailed projections of ground-borne vibration than it is to develop detailed projections of airborne noise. Accurate projections of ground-borne vibration require professionals with experience in performing and interpreting vibration propagation tests. As such, detailed vibration predictions are usually performed during the final design phase of a project when there is sufficient reason to suspect adverse vibration impact from the project. The procedure for Detailed Vibration Analysis presented in Chapter 11 is based on measurements to characterize vibration propagation at specific sites.

There is not always a clear distinction between general and detailed predictions. For example, it is often appropriate to use several representative measurements of vibration propagation along the planned alignment in developing generalized propagation curves. Other times, generalized prediction curves may be sufficient for the majority of the alignment, but with Detailed Analysis applied to particularly sensitive buildings such as a concert hall. The methods for analyzing transit vibration in this manual are consistent with those described in recognized handbooks and international standards.[1, 2]

The purpose of the General Assessment is to provide a relatively simple method of developing estimates of the overall levels of ground-borne vibration and noise that can be compared to the acceptability criteria given in Chapter 8. For many projects, particularly when comparing alternatives, this level of detail will be sufficient for the environmental impact assessment. Where there are potential problems, the Detailed Analysis is then undertaken during final design of the selected alternative to accurately define the level of impact and design mitigation measures. A Detailed Analysis usually will be required when designing special track-support systems such as floating slabs or ballast mats. Detailed Analysis is not usually required if, as is often the case, the mitigation measure consists of relocating a crossover or turnout. Usually, the General Assessment is adequate to determine whether a crossover needs to be relocated.

The basic approach for the General Assessment is to define a curve, or set of curves, that predicts the overall ground-surface vibration as a function of distance from the source, then apply adjustments to these curves to account for factors such as vehicle speed, building type, and receiver location within the building. Section 10.1 includes curves of vibration level as a function of distance from the source for the common types of vibration sources such as rapid transit trains and buses. When the vehicle type is not covered by the curves included in this section, it will be necessary to define an appropriate curve either by extrapolating from existing information or performing measurements at an existing facility.

10.1 SELECTION OF BASE CURVE FOR GROUND SURFACE VIBRATION LEVEL

The base curves for three standard transportation systems are defined in Figure 10-1. This figure shows typical ground-surface vibration levels assuming equipment in good condition and speeds of 50 mph for the rail systems and 30 mph for buses. The levels must be adjusted to account for factors such as different speeds and different geologic conditions than assumed. The adjustment factors are discussed in Section 10.2.

The curves in Figure 10-1 are based on measurements of ground-borne vibration at representative North American transit systems. The top curve applies to trains that are powered by diesel or electric locomotives. It includes intercity passenger trains and commuter rail trains. The curve for rapid transit rail cars covers both heavy and light-rail vehicles on at-grade and subway track. It is somewhat surprising that subway and at-grade track can be represented by the same curve since ground-borne vibration created by a train operating in a subway has very different characteristics than vibration from at-grade track. However, in spite of these differences, the overall vibration velocity levels are comparable. Subways tend to have more vibration problems than at-grade track. This is probably due to two factors: (1) subways are usually located in more densely developed areas, and (2) the airborne noise is usually a more serious problem for at-grade systems than the ground-borne vibration. Another difference between subway and at-grade track is that the ground-borne vibration from subways tends to be higher frequency than the vibration from at-grade track, which makes the ground-borne noise more noticeable.

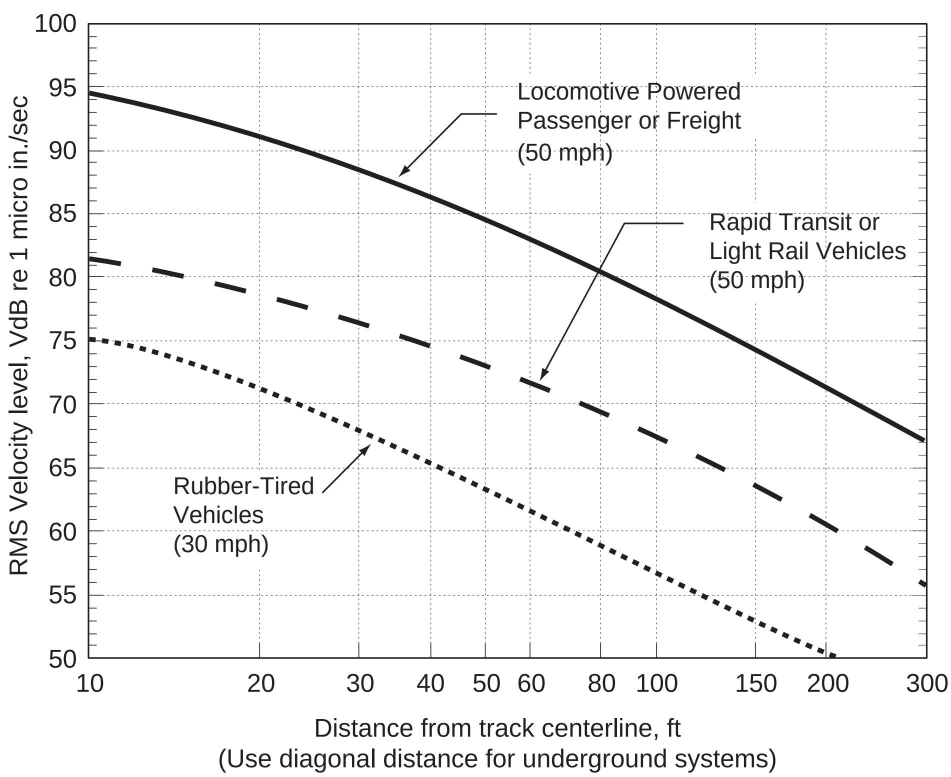

Figure 10-1. Generalized Ground Surface Vibration Curves

The curves in Figure 10-1 were developed from many measurements of ground-borne vibration. Experience with ground-borne vibration data is that, for any specific type of transit mode, a significant variation in vibration levels under apparently similar conditions is not uncommon. The curves in Figure

10-1 represent the upper range of the measurement data from well-maintained systems. Although actual levels fluctuate widely, it is rare that ground-borne vibration will exceed the curves in Figure 10-1 by more than one or two decibels unless there are extenuating circumstances, such as wheel- or running-surface defects.

One approach to dealing with the normal fluctuation is to show projections as a range. For example, the projected level from Figure 10-1 for an LRT system with train speeds of 50 mph is about 72 VdB at a distance of 60 feet from the track centerline, just at the threshold for acceptable ground-borne vibration for residential land uses. To help illustrate the normal fluctuation, the projected level of ground-borne vibration might be given as 67 to 72 VdB. This approach is not recommended since it tends to confuse the interpretation of whether or not the projected vibration levels exceed the impact threshold. However, because actual levels of ground-borne vibration will sometimes differ substantially from the projections, some care must be taken when interpreting projections. Some guidelines are given below:

1. Projected vibration is below the impact threshold. Vibration impact is unlikely in this case.
2. Projected ground-borne vibration is 0 to 5 decibels greater than the impact threshold. In this range there is still a significant chance that actual ground-borne vibration levels will be below the impact threshold. In this case, the impact would be reported in the environmental document as exceeding the applicable threshold and a commitment would be made to conduct more detailed studies to refine the vibration impact analysis during final design and determine appropriate mitigation, if necessary. A site-specific Detailed Analysis may show that vibration control measures are not needed.
3. Projected ground-borne vibration is 5 decibels or more greater than the impact threshold. Vibration impact is probable and Detailed Analysis will be needed during final design to help determine appropriate vibration control measures.

The two most important factors that must be accounted for in a General Assessment are the type of vibration source (the mode of transit) and the vibration propagation characteristics. It is well known that there are situations where ground-borne vibration propagates much more efficiently than normal. The result is unacceptable vibration levels at distances two to three times the normal distance. Unfortunately, the geologic conditions that promote efficient propagation have not been well documented and are not fully understood. Shallow bedrock or stiff clay soil often are involved. One possibility is that shallow bedrock acts to keep the vibration energy near the surface. Much of the energy that would normally radiate down is directed back towards the surface by the rock layer with the result that the ground surface vibration is higher than normal.

The selection of a base curve depends on the mode of rail transit under consideration. Appropriate correction factors are then added to account for any unusual propagation characteristics. For less common modes such as magnetically-levitated vehicles (maglev), monorail, or automated guideway transit (AGT), it is necessary to either make a judgment about which curve and adjustment factors best fit the mode or to develop new estimates of vibration level as a function of distance from the track. For example, the vibration from a rubber-tire monorail that will be operating on aerial guideway can be approximated using the bus/rubber tire systems with the appropriate adjustment for the aerial structure. Another example is a magnetic levitation system. Most of the data available on the noise and vibration characteristics of maglev vehicles comes from high-speed systems intended for inter-city service. Even though there is no direct contact between the vehicle and the guideway, the dynamic loads on the guideway can generate ground-borne vibration. Measurements on a German high-speed maglev resulted in ground-borne vibrations at 75 mph comparable to the base curve for rubber-tired vehicles at 30 mph.[3] Considerations for selecting a base curve are discussed below:

- **Intercity Passenger Trains:** Although intercity passenger trains can be an important source of environmental vibration, it is rare that they are significant for FTA-funded projects unless a new transit mode will use an existing rail alignment. When a new transit line will use an existing rail alignment, the changes in the intercity passenger traffic can result in either positive or negative impacts. Unless there are specific data available on the ground-borne vibration created by the train operations, the upper curve in Figure 10-1 should be used for intercity passenger trains.
- **Locomotive-Powered Commuter Rail:** The locomotive curve from Figure 10-1 should be used for any commuter rail system powered by either diesel or electric locomotives. The locomotives often create vibration levels that are 3 to 8 decibels higher than those created by the passenger cars. Self-powered electric commuter rail trains can be considered to be similar to rapid transit vehicles. Although they are relatively rare in the U.S., self-powered diesel multiple units (DMU's) create vibration levels somewhere between rapid transit vehicles and locomotive-powered passenger trains. When the axle loads and suspension parameters of a particular DMU are comparable to typical rapid transit vehicles, the rapid transit curve in Figure 10-1 can be used for that mode.
- **Subway Heavy Rail:** Complaints about ground-borne vibration are more common near subways than near at-grade track. This is not because subways create higher vibration levels than at-grade systems - rather it is because subways are usually located in high-density areas in close proximity to building foundations. When applied to subways, the rapid transit curve in Figure 10-1 assumes a relatively lightweight bored concrete tunnel in soil. The vibration levels will be lower for heavier subway structures such as cut-and-cover box structures and stations.
- **At-Grade Heavy Rail or LRT:** The available data show that heavy rail and light rail transit vehicles create similar levels of ground-borne vibration. This is not surprising since the vehicles have similar suspension systems and axle loads. Light-rail systems tend to have fewer problems with ground-borne vibration because of the lower operating speeds. Similar to the subway case, an adjustment factor must be used if the transit vehicle has a primary suspension that is stiff in the vertical direction.
- **Intermediate Capacity Transit:** The vibration levels created by an intermediate capacity transit system or an AGT system will depend on whether the vehicles have steel wheels or rubber wheels. If they have steel wheels, the transit car curve in Figure 10-1 should be used with appropriate adjustments for operating speed. The bus/rubber tire curve should be used for rubber-tired ICT systems.

- **Bus/Rubber Tire:** Rubber-tire vehicles rarely create ground-borne vibration problems unless there is a discontinuity or bump in the road that causes the vibration. The curve in Figure 10-1 shows the vibration level for a typical bus operating on smooth roadway.

10.2 ADJUSTMENTS

Once the base curve has been selected, the adjustments in Table 10-1 can be used to develop vibration projections for specific receiver positions inside buildings. All of the adjustments are given as single numbers to be added to, or subtracted from, the base level. The adjustment parameters are speed, wheel and rail type and condition, type of track support system, type of building foundation, and number of floors above the basement level. It should be recognized that many of these adjustments are strongly dependent on the frequency spectrum of the vibration source and the frequency dependence of the vibration propagation. The single number values are suitable for generalized evaluation of the vibration impact and vibration mitigation measures since they are based on typical vibration spectra. However, the single number adjustments are not adequate for detailed evaluations of impact of sensitive buildings or for detailed specification of mitigation measures. Detailed Analysis requires consideration of the relative importance of different frequency components.

<table>
<tr><th colspan="5">Table 10-1. Adjustment Factors for Generalized Predictions of
Ground-Borne Vibration and Noise</th></tr>
<tr><td colspan="5">Factors Affecting Vibration Source</td></tr>
<tr><th>Source Factor</th><th colspan="3">Adjustment to Propagation Curve</th><th>Comment</th></tr>
<tr><td rowspan="7">Speed</td><td rowspan="2"></td><td colspan="2">Reference Speed</td><td rowspan="7">Vibration level is approximately proportional to 20*log(speed/speed$_{ref}$). Sometimes the variation with speed has been observed to be as low as 10 to 15 log(speed/speed$_{ref}$).</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td><u>Vehicle Speed</u></td><td><u>50 mph</u></td><td><u>30 mph</u></td></tr>
<tr><td>60 mph</td><td>+1.6 dB</td><td>+6.0 dB</td></tr>
<tr><td>50 mph</td><td>0.0 dB</td><td>+4.4 dB</td></tr>
<tr><td>40 mph</td><td>-1.9 dB</td><td>+2.5 dB</td></tr>
<tr><td>30 mph
20 mph</td><td>-4.4 dB
-8.0 dB</td><td>0.0 dB
-3.5 dB</td></tr>
<tr><td colspan="5">Vehicle Parameters (not additive, apply greatest value only)</td></tr>
<tr><td>Vehicle with stiff primary suspension</td><td colspan="3">+8 dB</td><td>Transit vehicles with stiff primary suspensions have been shown to create high vibration levels. Include this adjustment when the primary suspension has a vertical resonance frequency greater than 15 Hz.</td></tr>
<tr><td>Resilient Wheels</td><td colspan="3">0 dB</td><td>Resilient wheels do not generally affect ground-borne vibration except at frequencies greater than about 80 Hz.</td></tr>
<tr><td>Worn Wheels or Wheels with Flats</td><td colspan="3">+10 dB</td><td>Wheel flats or wheels that are unevenly worn can cause high vibration levels. This can be prevented with wheel truing and slip-slide detectors to prevent the wheels from sliding on the track.</td></tr>
<tr><td colspan="5">Track Conditions (not additive, apply greatest value only)</td></tr>
<tr><td>Worn or Corrugated Track</td><td colspan="3">+10 dB</td><td>If both the wheels and the track are worn, only one adjustment should be used. Corrugated track is a common problem. Mill scale on new rail can cause higher vibration levels until the rail has been in use for some time.</td></tr>
<tr><td>Special Trackwork</td><td colspan="3">+10 dB</td><td>Wheel impacts at special trackwork will significantly increase vibration levels. The increase will be less at greater distances from the track.</td></tr>
<tr><td>Jointed Track or Uneven Road Surfaces</td><td colspan="3">+5 dB</td><td>Jointed track can cause higher vibration levels than welded track. Rough roads or expansion joints are sources of increased vibration for rubber-tire transit.</td></tr>
<tr><td colspan="5">Track Treatments (not additive, apply greatest value only)</td></tr>
<tr><td>Floating Slab Trackbed</td><td colspan="3">-15 dB</td><td>The reduction achieved with a floating slab trackbed is strongly dependent on the frequency characteristics of the vibration.</td></tr>
<tr><td>Ballast Mats</td><td colspan="3">-10 dB</td><td>Actual reduction is strongly dependent on frequency of vibration.</td></tr>
<tr><td>High-Resilience Fasteners</td><td colspan="3">-5 dB</td><td>Slab track with track fasteners that are very compliant in the vertical direction can reduce vibration at frequencies greater than 40 Hz.</td></tr>
</table>

Table 10-1. Adjustment Factors for Generalized Predictions of Ground-Borne Vibration and Noise (Continued)

Factors Affecting Vibration Path		
Path Factor	**Adjustment to Propagation Curve**	**Comment**
Resiliently Supported Ties	-10 dB	Resiliently supported tie systems have been found to provide very effective control of low-frequency vibration.
Track Configuration (not additive, apply greatest value only)		
Type of Transit Structure	Relative to at-grade tie & ballast: Elevated structure -10 dB Open cut 0 dB	The general rule is the heavier the structure, the lower the vibration levels. Putting the track in cut may reduce the vibration levels slightly. Rock-based subways generate higher-frequency vibration.
	Relative to bored subway tunnel in soil: Station -5 dB Cut and cover -3 dB Rock-based - 15 dB	
Ground-borne Propagation Effects		
Geologic conditions that promote efficient vibration propagation	Efficient propagation in soil +10 dB	Refer to the text for guidance on identifying areas where efficient propagation is possible.
	Propagation in rock layer **Dist.** / **Adjust.** 50 ft +2 dB 100 ft +4 dB 150 ft +6 dB 200 ft +9 dB	The positive adjustment accounts for the lower attenuation of vibration in rock compared to soil. It is generally more difficult to excite vibrations in rock than in soil at the source.
Coupling to building foundation	Wood Frame Houses -5 dB 1-2 Story Masonry -7 dB 3-4 Story Masonry -10 dB Large Masonry on Piles -10 dB Large Masonry on Spread Footings -13 dB Foundation in Rock 0 dB	The general rule is the heavier the building construction, the greater the coupling loss.
Factors Affecting Vibration Receiver		
Receiver Factor	**Adjustment to Propagation Curve**	**Comment**
Floor-to-floor attenuation	1 to 5 floors above grade: -2 dB/floor 5 to 10 floors above grade: -1 dB/floor	This factor accounts for dispersion and attenuation of the vibration energy as it propagates through a building.
Amplification due to resonances of floors, walls, and ceilings	+6 dB	The actual amplification will vary greatly depending on the type of construction. The amplification is lower near the wall/floor and wall/ceiling intersections.
Conversion to Ground-borne Noise		
Noise Level in dBA	Peak frequency of ground vibration: Low frequency (<30 Hz): -50 dB Typical (peak 30 to 60 Hz): -35 dB High frequency (>60 Hz): -20 dB	Use these adjustments to estimate the A-weighted sound level given the average vibration velocity level of the room surfaces. See text for guidelines for selecting low, typical or high frequency characteristics. Use the high-frequency adjustment for subway tunnels in rock or if the dominant frequencies of the vibration spectrum are known to be 60 Hz or greater.

Without careful consideration of the shape of the actual vibration spectra, an inappropriate vibration control measure may be selected that could actually cause an increase in the vibration levels.

The following guidelines are used to select the appropriate adjustment factors. Note that the adjustments for wheel and rail condition are not cumulative. The general rule-of-thumb to use when more than one adjustment may apply is to apply only the largest adjustment. For example: the adjustment for jointed track is 5 decibels and the adjustment for wheel flats is 10 decibels. In an area where there is jointed track and many vehicles have wheel flats, the projected vibration levels should be increased by 10 decibels, not 15 decibels.

- **Train Speed:** The levels of ground-borne vibration and noise vary approximately as 20 times the logarithm of speed. This means that doubling train speed will increase the vibration levels approximately 6 decibels and halving train speed will reduce the levels by 6 decibels. Table 10-1 tabulates the adjustments for reference vehicle speeds of 30 mph for rubber-tired vehicles and 50 mph for steel-wheel vehicles. The following relationship should be used to calculate the adjustments for other speeds.

$$adjustment(dB) = 20 \times \log\left(\frac{speed}{speed_{ref}}\right)$$

- **Vehicle:** The most important factors for the vehicles are the suspension system, wheel condition, and wheel type. Most new heavy rail and light rail vehicles have relatively soft primary suspensions. However, experience in Atlanta, New York, and other cities has demonstrated that a stiff primary suspension (vertical resonance frequency greater than 15 Hz) can result in higher than normal levels of ground-borne vibration. Vehicles for which the primary suspension consists of a rubber or neoprene "donut" around the axle bearing usually have a very stiff primary suspension with a vertical resonance frequency greater than 40 Hz.

  Deteriorated wheel condition is another factor that will increase vibration levels. It can be assumed that a new system will have vehicles with wheels in good condition. However, when older vehicles will be used on new track, it may be appropriate to include an adjustment for wheel condition. The reference curves account for wheels without defects, but wheels with flats or corrugations can cause vibration levels that are 10 VdB higher than normal. Resilient wheels will reduce vibration levels at frequencies greater than the effective resonance frequency of the wheel. Because this resonance frequency is relatively high, often greater than 80 Hz, resilient wheels usually have only a marginal effect on ground-borne vibration.

  It is important to use only one of the adjustments in this category, the greatest one that applies.

- **Track System and Support:** This category includes the type of rail (welded, jointed or special trackwork), the track support system, and the condition of the rail. The base curves all assume good-condition welded rail. Jointed rail causes higher vibration levels than welded rail; the amount higher depends on the condition of the joints. The wheel impacts at special trackwork, such as frogs at crossovers, create much higher vibration forces than normal. Because of the higher vibration levels at special trackwork, crossovers often end up being the principal areas of vibration impact on new systems. Modifying the track support system is one method of mitigating the vibration impact. Special track support systems such as ballast mats, high-resilience track fasteners, resiliently supported ties, and floating slabs have all been shown to be effective in reducing vibration levels.

  The condition of the running surface of the rails can strongly affect vibration levels. Factors such as corrugations, general wear, or mill scale on new track can cause vibration levels that are 5 to 15 decibels higher than normal. Mill scale will usually wear off after some time in service; however, the track must be ground to remove corrugations or to reduce the roughness from wear.

  Again, apply only one of the adjustments.

  Roadway surfaces in the case of rubber-tired systems are assumed to be smooth. Rough washboard surfaces, bumps or uneven expansion joints are the types of running surface defects that cause increased vibration levels over the smooth road condition.

- **Transit Structure:** The weight and size of a transit structure affects the vibration radiated by that structure. The general rule-of-thumb is that vibration levels will be lower for heavier transit structures. Hence, the vibration levels from a cut-and-cover concrete double-box subway can be assumed to be lower than the vibration from a lightweight concrete-lined bored tunnel. The vibration from elevated structures is lower than from at-grade track because of the mass and damping of the structure and the extra distance that the vibration must travel before it reaches the receiver. Elevated structures in automated guideway transit applications sometimes are designed to bear on building elements. These are a special case and may require detailed design considerations.

- **Propagation Characteristics:** In the General Assessment it is necessary to make a selection among the general propagation characteristics. For a subway, the selection is a fairly straightforward choice of whether or not the subway will be founded in bedrock. Bedrock is considered to be hard rock. It is usually appropriate to consider soft siltstone and sandstone to be more similar to soil than hard rock. As seen in Table 10-1, whether the subway is founded in soil or rock can be a 15 VdB difference in the vibration levels.

  When considering at-grade vibration sources, the selection is between "normal" vibration propagation and "efficient" vibration propagation. Efficient vibration propagation results in approximately 10 decibels higher vibration levels. This more than doubles the potential impact zone for ground-borne vibration. One of the problems with identifying the cause of efficient propagation is the difficulty in determining whether higher than normal vibration levels are due to geologic conditions or due to special source conditions (e.g. rail corrugations or wheel flats).

  Although it is known that geologic conditions have a significant effect on the vibration levels, it is rarely possible to develop more than a broad-brush understanding of the vibration propagation characteristics for a General Assessment. The conservative approach would be to use the 10-decibel adjustment for efficient propagation to evaluate all potential vibration impact. The problem with this approach is that it tends to greatly overstate the potential for vibration impact. Hence, it is best to review available geological data and any complaint history from existing transit lines and major construction sites near the transit corridor to identify areas where efficient propagation is possible. If there is any reason to suspect efficient propagation conditions, then a Detailed Analysis during final design would include vibration propagation tests at the areas identified as potentially efficient propagation sites.

Some geologic conditions are repeatedly associated with efficient propagation. Shallow bedrock, less than 30 feet below the surface, is likely to have efficient propagation. Other factors that can be important are soil type and stiffness. In particular, stiff clayey soils have sometimes been associated with efficient vibration propagation. Investigation of soil boring records can be used to estimate depth to bedrock and the presence of problem soil conditions.

A factor that can be particularly complex to address is the effect of vibration propagation through rock. There are three factors from Table 10-1 that need to be included when a subway structure will be founded in rock. First is the -15 decibel adjustment in the "Type of Transit Structure" category. Second is the adjustment based on the propagation distance in the "Geologic Conditions" category. This positive adjustment is applied to the distances shown in Figure 10-1; the adjustment increases with distance because vibration attenuates more slowly in rock than in the soil used as a basis for the reference curve. The third factor is in the "Coupling to Building" category. When a building foundation is directly on the rock layer, there is no "coupling loss" due to the weight and stiffness of the building. Use the standard coupling factors if there is at least a 10-foot layer of soil between the building foundation and the rock layer.

- **Type of Building and Receiver Location in Building:** Since annoyance from ground-borne vibration and noise is an indoor phenomenon, the effects of the building structure on the vibration must be considered. Wood frame buildings, such as the typical residential structure, are more easily excited by ground vibration than heavier buildings. In contrast, large masonry buildings with spread footings have a low response to ground vibration.

  Vibration generally reduces in level as it propagates through a building. As indicated in Table 10-1, a 1- to 2-decibel attenuation per floor is usually assumed. Counteracting this, resonances of the building structure, particularly the floors, will cause some amplification of the vibration. Consequently, for a wood-frame structure, the building-related adjustments nearly cancel out. The adjustments for the first floor assuming a basement are: -5 decibels for the coupling loss; -2 decibels for the propagation from the basement to the first floor; and +6 decibels for the floor amplification. The total adjustment in this case is -1 decibel.

- **Vibration to Ground-Borne Noise Adjustment**: It is possible to estimate the levels of radiated noise given the average vibration amplitude of the room surfaces (floors, walls and ceiling), and the total acoustical absorption in the room. The unweighted sound pressure level is approximately equal to the vibration velocity level when the velocity level is referenced to 1×10^{-6} inches/second.

However, to estimate the A-weighted sound level from the velocity level, it is necessary to have some information about the frequency spectrum. The A-weighting adjustment drops rapidly at low frequencies, reflecting the relative insensitivity of human hearing to low frequencies. For example, A-weighting is -16 dB at 125 Hz, -26 dB at 60 Hz and -40 dB at 30 Hz. Table 10-1 provides adjustments for vibration depending on whether it has low-frequency, typical or high-frequency characteristics. Some general guidelines for classifying the frequency characteristics are:

- Low Frequency: Low-frequency vibration characteristics can be assumed for subways surrounded by cohesiveless sandy soil or whenever a vibration isolation track support system will be used. Low-frequency characteristics can be assumed for most surface track.
- Typical: The typical vibration characteristic is the default assumption for subways. It should be assumed for subways until there is information indicating that one of the other assumptions is appropriate. It should be used for surface track when the soil is very stiff with a high clay content.
- High Frequency: High-frequency characteristics should be assumed for subways whenever the transit structure is founded in rock or when there is very stiff clayey soil.

10.3 INVENTORY OF VIBRATION-IMPACTED LOCATIONS

This chapter includes generalized curves for surface vibration for different transit modes along with adjustments to apply for specific operating conditions and buildings. The projected levels are then compared with the criteria in Chapter 8 to determine whether vibration impact is likely. The results of the General Assessment are expressed in terms of an inventory of all sensitive land uses where either ground-borne vibration or ground-borne noise from the project may exceed the impact thresholds. The General Assessment may include a discussion of mitigation measures which would likely be needed to reduce vibration to acceptable levels.

The purpose of the procedure is to develop a reasonably complete inventory of the buildings that may experience ground-borne vibration or noise that exceed the impact criteria. At this point, it is preferable to make a conservative assessment of the impact. That is, it is better to include some buildings where ground-borne vibration may be below the impact threshold than to exclude buildings where it may exceed the impact threshold. The inventory should be organized according to the categories described in Chapter 8. For each building where the projected ground-borne vibration or noise exceeds the applicable impact threshold, one or more of the vibration control options from Section 11.5 should be considered for applicability. See Section 11.4 for a more complete description of how the General Vibration Assessment fits into the overall procedure.

REFERENCES

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2. International Organization for Standardization, “Mechanical vibration – Ground-borne noise and vibration arising from rail systems,” ISO/FDIS 14837-1:2005.

3. U.S. Department of Transportation, Volpe National Transportation Systems Center, “Vibration Characteristics of the Transrapid TR08 Maglev System,” Report No. DOT-VNTSC-FRA-02-06, March 2002.

11. DETAILED VIBRATION ANALYSIS

The goal of the Detailed Analysis is to use all available tools to develop accurate projections of potential ground-borne vibration impact and, when necessary, to design mitigation measures. This is appropriate when the General Assessment has indicated impact and the project has entered the final design and engineering phase. It may also be appropriate to perform a Detailed Analysis at the outset when there are particularly sensitive land uses within the screening distances. Detailed Analysis will require developing estimates of the frequency components of the vibration signal, usually in terms of 1/3-octave-band spectra. Analytical techniques for solving vibration problems are complex and the technology continually advances. Consequently, the approach presented in this chapter focuses on the key steps usually taken by a professional in the field.

Three examples of cases where a Detailed Vibration Analysis might be required are:

Example 1: A particularly sensitive building such as a major concert hall is within the impact zone. A Detailed Analysis would ensure that effective vibration mitigation is feasible and economically reasonable.

Example 2: The General Assessment indicates that a proposed commuter rail project has the potential to create vibration impact for a large number of residential buildings adjacent to the alignment. The projections for many of the buildings exceed the impact threshold by less than 5 decibels, which means that more accurate projections may show that vibration levels will be below the impact criterion. Detailed Analysis will refine the impact assessment and help determine whether mitigation is needed.

Example 3: A transit alignment will be close to university research buildings where vibration-sensitive optical instrumentation is used. Vibration from the trains could make it impossible to continue using the building for this type of research. A Detailed Analysis would determine if it is possible to control the vibration from the trains such that sensitive instrumentation will not be affected.

A Detailed Vibration Analysis consists of three parts:

1. **Survey Existing Vibration.** Although knowledge of the existing levels of ground-borne vibration is not usually required for the assessment of vibration impact, there are times when a survey of the existing vibration is valuable. Examples include documenting existing background vibration at sensitive buildings, measuring the vibration levels created by sources such as existing rail lines, and, in some cases, characterizing the general background vibration in the project corridor. Characterizing the existing vibration is discussed in Section 11.1.
2. **Predict Future Vibration and Vibration Impact.** All of the available tools should be applied in a Detailed Analysis to develop the best possible estimates of the potential for vibration impact. Section 11.2 discusses an approach to projecting ground-borne vibration that involves performing tests to characterize vibration propagation at sites where significant impact is probable. Section 11.3 describes the vibration propagation test procedure and Section 11.4 discusses the assessment of vibration impact.
3. **Develop Mitigation Measures.** Controlling the impact from ground-borne vibration requires developing cost-effective measures to reduce the vibration levels. The Detailed Analysis helps to select practical vibration control measures that will be effective at the dominant vibration frequencies and compatible with the given transit structure and track support system. Vibration mitigation measures are discussed in Section 11.5.

The discussion in this chapter generally assumes that detailed vibration analysis applies to a steel-wheel/ rail system. The procedures could be adapted to bus systems. However, this is rarely necessary because vibration problems are very infrequent with rubber-tired transit.

11.1 CHARACTERIZING EXISTING VIBRATION CONDITIONS

Environmental vibration is rarely of sufficient magnitude to be perceptible or cause audible ground-borne noise unless there is a specific vibration source close by, such as a rail line. In most cases, feelable vibration inside a building is caused by equipment or activities within the building itself, such as heating and ventilation systems, footsteps or doors closing. Because the existing environmental vibration is usually below human perception, a limited vibration survey is sufficient even for a Detailed Analysis. This contrasts with analysis of noise impact where documenting the existing ambient noise level is required to assess the impact.

Examples of situations where measurements of the ambient vibration are valuable include:

- **Determining existing vibration at sensitive buildings:** Serious vibration impact may occur when there are vibration-sensitive manufacturing, research, or laboratory activities within the screening distances. Careful documentation of the pre-existing vibration provides valuable information on the real sensitivity of the activity to external vibration and gives a reference condition under which vibration is not a problem.

- **Using existing vibration sources to characterize propagation:** Existing vibration sources such as freight trains, industrial processes, quarrying operations, or normal traffic sometimes can be used to characterize vibration propagation. Carefully designed and performed measurements may eliminate the need for more complex propagation tests.
- **Documenting existing levels of general background:** Some measurements of the existing levels of background vibration can be useful simply to document that, as expected, the vibration is below the normal threshold of human perception. Existing vibration in urban and suburban areas is usually due to traffic. If a measurement site has existing vibration approaching the range of human perception (e.g., the maximum vibration velocity levels are greater than about 65 VdB), then this site should be carefully evaluated for the possibility of efficient vibration propagation. Areas with efficient vibration propagation could have vibration problems when the project is built.
- **Documenting vibration from existing rail lines:** Measurements to document the levels of vibration created by existing rail lines can be important in evaluating the impact of the new vibration source and determining vibration propagation characteristics in the area. As discussed in Chapter 8, if vibration from an existing rail line will be higher than that from the proposed transit trains, there may not be impact even though the normal impact criterion would be exceeded.

Although ground-borne vibration is almost exclusively a problem inside buildings, measurements of existing ambient vibration generally should be performed outdoors. Two important reasons for this are: (1) equipment inside the building may cause more vibration than exterior sources, and (2) the building structure and the resonances of the building can have strong, but difficult to predict, effects on the vibration. However, there are some cases where measurements of indoor vibration are important. Documenting the vibration levels inside a vibration-sensitive building can be particularly important since equipment and activities inside the building sometimes cause vibration greater than that due to external sources such as street traffic or aircraft overflights. Floor vibration measurements are taken near the center of a floor span where the vibration amplitudes are the highest.

The goal of most ambient vibration tests is to characterize the root mean square (rms) vertical vibration velocity level at the ground surface. In almost all cases it is sufficient to measure only vertical vibration and ignore the transverse components of the vibration. Although transverse components can transmit significant vibration energy into a building, the vertical component usually has greater amplitudes than transverse vibration. Moreover, vertical vibration is usually transmitted more efficiently into building foundations than transverse vibration.

The manner in which a transducer is mounted can affect the measured levels of ground-borne vibration. However, at the frequencies usually of concern for ground-borne vibration (less than about 200 Hz), straightforward methods of mounting transducers on the ground surface or on pavement are adequate for vertical vibration measurements. Quick-drying epoxy or beeswax is often used to mount transducers to smooth paved surfaces or to metal stakes driven into the ground. Rough concrete or rock surfaces require special mountings. One approach is to use a liberal base of epoxy to attach small aluminum blocks to the surface and then mount the transducers on the aluminum blocks.

Selecting sites for an ambient vibration survey requires good common sense. Sites selected to characterize a transit corridor should be distributed along the entire project and should be representative of the types of vibration environments found in the corridor. This would commonly include:

- measurements in quiet residential areas removed from major traffic arterials to characterize low-ambient vibrations;
- measurements along major traffic arterials and highways or freeways to characterize high-vibration areas;
- measurements in any area with vibration-sensitive activities; and
- measurements at any significant existing source of vibration such as railroad lines.

The transducers should be located near the building setback line for background vibration measurements. Ambient measurements along railroad lines ideally will include: multiple sites; several distances from the rail line at each site; and 4 to 10 train passbys for each test. Because of the irregular schedule for freight trains and the low number of operations each day, it is often impractical to perform tests at more than two or three sites along the rail line or to measure more than two or three passbys at each site. Rail type and condition strongly affect the vibration levels. Consequently, it is important to inspect the track at each measurement site to locate any switches, bad rail joints, corrugations, or other factors that could be responsible for higher than normal vibration levels.

The appropriate methods of characterizing ambient vibration are dependent on the type of information required for the analysis. Following are some examples:

- **Ambient Vibration:** Ambient vibration is usually characterized with a continuous 10- to 30-minute measurement of vibration. The L_{eq} of the vibration velocity level over the measurement period gives an indication of the average vibration energy. L_{eq} is equivalent to a long averaging time rms level. Specific events can be characterized by the maximum rms level (L_{max}) of the event or by performing a statistical analysis of rms levels over the measurement period. An rms averaging time of 1 second should be used for statistical analysis of the vibration level.
- **Specific Events:** Specific events such as train passbys should be characterized by the rms level during the time that the train passes by. If the locomotives have vibration levels more than 5 dB higher than the passenger or freight cars, a separate rms level for the locomotives should be obtained. The locomotives can usually be characterized by the L_{max} during the train passby. The rms averaging time or time constant should be 1 second when determining L_{max}. Sometimes it is adequate to use L_{max} to characterize the train passby, which is simpler to obtain than the rms averaged over the entire train passby.
- **Spectral Analysis:** When the vibration data will be used to characterize vibration propagation or for other special analysis, a spectral analysis of the vibration is required. An example would be if

vibration transmission of the ground is suspected of having particular frequency characteristics. For many analyses, 1/3-octave band charts are best for describing vibration behavior. Narrowband spectra also can be valuable, particularly for identifying pure tones and designing specific mitigation measures.

Note that it is preferable that ambient vibration be characterized in terms of the root mean square (rms) velocity level, not the peak particle velocity (ppv) as is commonly used to monitor construction vibration. As discussed in Chapter 7, rms velocity is considered more appropriate than ppv for describing human response to building vibration.

11.2 VIBRATION PREDICTION PROCEDURE

Predicting ground-borne vibration associated with a transportation project continues to be a developing field. Because ground-borne vibration is a complex phenomenon that is difficult to model and predict accurately, most projection procedures that have been used for transit projects rely on empirical data. The procedure described in this section is based on site-specific tests of vibration propagation. Developed under an FTA-funded research contract,[(1)] this procedure is recommended for detailed evaluations of ground-borne vibration. There have been other approaches to a prediction procedure including some that use pure numerical methods. For example, approaches using finite elements are being used to estimate ground-borne vibration from subway tunnels, but most numerical approaches are still in the early stages of development.

11.2.1 Overview of Prediction Procedure

The prediction method described in this section was developed to allow the use of data collected in one location to accurately predict vibration levels in another site where the geologic conditions may be completely different. The procedure is based on using a special measured function, called *transfer mobility*. Transfer mobility measured at an existing transit system is used to normalize ground-borne vibration data and remove the effects of geology. The normalized vibration is referred to as the force density. The force density can be combined with transfer mobility measurements at sensitive sites along a new project to develop projections of future ground-borne vibration.

Transfer mobility represents the relationship between a vibration source that excites the ground and the resulting vibration of the ground surface. It is a function of both frequency and distance from the source. The transfer mobility between two points completely defines the composite vibration propagation characteristics between the two points. In most practical cases, receivers are close enough to the train tracks that the vibration cannot be considered to be originating from a single point. The vibration source must be modeled as a line-source. Consequently, the point transfer mobility must be modified to account for a line-source. In the following text, TM_{point} is used to indicate the measured point-source transfer mobility and TM_{line} is used for the line-source transfer mobility derived from TM_{point}.

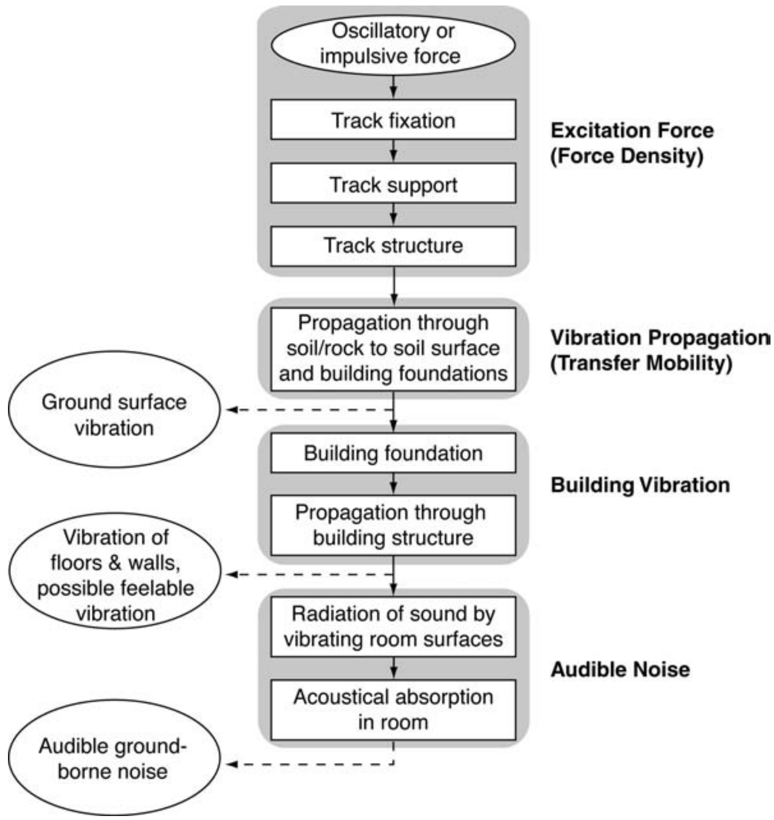

Figure 11-1. Block Diagram of Ground-Borne Vibration and Noise Model

The prediction procedure considers ground-borne vibration to be divided into several basic components as shown schematically in Figure 11-1. The components are:

1. **Excitation Force.** The vibration energy is created by oscillatory and impulsive forces. Steel wheels rolling on smooth steel rails create random oscillatory forces. When a wheel encounters a discontinuity such as a rail joint, an impulsive force is created. The force excites the transit structure, such as the subway tunnel, or the ballast for at-grade track. In the prediction method, the combination of the actual force generated at the wheel/rail interface and the vibration of the transit structure are usually combined into an equivalent force density level. The force density level describes the force that excites the soil/rock surrounding the transit structure.

2. **Vibration Propagation.** The vibration of the transit structure causes vibration waves in the soil that propagate away from the transit structure. The vibration energy can propagate through the soil or rock in a variety of wave forms. All ground vibration includes shear and compression waves. In addition, Rayleigh waves, which propagate along the ground surface, can be a major carrier of vibration energy. The mathematical modeling of vibration is complicated when, as is usually the case, there are soil strata with different elastic properties. As indicated in Figure 11-1, the

propagation through the soil/rock is modeled using the transfer mobility, which is usually determined experimentally.

The combination of the force density level and the transfer mobility is used to predict the ground-surface vibration. Here is the essential difference between the General and Detailed approaches: the projection process is simplified in a General Assessment by going directly to generalized estimates of the ground-surface vibration.

3. **Building Vibration.** When the ground vibration excites a building foundation, it sets the building into vibration motion and starts vibration waves propagating throughout the building structure. The interaction between the ground and the foundation causes some reduction in vibration levels. The amount of reduction is dependent on the mass and stiffness of the foundation. The more massive the foundation, the lower the response to ground vibration. As the vibration waves propagate through the building, they can create feelable vibration and can cause annoying rattling of windows and decorative items either hanging or on shelves.

4. **Audible Noise.** In addition to feelable vibration, the vibration of room surfaces radiates low-frequency sound that may be audible. As indicated in Figure 11-1, the sound level is affected by the amount of acoustical absorption in the receiver room.

A fundamental assumption of the prediction approach outlined here is that the force density, transfer mobility, and the building coupling to the ground are all independent factors. The following equations are the basis for the prediction procedure where all of the quantities are one-third octave band spectral levels in decibels with consistent reference values:

$$L_v = L_F + TM_{line} + C_{build}$$

$$L_A = L_v + K_{rad} + K_{A\text{-}wt}$$

where:

L_v = rms vibration velocity level,

L_A = A-weighted sound level,

L_F = force density for a line vibration source such as a train,

TM_{line} = line-source transfer mobility from the tracks to the sensitive site,

C_{build} = adjustments to account for ground–building foundation interaction and attenuation of vibration amplitudes as vibration propagates through buildings,

K_{rad} = adjustment to account for conversion from vibration to sound pressure level including accounting for the amount of acoustical absorption inside the room (A value of zero can be used for K_{rad} for typical residential rooms when the decibel reference value for L_v is 1 micro in./sec.[(1)]),

$K_{A\text{-}wt}$ = A-weighting adjustment at the 1/3-octave band center frequency.

All of the quantities given above are functions of frequency. The standard approach to dealing with the frequency dependence is to develop projections on a 1/3-octave band basis using the average values for each 1/3-octave band. The end results of the analysis are the 1/3-octave band spectra of the ground-borne vibration and the ground-borne noise. The spectra are then applied to the vibration criteria for Detailed Analysis. The A-weighted ground-borne noise level can be calculated from the vibration spectrum. This more detailed approach is in contrast to the General Assessment where the overall vibration velocity level and A-weighted sound level are predicted without any consideration of the particular frequency characteristics of the propagation path.

11.2.2 Major Steps in Detailed Analysis

The major steps in performing a Detailed Analysis are intended to obtain quantities for the equations given above. These are:

1. Develop estimates of the force density. The estimate of force density can be based on previous measurements or a special test program can be designed to measure the force density at an existing facility. If no suitable measurements are available, testing should be done at a transit facility with equipment similar to the planned vehicles. Adjustments for factors such as train speed, track support system, and vehicle suspension may be needed to match the force density to the conditions at a specific site. Some appropriate adjustments can be found in the report "State-of- the-Art Review: Prediction and Control of Ground-Borne Noise and Vibration from Rail Transit Trains."(2)
2. Measure the point-source transfer mobility at representative sites. The transfer mobility is a function of both frequency and distance from the source. Point-source transfer mobility is used for sources with short lengths, such as single vehicles or columns supporting elevated structures.
3. Use numerical integration to estimate a line-source transfer mobility from the point-source transfer mobilities. Line-source transfer mobility is applicable to long sources like trains.
4. Combine force density and line-source transfer mobility to project ground-surface vibration.
5. Add adjustment factors to estimate the building response to the ground-surface vibration and to estimate the A-weighted sound level inside buildings.

The two key elements of the transfer mobility procedure are a measured force function that represents the vibration energy put into the ground and a measured transfer mobility that characterizes the propagation of the vibration from the source to the receiver. The unit of force density is force divided by square root of train length, represented here in decibels relative to 1 $lb/(ft)^{1/2}$. The force density represents an incoherent line of vibration force equal to the length of transit trains. The process of estimating force density from train vibration and transfer mobility tests is discussed in Section 11.3. Figure 11-2 shows some trackbed force densities that have been developed from measurements of vibration from heavy and light rail transit vehicles. This figure provides a comparison of the vibration forces from heavy commuter trains and light rail transit vehicles with different types of primary suspensions illustrating the range of vibration forces commonly experienced in a transit system. A force density of a vehicle includes the characteristics of its track support system at the measurement site. Adjustments must be made to the force density to account for differences between the facility where the force density was measured and the new system being analyzed.

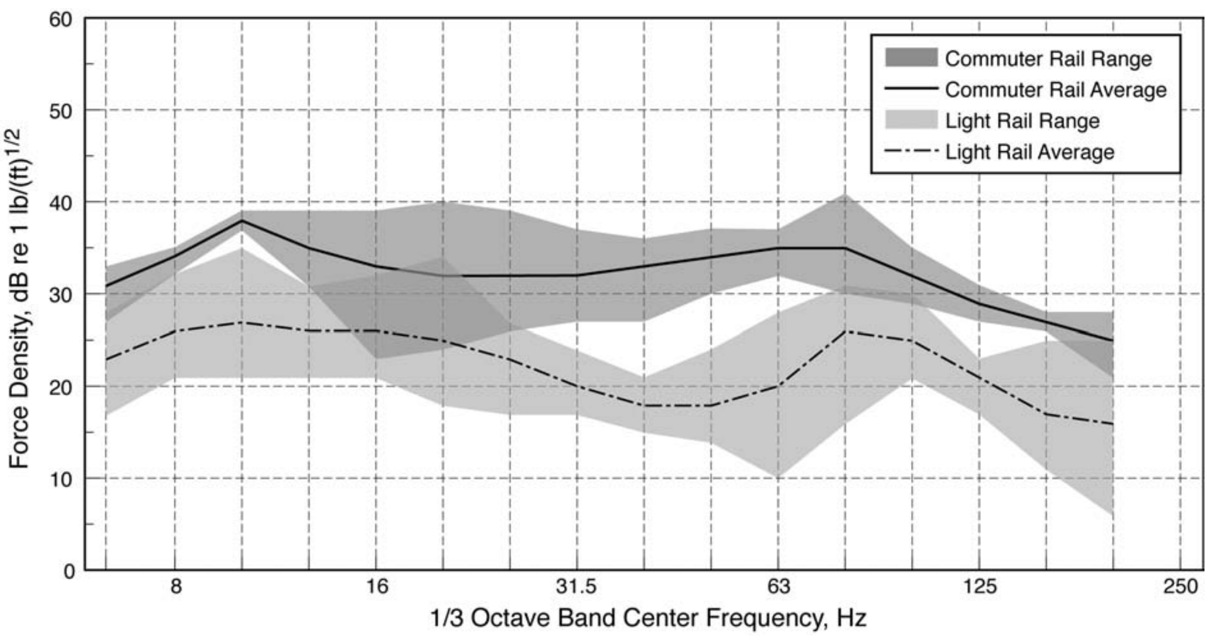

Figure 11-2. Typical Force Densities for Rail Transit Vehicles, 40 mph

The key elements of the vibration prediction procedure are implementation of field tests to measure the transfer mobility and the subsequent use of transfer mobility to characterize vibration propagation. The process of measuring transfer mobility involves impacting the ground and measuring the resulting vibration pulse at various distances from the impact. Standard signal-processing techniques are used to determine the transfer function, or frequency response function, between the exciting force and the resultant ground-surface vibration. Numerical regression methods are used to combine a number of two-point transfer functions into a smooth point-source transfer mobility that represents the average vibration propagation characteristics of a site as a function of both distance from the source and frequency. The transfer mobility is usually expressed in terms of a group of 1/3-octave band transfer mobilities. This processing is performed after transferring the data to a computer. Figure 11-3 shows the point-source transfer mobilities from a series of tests at the Transportation Technology Center in Pueblo, Colorado.(3,4,5,6)

Once the point-source transfer mobility has been defined, the line-source transfer mobility can be calculated using numerical integration techniques. This process has been described in a Transportation Research Board paper. (1) Figure 11-4 shows the line-source transfer mobilities that were derived from the point-source transfer mobilities shown in Figure 11-3. The line-source transfer mobilities are used to normalize measured vibration velocity levels from train passbys and to obtain force density.

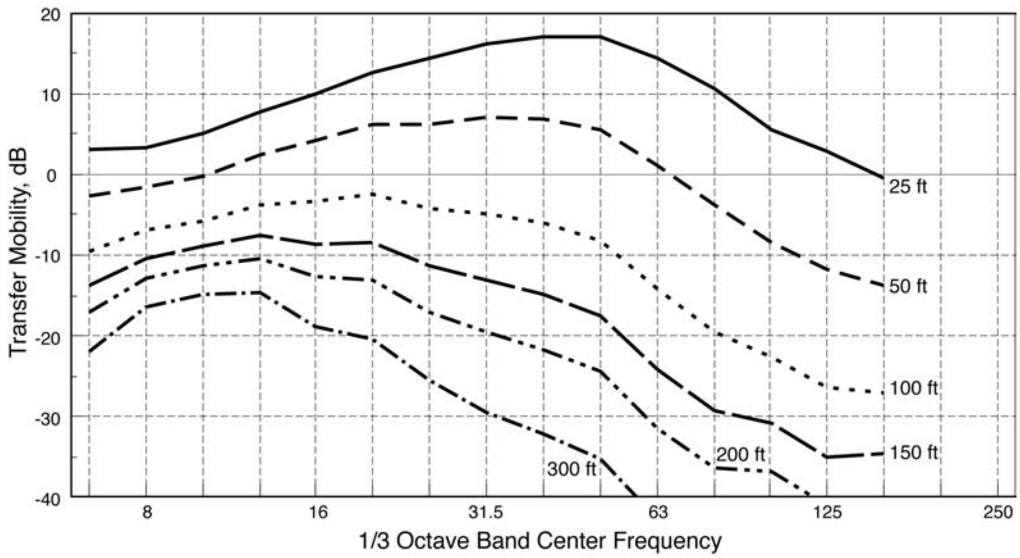

Figure 11-3. Example of Point-Source Transfer Mobility

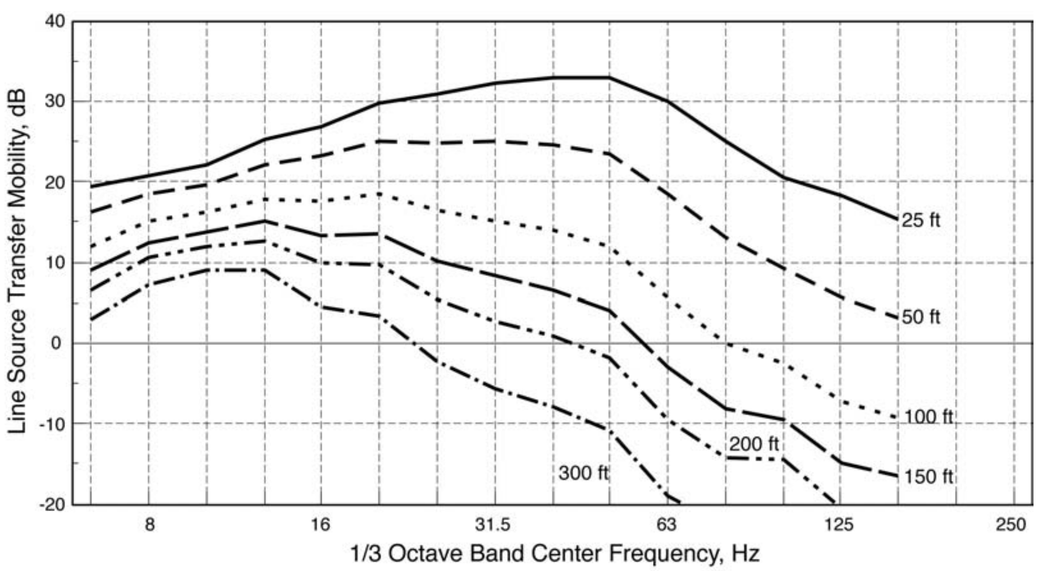

Figure 11-4. Example of Line-Source Transfer Mobility

The propagation of vibration from the building foundation to the receiver room is a very complex problem dependent on the specific design of the building. Detailed evaluation of the vibration propagation would require extensive use of numerical procedures such as the finite element method. Such a detailed evaluation is generally not practical for individual buildings considered in this manual. The propagation of vibration through a building and the radiation of sound by vibrating building surfaces is consequently estimated using simple empirical or theoretical models. The recommended procedures are outlined in the *Handbook of Urban Rail Noise and Vibration Control*.[7] The approach consists of adding the following adjustments to the 1/3-octave band spectrum of the projected ground-surface vibration:

1. **Building response or coupling loss.** This represents the change in the incident ground-surface vibration due to the presence of the building foundation. The adjustments in the *Handbook*, are shown in Figure 11-5. Note that the correction is zero when estimating basement floor vibration or vibration of at-grade slabs. Measured values may be used in place of these generic adjustments.

2. **Transmission through the building.** The vibration amplitude typically decreases as the vibration energy propagates from the foundation through the remainder of the building. The normal assumption is that vibration attenuates by 1 to 2 dB for each floor.

3. **Floor resonances.** Vibration amplitudes will be amplified because of resonances of the floor/ceiling systems. For a typical wood-frame residential structure, the fundamental resonance is usually in the 15- to 20-Hz range. Reinforced-concrete slab floors in modern buildings will have fundamental resonance frequencies in the 20- to 30- Hz range. An amplification resulting in a gain of approximately 6 dB should be used in the frequency range of the fundamental resonance.

   The projected floor vibration is used to estimate the levels of ground-borne noise. The primary factors affecting noise level are the average vibration level of the room surfaces and the amount of acoustical absorption within the room. As discussed above, the radiation adjustment is zero for typical rooms, which gives:

$$L_A \approx L_v + K_{A-wt}$$

   where L_A is the A-weighted sound level in a 1/3-octave band, L_v is the vibration velocity level in that band, and K_{A-wt} is the A-weighting adjustment at the center frequency of the 1/3-octave band. The A-weighted levels in the 1/3-octave bands are then combined to give the overall A-weighted sound level.

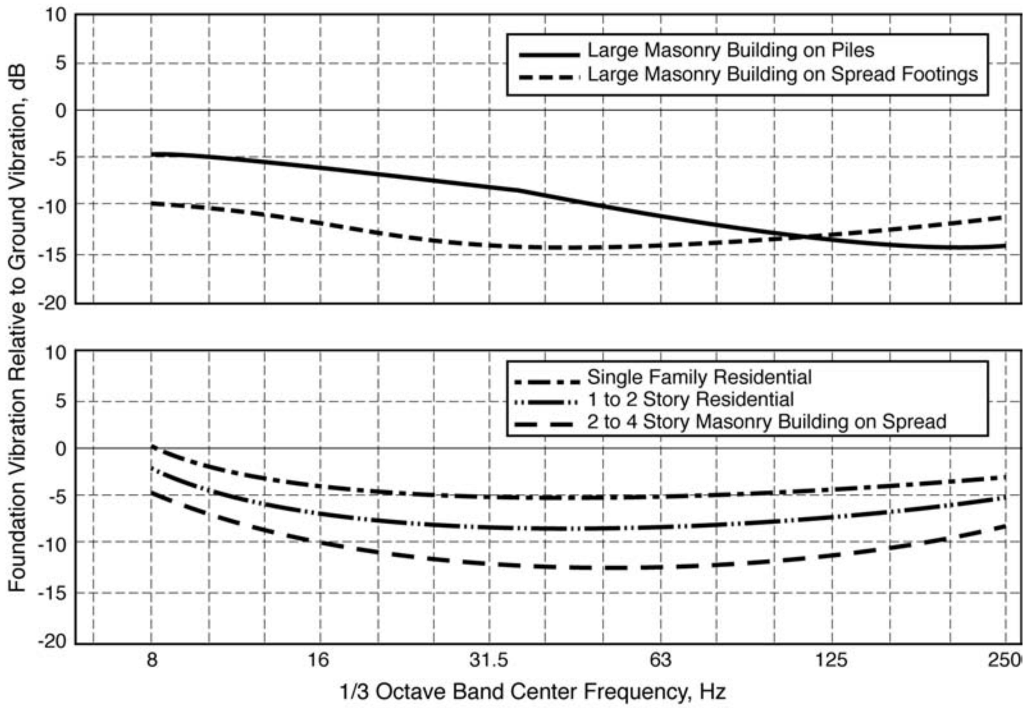

Figure 11-5. Foundation Response for Various Types of Buildings

11.3 MEASURING TRANSFER MOBILITY AND FORCE DENSITY

The test procedure to measure transfer mobility basically consists of dropping a heavy weight on the ground and measuring the force into the ground and the response at several distances from the impact. The goal of the test is to create vibration pulses that travel from the source to the receiver using the same path that will be taken by the transit system vibration. The transfer mobility expresses the relationship between the input force and the ground-surface vibration.

Figure 11-6 illustrates the field procedure for at-grade and subway testing of transfer mobility. A weight is dropped from a distance of 3 to 4 feet onto a force transducer. The responses of the force and vibration transducers are recorded on a multichannel tape recorder for later analysis in the laboratory. An alternative approach is to set up the analysis equipment in the field and capture the signals directly. This complicates the field testing but eliminates the laboratory analysis of tape-recorded data.

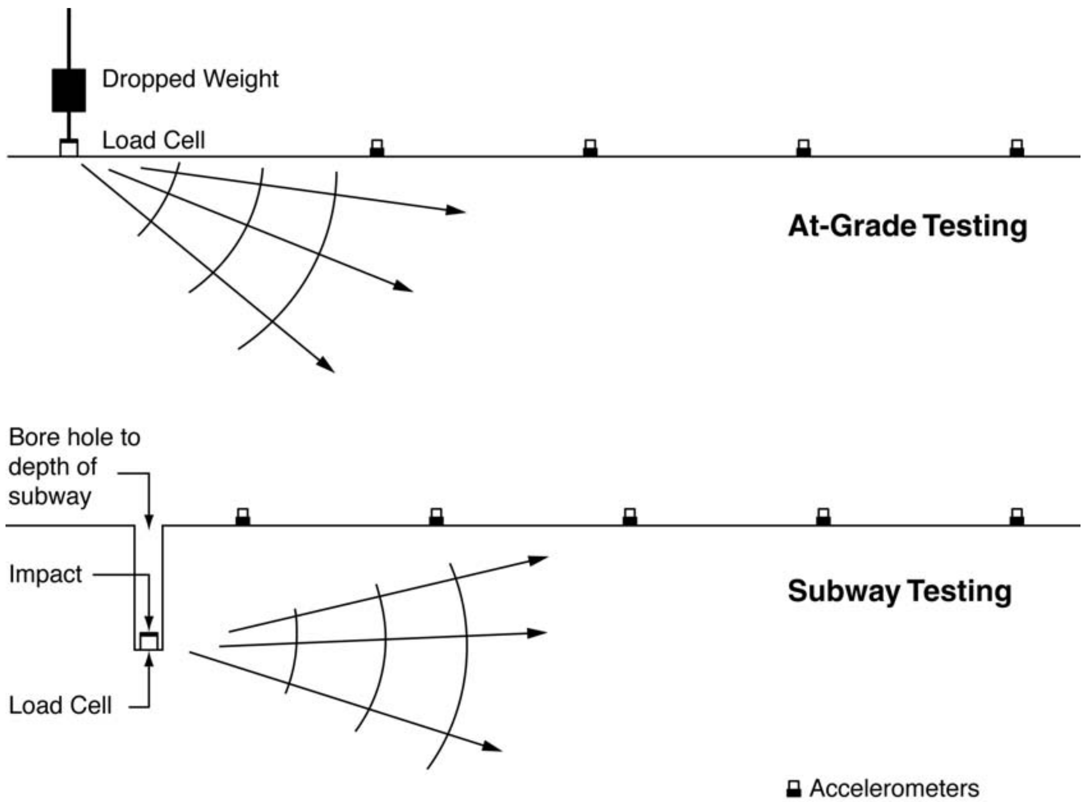

Figure 11-6. Test Configuration for Measuring Transfer Mobility

When the procedure is applied to subways, the force must be located at the approximate depth of the subway. This is done by drilling a bore hole and locating the force transducer at the bottom of the hole. The tests are usually performed at the same time that the bore holes are drilled. This allows using the soil-sampling equipment on the drill rig for the transfer mobility testing. The force transducer is attached to the bottom of the drill string and lowered to the bottom of the hole. A standard soil sampling hammer, which is usually a 140-pound weight dropped 18 inches onto a collar attached to the drill string, is used to excite the ground. The force transducer must be capable of operating under water if the water table is near the surface or a slurry drilling process is used.

11.3.1 Instrumentation

Performing a transfer mobility test requires specialized equipment. Most of the equipment is readily available from commercial sources. A load cell can be used as the force transducer. The force transducer should be capable of impact loads of 5,000 to 10,000 pounds. For borehole testing, the load cell must be hermetically sealed and capable of being used at the bottom of a 30- to 100-foot-deep hole partially filled with water. Typical instrumentation for the field-testing and laboratory analysis of transfer mobility is shown in Figure 11-7. Either accelerometers or geophones can be used as the vibration transducers. The

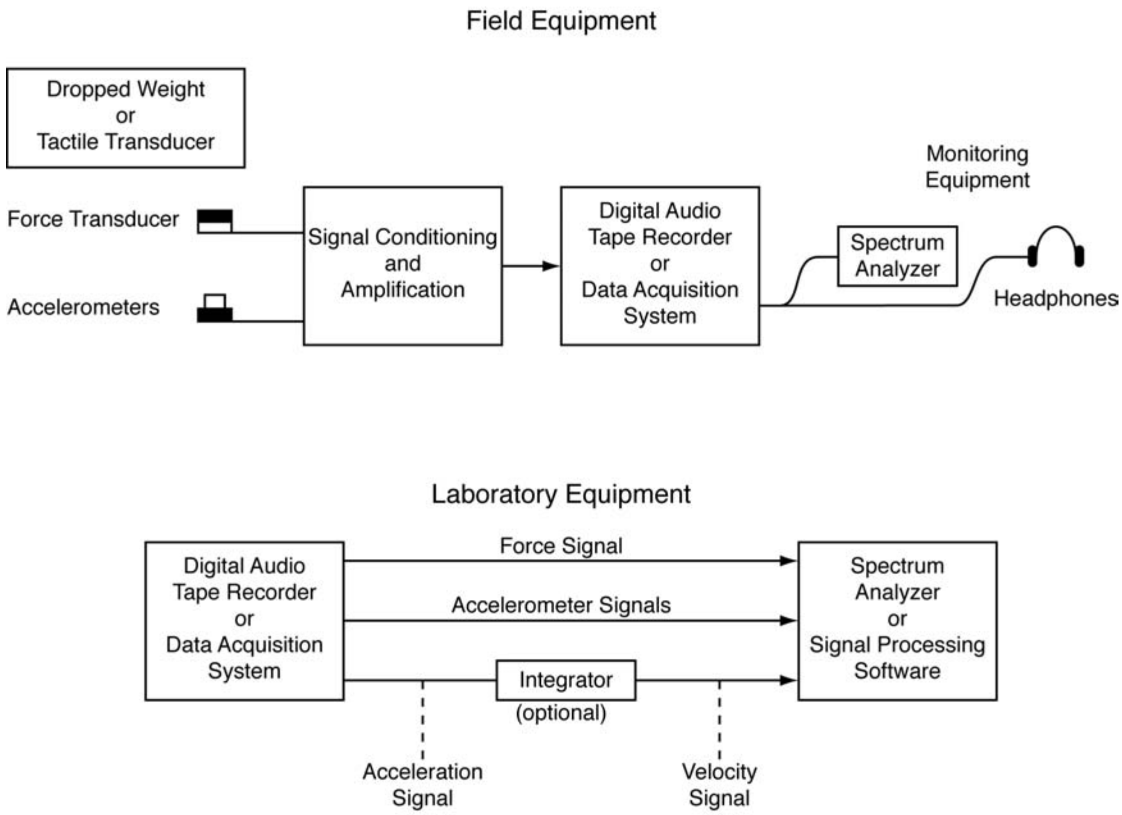

Figure 11-7. Equipment Required for Field Testing and Laboratory Analysis

requirement is that the transducers with the associated amplifiers be capable of accurately measuring levels of 0.0001 in./sec at 40 Hz and have a flat frequency response from 6 Hz to 400 Hz. Data must be acquired (either with digital audio tape or an alternative digital acquisition system) with a flat frequency response over the range of 6 to 400 Hz.

A narrowband spectrum analyzer or signal-processing software can be used to calculate the transfer function and coherence between the force and vibration data. The analyzer must be capable of capturing impulses from at least two channels to calculate the frequency spectrum of the transfer function between the force and vibration channels. All transfer functions should include the average of at least 20 impulses. The averaging of the impulses will provide significant signal enhancement, which is usually required to accurately characterize the transfer function. Signal enhancement is particularly important when the vibration transducer is more than 100 feet from the impact.

Transfer mobility may also be measured using other methods. One such method involves producing maximum-length sequence (MLS) force impulses with a tactile transducer. Signal-processing software is then used to calculate the transfer function from the MLS forces and measured vibrations. The MLS measurement method uses a pseudo-random binary sequence as the signal and has the advantage of increasing the signal-to-noise ratio of the measurement.

The laboratory equipment in Figure 11-7 shows using either a spectrum analyzer or signal-processing software to calculate the transfer function. Specialized multi-channel spectrum analyzers have built-in capabilities for computing transfer functions. The use of a spectrum analyzer has the advantage of being computationally efficient. On the other hand, signal-processing software can offer more flexibility in analyzing data signals and allows the use of different digital signal processing methods such as the MLS. Typical measurement programs involve acquisition of data in the field and later processing of the information in a laboratory. However, recent advances in instrumentation and signal-processing software allow data to be collected and analyzed while in the field.

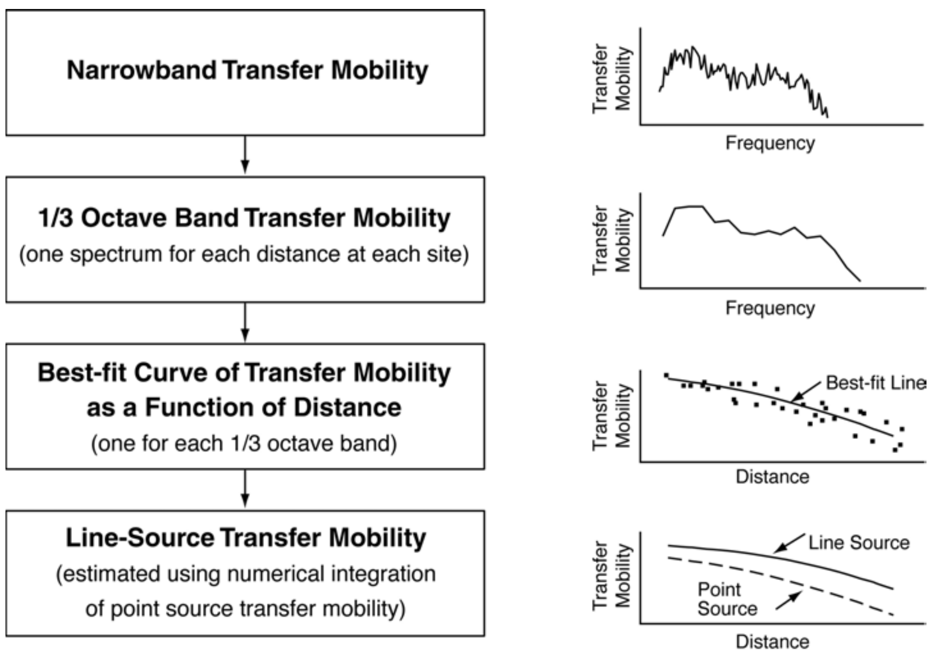

Figure 11-8. Analysis of Transfer Mobility

11.3.2 Analysis of Transfer Mobility Data

Two different approaches have been used to develop estimates of line-source transfer mobility. The first consists of using lines of transducers and the second consists of a line of impact positions. The steps to develop line-source transfer mobility curves from tests using one or more lines of transducers are shown in Figure 11-8. The procedure starts with the narrowband transfer function between source and receiver at each measurement position. There should be a minimum of four distances in any test line. Because of the possibility of local variations in propagation characteristics, if at all possible, two or more lines should be used to characterize a site. A total of 10 to 20 transducer positions are often used to characterize a site.

The first step in the analysis procedure is to calculate the equivalent 1/3-octave band transfer functions. This reduces each spectrum to 15 numbers. As shown in Figure 11-8, the 1/3-octave band spectrum is much smoother than the narrowband spectrum. The next step is to calculate a best-fit curve of transfer mobility as a function of distance for each 1/3-octave band. When analyzing a specific site, the best-fit curve will be based on 10 to 20 points. Up to several hundred points could be used to determine average best-fit curves for a number of sites.

The 1/3-octave band best-fit curves can be directly applied to point vibration sources. Buses can usually be considered to be point-sources, as can columns supporting elevated structures. However, for a line vibration source such as a train, numerical integration must be used to calculate an equivalent line-source transfer mobility. The numerical integration procedures are detailed in Reference 1.

The second procedure for estimating line-source transfer mobility, shown schematically in Figure 11-9, is best for detailed assessment of specific vibration paths or specific buildings. The vibration transducers are located at specific points of interest and a line of impacts is used. For example, a 165-foot train might be represented by a line of 11 impact positions along the track centerline at 15-foot intervals. It is possible to sum the point-source results using Simpson's rule for numerical integration to directly calculate line-source transfer mobility. This is a considerably more direct approach than is possible with lines of vibration transducers.

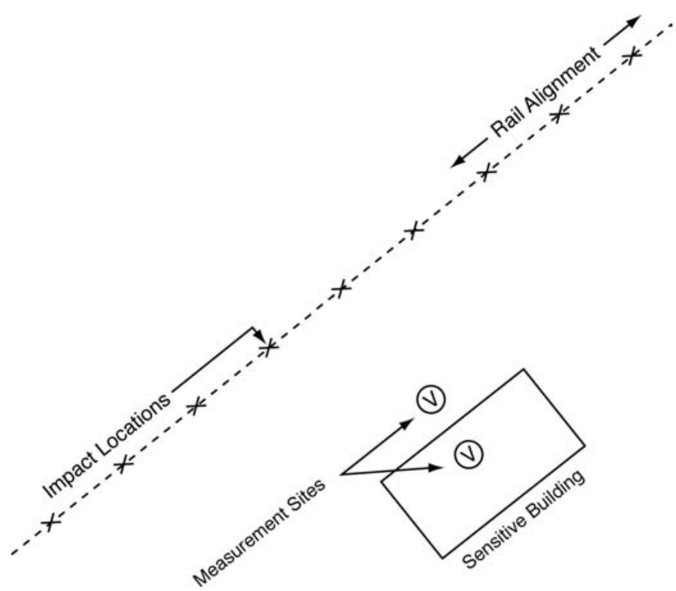

Figure 11-9. Schematic of Transfer Mobility Measurements Using a Line of Impacts

11.3.3 Deriving Force Density

Force Density is not a quantity that can be measured directly; it must be inferred from measurements of transfer mobility and train vibration at the same site. For deriving force density, the best results are achieved by deriving line-source transfer mobility from a line of impacts. The force density for each 1/3-octave band is then simply:

$$L_F = L_v - TM_{line}$$

where L_F is the force density, L_v is measured train ground-borne vibration, and TM_{line} is the line-source transfer mobility. The standard approach is to use the average force density from measurements at three or more positions.

11.4 ASSESSMENT OF VIBRATION IMPACT

The goals of the vibration assessment are to inventory all sensitive land uses that may be adversely impacted by the ground-borne vibration and noise from the proposed project and to determine the mitigation measures that will be required to eliminate or minimize the impact. This requires projecting the levels of ground-borne vibration and noise, comparing the projections with the impact criteria, and developing a list of suitable mitigation measures. Note that the General Assessment is incorporated as an intermediate step in the impact assessment because of its relative simplicity and potential to narrow the areas where Detailed Analysis needs to be done.

The assessment of vibration impact should proceed according to the following steps:

1. Screen the entire proposed transit alignment to identify areas where there is the potential of impact from ground-borne vibration. The vibration screening procedure is described in Chapter 9. If no sensitive land uses are within the screening distances, it is not necessary to perform any further assessment of ground-borne vibration.
2. Define the curves of ground-surface vibration level as a function of distance that can be used with the General Assessment. Usually this will mean selecting the appropriate curve from Chapter 10 for the proposed transit mode. For less common transit modes, it may be necessary to make measurements at an existing facility.
3. Use the General Assessment procedure to estimate vibration levels for specific buildings or groups of buildings. The projected levels are compared with the impact criteria for General Vibration Assessment (Tables 8-1 and 8-2) to determine whether vibration impact is likely. The goal of this step is to develop a reasonably accurate catalog of the buildings that will experience ground-borne vibration or noise levels that exceed the criteria. Applying the impact criteria for the General Assessment will result in a conservative assessment of the impact. That is, it is possible that some buildings that are identified as impacted may not be impacted under a more detailed analysis. However, at this stage it is better to include some buildings that may not be impacted than to

exclude some buildings that are likely to be impacted. In locations where the General Assessment indicates impact, the more refined techniques of Detailed Analysis would be employed.

4. In some cases it will be necessary to perform a vibration survey to characterize existing ambient vibration. As discussed in Section 11.1, although knowledge of the existing ambient vibration is not generally required to evaluate vibration impact, there are times when a survey of existing conditions is valuable. One common example is when a rail transit project will be located in an existing railroad right-of-way shared by freight trains. Chapter 8 includes some guidelines on how to account for existing vibration that is higher than the impact limit for the project vibration.

5. For areas where the General Assessment impact criteria are exceeded, review potential mitigation measures and assemble a list of feasible approaches to vibration control. To be feasible, the measure, or combination of measures, must be capable of providing a significant reduction of the vibration levels, at least 5 dB, while being reasonable from the standpoint of the added cost. The impact assessment and review of mitigation measures are preliminary at this point because vibration control is frequency-dependent, and specific recommendations of vibration control measures can be made only after evaluating the frequency characteristics of the vibration.

6. Use the Detailed Vibration Analysis to refine the impact assessment and to develop detailed vibration mitigation measures where needed. It is usually necessary to project vibration spectra at buildings which will be affected at levels higher than the impact thresholds (refer to Section 8.2). This type of assessment is normally performed as part of final design rather than during the environmental impact assessment stage. Because a Detailed Analysis is more accurate than a General Assessment, there will be times that the Detailed Analysis will show that the ground-borne vibration and noise levels will be below the applicable criteria and that mitigation is not required. If the projected levels are still above the limits, the spectra provided by the Detailed Analysis will be needed to evaluate vibration control approaches.

11.5 VIBRATION MITIGATION

The purpose of vibration mitigation is to minimize the adverse effects that the project ground-borne vibration will have on sensitive land uses. Because ground-borne vibration is not as common a problem as environmental noise, the mitigation approaches have not been as well defined. In some cases it has been necessary to develop innovative approaches to control the impact. Among the successful examples are the floating-slab systems that were developed for the San Francisco and Toronto rapid transit systems. However, the vibration control measures developed for rail transit systems are not effective for freight trains. The heavy axle loads associated with freight rail are outside the range of applicable design parameters for vibration reduction on lighter rail transit systems. Consequently the discussion in this section pertains to rail transit systems, not freight railroads. Any plan to relocate existing railroad tracks closer to vibration-sensitive sites in order to accommodate a new rail transit line in the right-of-way must be carefully considered since the increased vibration impact from freight trains will have to be borne by the community.

Although the focus is on rail systems in this section, there are very infrequent problems caused by buses and in these instances, the solution is rather straightforward. When buses do cause annoying ground-borne vibration, it is usually clear that the source of the problem is roadway roughness or unevenness caused by bumps, pot holes, expansion joints, or driveway transitions. Smoothing the roadway surface will usually solve the problem. In cases where a rubber-tired system runs inside a building, such as an airport people mover, vibration control may involve additional measures besides ensuring a smooth guideway. Loading and unloading of guideway support beams may generate dynamic forces that transmit into the building structure. Special guideway support systems may be required, similar to the discussion below regarding floating slabs.

The importance of adequate wheel and rail maintenance in controlling levels of ground-borne vibration cannot be overemphasized. Problems with rough wheels or rails can increase vibration levels by as much as 20 dB in extreme cases, negating the effects of even the most effective vibration control measures. It is rare that practical vibration control measures will provide more than 15 to 20 dB attenuation. When there are ground-borne vibration problems with existing transit equipment, the best vibration control measure often is to implement new or improved maintenance procedures. Grinding rough or corrugated rail and wheel truing to eliminate wheel flats and restore the wheel contour may provide more vibration reduction than would be obtainable from completely replacing the existing track system with floating slabs.

Given that the track and vehicles are in good condition, the options for further reductions in the vibration levels fit into one of seven categories: (1) maintenance procedures, (2) location and design of special trackwork, (3) vehicle modifications, (4) changes in the track support system, (5) building modifications, (6) adjustments to the vibration transmission path, and (7) operational changes.

Vibration reduction measures incur additional costs to a system. Some of the same treatments for noise mitigation can be considered for vibration mitigation. Costs for noise control measures are documented in a report from the Transit Cooperative Research Program (TCRP).[8] Where applicable to vibration reduction, costs for noise abatement methods from that report are given in the following discussion.

- **Maintenance:** As discussed above, effective maintenance programs are essential for controlling ground-borne vibration. When the wheel and rail surfaces are allowed to degrade the vibration levels can increase by as much as 20 dB compared to a new or well-maintained system. Some maintenance procedures that are particularly effective at avoiding increases in ground-borne vibration are:

    - Rail grinding on a regular basis. Rail grinding is particularly important for rail that develops corrugations. The TCRP report notes that periodic rail grinding actually results in a net savings per year on wheel and rail wear. Most transit systems contract out rail grinding, although some of the larger systems make the investment of approximately $1 million for the equipment and do their own grinding. Contractors typically charge a fixed amount per day for the equipment on site, plus an amount per pass-mile (one pass of the grinding machine for one mile). Typical fixed amounts would be $15,000 per day and $1000 per pass-mile.

- Wheel truing to re-contour the wheel, provide a smooth running surface, and remove wheel flats. The most dramatic vibration reduction results from removing wheel flats. However, significant improvements also can be observed simply from smoothing the running surface. A wheel truing machine costs approximately $1 million. The TCRP report figures a system with 700 vehicles would incur a yearly cost of $300,000 to $400,000 for a wheel truing program.
- Implement vehicle reconditioning programs, particularly when components such as suspension system, brakes, wheels, and slip-slide detectors will be involved. A slip-slide control system costs approximately $5,000 to $10,000 per vehicle, with a maintenance cost of $200 per year.
- Install wheel-flat detector systems to identify vehicles which are most in need of wheel truing. These systems are becoming more common on railroads and intercity passenger systems, but are relatively rare on transit systems. Therefore the costs are yet to be determined.

- **Planning and Design of Special Trackwork:** A large percentage of vibration impact from a new transit facility is often caused by wheel impacts at the special trackwork for turnouts and crossovers. When feasible, the most effective vibration control measure is to relocate the special trackwork to a less vibration-sensitive area. Sometimes this requires adjusting the location by several hundred feet and will not have a significant adverse impact on the operation plan for the system. Careful review of crossover and turnout locations during the preliminary engineering stage is an important step to minimizing potential for vibration impact. Another approach is to use special devices at turnouts and crossovers, special "frogs," that incorporate mechanisms to close the gaps between running rails. Frogs with spring-loaded mechanisms and frogs with movable points can significantly reduce vibration levels near crossovers. According to the TCRP report, a spring frog costs about $12,000, twice the cost of a standard frog. A movable point frog involves elaborate signal and control circuitry resulting in higher costs, approximately $200,000.

- **Vehicle Specifications:** The ideal rail vehicle, with respect to minimizing ground-borne vibration, should have a low unsprung weight, a soft primary suspension, a minimum of metal-to-metal contact between moving parts of the truck, and smooth wheels that are perfectly round. A limit for the vertical resonance frequency of the primary suspension should be included in the specifications for any new vehicle. A vertical resonance frequency of 12 Hz or less is sufficient to control the levels of ground-borne vibration. Some have recommended that transit vehicle specifications require that the vertical resonance frequency be less than 8 Hz.

- **Special Track Support Systems:** When the vibration assessment indicates that vibration levels will be excessive, it is usually the track support system that is changed to reduce the vibration levels. Floating slabs, resiliently supported ties, high-resilience fasteners, and ballast mats have all been used in subways to reduce the levels of ground-borne vibration. To be effective, all of these measures must be optimized for the frequency spectrum of the vibration. Most of these relatively standard procedures have been successfully used on several subway projects. Applications on at-grade and elevated track are less common. This is because vibration problems are less common for at-grade and elevated track; cost of the vibration control measures is a higher percentage of the construction costs of at-grade and elevated track; and exposure to the elements can require significant design modifications.

Each of the major vibration control measures for track support is discussed below. Costs for these treatments are not covered by the TCRP report, but are given as estimates based on transit agency experience.

- Resilient Fasteners: Resilient fasteners are used to fasten the rail to concrete track slabs. Standard resilient fasteners are very stiff in the vertical direction, usually in the range of 200,000 lb/in., although they do provide vibration reduction compared to some of the rigid fastening systems used on older systems (e.g., wood half-ties embedded in concrete). Special fasteners with vertical stiffness in the range of 30,000 lb/in. will reduce vibration by as much as 5 to 10 dB at frequencies above 30 to 40 Hz. Premium fasteners cost approximately $300 per track-foot, about 6 times the cost of standard fasteners.
- Ballast Mats: A ballast mat consists of a rubber or other type of elastomer pad that is placed under the ballast. The mat generally must be placed on a concrete pad to be effective. They will not be as effective if placed directly on the soil or the sub-ballast. Consequently, most ballast mat applications are in subway or elevated structures. Ballast mats can provide 10 to 15 dB attenuation at frequencies above 25 to 30 Hz. Ballast mats are often a good retrofit measure for existing tie-and-ballast track where there are vibration problems. Installed ballast mats cost approximately $180 per track-foot.
- Resiliently Supported Ties: The resiliently supported tie system consists of concrete ties supported by rubber pads. The rails are fastened directly to the concrete ties using standard rail clips. Existing measurement data indicate that resiliently supported ties may be very effective in reducing low-frequency vibration in the 15 to 40 Hz range. This makes them particularly appropriate for transit systems with vibration problems in the 20 to 30 Hz range. A resiliently supported tie system costs approximately $400 per track-foot. Although most commonly used in slab track or subway tunnel applications, another version of a resiliently supported tie system involves attaching thick rubber pads directly to the underside of ties in ballast. This treatment costs approximately the same as a ballast mat, or $180 per track foot.
- Floating Slabs: Floating slabs can be very effective at controlling ground-borne vibration and noise. They basically consist of a concrete slab supported on resilient elements, usually rubber or a similar elastomer. A variant that was first used in Toronto and is generally referred to as the double tie system, consists of 5-foot-long slabs with 4 or more rubber pads under each slab. Floating slabs are effective at frequencies greater than their single-degree-of-freedom vertical resonance frequency. The floating slabs used in

Washington DC, Atlanta, and Boston were all designed to have a vertical resonance in the 14 to 17 Hz range. A special floating slab in San Francisco's BART system uses a very heavy design with a resonance frequency in the 5 to 10 Hz frequency range. The primary disadvantage of floating slabs is that they tend to be the most expensive of the vibration control treatments. A typical double-tie floating slab system costs approximately $600 per track foot.

- o Other Marginal Treatments: Changing any feature of the track support system can change the levels of ground-borne vibration. Approaches such as using heavier rail, thicker ballast, or heavier ties can be expected to reduce the vibration levels. There also is some indication that vibration levels are lower with wood ties compared to concrete ties. However, there is little confirmation that any of these approaches will make a significant change in the vibration levels. This is unfortunate since modifications to the ballast, rails, or ties are virtually the only options for normal at-grade, tie-and-ballast track without resorting to a different type of track support system or widening the right-of-way to provide a buffer zone.

- **Building Modifications:** In some circumstances, it is practical to modify the impacted building to reduce the vibration levels. Vibration isolation of buildings basically consists of supporting the building foundation on elastomer pads similar to bridge bearing pads. Vibration isolation of buildings is seldom an option for existing buildings; normal applications are possible only for new construction. This approach is particularly important for shared-use facilities such as office space above a transit station or terminal. When vibration-sensitive equipment such as electron microscopes will be affected by transit vibration, specific modifications to the building structure may be the most cost-effective method of controlling the impact. For example, the floor upon which the vibration-sensitive equipment is located could be stiffened and isolated from the remainder of the building to reduce the vibration. Alternatively, the equipment could be isolated from the building at far less cost.

- **Trenches:** Use of trenches to control ground-borne vibration is analogous to controlling airborne noise with sound barriers. Although this approach has not received much attention in the U.S., there are cases where a trench can be a practical method for controlling transit vibration from at-grade track. A rule-of-thumb given by Richert and Hall(9) is that if the trench is located close to the source, the trench bottom must be at least 0.6 times the Rayleigh wavelength below the vibration source. For most soils, Rayleigh waves travel at around 600 ft/sec which means that the wavelength at 30 Hz is 20 ft. This means that the trench must be approximately 15 ft deep to be effective at 30 Hz.

  A trench can be effective as a vibration barrier if it is either open or solid. The Toronto Transit Commission tested a trench filled with styrofoam to keep it open and reported successful performance over a period of at least one year. Solid barriers can be constructed with sheet piling or concrete poured into a trench.

- **Operational Changes:** The most obvious operational change is to reduce the vehicle speed. Reducing the train speed by a factor of two will reduce vibration levels approximately 6 dB. Other operational changes that can be effective in special cases are:

    - Use the equipment that generates the lowest vibration levels during the nighttime hours when people are most sensitive to vibration and noise.
    - Adjust nighttime schedules to minimize movements in the most sensitive hours.

  While there are tangible benefits from speed reductions and limits on operations during the most sensitive time periods, these types of measures are usually not practical from the standpoint of service requirements. Furthermore, vibration reduction achieved through operating restrictions requires continuous monitoring and will be negated if vehicle operators do not adhere to established policies. As with the options for noise control, FTA does not recommend limits on operations as a way to reduce vibration impacts.

- **Buffer Zones:** Expanding the rail right-of-way sometimes will be the most economical method of reducing the vibration impact. A similar approach is to negotiate a vibration easement from the affected property owners, for example, a row of single-family homes adjacent to a proposed commuter rail line. However, there may be legal limitations on the ability of funding agencies to acquire land strictly for the purpose of mitigating vibration (or noise) impact.

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12. NOISE AND VIBRATION DURING CONSTRUCTION

Construction often generates community noise/vibration complaints, even when it takes place over a limited time frame. In recent years, public concerns about construction noise and vibration have increased significantly, due partly to lengthy periods of heavy construction on some “mega-projects” and also to the increasing prevalence of nighttime construction that is undertaken to avoid disrupting workday road and rail traffic. Noise and vibration complaints typically arise from interference with people's activities, especially when the adjacent community has no clear understanding of the extent or duration of the construction. Misunderstandings can arise when the contractor is considered to be insensitive by the community, even though the contractor believes the work is being performed in compliance with local ordinances. This situation underscores the need for early identification and assessment of potential problem areas.

An assessment of noise and vibration impact during construction can be made by following procedures outlined in this chapter. The type of assessment – qualitative or quantitative – and the level of analysis will be determined based on the scale of the project and surrounding land use. In cases where a full quantitative assessment is not warranted, a qualitative assessment of the construction noise and vibration environment can lead to greater understanding and tolerance in the community. For major projects with extended periods of construction at specific locations, a quantitative assessment can aid contractors in making bids by allowing changes in construction approach and including mitigation costs before the construction plans are finalized.

12.1 CONSTRUCTION NOISE ASSESSMENT

Noise impacts from construction may vary greatly depending on the duration and complexity of the project. The level of detail of a construction noise assessment depends on the scale and the type of project and the stage of environmental review. Many small projects need no construction noise assessment at all.

Examples include installation of safety features like grade-crossing signals, track improvements within the right-of-way, and erecting small buildings and facilities which are similar in scale to the surrounding development. For projects like these, it would suffice to describe the length of time of construction, the loudest equipment to be used, expected truck access routes, and avoidance of nighttime activity.

Other projects involving a limited period of construction time – less than a month in a noise-sensitive area – may warrant a qualitative treatment because of nearby noise-sensitive land uses. In these cases, the assessment may simply be a qualitative description of the equipment to be used, the duration of construction, and any mitigation requirements placed on particularly noisy operations. Where the length of construction in noise-sensitive areas is expected to last for more than several months or particularly noisy equipment will be involved, then construction noise impacts may be determined in considerable detail. In any case, a likely scenario of the planned construction methods should be described in the environmental document. At this early stage it may be possible to describe certain basic measures that would be taken to reduce the potential impact, for example, prohibiting the noisiest construction activities during nighttime. However, it may be prudent to defer final decisions on noise control measures until the project and construction plans are defined in greater detail during final design.

Qualitative Assessments. In cases where a qualitative construction noise assessment is appropriate, the following descriptions would be included:

- Duration of construction (overall and at specific locations)
- Equipment expected to be used, e.g., noisiest operations
- Schedule with limits on times of operation, e.g., daytime use only
- Monitoring of noise
- Forum for communicating with the public
- Commitments to limit noise levels to certain levels, including any local ordinances that apply
- Consideration of application of noise control treatments used successfully in other projects

Community relations will be important in these cases; early information disseminated to the public about the kinds of equipment, expected noise levels and durations will help to forewarn potentially affected neighbors about the temporary inconvenience. In these cases, a general description of the variation of noise levels during a typical construction day may be helpful. The criteria in Section 12.1.3 are not applied to qualitative assessments.

Quantitative Assessments. Factors that influence the decision to perform a quantitative construction noise assessment include the following:

- Scale of the project
- Proximity of noise-sensitive land uses to the construction zones

- Number of noise-sensitive receptors in the project area
- Duration of construction activities near noise-sensitive receptors
- Schedule (the construction days, hours and time periods)
- Method (e.g., cut-and-cover vs. bored tunneling)
- Concern about construction noise expressed in comments by the general public (scoping, public meetings)

A quantitative construction noise assessment requires information about source levels, operations, proximity of noise sensitive locations, and criteria against which the levels will be compared. These elements of assessment are described in the following sections.

12.1.1 Quantitative Noise Assessment Methods

A quantitative construction noise assessment is performed by comparing the predicted noise levels with impact criteria appropriate for the construction stage. The approach requires an appropriate descriptor, a standardized prediction method and a set of recognized criteria for assessing the impact.

The *descriptor* used for construction noise is the L_{eq}. This unit is appropriate for the following reasons:

- It can be used to describe the noise level from operation of each piece of equipment separately and is easy to combine to represent the noise level from all equipment operating during a given period.
- It can be used to describe the noise level during an entire phase.
- It can be used to describe the average noise over all phases of the construction.

The recommended *method* for predicting construction noise impact for major transit projects requires:

- An emission model to determine the noise generated by the equipment at a reference distance.
- A propagation model that shows how the noise level will vary with distance.
- A way of summing the noise of each piece of equipment at locations of noise sensitivity.

The first two components of the method are related by the following equation:

$$L_{eq}(equip) = E.L. + 10\log(U.F.) - 20\log(D/50) - 10G\log(D/50)$$

where: L_{eq} *(equip)* is the L_{eq} at a receiver resulting from the operation of a single piece of equipment over a specified time period

E.L. is the noise emission level of the particular piece of equipment at the reference distance of 50 feet, taken from Table 12-1

G is a constant that accounts for topography and ground effects, taken from Figure 6-5 (Chapter 6)

D is the distance from the receiver to the piece of equipment, and

U.F. is a usage factor that accounts for the fraction of time that the equipment is in use over the specified time period.

The combination of noise from several pieces of equipment operating during the same time period is obtained from decibel addition of the L_{eq} of each single piece of equipment found from the above equation.

General Assessment

The approach can be as detailed as necessary to characterize the construction noise by specifying the various quantities in the equation. For projects in an early assessment stage when the equipment roster and schedule are undefined, only a rough estimate of construction noise levels is practical.

The following assumptions are adequate for a general assessment of each phase of construction:

- Full power operation for a time period of one hour is assumed because most construction equipment operates continuously for periods of one hour or more at some point in the construction period. Therefore, U.F. = 1, and 10 log(U.F.) = 0.

- Free-field conditions are assumed and ground effects are ignored. Consequently, G = 0.

- Emission level at 50 feet, E.L., is taken from Table 12-1.

- All pieces of equipment are assumed to operate at the center of the project, or centerline, in the case of a guideway or highway construction project.

- The predictions include only the two noisiest pieces of equipment expected to be used in each construction phase.

Detailed Assessment

A more detailed approach can be used if warranted, such as when a large number of noise-sensitive sites are adjacent to a construction project or where contractors are faced with stringent local ordinances or heightened public concerns expressed in early outreach efforts. Additional details include:

- Duration. Long-term construction project noise impact is based on a 30-day average L_{dn}, the times of day of construction activity (nighttime noise is penalized by 10 dB in residential areas), and the percentage of time the equipment is to be used during a period of time which will affect U.F. For example, an 8-hour L_{eq} is determined by making U.F. the percentage of time each individual piece of equipment operates under full power in that period. Similarly, the 30-day average L_{dn} is determined from the U.F. expressed by the percentage of time the equipment is used during the daytime hours (7 a.m. to 10 p.m.) and nighttime (10 p.m. to 7 a.m.), separately over a 30-day period. However, to account for increased sensitivity to nighttime noise, the nighttime percentage is multiplied by 10 before performing the computation.

- Site Characteristics. Taking into account the site topography, natural and man-made barriers and ground effects will involve the factor G. Use Figure 6-5 (Chapter 6) to calculate G.

- Noise Sources. Measuring or certifying the emission level of each piece of equipment will refine E.L.

- Site Layout. Determining the location of each piece of equipment while it is working will specify the distance factor D more accurately.

- Combined Sources. Including all pieces of equipment in the computation of the 8-hour L_{eq} and the 30-day average L_{dn} will determine the total noise levels using Table 6-11 (Chapter 6).

12.1.2 Noise from Typical Construction Equipment and Operations

The noise levels generated by construction equipment will vary greatly depending on factors such as the type of equipment, the specific model, the operation being performed, and the condition of the equipment. The equivalent sound level (L_{eq}) of the construction activity also depends on the fraction of time that the equipment is operated over the time period of construction. The dominant source of noise from most construction equipment is the engine, usually a diesel, often without sufficient muffling. In a few cases, such as impact pile-driving or pavement-breaking, noise generated by the process dominates.

For considerations of noise assessment, construction equipment can be considered to operate in two modes, stationary and mobile. Stationary equipment operates in one location for one or more days at a time, with either a fixed power operation (pumps, generators, compressors) or a variable noise operation (pile drivers, pavement breakers). Mobile equipment moves around the construction site with power applied in cyclic fashion (bulldozers, loaders), or to and from the site (trucks). The movement around the site is handled in the construction noise prediction procedure discussed earlier in this chapter. Variation in power imposes additional complexity in characterizing the noise source level from a piece of equipment. This is handled by describing the noise at a reference distance from the equipment operating at full power and adjusting it based on the duty cycle of the activity to determine the L_{eq} of the operation. Standardized procedures for measuring the exterior noise levels for the certification of mobile and stationary construction equipment have been developed by the Society of Automotive Engineers. [1,2] Typical noise levels from representative pieces of equipment are listed in Table 12-1. These source levels can be used in FHWA's Windows-based screening tool, "Roadway Construction Noise Model" (RCNM), for the prediction of construction noise.[3]

Construction activities are characterized by variations in the power expended by equipment, with resulting variation in noise levels with time. Variation in the power is expressed in terms of the previously mentioned "usage factor" of the equipment, which is the percentage of time during the workday that the equipment is operating at full power. Time-varying noise levels are converted to a single number (L_{eq}) for each piece of equipment during the operation. Besides having daily variations in activities, major construction projects are accomplished in several different phases. Each phase has a specific equipment mix depending on the work to be accomplished during that phase.

As a result of the equipment mix, each phase has its own noise characteristics; some have higher continuous noise levels than others, some have high impact noise levels. The purpose of the quantitative assessment is to determine not only the levels, but also the duration of the noise. The L_{eq} of each phase is determined by combining the L_{eq} contributions from each piece of equipment used in that phase. The impact and the consequent noise mitigation approaches depend on the criteria to be used in assessing impact, as discussed in the next section.

Table 12-1. Construction Equipment Noise Emission Levels

Equipment	Typical Noise Level (dBA) 50 ft from Source
Air Compressor	81
Backhoe	80
Ballast Equalizer	82
Ballast Tamper	83
Compactor	82
Concrete Mixer	85
Concrete Pump	82
Concrete Vibrator	76
Crane, Derrick	88
Crane, Mobile	83
Dozer	85
Generator	81
Grader	85
Impact Wrench	85
Jack Hammer	88
Loader	85
Paver	89
Pile-driver (Impact)	101
Pile-driver (Sonic)	96
Pneumatic Tool	85
Pump	76
Rail Saw	90
Rock Drill	98
Roller	74

Table 12-1. Construction Equipment Noise Emission Levels (continued)	
Equipment	**Typical Noise Level (dBA) 50 ft from Source**
Saw	76
Scarifier	83
Scraper	89
Shovel	82
Spike Driver	77
Tie Cutter	84
Tie Handler	80
Tie Inserter	85
Truck	88

Table based on an EPA Report,[4] measured data from railroad construction equipment taken during the Northeast Corridor Improvement Project, and other measured data.

12.1.3 Construction Noise Criteria

No standardized *criteria* have been developed for assessing construction noise impact. Consequently, criteria must be developed on a project-specific basis unless local ordinances can be found to apply. Generally, local noise ordinances are not very useful in evaluating construction noise. They usually relate to nuisance and hours of allowed activity and sometimes specify limits in terms of maximum levels, but are generally not practical for assessing the impact of a construction project. Project construction noise criteria should take into account the existing noise environment, the absolute noise levels during construction activities, the duration of the construction, and the adjacent land use. While it is not the purpose of this manual to specify standardized criteria for construction noise impact, the following guidelines can be considered reasonable criteria for assessment. If these criteria are exceeded, there may be adverse community reaction.

General Assessment

Estimate the combined noise level in one hour from the two noisiest pieces of equipment, assuming they both operate at the same time. Then identify locations where the level exceeds the following:

Land Use	One-hour L_{eq} (dBA)	
	Day	Night
Residential	90	80
Commercial	100	100
Industrial	100	100

Detailed Assessment

Where a more refined analysis is needed, predict the noise level in terms of 8-hour L_{eq} and 30-day averaged L_{dn} and compare to criteria in the following table:

Land Use	8-hour L_{eq} (dBA)		L_{dn} (dBA)
	Day	Night	30-day Average
Residential	80	70	75[a]
Commercial	85	85	80[b]
Industrial	90	90	85[b]

[a] In urban areas with very high ambient noise levels (L_{dn} > 65 dB), L_{dn} from construction operations should not exceed existing ambient + 10 dB.

[b] Twenty-four-hour L_{eq}, not L_{dn}.

12.1.4 Mitigation of Construction Noise

After using the above approaches to locate potential impacts from construction noise, the next step is to identify appropriate control measures. Three categories of noise control approaches, with examples, are given below:

1. *Design considerations and project layout:*
   - Construct noise barriers, such as temporary walls or piles of excavated material, between noisy activities and noise-sensitive receivers.
   - Re-route truck traffic away from residential streets, if possible. Select streets with fewest homes if no alternatives are available.
   - Site equipment on the construction lot as far away from noise-sensitive sites as possible.
   - Construct walled enclosures around especially noisy activities or clusters of noisy equipment. For example, shields can be used around pavement breakers and loaded vinyl curtains can be draped under elevated structures.

2. *Sequence of operations:*
   - Combine noisy operations to occur in the same time period. The total noise level produced will not be significantly greater than the level produced if the operations were performed separately.
   - Avoid nighttime activities. Sensitivity to noise increases during the nighttime hours in residential neighborhoods.

3. *Alternative construction methods:*

   - Avoid use of an impact pile driver where possible in noise-sensitive areas. Drilled piles or the use of a sonic or vibratory pile driver are quieter alternatives where the geological conditions permit their use.
   - Use specially-quieted equipment, such as quieted and enclosed air compressors and properly-working mufflers on all engines.
   - Select quieter demolition methods, where possible. For example, sawing bridge decks into sections that can be loaded onto trucks results in lower cumulative noise levels than impact demolition by pavement breakers.

If possible, the environmental impact assessment should include descriptions of how each impacted location will be treated with one or more mitigation measures. However, with a large, complex project, the information available during the preliminary engineering phase may not allow final decisions to be made on all specific mitigation measures. In such cases, it is appropriate to describe and commit to a mitigation plan that will be developed during final design. The objective of the plan should be to minimize construction noise using all reasonable (i.e., cost vs. benefit) and feasible (i.e., physically achievable) means available. Components of the plan may include some or all of the following provisions which would be specified in construction contracts:

- *Equipment noise emission limits*. These are absolute noise limits applied to generic classes of equipment at a reference distance (typically 50 feet). The limits should be set no higher than what is reasonably achievable for well-maintained equipment with effective mufflers. Lower limits that require source noise control may be appropriate for certain equipment when needed to minimize community noise impact, if reasonable and feasible. Provisions could also be included to require equipment noise certification testing prior to use on site.
- *Lot-line construction noise limits*. These are noise limits that apply at the lot line of specific noise-sensitive properties. The limits are typically specified in terms of both noise exposure (usually Leq over a 20-30 minute period) and maximum noise level. They should be based on local noise ordinances, if applicable, as well as pre-construction baseline noise levels; limits that are 3-5 decibels above the baseline are often used.
- *Operational and/or equipment restrictions*. It may be necessary to prohibit or restrict certain construction equipment and activities near residential areas during nighttime hours. This is particularly true for activities that generate tonal, impulsive or repetitive sounds, such as back-up alarms, hoe ram demolition and pile-driving.
- *Noise abatement requirements*. In some cases specifications may be provided for particular noise control treatments, based on the results of the design analysis and/or prior commitments made to the public by civic authorities. An example would be the requirement for a temporary noise barrier to shield a particular community area from noisy construction activities.

- *Noise monitoring plan requirement*s. Plans can be developed for pre-project noise monitoring to establish baseline noise levels at sensitive locations, as well as for periodic equipment and lot-line noise monitoring during the construction period. The plan should outline the measurement and reporting methods that will be used to demonstrate compliance with the project noise limits.
- *Noise control plan requirements*. For major construction projects, specifications have required the preparation and submission of noise control plans on a periodic basis (e.g., every six months). These plans should predict the construction noise at noise-sensitive receptor locations based on the proposed construction equipment and methods. If the analysis predicts that the specified noise limits will be exceeded, the plan should specify the mitigation measures that will be applied and should demonstrate the expected noise reductions these measures will achieve. The objective of this proactive approach is to minimize the likelihood of community noise complaints by ensuring that any necessary mitigation measures are included in the construction plans.
- *Compliance enforcement program*. If construction noise is a significant issue in the community, it is important that a program be put in place to monitor contractor compliance with the noise control specifications and mitigation plan. It is best that this function be performed by a construction management team on behalf of the public agency.
- *Public information and complaint response procedures*. To maintain positive community relations, the public should be kept informed about the construction plans and efforts to minimize noise, and procedures should be established for prompt response and corrective action with regard to noise complaints during construction.

Most of these provisions are appropriate for very large projects where construction activity will continue for many months, if not years. References 4 and 5 contain details on dealing with construction noise on major transportation projects. [5,6]

12.2 CONSTRUCTION VIBRATION ASSESSMENT

Construction activity can result in varying degrees of ground vibration, depending on the equipment and methods employed. Operation of construction equipment causes ground vibrations that spread through the ground and diminish in strength with distance. Buildings founded on the soil in the vicinity of the construction site respond to these vibrations, with varying results ranging from no perceptible effects at the lowest levels, low rumbling sounds and perceptible vibrations at moderate levels, and slight damage at the highest levels. As expressed previously in this chapter with respect to construction noise, the type of assessment – qualitative or quantitative – and the level of construction vibration analysis will be determined by factors related to the scale of the project and the sensitivity of the surrounding land use. A quantitative analysis should be conducted in cases where construction vibration may result in prolonged annoyance or building damage.

Ground vibrations from construction activities do not often reach the levels that can damage structures, but they can achieve the audible and feelable ranges in buildings very close to the site. A possible exception is the case of fragile buildings, many of them old, where special care must be taken to avoid damage. The construction vibration criteria include special consideration for such buildings. The construction activities that typically generate the most severe vibrations are blasting and impact pile-driving.

In cases where prolonged annoyance or damage from construction vibrations are not expected, a qualitative assessment is appropriate. Such an assessment should include a description of the duration and the type of equipment to be used during the construction, with an explanation of how the ground-borne vibration will be maintained at an acceptable level. For example, if the equipment is of the type that generates little or no ground vibration – air compressors, light trucks, hydraulic loaders, etc. – a simple explanation is sufficient and no quantitative analysis is necessary.

12.2.1 Quantitative Construction Vibration Assessment Methods

Construction vibration should be assessed quantitatively in cases where there is significant potential for impact from construction activities. Such activities include blasting, pile-driving, vibratory compaction, demolition, and drilling or excavation in close proximity to sensitive structures. The recommended procedure for estimating vibration impact from construction activities is as follows:

Damage Assessment

- Select the equipment and associated vibration source levels at a reference distance of 25 feet from Table 12-2.
- Make the propagation adjustment according to the following formula (this formula is based on point sources with normal propagation conditions):

$$PPV_{equip} = PPV_{ref} \times (25/D)^{1.5}$$

where: PPV (equip) is the peak particle velocity in in/sec of the equipment adjusted for distance

PPV (ref) is the reference vibration level in in/sec at 25 feet from Table 12-2

D is the distance from the equipment to the receiver.

- Apply the vibration damage criteria from Table 12-3.

Annoyance Assessment

- If desired for consideration of annoyance or interference with vibration-sensitive activities, estimate the vibration level L_v at any distance D from the following equation and apply the vibration impact criteria for General Assessment in Chapter 8 for vibration-sensitive sites:

$$L_v(D) = L_v(25\text{ ft}) - 30\log(D/25)$$

12.2.2 Vibration Source Levels from Construction Equipment

Ground-borne vibration related to human annoyance is generally related to root mean square (rms) velocity levels expressed in VdB. However, a major concern with regard to construction vibration is building damage. Consequently, construction vibration is generally assessed in terms of peak particle velocity (PPV), as defined in Chapter 7.1.2. The relationship of PPV to rms velocity is expressed in terms of the "crest factor," defined as the ratio of the PPV amplitude to the rms amplitude. Peak particle velocity is typically a factor of 1.7 to 6 times greater than rms vibration velocity.

Various types of construction equipment have been measured under a wide variety of construction activities with an average of source levels reported in terms of velocity as shown in Table 12-2. In this table, a crest factor of 4 (representing a PPV-rms difference of 12 VdB) has been used to calculate the approximate rms vibration velocity levels from the PPV values. Although the table gives one level for each piece of equipment, it should be noted that there is a considerable variation in reported ground vibration levels from construction activities. The data provide a reasonable estimate for a wide range of soil conditions.

Table 12-2. Vibration Source Levels for Construction Equipment (From measured data.[7,8,9,10])

Equipment		PPV at 25 ft (in/sec)	Approximate L_v† at 25 ft
Pile Driver (impact)	upper range	1.518	112
	typical	0.644	104
Pile Driver (sonic)	upper range	0.734	105
	typical	0.170	93
Clam shovel drop (slurry wall)		0.202	94
Hydromill (slurry wall)	in soil	0.008	66
	in rock	0.017	75
Vibratory Roller		0.210	94
Hoe Ram		0.089	87
Large bulldozer		0.089	87
Caisson drilling		0.089	87
Loaded trucks		0.076	86
Jackhammer		0.035	79
Small bulldozer		0.003	58

† RMS velocity in decibels (VdB) re 1 micro-inch/second

12.2.2 Construction Vibration Criteria

For evaluating potential annoyance or interference with vibration-sensitive activities due to construction vibration, the criteria for General Assessment in Chapter 8 can be applied. In most cases, however, the primary concern regarding construction vibration relates to potential damage effects. Guideline vibration damage criteria are given in Table 12-3 for various structural categories.[10] In this table, a crest factor of 4 (representing a PPV-rms difference of 12 VdB) has been used to calculate the approximate rms vibration velocity limits from the PPV limits. These limits should be viewed as criteria that should be used during the environmental impact assessment phase to identify problem locations that must be addressed during final design.

Table 12-3. Construction Vibration Damage Criteria[11]

Building Category	**PPV (in/sec)**	**Approximate L_v†**
I. Reinforced-concrete, steel or timber (no plaster)	0.5	102
II. Engineered concrete and masonry (no plaster)	0.3	98
III. Non-engineered timber and masonry buildings	0.2	94
IV. Buildings extremely susceptible to vibration damage	0.12	90

† RMS velocity in decibels (VdB) re 1 micro-inch/second

12.2.3 Construction Vibration Mitigation

After using the above methods to locate potential human impacts or building damage from construction vibrations, the next step is to identify control measures. Similar to the approach for construction noise, mitigation of construction vibration requires consideration of equipment location and processes, as follows:

1. *Design considerations and project layout:*
   - Route heavily-loaded trucks away from residential streets, if possible. Select streets with fewest homes if no alternatives are available.
   - Operate earth-moving equipment on the construction lot as far away from vibration-sensitive sites as possible.
2. *Sequence of operations:*
   - Phase demolition, earth-moving and ground-impacting operations so as not to occur in the same time period. Unlike noise, the total vibration level produced could be significantly less when each vibration source operates separately.

- Avoid nighttime activities. People are more aware of vibration in their homes during the nighttime hours.

3. *Alternative construction methods:*

- Avoid impact pile-driving where possible in vibration-sensitive areas. Drilled piles or the use of a sonic or vibratory pile driver causes lower vibration levels where the geological conditions permit their use (however, see cautionary note below).
- Select demolition methods not involving impact, where possible. For example, sawing bridge decks into sections that can be loaded onto trucks results in lower vibration levels than impact demolition by pavement breakers, and milling generates lower vibration levels than excavation using clam shell or chisel drops.
- Avoid vibratory rollers and packers near sensitive areas.

Pile-driving is one of the greatest sources of vibration associated with equipment used during construction of a project. The source levels in Table 12-2 indicate that sonic pile drivers may provide substantial reduction of vibration levels. However, there are some additional vibration effects of sonic pile drivers that may limit their use in sensitive locations. A sonic pile driver operates by continuously shaking the pile at a fixed frequency, literally vibrating it into the ground. Vibratory pile drivers operate on the same principle, but at a different frequency. However, continuous operation at a fixed frequency may be more noticeable to nearby residents, even at lower vibration levels. Furthermore, the steady-state excitation of the ground may induce a growth in the resonant response of building components. Resonant response may be unacceptable in cases of fragile buildings or vibration-sensitive manufacturing processes. Impact pile drivers, on the other hand, produce a high vibration level for a short time (0.2 seconds) with sufficient time between impacts to allow any resonant response to decay.

As with construction noise, in many cases the information available during the preliminary engineering phase will not be sufficient to define specific construction vibration mitigation measures. In such cases, it is appropriate to describe and commit to a mitigation plan that will be developed and implemented during the final design and construction phases of the project. The objective of the plan should be to minimize construction vibration damage using all reasonable and feasible means available. The plan should provide a procedure for establishing threshold and limiting vibration values for potentially affected structures based on an assessment of each structure's ability to withstand the loads and displacements due to construction vibrations. The plan should also include the development of a vibration monitoring plan during final design and the implementation of a compliance monitoring program during construction.

REFERENCES

1. Society of Automotive Engineers, "Exterior Sound Level Measurement Procedure for Powered Mobile Construction Equipment," SAE Recommended Practice J88a, 1976.

2. Society of Automotive Engineers, "Sound Levels for Engine Powered Equipment," SAE Standard J952b, 1976.

3. U.S. Department of Transportation, Federal Highway Administration. "FHWA Roadway Construction Noise Model User's Guide," FHWA-HEP-05-054, January 2006. (Available on Web site: www.rcnm.us)

4. U.S. Environmental Protection Agency, "Noise from Construction Equipment and Operations, Building Equipment and Home Appliances," NTID300.1, December 31, 1971.

5. E. Thalheimer, "Construction noise control program and mitigation strategy at the Central Artery/Tunnel Project," Noise Control Eng. J. 48(5), September – October 2000, pp. 157 – 165.

6. U.S. Department of Transportation, Federal Highway Administration. "Highway Construction Noise Handbook," to be issued mid-year 2006.

7. D.J. Martin, "Ground Vibrations from Impact Pile Driving during Road Construction," Supplementary Report 544, United Kingdom Department of the Environment, Department of Transport, Transport and Road Research Laboratory, 1980.

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9. J.F. Wiss, "Damage Effects of Pile Driving Vibrations," Highway Research Record, No. 155, Highway Research Board, 1967.

10. David A. Towers, "Ground-borne Vibration from Slurry Wall Trench Excavation for the Central Artery/Tunnel Project Using Hydromill Technology," Proc. InterNoise 95, Newport Beach, CA, July 1995.

11. Swiss Consultants for Road Construction Association, "Effects of Vibration on Construction," VSS-SN640-312a, Zurich, Switzerland, April 1992.

13. DOCUMENTATION OF NOISE AND VIBRATION ASSESSMENT

To be effective, the noise and vibration analysis must be presented to the public in a clear, yet comprehensive manner. The mass of technical data and information necessary to withstand scrutiny in the environmental review process must be documented in a way that remains intelligible to the public. Justification for all assumptions used in the analysis, such as selection of representative measurement sites and all baseline conditions, must be presented for review. For large-scale projects, the environmental document contains a condensation of essential information in order to maintain a reasonable size. For these projects, separate technical reports are usually prepared as supplements to the environmental impact statement (EIS) or environmental assessment (EA). For smaller projects, or ones with minimal noise or vibration impact, all the technical information may be presented in the environmental document itself. This chapter gives guidance on how the necessary noise and vibration information should be included in the project's environmental documentation.

13.1 THE TECHNICAL REPORT ON NOISE AND VIBRATION

A separate technical report is often prepared as a supplement to the environmental document (EIS or EA). A technical report is appropriate in cases when the wealth of data can not all be placed in the environmental document. The details of the analysis are important for establishing the basis for the assessment. Consequently, all the details in the technical report should be contained in a well-organized format for easy access to the information. While the technical report is not intended to be a primer on the subject, the technical data and descriptions should be presented in a manner that can be understood by the general public. All the necessary background information should be present in the technical report, including tables, maps, charts, drawings and references that may be too detailed for the environmental document, but which are important in helping to draw conclusions about the project's noise and vibration impacts and mitigation options.

13.1.1 Organization of Technical Report

The technical report on noise/vibration should contain the following major subject headings, along with the key information content described below. If both noise and vibration have been analyzed, it is generally preferable to separate the noise and vibration sections; as shown in this guidance manual, the approaches to the two topics are quite different.

- **Overview**: This section contains a brief description of the project and an overview of the noise/vibration concerns. It sets forth the initial considerations in framing the scope of the study.
- **Inventory of Noise/Vibration-Sensitive Sites**: The approach for selecting noise- and vibration-sensitive sites should be described in sufficient detail to demonstrate completeness. Sites and site descriptions are to be included.
- **Measurements of Existing Noise/Vibration Conditions:** The basis for selecting measurement sites should be documented, along with tables of sites coordinated with maps showing locations of sites. If the measurement data are used to estimate existing conditions at other locations, the rationale and the method should be included. Measurement procedures should be fully described. Tables of measurement instruments should include manufacturer, type, serial number and date of most recent calibration by authorized testing laboratory. Measurement periods, including time of day and length of time at each site should be shown to demonstrate adequate representation of the ambient conditions. The measurement data should be presented in well organized form in tables and figures. A summary and interpretation of measured data should be included.
- **Special Measurements Related to the Project:** Some projects require specialized measurements at sensitive sites, such as outdoor-to-indoor noise level reduction of homes, or transmission of vibrations into concert halls and recording studios. Other projects may need special source-level characterization. Full description of the measurements and the results should be included.
- **Predictions of Noise/Vibration from the Project:** The prediction model used for estimating future project conditions should be fully described and referenced. Any changes or extensions to the models recommended in this manual should be fully described so that the validity of the adjustments can be confirmed. Specific data used as input to the models should be listed. Computed levels should be tabulated and illustrated by contours, cross-sections or shaded mapping. It is important to illustrate noise/vibration impacts with base maps at a scale with enough detail to provide location reference for the reader.
- **Noise/Vibration Criteria:** Impact criteria for the project should be fully described and referenced (refer to Chapters 3 and 8). In addition, any applicable local ordinances should be described. Tables specifying the criteria levels should also be included. If the project involves considerable construction, and a separate construction noise and vibration analysis will be included, then construction criteria should appear in a separate section with its own assessment.
- **Noise/Vibration Impact Assessment:** The impact assessment should be described according to the procedures outlined in this manual. A resulting impact inventory should be presented for each alternative mode or alignment in a format that allows ready comparison among alternatives. The

inventory should be tabulated according to the different types of land uses affected. The results of the assessment may be presented both before and after mitigation.

- **Noise/Vibration Mitigation:** The mitigation section of the technical report should begin with a summary of all treatments considered, even if some are not carried to final consideration. Final candidate mitigation treatments should be considered separately with description of the features of the treatment, costs, expected benefit in reducing impacts, locations where the benefit would be realized and discussion of practicality of implementing alternative treatments. With respect to noise impacts, enough information is to be included to allow the project sponsor and FTA to reach decisions on mitigation prior to issuance of the final environmental document.

- **Construction Noise/Vibration Impacts:** Criteria adopted for construction noise or vibration should be described, if appropriate. According to Chapter 12, these may be adopted on a project-specific basis. The method used for predicting construction noise or vibration should be described along with inputs to the models, such as equipment roster by construction phase, equipment source levels, assumed usage factors and other assumed site characteristics. The predicted levels should be shown for sensitive sites and short-term impacts should be identified. In cases where construction impacts appear to be problematic, feasible abatement methods should be discussed in enough detail such that construction contract documents could include mitigation measures.

- **References:** References should be provided for all criteria, approaches and data used in the analyses, including other reports related to the project which may be relied on for information, e.g., geotechnical reports.

13.2 THE ENVIRONMENTAL DOCUMENT

The environmental document typically includes noise and vibration information in three places: a section of the chapter on the affected environment (existing conditions) and two sections in the chapter on environmental consequences (the long-term impacts from operations and short-term impacts from construction activity). The noise and vibration information presented in the environmental document is a summary of the comprehensive information from the technical report with emphasis on presenting the salient points of the analysis in a format and style which affected property owners and other interested citizens can understand. Smaller projects may have all of the technical information contained within the environmental document, requiring special care in summarizing technical details to convey the information adequately.

The environmental document provides full disclosure of noise and vibration impacts, including identification of locations where impacts cannot be mitigated satisfactorily. An EIS describes significant impacts and tells what the Federal agency intends to do about them. For projects handled with EA's, completion of the environmental review with a finding of no significant impact (FONSI) may depend on mitigation being incorporated in the proposed project. The specific way mitigation is handled in the environmental document depends on the type of impact (noise or vibration) and the stage of project development and environmental review.

In general, airborne noise impacts can be accurately predicted in the preliminary engineering stage. Since the environmental review for major investment projects is completed during preliminary engineering, it is possible to specify, and commit to implement, any needed noise mitigation measures in the final environmental document (Final EIS or FONSI). With major investments, as well as small projects like bus terminals and garages, it is expected that decisions on noise mitigation will be made before the final document is approved; thus timely development of design, feasibility and cost information needed to reach decisions on noise mitigation is essential. For major investments in the Alternatives Analysis/Draft EIS stage, the emphasis is not on mitigation but rather a broad comparison among the alternatives concerning the magnitude and extent of noise impacts. If it seems likely that mitigation would be required for at least some major investment alternatives, this can be discussed in a general way while touching on the remaining stages of project development and how decisions on mitigation fit in. Finally, there are other projects for which the preferred alternative is identified at the outset in the Draft EIS or EA. With the focus on a single alternative, noise impacts can be accurately identified in the draft document. If mitigation is needed, mitigation options should be explored in the draft; however firm decisions on mitigation can be deferred to the final document.

Predicting vibration impacts accurately is a more complex undertaking because ground-borne vibration may be strongly influenced by subsurface conditions. The geotechnical studies that reveal these conditions are normally undertaken during the final design stage after the NEPA process has been completed. Thus, for ground-borne vibration and noise, the final environmental document will usually not be able to state with certainty whether or not mitigation is needed. The final environmental document will rely on a General Assessment for ground-borne vibration and noise to identify potential problem areas. If there are such areas, there should be a commitment in the final document to conduct a Detailed Analysis during final design to complete the impact assessment and help determine the need for mitigation. The final environmental document should present a preliminary assessment using the vibration impact criteria for the General Assessment. If it appears the criteria cannot be met, the document would discuss various control measures that could be used and the likelihood that the criteria could be met through the use of one or more of the measures. It may be possible to state a commitment in the final environmental document to adhere to the impact criteria for the Detailed Analysis, while deferring the selection of specific vibration control measures until the completion of detailed studies in final design.

After a final environmental document is approved, the described mitigation measures are incorporated by reference in the actual grant agreements signed by FTA and the project sponsor. Thus, they become contractual conditions that must be adhered to by the project sponsor.

13.2.1 Organization of Noise and Vibration Sections of Environmental Documents

Chapter on Affected Environment (Existing Conditions)

This chapter describes the pre-project setting, including the existing noise and vibration conditions, that will likely be affected by one or more of the alternatives. The primary function of this chapter is to establish the focus and baseline conditions for later chapters discussing environmental impacts. Consequently, it is a good place to put basic information on noise and vibration descriptors and effects, as well as describing the characteristics in the vicinity of the project. Again, it is preferable to separate the noise and vibration sections.

- **Description of Noise/Vibration Descriptors, Effects and Typical Levels:** Information from Chapters 2 and 7 of this manual can be used to provide a background for the discussions of noise/vibration levels and characteristics to follow. Illustrative material to guide the reader in understanding typical levels is helpful.
- **Inventory of Noise/Vibration-Sensitive Sites:** The approach for selecting noise/vibration-sensitive sites should be described in sufficient detail to demonstrate completeness. Sites and site descriptions are to be included.
- **Noise/Vibration Measurements:** A summary of the site selection procedure should be included along with tables of sites coordinated with maps showing locations of sites. The measurement approach should be summarized with justification for the measurement procedures used. The measurement data should be presented in well organized form in tables and figures. To save space, the results are often included with the table of sites described above. In some cases, measurements may be supplemented or replaced by collected data relevant to the noise and vibration characteristics of the area. For example, soils information for estimating ground-borne vibration propagation characteristics may be available from other projects in the area. Fundamental to this section is a summary and interpretation of how the collected data define the project setting.

Chapter on Environmental Consequences.

The section on long-term impacts - the impacts due to operation of the project - should be organized according to the following order:

- **Overview of Approach:** A summary of the assessment procedure for determining noise/vibration impacts is provided as a framework for the following sections.
- **Estimated Noise/Vibration Levels:** A general description of prediction models used to estimate project noise/vibration levels should be provided. Any distinguishing features unique to the project, such as source levels associated with various technologies, should be described. The results of the predictions for various alternatives should be described in general terms first, followed by a detailed accounting of predicted noise levels. This information should be supplemented with tables and

illustrated by contours, cross-sections or shaded mapping. If contours are included in a technical report, then it is not necessary to repeat them here.

- **Criteria for Noise/Vibration Impact:** Impact criteria for the project should be fully described and referenced (refer to Chapters 3 and 8). In addition, any applicable local ordinances should be described. Tables listing the criterion levels should be included.
- **Impact Assessment:** The impact assessment can be a section by itself or can be combined with the section above. It is important to provide a description of locations where noise/vibration impact is expected to occur without implementation of mitigation measures, based on the predicted future levels, existing levels and application of the impact criteria. Inventory tables of impacted land uses should be used to quantify the impacts for comparisons among alternatives. The comprehensive list of noise/vibration-sensitive sites identified in the Affected Environment chapter should be included in this inventory table.
- **Noise/Vibration Mitigation Measures:** Perhaps the most significant difference between the technical report and the environmental document is in the area of mitigation. Whereas the technical report discusses options and may make recommendations, the environmental document provides the vehicle for reaching decisions on appropriate mitigation measures with consideration given to environmental benefits, feasibility and cost. This section should begin with a summary of the noise/vibration mitigation measures considered for the impacted locations. The specific measures selected for implementation should be fully described. Reasons for dismissing any abatement measures should also be clearly stated, especially if such non-implementation results in significant adverse effects. In cases where it is not possible to commit to a specific mitigation measure in the final environmental document, it may be possible to commit to a certain level of noise/vibration reduction, for example, adherence to the impact criteria specified in Chapters 3 and 8.
- **Unavoidable Adverse Environmental Effects:** If it is projected that adverse noise/vibration impacts will result after all reasonable abatement measures have been incorporated, these impacts are identified in this section.

Impacts During Construction

The environmental document may have a separate section on short-term impacts due to project construction, depending on the scale of the project. For a major project there may be a special section on construction noise/vibration impacts; this section should be organized according to the comprehensive outline described above. For projects with relatively minor effects, a briefer format should be utilized, with a section included in the chapter on Environmental Consequences.

APPENDICES

APPENDIX A. GLOSSARY OF TERMS[1, 2]

A-weighting – A standardized filter used to alter the sensitivity of a sound level meter with respect to frequency so that the instrument is less sensitive at low and high frequencies where the human ear is less sensitive. Also written as dBA.

Accelerometer – A transducer that converts vibratory motion to an electrical signal proportional to the acceleration of that motion.

Ambient – The pre-project background noise or vibration level.

Amplitude – Difference between the extremes of an oscillating signal.

Alignment – The horizontal location of a railroad or transit system as described by curved and tangent track.

At-grade – Tracks on the ground surface.

Automated Guideway Transit (AGT) – Guided steel-wheel or rubber-tired transit passenger vehicles operating singly or in multi-car trains with a fully automated system on fixed guideways along an exclusive right-of-way. AGT includes personal rapid transit, group rapid transit and automated people mover systems.

Auxiliaries – The term applied to a number of separately driven machines, operated by power from the main engine or electric generation. They include the air compressor, radiator fan, traction motor blower, and air conditioning equipment.

Ballast mat – A 2- to 3-inch-thick elastomer mat placed under the normal track ballast on top of a rigid slab or packed sub-grade.

Ballast – Granular material placed on the trackbed for the purpose of holding the track in line and at surface.

Bus Rapid Transit (BRT) - A type of limited-stop bus operation that relies on technology to help speed up the service. Buses can operate on exclusive transitways, high-occupancy-vehicle lanes, expressways, or ordinary streets.

Catenary – On electric railroad and light rail transit systems, the term describing the overhead conductor that is contacted by the pantograph or trolley, and its support structure.

Commuter rail – Conventional passenger railroad serving areas surrounding an urban center. Most commuter railroads utilize locomotive-hauled coaches, often in push-pull configuration.

Consist – The total number and type of cars, locomotives, or transit vehicles in a trainset.

Continuous welded rail – A number of rails welded together to form unbroken lengths of track without gaps or joints.

Corrugated rail – A rough condition of alternating ridges and grooves which develops on the rail head in service.

Crest factor - The ratio of peak particle velocity to maximum RMS amplitude in an oscillating signal.

Criteria – Plural form of “criterion,” the relationship between a measure of exposure (e.g., sound or vibration level) and its corresponding effect.

Cross tie – The transverse member of the track structure to which the rails are spiked or otherwise fastened to provide proper gage and to cushion, distribute, and transmit the stresses of traffic through the ballast to the trackbed.

Crossover – Two turnouts with the track between the frogs arranged to form a continuous passage between two nearby and generally parallel tracks.

Cumulative – The summation of individual sounds into a single total value related to the effect over time.

Cut – A term used to describe a trackbed at a lower level than the surrounding ground.

dB – see Decibel.

dBA – see A-weighting.

Decibel – The standard unit of measurement for sound pressure level and vibration level. Technically, a decibel is the unit of level which denotes the ratio between two quantities that are proportional to power; the number of decibels is 10 times the logarithm of this ratio. Also written as dB.

Descriptor – A quantitative metric used to identify a specific measure of sound level.

DMU – Diesel-powered multiple unit. See Multiple Unit.

DNL – see $L_{dn.}$

Electrification – A term used to describe the installation of overhead wire or third rail power distribution facilities to enable operation of trains.

Embankment – A bank of earth, rock or other material constructed above the natural ground surface.

Equivalent Level – The level of a steady sound which, in a stated time period and at a stated location, has the same sound energy as the time-varying sound. Also written as L_{eq}.

Ferry boat – A transit mode comprised of vessels to carry passengers and/or vehicles over a body of water.

Fixed guideway – A mass transit facility with a separate right-of-way for the exclusive use of public transportation and other high-occupancy vehicles.

Flange – The vertical projection along the inner rim of a wheel that serves, together with the corresponding projection of the mating wheel of a wheel set, to keep the wheel set on the track.

Floating slab – A special track support system for vibration isolation, consisting of concrete slabs supported on resilient elements, usually rubber or similar elastomer.

Frequency – The number of times that a periodically occurring quantity repeats itself in a specified period. With reference to noise and vibration signals, the number of cycles per second.

Frequency spectrum – Distribution of frequency components of a noise or vibration signal.

Frog – A track structure used at the intersection of two running rails to provide support for wheels and passageways for their flanges, thus permitting wheels on either rail to cross the other.

Gage (of track) – The distance between the rails on a track.

Grade crossing – The point where a rail line and a motor vehicle road intersect.

Guideway – Supporting structure to form a track for rolling or magnetically-levitated vehicles.

Head-End Power (HEP) – A system of furnishing electric power for a complete railway train from a single generating plant in the locomotive.

Heavy rail – See Rail Rapid Transit.

Hertz (Hz) -- The unit of acoustic or vibration frequency representing cycles per second.

Hourly Average Sound Level – The time-averaged A-weighted sound level, over a 1-hour period, usually calculated between integral hours. Also written as L_{1h}.

Hybrid Bus – A rubber-tired vehicle that features a hybrid diesel-electric propulsion system. A diesel engine runs an electric generator that powers the entire vehicle including electric drive motors that deliver power to the wheels.

Idle – The speed at which an engine runs when it is not under load.

Intermediate Capacity Transit (ICT) – A transit system with less capacity than rail rapid transit, but more capacity than typical bus operations. Examples of ICT include bus rapid transit (BRT), automated guideway transit (AGT), monorails and trolleys.

Intermodal facility – Junction of two or more modes of transportation where transfers may occur.

Jointed rail – A system of joining rails with steel members designed to unite the abutting ends of contiguous rails.

L_{1h} – see Hourly Average Sound Level

L_{dn} – Day-Night Sound Level. The sound exposure level for a 24-hour day calculated by adding the sound exposure level obtained during the daytime (7 a.m. to 10 p.m.) to 10 times the sound exposure level obtained during the nighttime (10 p.m. to 7 a.m.). This unit is used throughout the U.S. for environmental impact assessment. Also written as DNL.

L_{eq} – see Equivalent Level

Light Rail Transit (LRT) – A mode of public transit with tracked vehicles in multiple units operating in mixed traffic conditions on streets as well as sections of exclusive right-of-way. Vehicles are generally powered by electricity from overhead lines.

Locomotive – A self-propelled, non-revenue rail vehicle designed to convert electrical or mechanical energy into tractive effort to haul railway cars. (see also Power Unit)

Main line – The principal line or lines of a railway.

Maglev – Magnetically-levitated vehicle; a vehicle or train of vehicles with guidance and propulsion provided by magnetic forces. Support can be provided by either an electrodynamic system wherein a moving vehicle is lifted by magnetic forces induced in the guideway, or an electromagnetic system wherein the magnetic lifting forces are actively energized in the guideway.

Maximum Sound Level – The highest exponential-time-average sound level, in decibels, that occurs during a stated time period. Also written as L_{max}. The standardized time periods are 1 second for $L_{max, slow}$ and 0.125 second for $L_{max, fast}$.

Metric – Measurement value, or descriptor.

Monorail – Guided transit vehicles operating on or suspended from a single rail, beam or tube.

Multiple Unit (MU) – A term referring to the practice of coupling two or more diesel-powered or electric-powered passenger cars together with provision for controlling the traction motors on all units from a single controller.

Noise – Any disagreeable or undesired sound or other audible disturbance.

Octave band – A standardized division of a frequency spectrum in which the interval between two divisions is a frequency ratio of 2.

One-third octave band – A standardized division of a frequency spectrum in which the octave bands are divided into thirds for more detailed information. The interval between center frequencies is a ratio of 1.25.

Pantograph – A device for collecting current from an overhead conductor (catenary), consisting of a jointed frame held up by springs or compressed air and having a current collector at the top.

Park-and-ride facility – A parking garage and/or lot used for parking passengers' automobiles while they use transit agency facilities and vehicles.

Peak factor – see Crest factor.

Plan-and-profile – Mapping used by transportation planners that shows two-dimensional plan views (x- and y- axes) on the same page as two-dimensional profiles (x- and z-axes) of a road or track.

Peak Particle Velocity (ppv) – The peak signal value of an oscillating vibration velocity waveform. Usually expressed in inches/second in the United States.

Peak-to-Peak (P-P) Value – Of an oscillating quantity, the algebraic difference between the extreme values of the quantity.

Power unit – A self-propelled vehicle, running on rails and having one or more electric motors that drive the wheels and thereby propel the locomotive and train. The motors obtain electrical energy either from a rail laid near to, but insulated from, the track rails, or from a wire suspended above the track. Contact with the wire is made by a pantograph mounted on top of the unit.

Pure tone – Sound of a single frequency.

Radius of curvature – A measure of the severity of a curve in a track structure based on the length of the radius of a circle that would be formed if the curve were continued.

Rail – A rolled steel shape, commonly a T-section, designed to be laid end to end in two parallel lines on cross ties or other suitable supports to form a track for railway rolling stock.

Rail Rapid Transit – (often called "Heavy Rail Transit") A mode of public transit with tracked vehicles in multiple units operating in exclusive rights-of-way. Trains are generally powered by electricity from a third rail alongside the track.

Receiver/Receptor – A stationary far-field position at which noise or vibration levels are specified.

Resonance frequency – The phenomenon that occurs in a structure under conditions of forced vibration such that any change in frequency of excitation results in a decrease in response.

Right-of-Way – Lands or rights used or held for railroad or transit operation.

Root Mean Square (rms) – The square root of the mean-square value of an oscillating waveform, where the mean-square value is obtained by squaring the value of amplitudes at each instant of time and then averaging these values over the sample time.

RMS Velocity Level (L_V) – See "Vibration Velocity Level."

SEL – see Sound Exposure Level.

Sound Exposure Level – The level of sound accumulated over a given time interval or event. Technically, the sound exposure level is the level of the time-integrated mean square A-weighted sound for a stated time interval or event, with a reference time of one second. Also written as SEL.

Sound – A physical disturbance in a medium that is capable of being detected by the human ear.

Spectrum – See Frequency Spectrum.

Sub-Ballast – Any material of a superior character, which is spread on the finished subgrade of the roadbed and below the top-ballast, to provide better drainage, prevent upheaval by frost, and better distribute the load over the roadbed.

Subgrade – The finished surface of the roadbed below the ballast and track.

Suburban bus – Bus similar to an intercity bus with high-backed seats but no luggage compartment, used in express mode to city centers from suburban locations.

Switch – A track structure used to divert rolling stock from one track to another.

Tangent Track – Track without curvature.

Track – An assembly of rail, ties and fastenings over which cars, locomotives, and trains are moved.

Traction Motor – A specially designed direct current series-wound motor mounted on the trucks of locomotives and self-propelled cars to drive the axles.

Trainset – A group of coupled cars including at least one power unit.

Transducer – Device designed to receive an input signal of a given kind (motion, pressure, heat, etc.) and to provide an output signal of a different kind (electrical voltage, amperage, etc.) in such a manner that desired characteristics of the input signal appear in the output signal for measurement purposes.

Transit center – A fixed location where passengers interchange from one route or vehicle to another.

Trolley bus – A rubber-tired, electrically-powered bus operating on city streets drawing power from overhead lines.

Truck – The complete assembly of parts including wheels, axles, bearings, side frames, bolster, brake rigging, springs and all associated connecting components, the function of which is to provide support, mobility and guidance to a railroad car or locomotive.

Trunk line – See Mainline. The mainline of a commuter railroad where the branch line traffic is combined.

Turnout – An arrangement of a switch and a frog with closure rails, by means of which rolling stock may be diverted from one track to another.

VdB – see Vibration Velocity Level.

Vibration Velocity Level (L_V) – Ten times the common logarithm of the ratio of the square of the amplitude of the RMS vibration velocity to the square of the amplitude of the reference RMS vibration velocity. The reference velocity in the United States is one micro-inch per second. Also written as VdB.

Vibration – An oscillation wherein the quantity is a parameter that defines the motion of a mechanical system.

Wheel Flat – A localized flat area on a steel wheel of a rail vehicle, usually caused by skidding on steel rails, causing a discontinuity in the wheel radius.

Wheel Squeal – The noise produced by wheel-rail interaction, particularly on a curve where the radius of curvature is smaller than allowed by the separation of the axles in a wheel set.

REFERENCES

1. American National Standards Institute, “Acoustical Terminology,” ANSI S1.1-1994

2. American Public Transportation Association, “Public Transportation Factbook,” 55th Edition, March 2004.

APPENDIX B. BACKGROUND FOR TRANSIT NOISE IMPACT CRITERIA

The noise criteria, presented in Chapter 3 of this manual, have been developed based on well-documented criteria and research into human response to community noise. The primary goals in developing the noise criteria were to ensure that the impact limits be firmly founded in scientific studies, be realistically based on noise levels associated with new transit projects, and represent a reasonable balance between community benefit and project costs. This appendix provides the background information.

B.1 RELEVANT LITERATURE

Following is an annotated list of the documents that are particularly relevant to the noise impact criteria:

1. US Environmental Protection Agency "Levels Document":(1) This report identifies noise levels consistent with the protection of public health and welfare against hearing loss, annoyance, and activity interference. It has been used as the basis of numerous community noise standards and ordinances.

2. CHABA Working Group 69, "Guidelines for Preparing Environmental Impact Statements on Noise":(2) This report was the result of deliberations by a group of leading acoustical scientists with the goal of developing a uniform national method for noise impact assessment. Although the CHABA's proposed approach has not been adopted, the report serves as an excellent resource documenting research in noise effects. It provides a strong scientific basis for quantifying impacts in terms of L_{dn}.

3. American Public Transit Association Guidelines:(3) The noise and vibration sections of the APTA Guidelines have been used successfully in the past for the design of rail transit facilities. The APTA Guidelines include criteria for acceptable community noise and vibration. Experience has shown that meeting the APTA Guidelines will usually result in acceptable noise levels. However, there are some problems in using the APTA Guidelines for environmental assessment purposes. The criteria are in terms of L_{max} for conventional rail rapid transit vehicles and they cannot be used to compare among

different modes of transit. Since the APTA Guidelines are expressed in terms of maximum passby noise, they are not sensitive to the frequency or duration of noise events for transit modes other than conventional rail rapid transit operations with 5- to 10-minute headways. Therefore, the APTA criteria are questionable for assessing the noise impact of other transit modes which differ from conventional rapid transit with respect to source emission levels and operating characteristics (e.g., commuter rail, AGT and a variety of bus projects).

4. "Synthesis of Social Surveys on Noise Annoyance":(4) In 1978, Theodore J. Schultz, an internationally known acoustical scientist, synthesized the results of a large number of social surveys, each concerning annoyance due to transportation noise. Remarkable consistency was found in a group of these surveys, and the author proposed that their average results be taken as the best available prediction of transportation noise annoyance. This synthesis has received essentially unanimous acceptance by acoustical scientists and engineers. The "universal" transportation response curve developed by Schultz (Figure 2-7) shows that the percent of the population highly annoyed by transportation noise increases from zero at an L_{dn} of approximately 50 dBA to 100-percent when L_{dn} is about 90 dBA. Most significantly, this curve indicates that for the same increase in L_{dn}, there is a greater increase in the number of people highly annoyed at high noise levels than at low noise levels. In other words, a 5 dB increase at low ambient levels (40 - 50 dB) has less impact than at higher ambient levels (65 - 75 dB). A recent update of the original research, containing several railroad, transit and street traffic noise surveys, confirmed the shape of the original Schultz curve.(5)

5. HUD Standards:(6) The U.S. Department of Housing and Urban Development has developed noise standards, criteria and guidelines to ensure that housing projects supported by HUD achieve the goal of a suitable living environment. The HUD site acceptability standards define 65 dB (L_{dn}) as the threshold for a normally unacceptable living environment and 75 dB (L_{dn}) as the threshold for an unacceptable living environment.

B.2 BASIS FOR NOISE IMPACT CRITERIA CURVES

The lower curve in Figure 3-1 representing the onset of Moderate Impact is based on the following considerations:

- The EPA finding that a community noise level of L_{dn} less than or equal to 55 dBA is "requisite to protect public health and welfare with an adequate margin of safety."(1)

- The conclusion by EPA and others that a 5 dB increase in L_{dn} or L_{eq} is the minimum required for a change in community reaction.

- The research finding that there are very few people highly annoyed when the L_{dn} is 50 dBA, and that an increase in L_{dn} from 50 dBA to 55 dBA results in an average of 2% more people highly annoyed (see Figure 2-10 in Chapter 2).

Consequently, the change in noise level from an existing ambient level of 50 dBA to a cumulative level of 55 dBA caused by a project is assumed to be a minimal impact. Expressed another way, this is considered to be the lowest threshold where impact starts to occur. Moreover, the 2% increment represents the minimum measurable change in community reaction. Thus the curve's hinge point is placed at a project noise level of 53 dBA and an existing ambient noise level of 50 dBA, the combination of which yields a cumulative level of 55 dBA. The remainder of the lower curve in Figure 3-1 was determined from the annoyance curve (Figure 2-10) by allowing a fixed 2% increase in annoyance at other levels of existing ambient noise. As cumulative noise increases, it takes a smaller and smaller increment to attain the same 2% increase in highly annoyed people. While it takes a 5 dB noise increase to cause a 2% increase in highly annoyed people at an existing ambient noise level of 50 dB, an increase of only 1 dB causes the 2% increase of highly annoyed people at an existing ambient noise level of 70 dB.

The upper curve delineating the onset of Severe Impact was developed in a similar manner, except that it was based on a total noise level corresponding to a higher degree of impact. The Severe Noise Impact curve is based on the following considerations:

- The Department of Housing and Urban Development (HUD) in its environmental noise standards defines an L_{dn} of 65 as the onset of a normally unacceptable noise zone.[(6)] Moreover, the Federal Aviation Administration (FAA) considers that residential land uses are not compatible with noise environments where L_{dn} is greater than 65 dBA [(7)].

- The common use of a 5 dBA increase in L_{dn} or L_{eq} as the minimum required for a change in community reaction.

- The research finding that the foregoing step represents a 6.5% increase in the number of people highly annoyed (see Figure 2-10 in Chapter 2).

Consequently, the increase in noise level from an existing ambient level of 60 dBA to a cumulative level of 65 dBA caused by a project represents a change from an acceptable noise environment to the threshold of an unacceptable noise environment. This is considered to be the level at which severe impact starts to occur. Moreover, the 6.5% increment represents the change in community reaction associated with severe impact. Thus the upper curve's hinge point is placed at a project noise level of 63 dBA and existing ambient noise level of 60 dBA, the combination of which yields a cumulative level of 65 dBA. The remainder of the upper curve in Figure 3-1 was determined from the annoyance curve (Figure 2-10) by fixing the 6.5% increase in annoyance at all existing ambient noise levels.

Both curves incorporate a maximum limit for the transit project noise in noise-sensitive areas. Independent of existing noise levels, Moderate Impact for land use categories 1 and 2 is considered to occur whenever the transit L_{dn} equals or exceeds 65 dBA and Severe Impact occurs whenever the transit L_{dn} equals or exceeds 75 dBA. These absolute limits are intended to restrict activity interference caused by the transit project alone.

Both curves also incorporate a maximum limit for cumulative noise increase at low existing noise levels (below about 45 dBA). This is a conservative measure that reflects the lack of social survey data on people's reaction to noise at such low ambient levels. Similar to the FHWA approach in assessing the relative impact of a highway project, the transit noise criteria include caps on noise increase of 10 dB and 15 dB for Moderate Impact and Severe Impact, respectively, relative to the existing noise level.

Finally, it should be noted that due to the types of land use included in Category 3, the criteria allow the project noise for Category 3 sites to be 5 decibels greater than for Category 1 and Category 2 sites. This difference is reflected by the offset in the vertical scale on the right side of Figure 3-1. With the exception of active parks, which are clearly less sensitive to noise than Category 1 and 2 sites, Category 3 sites include primarily indoor activities and thus the criteria account for some noise reduction provided by the building structure.

B.3 EQUATIONS FOR NOISE IMPACT CRITERIA CURVES

The noise impact criteria can be quantified through the use of mathematical equations which approximate the curves shown in Figure 3-1. These equations may be useful when performing the noise assessment methodology through the use of spreadsheets, computer programs or other analysis tools. Otherwise, such mathematical detail is generally not necessary in order to properly implement the criteria, and direct use of Figure 3-1 is likely to be adequate and less time-consuming.

A total of four continuous curves are obtained from the criteria: two threshold curves ("Moderate Impact" and "Severe Impact") for Category 1 and 2; and two for Category 3. Note that for each level of impact, the overall curves for Categories 1 and 2 are offset by 5 dB from Category 3. While each curve is graphically continuous, it is defined by a set of three discrete equations which represent three "regimes" of existing noise exposure. These equations are approximately continuous at the transition points between regimes.

The first equation in each set is a linear relationship, representing the portion of the curve in which the existing noise exposure is low and the allowable increase is capped at 10 dB and 15 dB for Moderate Impact and Severe Impact, respectively. The second equation in each set represents the impact threshold over the range of existing noise exposure for which a fixed percentage of increase in annoyance is allowed, as described in the previous section. This curve, a third-order polynomial approximation derived from the Schultz curve,[(4)] covers the range of noise exposure encountered in most populated areas and is used in determining noise impact in the majority of cases for transit projects. Finally, the third equation in each of the four sets represents the absolute limit of project noise imposed by the criteria, for areas with high existing noise exposure. For land use category 1 and 2, this limit is 65 dBA for Moderate Impact and 70 dBA for Severe Impact. For land use category 3, the limit is 75 dBA for Moderate Impact and 80 dBA for Severe Impact.

The four sets of equations corresponding to the curves are given below. Each curve represents a threshold of noise impact, with impact indicated for points on or above the curve.

Threshold of Moderate Impact:

$$L_P = \begin{cases} 11.450 + 0.953 L_E & L_E < 42 \\ 71.662 - 1.164 L_E + 0.018 L_E^{\,2} - 4.088 \times 10^{-5} L_E^{\,3} & 42 \le L_E \le 71 \\ 65 & L_E > 71 \end{cases} \Bigg\} \text{Category 1 and 2}$$

$$L_P = \begin{cases} 16.450 + 0.953 L_E & L_E < 42 \\ 76.662 - 1.164 L_E + 0.018 L_E^{\,2} - 4.088 \times 10^{-5} L_E^{\,3} & 42 \le L_E \le 71 \\ 70 & L_E > 71 \end{cases} \Bigg\} \text{Category 3}$$

Threshold of Severe Impact:

$$L_P = \begin{cases} 17.322 + 0.940 L_E & L_E < 44 \\ 96.725 - 1.992 L_E + 3.02 \times 10^{-2} L_E^{\,2} - 1.043 \times 10^{-4} L_E^{\,3} & 44 \le L_E \le 77 \\ 75 & L_E > 77 \end{cases} \Bigg\} \text{Category 1 and 2}$$

$$L_P = \begin{cases} 22.322 + 0.940 L_E & L_E < 44 \\ 101.725 - 1.992 L_E + 3.02 \times 10^{-2} L_E^{\,2} - 1.043 \times 10^{-4} L_E^{\,3} & 44 \le L_E \le 77 \\ 80 & L_E > 77 \end{cases} \Bigg\} \text{Category 3}$$

where L_E is the existing noise exposure in terms of L_{dn} or L_{eq}(h) and L_P is the project noise exposure which determines impact, also in terms of L_{dn} or L_{eq}(h).

REFERENCES

1. U.S. Environmental Protection Agency, "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety," EPA report number 550/9-74-004, March 1974.

2. National Academy of Sciences, "Guidelines for Preparing Environmental Impact Statements on Noise," Report from Committee on Bioacoustics and Biomechanics (CHABA) Working Group 69, February 1977.

3. American Public Transit Association, *1981 Guidelines for Design of Rapid Transit Facilities*, Section 2.7, "Noise and Vibration," 1981.

4. T.J. Schultz, "Synthesis of Social Surveys on Noise Annoyance," Journal of the Acoustical Society of America, Vol. 64, No. 2, pp. 377-405, August 1978.

5. S. Fidell, D.S. Barber and T.J. Schultz, "Updating a Dosage-Effect Relationship for the Prevalence of Annoyance Due to General Transportation Noise," Journal of the Acoustical Society of America, Vol. 89, No. 1, January 1991.

6. U.S. Department of Housing and Urban Development, "Environmental Criteria and Standards", 24 CFR Part 51,v 12 July 1979; amended by 49 FR 880, 6 January 1984.

7. U.S. Department of Transportation, Federal Aviation Administration, "Federal Aviation Regulations Part 150: Airport Noise Compatibility Planning," January 1981.

APPENDIX C. SELECTING RECEIVERS OF INTEREST

This appendix provides additional detail in selecting receivers of interest for those users desiring such detail. The general approach given in Chapter 6 includes the following guidelines:

- Every major public building or site with noise-sensitive indoor use within the noise study area should be selected as a separate receiver of interest.
- Each isolated residence and small outdoor noise-sensitive area within the noise study area should be selected as a separate receiver of interest in the same manner as for public buildings.
- In contrast, groups of residences and larger outdoor noise-sensitive areas within the noise study area should be "clustered" and a receiver of interest selected from each cluster. Clustering reduces the number of computations later needed, especially for large-scale projects where a great number of noise-sensitive sites may be affected. For this approach to work, however, it is essential that the receiver selected provide an accurate representation of the noise environment of the cluster.

This appendix elaborates on the clustering procedure. In brief: (1) Cluster boundaries are first drawn relative to the proposed project, either running parallel to a linear project or circling major stationary sources. These boundaries approximate contours of equal project noise. (2) Then a separate set of cluster boundaries is drawn parallel to, or circling, major sources of ambient noise to approximate contours of ambient noise. (3) Finally, a third set of cluster boundaries may further subdivide the noise study area, if there are changes in project layout or operations along the corridor.

Following are suggested procedures for drawing cluster boundaries and for selecting a receiver of interest from each cluster:

Boundaries along the proposed project. First draw cluster boundaries along the proposed project, to separate clusters based upon distance from the project. Draw such cluster boundaries for all sources that are listed as "Major" in Table 6-2.

Within both residential and noise-sensitive outdoor areas:

- **Primary project source.** Draw cluster boundaries at the following distances from the near edge of the primary project source: 0 feet, 50 feet, 100 feet, 200 feet, 400 feet, and 800 feet. If the primary project source is a linear source, such as a rail line, draw these boundaries as lines parallel to the proposed right-of-way line. Around major stationary sources, draw these boundaries as approximate circles around the source, starting at the property line. Do not extend boundaries beyond the noise study area, identified in the Screening Procedure of Chapter 4 or the General Assessment of Chapter 5.
- **Remaining project sources**. Repeat this for all other project sources listed as Major in Table 6-2, such as substations and crossing signals. If several project sources are located approximately together, only one need be considered here, since the others would produce approximately the same boundaries. It is good practice to optimize the number of clusters for a project, to avoid needlessly complicating the procedure.

Where rows of buildings parallel the transit corridor:

- Check that cluster boundaries fall between the following rows of buildings, counting back away from the proposed project:

  Between rows 1 and 2

  Between rows 2 and 3

  Between rows 4 and 5

  If not, add cluster boundaries between these rows.

Boundaries along sources of ambient noise. Next, draw cluster boundaries along all major sources of ambient noise, based upon distance from these sources.

- Along all interstates and major roadway arterials, draw cluster boundaries at the following distances from the near edge of the roadway: 0 feet, 100 feet, 200 feet, and 500 feet.
- Along all other roadways that have state or county numbering, draw cluster boundaries at 0 feet and 100 feet from the near edge of the roadway.
- For all major industrial sources of noise, draw cluster boundaries that circle the source, at the following distances from the near property line of the source: 0 feet, 100 feet, 200 feet, 400 feet.

Further boundaries based upon changes in project layout or operations along the corridor. Where proposed project layout or operating conditions change significantly along the corridor, further subdivision is needed to account for changes in project noise. Draw a cluster boundary perpendicular to the corridor, extending straight outward to both sides, at the following locations:

- Where parallel tracks, previously separated by more than 100 feet or so, come closer together
- Approximately where speed and/or throttle is reduced approaching stations and where steady service speed is reached after departing stations.
- Approximately 200 feet up and down the line from grade-crossing bells
- At transitions from jointed to welded rail
- At transitions from one type of cross section to another -- from among these types: on structure, on fill, at grade, and in cut.
- At transitions from open terrain to heavily wooded terrain
- At transitions between areas free of locomotive-horn noise and areas subject to this noise source
- Any other positions along the line where project noise is expected to change significantly -- such as up and down the line from tight curves where wheels may squeal

Selection of a receiver of interest from each cluster. The cluster boundaries divide the land area into clusters of miscellaneous shape. Each of these pieces constitutes an area that will be represented by a single receiver of interest.

- For residential clusters, locate this receiver of interest within the cluster at the house closest to the proposed project. If in doubt, select the one furthest from significant sources of ambient noise.
- For outdoor noise-sensitive clusters, such as an urban park or amphitheater, locate this receiver of interest within the cluster at the closest point of active noise-sensitive use. If in doubt, select the one furthest from significant sources of ambient noise.

In following the foregoing procedures, some clusters may fall between areas with receivers of interest. This could occur, for example, when operational changes or track layouts change in an open undeveloped area. Retain such clusters -- that is, do not merge them with adjacent ones -- but do not select a receiver of interest from them.

Example C-1. Receivers of Interest and Cluster Boundaries

An example of receivers of interest and cluster boundaries is shown in Figure C-1. In this hypothetical situation, a new rail transit line, labeled "new rail line," is proposed along a major urban street with commercial land use. A residential area is located adjacent to the commercial strip, starting about one-half block from the proposed transit alignment. A major arterial, labeled "highway," crosses the alignment.

Following the procedure described in this appendix, the first step is to draw cluster boundaries along the **proposed primary project source** (in this case, the new rail line) at distances of 0 feet from the right-of-way line (edge of the street in this example), 50 feet, 100 feet, 200 feet, 400 feet, and 800 feet. These lines are shown with distances labeled at the top of the figure. This is proposed to be a constant speed section of track, so there are no changes in boundaries due to changes in operations along the corridor. Moreover, no **other project sources** are shown here, although if there had been a station with a parking lot, lines would have been drawn enveloping the station site at the specified distances from the property line. However, this example does show **rows of buildings parallel** to the transit corridor. The first set of lines satisfies the requirement that cluster boundaries fall between rows 1 and 2, and between rows 2 and 3, but there is no line between rows 4 and 5. Consequently, a cluster boundary (labeled "R" at the top of the figure) has been drawn between the 4th and 5th row of buildings.

Next, cluster boundaries are to be drawn along major sources of ambient noise. The roadway arterial (labeled "highway") is the only major source of ambient noise shown. Again following the procedure described in this appendix, cluster boundaries are drawn at 0 feet, 100 feet, 200 feet and 500 feet from the near edge of the roadway, both sides. These lines are shown with distances labeled at the side of the figure.

The foregoing describes the procedures for drawing all the lines defining the cluster boundaries shown in Figure C-1. The next step is to **select a receiver of interest within each cluster**. These are shown as filled circles in the figure. Some receivers of interest are labeled for use as examples in Appendix D. Taking the shaded cluster with "Rec 3" as an example: the cluster is located at the outer edge of influence from the major source ("highway"), where local street traffic takes over from the highway as the dominant source for ambient noise, which would be verified by a measurement. "Rec 3" is chosen to represent this cluster because it is among the houses closest to the proposed project source in this cluster and it is in the middle of the block affected by the dominant local street. Ambient noise levels at one end of the cluster may be influenced more by the highway and the other end may be affected more by the cross street, but the majority of the cluster would be represented by receiver site "Rec 3."

End of Example C-1

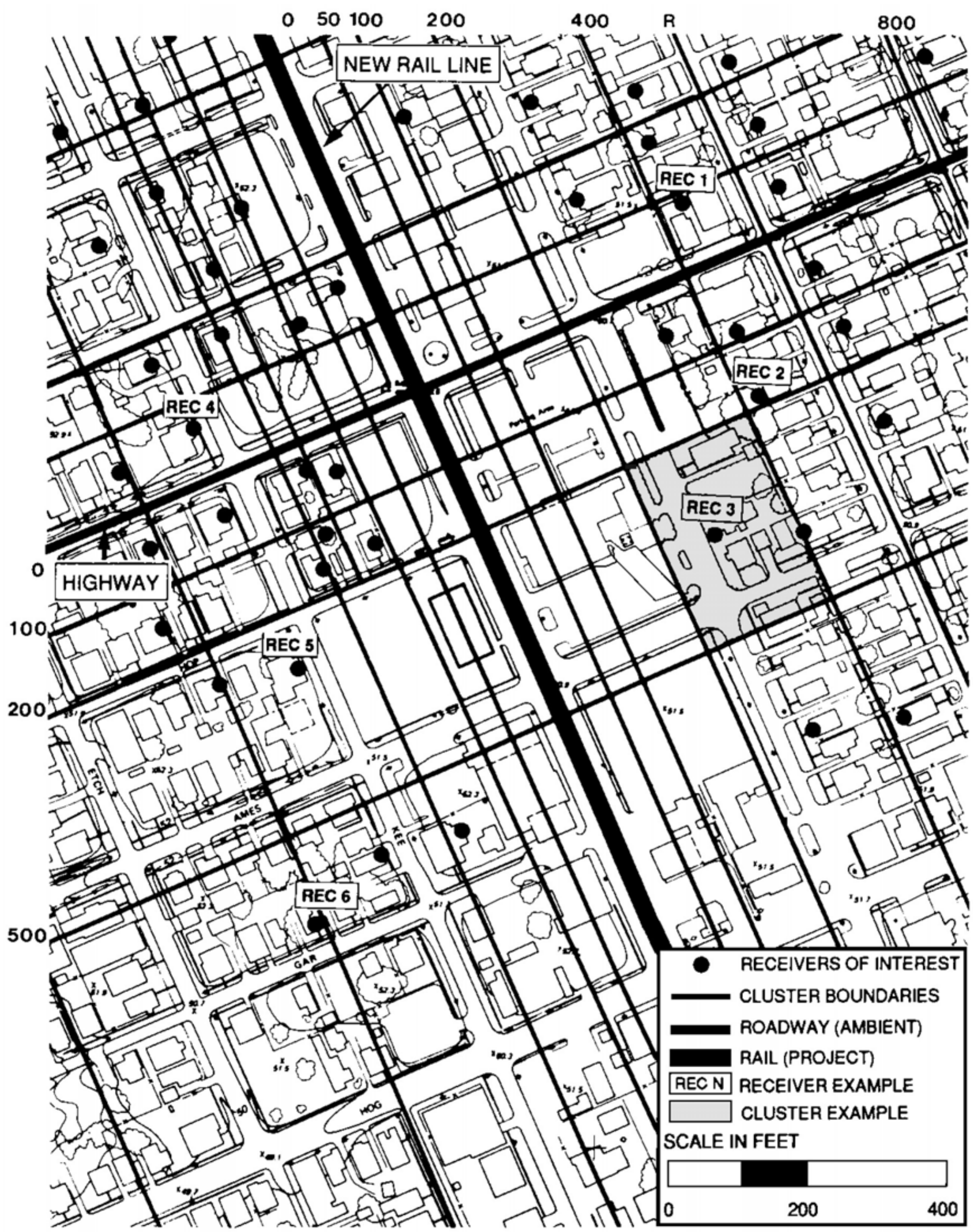

Figure C-1. Example of Receiver Map Showing Cluster Boundaries

APPENDIX D. DETERMINING EXISTING NOISE

This appendix provides additional detail in determining existing noise by: (1) full measurement, (2) computation from partial measurements, and (3) tabular look-up. Note that the words "existing noise" and "ambient noise" are often used interchangeably.

Continuing with the example from Figure C-1, the ambient noise at the selected receivers of interest, labeled "REC 1,2,3...," can be determined according to the following methods.

- Existing noise at REC 1 is due to the highway at the side of this church. L_{eq} during a typical church hour was measured in full. – OPTION 1 below
- Existing noise at REC 2, a residence, is due to a combination of the highway and local streets. L_{dn} was measured in full. – OPTION 2 below
- Existing noise at REC 3 is due to the street in front of this residence. L_{dn} was computed from three hourly L_{eq} measurements. – OPTION 3 below
- Existing noise at REC 4, a residence, is due to the highway. Since the highway has a predictable diurnal pattern, L_{dn} was computed from one hourly L_{eq} measurement. – OPTION 4 below
- Existing noise at REC 5, a residence, is due to Kee Street. L_{dn} was computed from L_{dn} at the comparable REC 3, which is also affected by local street traffic and is a comparable distance from the highway. – OPTION 5 below
- Existing noise at REC 6, a residence, is due to local traffic. L_{dn} was estimated by table look-up, based upon population density along this corridor. – OPTION 6 below

The full set of options for determining existing noise at receivers of interest is as follows:

- For non-residential land uses, measure a full hour's L_{eq} at the receiver of interest, during a typical hour of use on two non-successive days. The hour chosen should be the one in which maximum project activity will occur. The L_{eq} will be accurately represented.-- OPTION 1

- The three options for residential land uses are:
  - Measure a full day's L_{dn}. The L_{dn} will be accurately represented. – OPTION 2
  - Measure the hourly L_{eq} for three typical hours: peak traffic, midday and late night. Then compute the L_{dn} from these three hourly L_{eq}'s. The computed L_{dn} will be slightly underestimated. – OPTION 3
  - Measure the hourly L_{eq} for one hour of the day only, preferably during midday. Then compute the L_{dn} from this hourly L_{eq}. The computed L_{dn} will be moderately underestimated. – OPTION 4
- For all land uses, compute either the L_{eq} or the L_{dn} from a measured value at a nearby receiver – one where the ambient noise is dominated by the same noise source. The computed value will be represented with only moderate precision. – OPTION 5
- For all land uses, estimate either the L_{eq} or the L_{dn} from a table of typical values, depending upon distance from major roadways or upon population density. The resulting values will be significantly underestimated. – OPTION 6

Option 1: For non-residential land uses, measure the hourly L_{eq} for the hour of interest

Full one-hour measurements are the most precise way to determine existing noise for non-residential receivers of interest. Such full-duration measurements are preferred over all other options. The following procedures apply to full-duration measurements:

- Measure a full hour's L_{eq} at the receiver of interest on at least two non-successive days during a typical hour of use. This would generally be between noon Monday and noon Friday, but weekend days may be appropriate for places of worship. On both days, the measured hour must be the same as that for which project noise is computed: the loudest facility hour that overlaps hours of noise-sensitive activity at the receiver.
- At all sites, locate the measurement microphone as shown in Figure 6-9, depending upon the relative orientation of project and ambient sources. Desired is a microphone location that is shielded somewhat from the ambient source. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.
- Undertake all measurements in accordance with good engineering practice.

Option 2: For residential land uses, measure the L_{dn} for a full 24 hours

Full 24-hour measurements are the most precise way to determine ambient noise for residential receivers of interest. Such full-duration measurements are preferred over all other options. The following procedures apply to full-duration measurements:

- Measure a full 24-hour's L_{dn} at the receiver of interest, for a single weekday (generally between noon Monday and noon Friday).
- At all sites, locate the measurement microphone as shown in Figure 6-9, depending upon the relative orientation of project and ambient sources. Desired is a microphone location that is shielded somewhat from the ambient source. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.
- Undertake all measurements in accordance with good engineering practice.

Option 3: For residential land uses, measure the hourly L_{eq} for three hours and then compute L_{dn}

An alternative way to determine L_{dn}, less precise than its full-duration measurement, is to measure hourly L_{eq}'s for three typical hours of the day and then to compute the L_{dn} from these three hourly L_{eq}'s. The following procedures apply to this partial-duration measurement option for L_{dn}:

- Measure the one-hour L_{eq} during each of the following time periods: once during peak-hour roadway traffic, once midday between the morning and afternoon roadway-traffic peak hours, and once during late night between midnight and 5 am.
- Compute L_{dn} with the following equation:

$$\boxed{L_{dn} \approx 10\log\left[(3)\cdot 10^{\frac{L_{eq}(\text{peakhour})-2}{10}} + (12)\cdot 10^{\frac{L_{eq}(\text{midday})-2}{10}} + (9)\cdot 10^{\frac{L_{eq}(\text{latenight})+8}{10}}\right] - 13.8}$$

  This value of L_{dn} will be slightly underestimated due to the subtraction of 2 decibels from each of the measured levels before their combination. As explained previously, this underestimate is intended to compensate for the reduced precision of the computed L_{dn} here, compared to its full-duration measurement.

- At all sites, locate the measurement microphone as shown in Figure 6-9, depending upon the relative orientation of project and ambient sources. Desired is a microphone location that is shielded somewhat from the ambient source. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.
- Undertake all measurements in accordance with good engineering practice.

Option 4: For residential land uses, measure the hourly L_{eq} for one hour and then compute L_{dn}

The next level down in precision is to determine L_{dn} by measuring the hourly L_{eq} for one hour of the day and then to compute L_{dn} from this hourly L_{eq}. This method is useful when there are many sites in a General

Assessment, or when checking whether a particular receiver of interest represents a cluster in a Detailed Analysis. The following procedures apply to this partial-duration measurement option for L_{dn}:

- Measure the one-hour L_{eq} during any hour of the day. The loudest hour during the daytime period is preferable. If this hour is not selected, then other hours may be used with less precision.
- Convert the measured hourly L_{eq} to L_{dn} with the applicable equation:

$$\boxed{\begin{array}{r} \text{For measurements between 7am and 7pm}: L_{dn} \approx L_{eq} - 2 \\ \text{For measurements between 7pm and 10pm}: L_{dn} \approx L_{eq} + 3 \\ \text{For measurements between 10pm and 7am}: L_{dn} \approx L_{eq} + 8 \end{array}}$$

  The resulting value of L_{dn} will be moderately underestimated due to the use of the adjustment constants in these equations. As explained previously, this underestimate is intended to compensate for the reduced precision of the computed L_{dn} here, compared to the more precise methods of determining L_{dn}.

- At all sites, locate the measurement microphone as shown in Figure 6-9, depending upon the relative orientation of project and existing sources. Desired is a microphone location that is shielded somewhat from the ambient source. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.
- Undertake all measurements in accordance with good engineering practice

Option 5: For all land uses, compute either L_{eq} or L_{dn} from a nearby measured value

A computation method comparable in precision to Option 4 is to determine the ambient noise, either L_{eq}(h) or $L_{dn,}$ from a measured value at a nearby receiver – one where the ambient noise is dominated by the same noise source. This method is used to characterize noise in several neighborhoods by using a single representative receiver. Care must be taken to ensure that the measurement site has a similar noise environment to all areas represented. If measurements made by others are available, and the sites are equivalent, they can be used to reduce the amount of project noise monitoring. The following procedures apply to this computation of ambient noise at the receiver of interest:

- Choose another receiver of interest, called the "comparable receiver," at which:
  - o The same source of ambient noise dominates.
  - o The ambient $L_{CompRec}$ was measured with either OPTION 1 or OPTION 2 above.
  - o The ambient measurement at the comparable receiver was made in direct view of the major source of ambient noise, unshielded from it by noise barriers, terrain, rows of buildings, or dense tree zones.

- From a plan or aerial photograph, determine: (1) the distance $D_{CompRec}$ from the comparable receiver to the near edge of the ambient source, and (2) the distance $D_{ThisRec}$ from this receiver of interest to the near edge of the ambient source.
- Also determine N, the number of rows of buildings that intervene between the receiver of interest and the ambient source.
- Compute the ambient level at this receiver of interest with the applicable equation:

If roadway sources dominate:
$$L_{ThisRec} \approx L_{CompRec} - 15\log\left(\frac{D_{ThisRec}}{D_{CompRec}}\right) - 3N$$

If other sources dominate:
$$L_{ThisRec} \approx L_{CompRec} - 25\log\left(\frac{D_{ThisRec}}{D_{CompRec}}\right) - 3N$$

The resulting value of $L_{ThisRec}$ will be moderately underestimated. As explained previously, this underestimate is intended to compensate for the reduced precision of the computed L_{dn} here, compared to the more precise methods of determining ambient noise levels.

Option 6: For all land uses, estimate either $L_{eq}(h)$ or L_{dn} from a table of typical values

The least precise way to determine the ambient noise is to estimate it from a table. A tabular look-up can be used to establish baseline conditions for a General Noise Assessment if a noise measurement can not be made. It should not be used for a Detailed Noise Analysis. For this estimate of ambient noise:

- Read the ambient noise estimate from the relevant portion of Table 5-7. These tabulated estimates depend upon distance from major roadways, rail lines or upon population densities. In general, these tabulated values are significant underestimates. As explained previously, underestimates here are intended to compensate for the reduced precision of the estimated ambients, compared to the options that incorporate some degree of measurements.

APPENDIX E. COMPUTING SOURCE REFERENCE LEVELS FROM MEASUREMENTS

This appendix contains the procedures for computing source reference levels (SEL_{ref}) from source measurements in cases where the Source Reference Tables in Chapter 6 indicate measurements are preferred.

For vehicle passbys, the closeby source measurements may be either of the vehicle's sound exposure level (SEL) or of its maximum noise level (L_{max}). Both these descriptors can be measured directly by commonly available sound level meters. L_{max}'s are allowed here for several reasons. Often L_{max} measurements are available from transit-equipment manufacturers. For some transit systems, equipment specifications will limit closeby L_{max}'s to some particular value. And in some situations, closeby source measurements may be taken as part of the environmental study for more precision than is possible with the reference-level table.

For non-passby sources, the closeby source measurements must be of the source's SEL over one source "event." The source "event" duration may be chosen for measurement convenience; it will subtract out of the computation when the measured value is converted to reference operating conditions later in this section.

This manual does not specify elaborate methods for undertaking such closeby source measurements, nor that these measurements be at the reference conditions discussed in the main text. Required are measurements that conform to good engineering practice, guided by the standards of the American National Standards Institute and other such organizations (see References 2, 3 and 4 of Chapter 6).

For passbys of both highway and rail vehicles, the following conditions are required in addition to good engineering practice:

- Measured vehicles must be representative of project vehicles in all aspects, including representative acceleration and speed conditions for buses.

- Track must be relatively free of corrugations and train wheels relatively free of flats, unless these conditions are typical of the proposed project.
- Road surfaces must be smooth and dry, unless these conditions are typical of the proposed project.
- Perpendicular distance between the measurement position and the source's centerline must be 100 feet or less.
- Vehicle speed must be 30 miles per hour or greater, unless typical project speeds are less than that.
- No noise barriers, terrain, buildings, or dense tree zones may break the lines-of-sight between the source and the measurement position.

For sources other than vehicle passbys, the following conditions are required in addition to good engineering practice:

- Measured source operations must be representative of project operations in all aspects.
- The following ratio must be 2 or less:

  distance to the furthest source component
  divided by
  distance to the closest source component

  In addition, the distance to the closest source component must be 200 feet or less. If both these conditions cannot simultaneously be met, then separate closeby measurements must be made of individual components of this source, for which these distance conditions can be met.

- The following ratio must be 2 or less:

  lateral length of the source area, measured perpendicular to the general line-of-sight between source and measurement position
  divided by
  distance to the closest source component

  If this condition cannot be met, then separate closeby measurements must be made of individual components of this source, for which this condition can be met.

- No noise barriers, terrain, buildings, or dense tree zones may break the lines-of-sight between the source and the measurement position.

When closeby source measurements are made under non-reference conditions, the equations in Table E-1 are used to convert the measured values to Source Reference Levels. Detailed procedures follow. Note that each vehicle type must be measured and converted separately. Note that this computation requires that all measured vehicles be of the same type. For trains of mixed consists, see Appendix F. For rail vehicles, measure/convert a group of locomotives **or** a group of cars separately.

<u>If SEL was measured for a highway-vehicle passby, or a passby of a group of identical rail vehicles:</u>

- Collect the following input information:
  - SEL_{meas}, the measured SEL for the vehicle passby
  - N, the consist of the measured group of rail cars or group of locomotives
  - T, the average throttle setting of the measured diesel-powered locomotive(s)
  - S_{meas}, the measured passby speed, in miles per hour
  - D_{meas}, the closest distance between the measurement position and the source, in feet
- Compute the Source Reference Level -- SEL_{ref} -- from the **first** equation in Table E-1.

Example E-1. Computation of SEL_{ref} from SEL Measurement of Fixed-Guideway Source

A passby of two diesel-powered locomotives was measured at

SEL_{meas} = 90 dBA.

For this measurement,

N = 2
T = 6
S_{meas} = 55 miles per hour, and
D_{meas} = 65 feet.

The resulting SEL_{ref} = 86.5 dBA.

End of Example E-1

<u>If SEL was measured for a stationary noise source:</u>

- Collect the following input information:
  - SEL_{meas}, the measured SEL for the noise source, for whatever source "event" is convenient to measure
  - E_{meas}, the event duration, in seconds
  - D_{meas}, the closest distance between the measurement position and the source, in feet
- Compute the Source Reference Level -- SEL_{ref} -- from the **second** equation in Table E-1.

Example E-2. Computation of SEL_{ref} from SEL Measurement of Stationary Source

A signal crossing was measured for a 10-second "event" at

SEL_{meas} = 70.

For this measurement,

E_{meas} = 10 seconds and
D_{meas} = 25 feet.

The resulting SEL_{ref} = 89.5 dBA.

End of Example E-2

<u>If L_{max} was measured for a passby of a group of identical rail vehicles:</u>

- Collect the following input information:
  - L_{max}, measured for the group passby
  - N, the consist of the measured group of rail cars or group of locomotives
  - T, the average throttle setting of the measured diesel-powered locomotive(s)
  - S_{meas}, the measured passby speed, in miles per hour
  - D_{meas}, the closest distance between the measurement position and the source, in feet
  - L_{meas}, the total length of the measured group of locomotives or group of rail cars, in feet

- Compute the Source Reference Level -- SEL_{ref} -- from the **third or fourth** equations in Table E-1, depending on whether the sources are locomotives or rail cars.

Example E-3. Computation of SEL_{ref} from L_{max} Measurement of Fixed-Guideway Source

A passby of a 4-car consist of 70-ft long rail cars was measured at

L_{max} = 90.

For this measurement,

N = 4
S_{meas} = 70 miles per hour
D_{meas} = 65 feet, and
L_{meas} = 280 feet.

Using the fourth equation in Table E-1,

$\propto$ = 1.14

and the resulting SEL_{ref} = 86.7 dBA.

End of Example E-3

<u>If L_{max} was measured for a highway-vehicle passby:</u>

- Collect the following input information:
  - L_{max}, measured for the highway-vehicle passby
  - S_{meas}, the vehicle speed, in miles per hour
  - D_{meas}, the closest distance between the measurement position and the source, in feet
- Compute the Source Reference Level -- SEL_{ref} -- from the **fifth** equation in Table E-1.

Example E-4. Computation of SEL_{ref} from L_{max} Measurement of Highway Vehicle Source

A bus was measured at

L_{max} = 78 dBA.

For this measurement,

S_{meas} = 40 miles per hour and
D_{meas} = 80 feet.

Using the fifth equation in Table E-1, the resulting SEL_{ref} = 87.8 dBA.

End of Example E-4

Table E-1. Conversion to Source Reference Levels at 50 feet for Transit Noise Sources

Measured Quantity	Noise Source	Equation
SEL	Vehicle passby	$SEL_{ref} = SEL_{meas} + 10\log\left(\frac{S_{meas}}{50}\right) + 10\log\left(\frac{D_{meas}}{50}\right) + C_{consist} + C_{emissions}$
	Stationary noise source	$SEL_{ref} = SEL_{meas} - 10\log\left(\frac{E_{meas}}{3600}\right) + 20\log\left(\frac{D_{meas}}{50}\right)$
L_{max}	Rail-vehicle passby, locomotives only	$SEL_{ref} = L_{max} + 10\log\left(\frac{L_{meas}}{50}\right) + 10\log\left(\frac{D_{meas}}{50}\right) - 10\log(2\propto) + C_{consist} + C_{emissions} + 3.3$
	Rail-vehicle passby, cars only	$SEL_{ref} = L_{max} + 10\log\left(\frac{L_{meas}}{50}\right) + 10\log\left(\frac{D_{meas}}{50}\right) - 10\log[2\propto + \sin(2\propto)] + C_{consist} + C_{emissions} + 3.3$
	Highway-vehicle passby	$SEL_{ref} = L_{max} + 20\log\left(\frac{D_{meas}}{50}\right) + C_{emissions} + 3.3$

Vehicle Type	Expression for $C_{consist}$	Expression for $C_{emissions}$
Locomotives	-10 log (N)	0 For T<6 -2(T-5) For T ≥ 6
Rail Cars	-10 log (N)	$-30\log\left(\frac{S_{meas}}{50}\right)$
Buses	0	$-25\times\log\left(\frac{S_{meas}}{50}\right)$
Automobiles	0	$-38.1\times\log\left(\frac{S_{meas}}{50}\right)$

N = consist, (number of locomotives *or* rail cars in the measured group)
T = average throttle setting of measured diesel – electric locomotive(s)
D_{meas} = closest distance between measurement position and source, in feet
E_{meas} = event duration of measurement, in seconds
L_{meas} = total length of measured group of locomotives *or* rail cars, in feet
S_{meas} = speed of measured vehicle(s), in miles per hour

$\propto = \arctan\left(\frac{L_{meas}}{2D_{meas}}\right)$, in radians

APPENDIX F. COMPUTING MAXIMUM NOISE LEVEL (L_{max}) FOR A SINGLE TRAIN PASSBY

This appendix provides procedures for the computation of L_{max} for a single train passby, for those readers desiring such procedures. Table F-1 contains the equations to compute L_{max}. The procedure is summarized as follows.

- Collect the following input information:
  - o SEL_{ref}'s from Chapter 6, specific to both the locomotive type and car type of the train
  - o N_{locos}, the number of locomotives in the train
  - o N_{cars}, the number of cars in the train
  - o L_{locos}, the total length of the train's locomotive(s), in feet (or N_{locos}(unit length)
  - o L_{cars}, the total length of the train's set of rail car(s), in feet (or N_{cars}(unit length)
  - o S, the train speed, in miles per hour
  - o D, the closest distance between the receiver of interest and the train, in feet

- Compute $L_{max,locos}$ from the locomotive(s) using the first equation in Table F-1.
- Compute $L_{max,cars}$ from the rail car(s) using the second equation in Table F-1.
- Choose the larger of the two L_{max}'s as the L_{max} for the total train passby.

Table F-1. Conversion to L_{max} at the Receiver, for a Single Train Passby	
Source	**Equation**
Locomotives	$L_{\max,locos} = SEL_{locos} + 10\log\left(\frac{S}{50}\right) - 10\log\left(\frac{L}{50}\right) + 10\log(2\propto) - 3.3$
Rail Cars	$L_{\max,cars} = SEL_{cars} + 10\log\left(\frac{S}{50}\right) - 10\log\left(\frac{L}{50}\right) + 10\log[2\propto + \sin(2\propto)] - 3.3$
Total Train	$L_{\max,total} = \max[L_{\max,locos}\, or L_{\max,cars}]$

D = closest distance between receiver and source, in feet
L = total length of measured group of locomotive(s) *or* rail car(s), in feet
S = vehicle speed, in miles per hour
$\propto = \arctan\left(\frac{L}{2D}\right)$, in radians

Example F-1. Computation of L_{max} for Train Passby

A commuter train will pass by a receiver of interest and its L_{max} is desired. For this train, the following conditions apply:

SEL_{ref}	=	92 dB for locomotives and
	=	82 dB for rail cars
N_{locos}	=	1
N_{cars}	=	6
S	=	43 miles per hour
D	=	125 feet.

The locomotive and rail cars each have a unit length of 70 feet. Therefore,

L_{locos}	=	70 feet
L_{cars}	=	420 feet

Using the equations in Table F-1,

$\propto_{locos}$	=	0.27
$\propto_{cars}$	=	1.03

and the resulting Lmax's are as follows:

$L_{max,locos}$	=	84 dBA
$L_{max,cars}$	=	74 dBA
$L_{max,total}$	=	84 dBA.

End of Example F-1

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U.S. Department of Transportation
http://www.fta.dot.gov

C57.12.90™

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Abstract: Methods for performing tests specified in IEEE Std C57.12.00™ and other standards applicable to liquid-immersed distribution, power, and regulating transformers are described. Instrument transformers, step-voltage and induction voltage regulators, arc furnace transformers, rectifier transformers, specialty transformers, grounding transformers, and mine transformers are excluded. This standard covers resistance measurements, polarity and phase-relation tests, ratio tests, no-load loss and excitation current measurements, impedance and load loss measurements, dielectric tests, temperature tests, short-circuit tests, audible sound level measurements, and calculated data.
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Introduction

This introduction is not part of IEEE Std C57.12.90-2010, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers.

This document is a voluntary consensus standard. Its use may become mandatory only when required by a duly constituted legal authority or when specified in a contractual relationship. To meet specialized needs and to allow innovation, specific changes are permissible when mutually determined by the purchaser and manufacturer, provided that such changes do not violate existing laws and are considered technically adequate for the function intended.

When this standard is used on a mandatory basis, the word *shall* indicates mandatory requirements, and the words *should* and *may* refer to matters that are recommended or permissive, but not mandatory. The word *must* has been removed from this revision and replaced with *shall* to conform with the *IEEE Standards Style Manual*.

This standard is on a continuous revision cycle and is constantly being reviewed and updated. One can go to the website www.transformerscommittee.org to seek out information on select activities and participate in upcoming changes. Following is a brief summary of the noneditorial changes in this revision:

— Normative references and bibliography. Throughout this document, dated references have been changed to undated references, except in cases where a specific clause, table, figure, or equation is cited.

— Clause 5 introductory paragraph and 5.1.1 and 5.1.2. These passages have been slightly revised:

— Subclause 5.3. This subclause on resistance measurement methods has been changed to promote the voltmeter-ammeter method over the bridge method.

— Subclause 5.4. Resistance measurements connections and reporting have been added.

— New subclause 9.5.5. This new subclause provides a test method for zero-sequence impedance measurement on transformers with interconnected windings.

— Subclause 10.2.2.1. This subclause on switching impulse wave polarity has been changed to require negative polarity instead of an option between positive or negative polarity.

— Subclause 10.3.1.1. This subclause on full-wave impulse testing has been completely rewritten.

— Subclause 10.3.1.3. This subclause on chopped-wave impulse testing has been completely rewritten.

— Subclause 10.3.2.5. This subclause on nonlinear protective devices has been completely rewritten.

— Subclauses 10.5 to 10.10. These subclauses on low-frequency tests have been revised.

— Former subclause 10.10.5. This subclause on temperature correction factors of insulation power factor has been deleted.

— New Annex B. This normative annex presents frequency conversion factors for conversions from 50 Hz to 60 Hz and vice versa.

Technical revisions were prepared by various groups within the IEEE Transformers Committee and have been balloted and approved by these groups through the subcommittee level.

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IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers

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1. Overview

1.1 Scope

This standard describes methods for performing tests specified in IEEE Std C57.12.00™ and other standards applicable to liquid-immersed distribution, power, and regulating transformers.[1] It is intended for use as a basis for performance and proper testing of such transformers.

This standard applies to all liquid-immersed transformers, except instrument transformers, step-voltage and induction voltage regulators, arc furnace transformers, rectifier transformers, specialty transformers, grounding transformers, and mine transformers.

Transformer requirements and specific test criteria are not a part of this standard, but they are contained in appropriate standards, such as IEEE Std C57.12.00, ANSI C57.12.10 [B1],[2] IEEE Std C57.12.20™, and IEEE Std C57.12.40™ [B10], or in user specifications.

[1] Information on references can be found in Clause 2.
[2] The numbers in brackets correspond to the numbers in the bibliography in Annex C.

1.2 Purpose

The purpose of this standard is to provide test procedure information for tests specified in IEEE Std C57.12.00 and other standards applicable to liquid-immersed distribution, power, and regulating transformers. It is intended for use as a basis for performance and proper testing of such transformers.

1.3 Word usage

When this standard is used on a mandatory basis, the word *shall* indicates mandatory requirements. The words *should* or *may* refer to matters that are recommended or permitted but not mandatory.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI C57.12.25, American National Standard for Transformers—Pad-Mounted, Compartmental-Type, Self-Cooled, Single-Phase Distribution Transformers with Separable Insulated High-Voltage Connectors; High-Voltage, 34 500 GrdY/19 920 Volts and Below; Low-Voltage, 240/120 Volts; 167 kVA and Smaller—Requirements.[3]

ANSI C84.1, American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hertz).

ANSI S1.4, American National Standard for Sound Level Meters.

ANSI S1.11, American National Standard for Octave Band and Fractional-Octave-Band Analog and Digital Filters.

IEEE Std 4™, IEEE Standard Techniques for High-Voltage Testing.[4, 5]

IEEE Std C57.12.00™, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.12.00™-2010, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers (specifically, Clause 7 and Clause 10; 4.1.2, 4.1.6.1, 5.9, 5.10, 5.11.2, 7.1.4.1, 9.1, 9.4; Table 5, Table 4, Table 13, and Table 18).

IEEE Std C57.12.20™, IEEE Standard for Overhead-Type Distribution Transformers, 500 kVA and Smaller: High Voltage, 34 500 V and Below; Low Voltage, 7970/13 800Y V and Below.

IEEE Std C57.12.22™, American National Standard for Transformers—Pad-Mounted, Compartmental-Type, Self-Cooled Three-Phase Distribution Transformers With High-Voltage Bushings, 2500 kVA and Smaller: High Voltage, 34 500 Grd Y/19 920 Volts and Below; Low Voltage, 480 Volts and Below.

[3] ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).
[4] IEEE publications are available from the Institute of Electrical and Electronics Engineers Inc., 445 Hoes Lane, Piscataway, NJ 08854, USA (http://standards.ieee.org/).
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IEEE Std C57.12.23™, IEEE Standard for Submersible Single-Phase Transformers: High Voltage 25 000 V and Below; Low Voltage 600 V and below.

IEEE Std C57.12.24™, IEEE Standard for Submersible, Three-Phase Transformers, 3750 kVA and Smaller: High Voltage, 34 500 GrdY/19 920 Volts and Below; Low Voltage, 600 Volts and Below.

IEEE Std C57.12.26™, IEEE Standard for Pad-Mounted, Compartmental-Type, Self-Cooled, Three-Phase Distribution Transformers for Use With Separable Insulated High-Voltage Connectors (34 500 Grd Y/ 19 920 V and Below; 2500 kVA and Smaller).

IEEE Std C57.12.36™, IEEE Standard Requirements for Liquid-Immersed Distribution Substation Transformers.

IEEE Std C57.12.80™, IEEE Standard Terminology for Power and Distribution Transformers.

IEEE Std C57.19.00™, IEEE Standard General Requirements and Test Procedures for Power Apparatus Bushings.

IEEE Std C57.19.01™, IEEE Standard Performance Characteristics and Dimensions for Outdoor Apparatus Bushings.

IEEE Std C57.91™-1995, IEEE Guide for Loading Mineral-Oil-Immersed Transformers.

IEEE Std C57.98™, IEEE Guide for Transformer Impulse Tests.

IEEE Std C57.113™, IEEE Recommended Practice for Partial Discharge Measurement in Liquid-Filled Power Transformers and Shunt Reactors.

3. Definitions

For the purposes of this document, the following terms and definitions apply. IEEE Std C57.12.80 and *The IEEE Standards Dictionary: Glossary of Terms & Definitions* should be referenced for terms not defined in this clause.[6]

actual time to crest: The time interval from the start of the transient to the time when the maximum amplitude is reached.

ambient sound pressure level: The sound pressure level measured at the test facility or at the substation without the transformer energized.

A-weighted sound level: Loudness that is measured with a sound level meter using the A-weighted response filter that is built into the meter circuitry. The A-weighting filter is commonly used to measure community noise, and it simulates the frequency response of the human ear.

C-weighted sound level: Loudness that is measured with a sound level meter using the C-weighted filter that is built into the sound level meter. The C-weighting has only little dependence on frequency over the greater part of the audible frequency range.

efficiency (of a transformer): The ratio of the useful power output of a transformer to the total power input.

guard: One or more conducting elements arranged and connected on an electrical instrument or measuring circuit to divert unwanted currents from the measuring means.

[6] *The IEEE Standards Dictionary: Glossary of Terms & Definitions* is available at http://shop.ieee.org/.

semi-reverberant facility: A room with a solid floor and an undetermined amount of sound-absorbing materials on the walls and ceiling.

sound pressure level L_p in decibels: Twenty times the logarithm to the base ten of the ratio of the measured sound pressure (P) to a reference pressure (P_o) of 20 µPa or

$$L_p = 20 \log_{10}\left(\frac{P}{P_o}\right)$$

sound power level L_w in decibels: Ten times the logarithm to the base ten of the emitted sound power (w) to a reference power (w_o) of 10^{-12} W or

$$L_w = 10 \log_{10}\left(\frac{w}{w_o}\right)$$

time to first voltage zero on the tail of the wave: The time interval from the start of the transient to the time when the first voltage zero occurs on the tail of the wave.

total losses: The sum of the no-load losses and the load losses.

4. General

4.1 Types of tests

Various types of tests (routine, design, conformance, and other) are defined in IEEE Std C57.12.80.

4.2 Test requirements

A general summary of test requirements is included in Table 18 of IEEE Std C57.12.00-2010 and indicates which tests are normally considered routine, design, or other, by size and class.

4.3 Test sequence

See 10.1.5.1 for the sequence of dielectric tests when lightning impulse or switching impulse tests are specified.

NOTE—To minimize potential damage to the transformer during testing, the resistance, polarity, phase relation, ratio, no-load loss and excitation current, impedance, and load loss tests (and temperature-rise tests, when applicable) should precede dielectric tests. Using this sequence, the beginning tests involve voltages and currents, which are usually reduced as compared with rated values, thus tending to minimize damaging effects to the transformer.[7]

4.4 Instrumentation

Although the figures in this standard show conventional meters, adequate digital readout measuring devices and digital sampling techniques with computer calculations are considered to be satisfactory alternatives.

[7] Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

5. Resistance measurements

Resistance measurements are of fundamental importance for the following purposes:

a) Calculation of the I^2R component of conductor losses

b) Calculation of winding temperatures at the end of a temperature test

c) As a quality control test of the manufacturing process

d) As a base for assessing possible damage in the field

5.1 Determination of cold temperature

The cold temperature of the winding shall be determined as accurately as possible when measuring the cold resistance. The precautions in 5.1.1, 5.1.2, and 5.1.3 shall be observed.

5.1.1 General

Cold-resistance measurements shall be made on a transformer only when the liquid or winding temperature is stable. The temperature is considered stable if the top liquid temperature does not vary more than 2 °C in a 1 h period.

5.1.2 Transformer windings immersed in insulating liquid

The temperature of the windings shall be assumed to be the same as the average temperature of the insulating liquid, provided

a) The windings have been under insulating liquid with no excitation and with no current in the windings for a minimum of 3 h for a transformer without pumps and for 1 h for transformer with pumps running before the cold resistance is measured.

b) The temperature of the insulating liquid has stabilized, and the difference between top and bottom temperature does not exceed 5 °C.

5.1.3 Transformer windings out of insulating liquid

The temperature of the windings shall be recorded as the average of several thermometers or thermocouples inserted between the coils, with care used to see that their measuring points are as nearly as possible in actual contact with the winding conductors. It should not be assumed that the windings are at the same temperature as the surrounding air.

5.2 Conversion of resistance measurements

Cold winding resistance measurements are normally converted to a standard reference temperature (T_s) equal to the rated average winding temperature rise plus 20 °C. In addition, it may be necessary to convert the resistance measurements to the temperature at which the impedance loss measurements were made. The conversions are accomplished by Equation (1):

$$R_s = R_m \frac{T_s + T_k}{T_m + T_k} \tag{1}$$

where

- R_s is the resistance at desired temperature T_s (Ω)
- R_m is the measured resistance (Ω)
- T_s is the desired reference temperature (°C)
- T_m is the temperature at which resistance was measured (°C)
- T_k is 234.5 °C (copper) or 225 °C (aluminum)

NOTE—The value of T_k may be as high as 230 °C for alloyed aluminum.

5.3 Resistance measurement methods

5.3.1 Voltmeter–ammeter method

The voltmeter-ammeter method is the most common method used for transformer winding resistance measurement. Resistance-measuring systems employing computer-controlled digital voltmeters, current-measuring shunts, and/or digital ammeters of appropriate accuracy are commonly used for cold-resistance measurements and in connection with temperature-rise determinations.

To use this method, the following steps should be taken:

a) Measurement is made with direct current, and simultaneous readings of current and voltage are taken using the connections in Figure 1. The required resistance is calculated from the readings in accordance with Ohm's Law. Electronic switching power supplies may be used as voltage sources; however, batteries or filtered rectifiers may also be used, especially in instances where less ripple is desired in the measurement. Automatic recording of the resistance data is recommended so that the time to saturation and the variability of the resistance readings after stabilization can be documented.

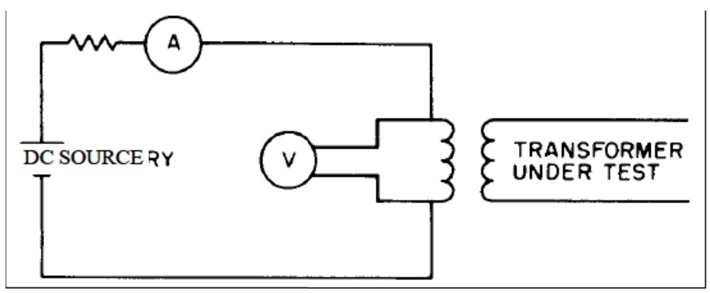

Figure 1—Connections for voltmeter-ammeter method of resistance measurement

b) The voltmeter leads shall be independent of the current leads and shall be connected as closely as possible to the terminals of the winding to be measured. This step is to avoid including in the reading the resistances of current-carrying leads and their contacts and of extra lengths of leads.

c) When making manual resistance measurements:

   1) The measuring instruments shall have ranges that are close to full scale to minimize errors of observation.

   2) The voltmeter may be disconnected from the circuit before switching the current on or off to protect the voltmeter from injury by off-scale deflections. To protect test personnel from inductive kick, the current may be switched off by a suitably insulated switch with a protective circuit to discharge the energy.

3) Due to inaccuracy of deflecting ammeters and voltmeters, current shunts and digital voltmeters or high-accuracy digital ammeters or other high accuracy instrumentation should be used that meets the requirement of IEEE Std C57.12.00.

d) Resistance is recommended to be measured at intervals of 5 s to 10 s, and the readings used shall be after the current and voltage have reached steady-state values.

When measuring the cold resistance, preparatory to making a heat run, note the time required for the readings to become constant. That period of time should be allowed to elapse before taking the first reading when final winding hot-resistance measurements are being made. The residual flux in the core should be made the same for both the cold-resistance and hot-resistance measurements by saturating the core with direct current prior to the measurement.

In general, the winding will exhibit a long time constant. To reduce the time required for the current to reach its steady-state value, a noninductive external resistor may be added in series with the dc source. It may then be necessary to increase the source voltage to compensate for the voltage drop in the series resistor. The time will also be reduced by passing a direct current through other windings in either the same polarity as the winding being tested for windings on the same phase or opposite polarity for other phases during these tests. For delta-connected windings, the time can also be reduced by opening the delta connection.

e) It is recommended that ten or more readings, but a minimum of four readings, should be used for each cold-resistance measurement, and the average of the resistances calculated from these measurements shall be considered to be the resistance of the circuit. The current used shall not exceed 15% of the rated current of the winding whose resistance is to be measured. Larger values may cause inaccuracy by heating the winding and thereby changing its temperature and resistance.

5.3.2 Bridge method

Bridge methods may be used.

NOTE—For resistance values of 1 Ω or more, a Wheatstone Bridge (or equivalent) is commonly used; for values less than 1 Ω, a Kelvin Bridge (or equivalent) is commonly used.

5.4 Resistance measurement connections and reporting

The individual phase- or terminal-to-terminal resistance readings shall be reported along with the sum total winding resistance.

5.4.1 Wye windings

For wye windings, the reported resistance measurement may be from terminal to terminal or from terminal to neutral. For the reported total winding resistance, the resistance of the lead from the neutral connection to the neutral bushing may be excluded. For terminal-to-terminal measurements, the total resistance reported is the sum of the three measurements divided by two.

5.4.2 Delta windings

For delta windings, the reported resistance measurement may be from terminal to terminal with the delta closed or from terminal to terminal with the delta open to obtain the individual phase readings. The reported total winding resistance is the sum of the three phase readings if the delta is open. If the delta is closed, the reported total winding resistance is the sum of the three phase-to-phase readings times 1.5.

5.4.3 Autotransformer windings

For autotransformer winding resistance measurements, the following method or an equivalent method shall be used. For the series winding resistance, the current shall be circulated between the high-voltage and neutral terminals, and the voltage shall be measured between the high-voltage terminal and the low-voltage terminal. For the common winding resistance, the current shall be circulated between the high-voltage and neutral terminals, and the voltage shall be measured between the low-voltage and neutral terminals. If needed, for the resistance of the lead and in-line windings (if any) between the low-voltage terminal and the neutral connection, the current shall be applied between the high-voltage terminal and the low-voltage terminal, and the voltage shall be measured between the low-voltage terminal and the neutral terminal.

6. Polarity and phase-relation tests

Polarity and phase-relation tests are of interest primarily because of their bearing on paralleling or banking two or more transformers. Phase-relation tests are made to determine angular displacement and relative phase sequence.

6.1 Subtractive and additive polarity

Windings arranged for subtractive polarity and additive polarity are shown in Figure 2 and Figure 3.

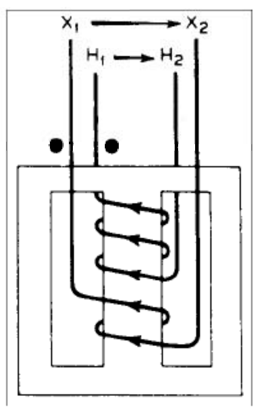

Figure 2—Windings: subtractive polarity

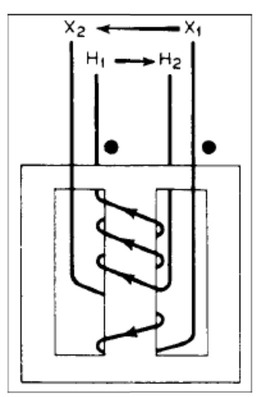

Figure 3—Windings: additive polarity

Leads and polarity marks arranged for subtractive polarity and additive polarity are shown in Figure 4 and Figure 5.

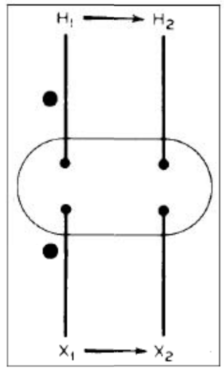

Figure 4—Leads and polarity marks: subtractive polarity

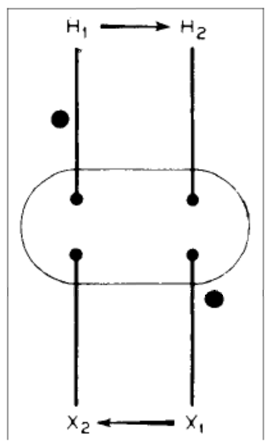

Figure 5—Leads and polarity marks: additive polarity

6.2 Polarity tests: single-phase transformers

Polarity tests on single-phase transformers shall be made in accordance with one of the following methods:

a) Inductive kick

b) Alternating voltage

c) Comparison

d) Ratio bridge

6.2.1 Polarity by inductive kick

The polarity of transformers with leads arranged as shown in Figure 2 through Figure 5 may be determined when making resistance measurements as follows:

a) With direct current passing through the high-voltage winding, connect a high-voltage direct-current voltmeter across the high-voltage winding terminals to obtain a small deflection of the pointer.

b) Transfer the two voltmeter leads directly across the transformer to the adjacent low-voltage leads, respectively.

NOTE—For example, in Figure 5, the voltmeter lead connected to H_1 will be transferred to X_2 as the adjacent lead, and that connected to H_2 to X_1.

c) Break direct-current excitation, thereby inducing a voltage in the low-voltage winding (inductive kick), which will cause deflection in the voltmeter. The deflection is interpreted in item d and item e.

d) When the pointer swings in the opposite direction (negative), the polarity is subtractive.

e) When the pointer swings in the same direction as before (positive), the polarity is additive.

6.2.2 Polarity by alternating-voltage test

For transformers having a ratio of transformation of 30 to 1 or less, the H_1 lead shall be connected to the adjacent low-voltage lead (X_1 in Figure 6).

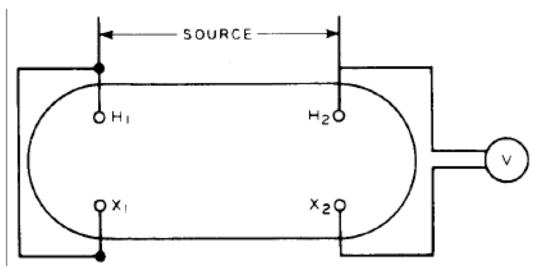

Figure 6—Polarity by alternating-voltage test

Any convenient value of alternating voltage shall be applied to the full high-voltage winding. Readings are taken of the applied voltage and the voltage between the right-hand adjacent high-voltage and low-voltage leads.

When the latter reading is greater than the former, the polarity is additive.

When the latter voltage reading is less than the former (indicating the approximate difference in voltage between the high-voltage and low-voltage windings), the polarity is subtractive.

6.2.3 Polarity by comparison

When a transformer of known polarity and of the same ratio as the unit under test is available, the polarity can be checked by comparison, as follows, similar to the comparison method used for the ratio test (see Figure 9 and Figure 10):

a) Connect the high-voltage windings of both transformers in parallel by connecting similarly marked leads together.

b) Connect the low-voltage leads, X_2, of both transformers together, leaving the X_1 leads free.

c) With these connections, apply a reduced value of voltage to the high-voltage windings and measure the voltage between the two free leads.

A zero or negligible reading of the voltmeter will indicate that the relative polarities of both transformers are identical.

An alternative method of checking the polarity is to substitute a low-rated fuse or suitable lamps for the voltmeter. This procedure is recommended as a precautionary measure before connecting the voltmeter.

6.2.4 Polarity by ratio bridge

The ratio bridge described in 7.3.3 can also be used to test polarity.

6.3 Polarity and phase-relation tests: polyphase transformers

6.3.1 Polarity of polyphase transformers

Each phase of a polyphase transformer shall have the same relative polarity when tested in accordance with one of the methods described for single-phase transformers.

6.3.2 Phase-relation tests

6.3.2.1 Test for phasor diagram for transformers with a ratio of transformation of 30 to 1 or less

The phasor diagram of any three-phase transformer that defines the angular displacement and phase sequence can be verified as follows:

- Connect the H_1 and X_1 leads together to excite the unit at a suitable, low, three-phase voltage.
- Take voltage measurements between the various pairs of leads.
- Either plot these values or compare them for their relative order of magnitude with the help of the corresponding diagram in Figure 7 or Figure 8.

Typical check measurements are to be taken, and their relative magnitudes are also to be indicated.

6.3.2.2 Zigzag windings

Equal zig and zag windings are usually necessary for zigzag transformers although unequal windings may be used for special applications.

No required test is proposed to determine the phase relationships between the line-end and neutral-end sections of a zigzag winding. However, it is recommended that a test connection be made to the junction of the two winding sections and that tests be made during manufacture to prove the desired phase relationships.

For the purpose of designation in Figure 7, zigzag windings are arbitrarily defined as windings whose line-end section is rotated 60° counterclockwise with respect to the neutral-end section.

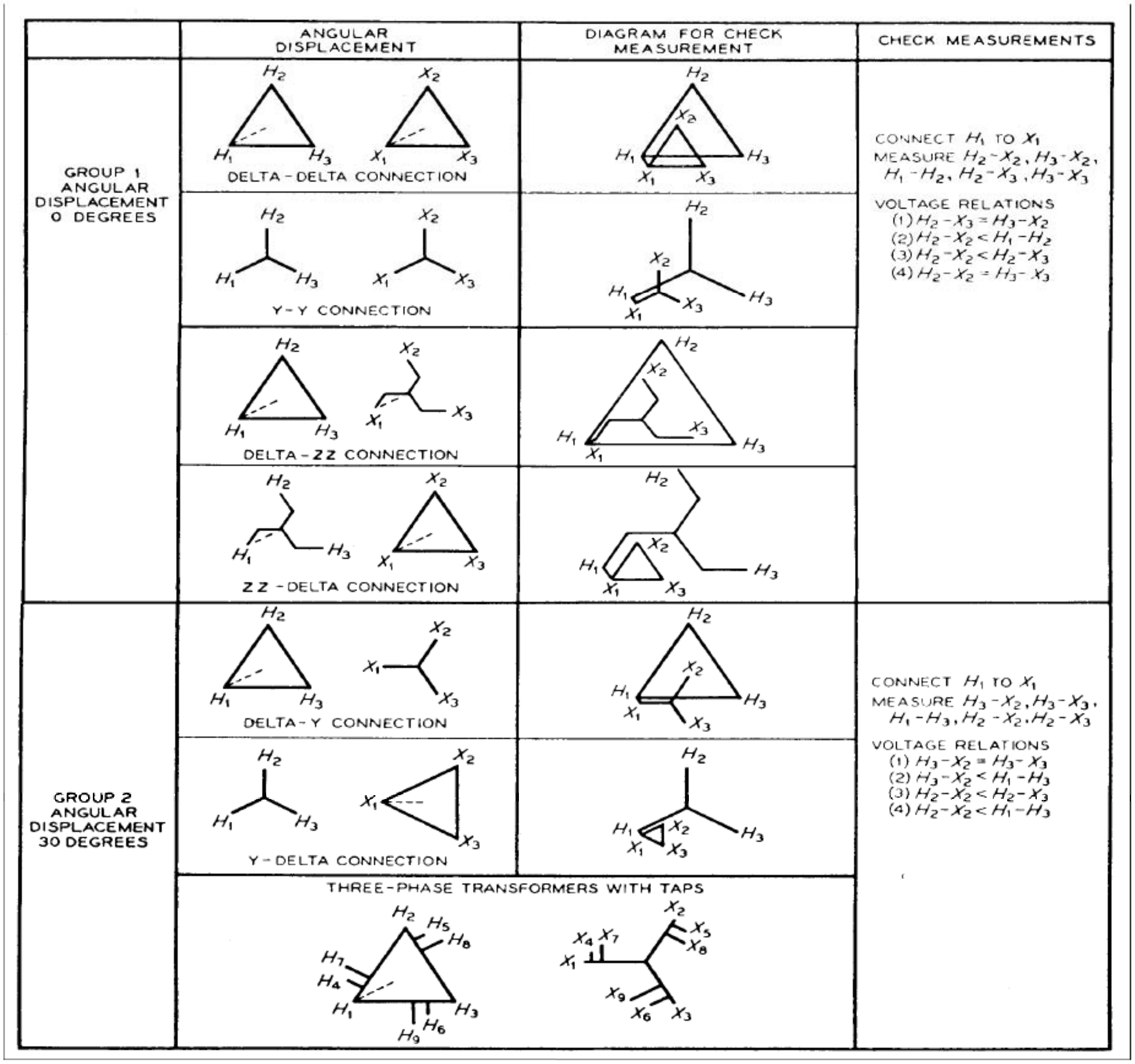

Figure 7—Transformer lead markings and voltage-phasor diagrams for three-phase transformer connections

6.3.2.3 Six-phase windings

Six-phase windings with no neutral connection shall be temporarily connected in delta (Δ) or wye (Y) for the test for phasor diagram.

6.3.2.4 Test of phase relation with ratio bridge

The ratio bridge described in 7.3.3 can also be used to test phase relationships.

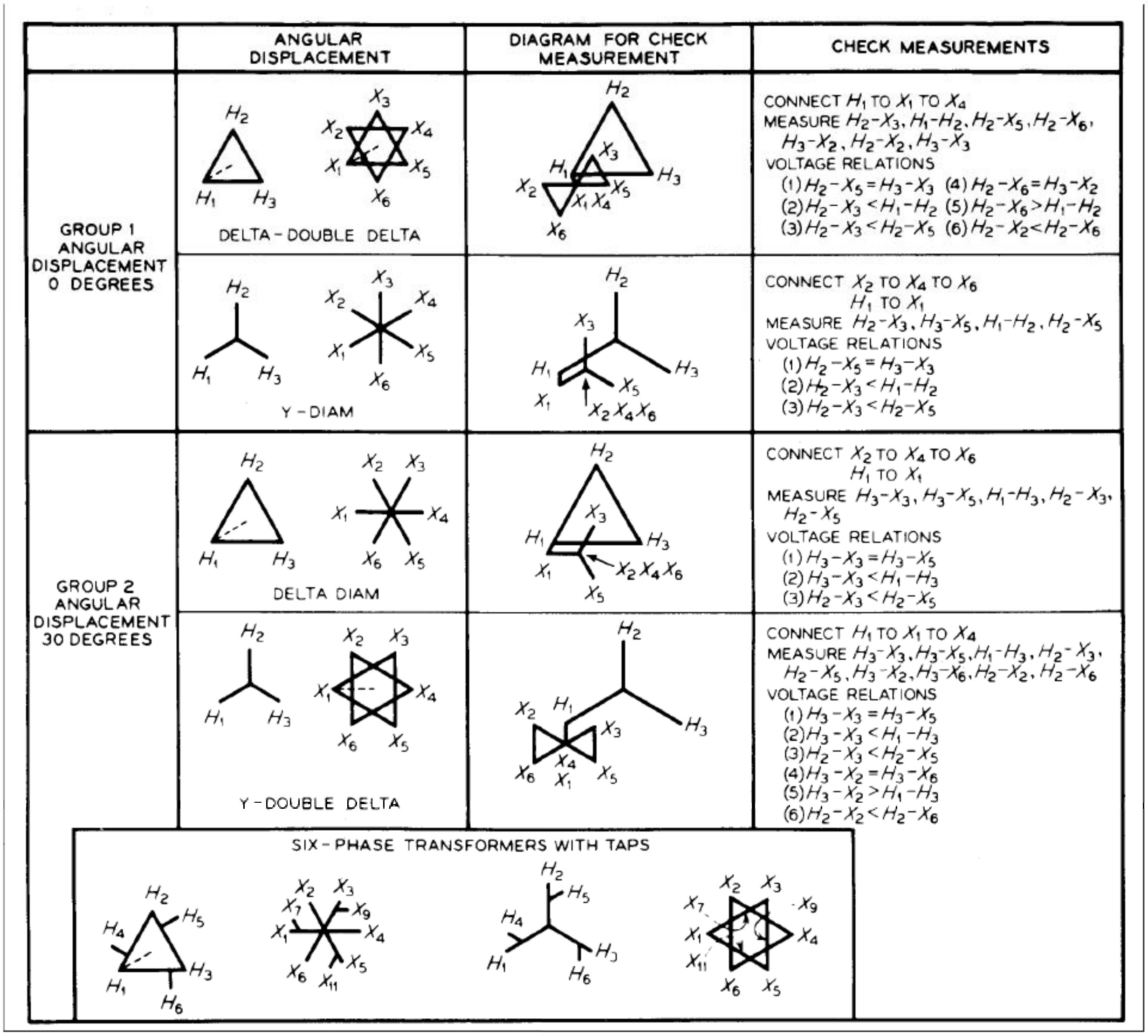

Figure 8—Transformer lead markings and voltage-phasor diagrams for six-phase transformer connections

6.3.3 Phase-sequence test

The phase-sequence indicator may incorporate either a three-phase induction motor or a split-phase circuit. It should be connected first to the higher voltage leads with the transformer excited three-phase at a low voltage suitable for the indicator and the direction of rotation or the indication of the instrument noted.

The indicator is then transferred to the low-voltage side of the transformer by connecting the lead that was connected to H_1 to X_1, connecting the lead that was connected to H_2 to X_2, and connecting the lead that was connected to H_3 to X_3.

The transformer is again excited at a suitable voltage (without changing the excitation connections), and the indication is again noted.

The phase sequence of the transformer is correct when the indication is the same in both cases.

Six-phase secondaries with no neutral connection also have to be connected temporarily in delta or wye for this test. When a six-phase neutral is available, the phase-sequence indicator leads should be transferred from H_1 to X_1, from H_2 to X_3, and from H_3 to X_5, respectively, and the direction of rotation should be noted. The test should then be repeated by transferring the leads from H_1 to X_2, from H_2 to X_4, and from H_3 to X_6, respectively, and noting the indication, which should be the same as before.

6.3.3.1 Limitation of the phase-sequence test

The preceding method (phase-sequence test) does not disclose the angular displacement of the transformer.

6.3.3.2 Test of phase sequence with ratio bridge

The ratio bridge described in 7.3.3 can also be used to test phase sequence.

7. Ratio tests

7.1 General

The turns ratio of a transformer is the ratio of the number of turns in the high-voltage winding to that in the low-voltage winding.

7.1.1 Taps

When a transformer has taps for changing its voltage ratio, the turns ratio is based on the number of turns corresponding to the normal rated voltage of the respective windings to which operating and performance characteristics are referred.

When the transformer has taps, the turns ratio shall be determined for all taps and for the full winding.

7.1.2 Voltage and frequency

The ratio test shall be made at rated or lower voltage and rated or higher frequency.

7.1.3 Three-phase transformers

In the case of three-phase transformers, when each phase is independent and accessible, single-phase power should be used, although, when convenient, three-phase power may be used.

7.1.4 Three-phase transformers with inaccessible neutrals

Transformers that have wye connections but do not have the neutral of the wye brought out shall be tested for ratio with three-phase power. Any inequality in the magnetizing characteristics of the three phases will result in a shift of the neutral and thereby cause unequal phase voltages. When such inequality is found, the connection should be changed, either to a delta or to a wye connection, and the line voltages should be measured. When the measured line voltages are equal to the proper value (1.73 times the phase voltages when connected in wye), the ratio is correct.

7.2 Tolerances for ratio

See 9.1 of IEEE Std C57.12.00-2010.

7.3 Ratio test methods

7.3.1 Voltmeter method

Two voltmeters shall be used (with voltage transformers when necessary): one to read the voltage of the high-voltage winding and the other, the low-voltage winding.

The two voltmeters shall be read simultaneously.

A second set of readings shall be taken with the instruments interchanged, and the average of the two sets of readings shall be taken to compensate for instrument errors.

Voltage transformer ratios should yield approximately the same readings on the two voltmeters. Compensation for instrument errors by an interchange of instruments will otherwise not be satisfactory, and it will be necessary to apply appropriate corrections to the voltmeter readings.

Tests shall be made with no less than four voltages in approximately 10% steps, and the average result shall be taken as the true value. These several values should check within 1%. Otherwise, the tests shall be repeated with other voltmeters.

When appropriate corrections are applied to the voltmeter readings, tests may be made at only one voltage.

When several transformers of duplicate rating are to be tested, work may be expedited by applying the foregoing tests to only one unit and then comparing the other units with this one as a standard, in accordance with the comparison transformer method discussed in 7.3.2.

7.3.2 Comparison method

A convenient method of measuring the ratio of a transformer is by comparison with a transformer of known ratio.

The transformer to be tested is excited in parallel with a transformer of the same nominal ratio, and the two secondaries are connected in parallel but with a voltmeter or detector in the connection between two terminals of similar polarity (see Figure 9). The voltmeter or detector indicates the difference in voltage. This method is more accurate than the following alternative method.

For an alternative method, the transformer to be tested is excited in parallel with a transformer of known ratio, and the voltmeters are arranged to measure the two secondary voltages (see Figure 10). The voltmeters shall be interchanged, and the test shall be repeated. The averages of the results are the correct voltages.

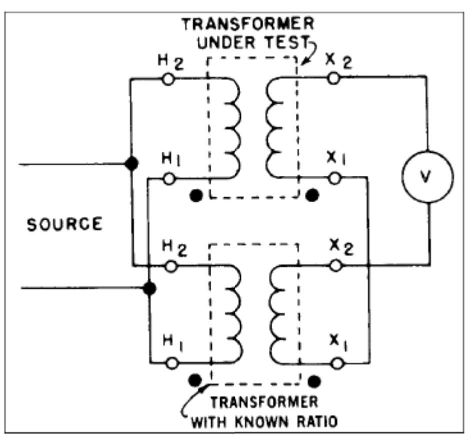

Figure 9—Voltmeter arranged to read the difference between the two secondary voltages

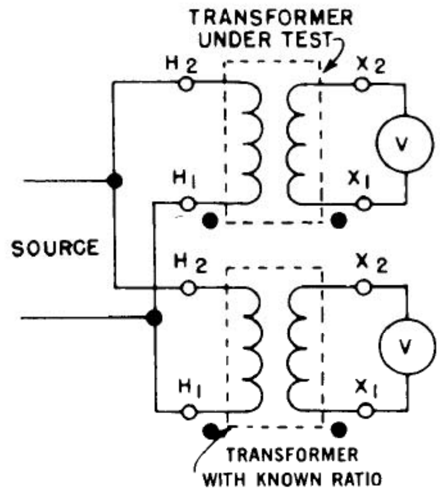

Figure 10—Voltmeters arranged to read the two secondary voltages

NOTE—Readings are repeated after interchanging voltmeters.

7.3.3 Ratio bridge

A bridge using the basic circuit of Figure 11 may be used to measure ratio. When detector DET is in balance, the transformer ratio is equal to R/R_1.

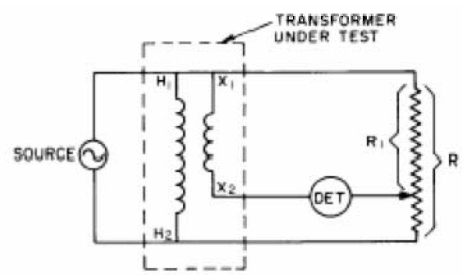

Figure 11—Basic circuit of ratio bridge

NOTE 1—Measurement of ratio using circuits of this type has also been described as ratio by resistance potentiometer.

NOTE 2—More accurate results can be obtained using a ratio bridge that provides phase-angle correction.

NOTE 3—The ratio bridge can also be used to test polarity, phase relation, and phase sequence.

8. No-load losses and excitation current

8.1 General

No-load (excitation) losses are losses that are incident to the excitation of the transformer. No-load losses include core loss, dielectric loss, conductor loss in the winding due to excitation current, and conductor loss due to circulating current in parallel windings. These losses change with the excitation voltage.

Excitation current (no-load current) is the current that flows in any winding used to excite the transformer when all other windings are open-circuited. It is generally expressed in percent of the rated current of the winding in which it is measured.

The no-load losses consist primarily of the core loss in the transformer core, which is a function of the magnitude, frequency, and waveform of the impressed voltage. No-load losses also vary with temperature and are particularly sensitive to differences in waveform; therefore, no-load loss measurements will vary markedly with the waveform of the test voltage.

In addition, several other factors affect the no-load losses and excitation current of a transformer. The design-related factors include the type and thickness of core steel, the core configuration, the geometry of core joints, and the core flux density.

Factors that cause differences in the no-load losses of transformers of the same design include variability in characteristics of the core steel, mechanical stresses induced in manufacturing, variation in gap structure, and core joints.

8.2 No-load loss test

The purpose of the no-load loss test is to measure no-load losses at a specified excitation voltage and a specified frequency. The no-load loss determination shall be based on a sine-wave voltage, unless a different waveform is inherent in the operation of the transformer. The average-voltage voltmeter method is the most accurate method for correcting the measured no-load losses to a sine-wave basis and is recommended. This method employs two parallel-connected voltmeters: one is an average-responding [but root mean square (rms) calibrated] voltmeter (V_a), and the other is a true rms-responding voltmeter (V_r). The test voltage is adjusted to the specified value as read by the average-responding voltmeter. The readings of both voltmeters are employed to correct the no-load losses to a sine-wave basis, using Equation (2) in accordance with 8.3.

8.2.1 Connection diagrams

Tests for the no-load loss determination of a single-phase transformer are carried out using the schemes depicted in Figure 12 and Figure 13. Figure 12 shows the necessary equipment and connections when instrument transformers are not required. When instrument transformers are required, as is generally the case, the equipment and connections shown in Figure 13 apply. If necessary, correction for losses in connected measurement instruments may be made by disconnecting the transformer under test and noting the wattmeter reading at the specified test circuit voltage. These losses represent the losses of the connected instruments (and voltage transformer, if used). They may be subtracted from the earlier wattmeter reading to obtain the no-load loss of the transformer under test.

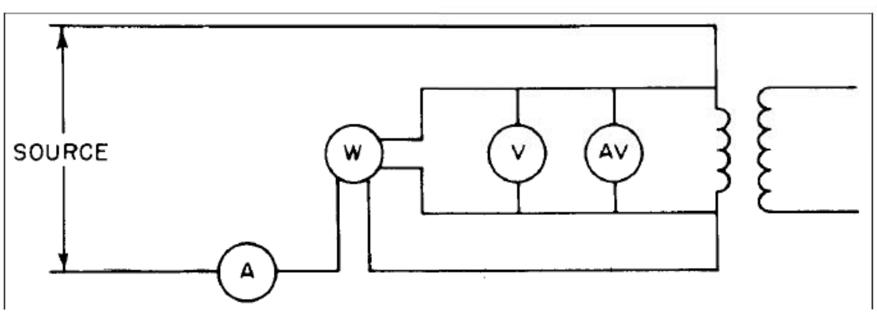

Figure 12—Connections for no-load loss test of a single-phase transformer without instrument transformers

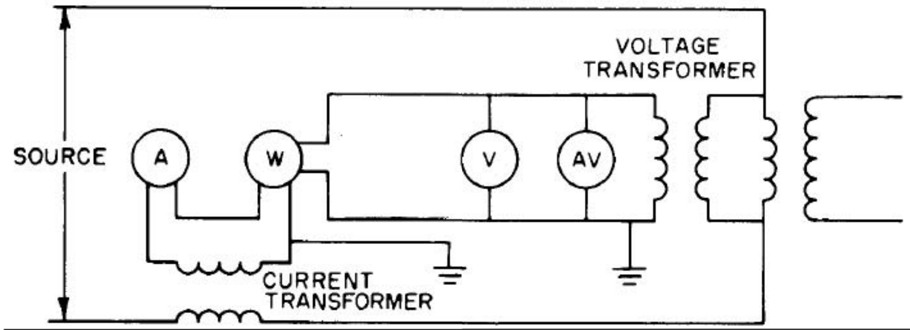

Figure 13—Connections for a no-load loss test of a single-phase transformer with instrument transformers

Tests for the no-load loss determination of a three-phase transformer shall be carried out by using the three wattmeter method. Figure 14 is a schematic representation of the equipment and connections necessary for conducting no-load loss measurements of a three-phase transformer when instrument transformers are necessary.

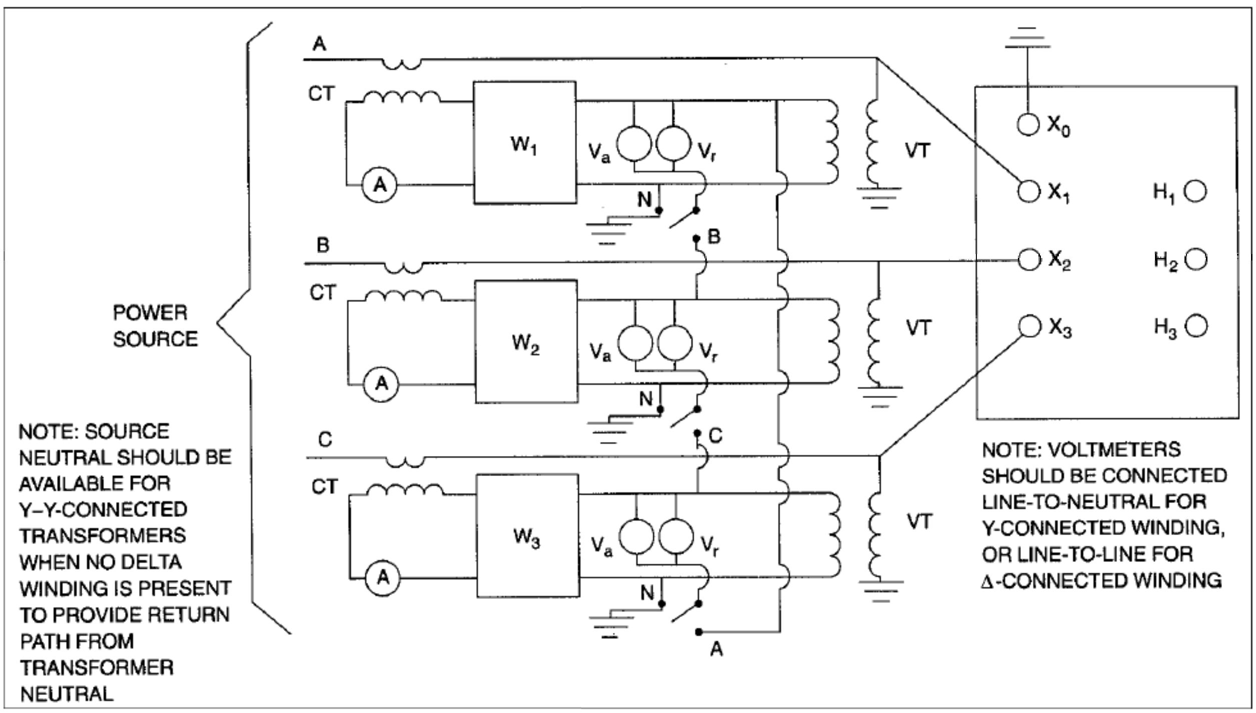

Figure 14—Three-phase transformer connections for no-load loss and excitation current tests using three-wattmeter method

8.2.2 Voltmeter connections

When correcting to a sine-wave basis using the average-voltage voltmeter method, attention shall be paid to the voltmeter connections because the line-to-line voltage waveform may differ from line-to-neutral voltage waveform. Therefore, depending on whether the transformer windings energized during the test are connected delta or wye, the voltmeter connections shall be such that the waveform applied to the voltmeters is the same as the waveform across the energized windings.

8.2.3 Energized windings

Either the high- or low-voltage winding of the transformer under test may be energized, but it is generally more convenient to make this test using the low-voltage winding. In any case, the full winding (not merely a portion of the winding) should be used whenever possible. If, for some unusual reason, only a portion of a winding is excited, this portion shall not be less than 25% of the winding.

8.2.4 Voltage and frequency

The operating and performance characteristics of a transformer are based on rated voltage and rated frequency, unless otherwise specified. Therefore, the no-load loss test is conducted with rated voltage impressed across the transformer terminals, using a voltage source at a frequency equal to the rated frequency of the transformer under test, unless otherwise specified.

To determine no-load losses of a single-phase transformer or a three-phase transformer, the frequency of the test source should be within ± 0.5% of the rated frequency of the transformer under test. The voltage shall be adjusted to the specified value as indicated by the average-voltage voltmeter. Simultaneous values of rms voltage, rms current, electrical power, and the average-voltage voltmeter readings shall be recorded. For a three-phase transformer, the average of the three voltmeter readings shall be the desired nominal value.

8.3 Waveform correction of no-load losses

The eddy-current component of the no-load loss varies with the square of the rms value of excitation voltage and is substantially independent of the voltage waveform. When the test voltage is held at the specified value as read on the average-voltage voltmeter, the actual rms value of the test voltage may not be equal to the specified value. The no-load losses of the transformer corrected to a sine-wave basis shall be determined from the measured value using Equation (2):

$$P_c(T_m) = \frac{P_m}{P_1 + kP_2} \tag{2}$$

where

T_m	is the average oil temperature at the time of test (°C)
$P_c(T_m)$	is the no-load losses, corrected for waveform, at temperature T_m
P_m	is measured no-load losses at temperature T_m
P_1	is per-unit hysteresis loss
P_2	is per-unit eddy-current loss
k	is $\left(\frac{E_r}{E_a}\right)^2$
E_r	is the test voltage measured by rms voltmeter
E_a	is the test voltage measured by average-voltage voltmeter

The actual per-unit values of hysteresis and eddy-current losses should be used if available. If actual values are not available, it is suggested that the two loss components be assumed equal in value and that they each be assigned a value of 0.5 per unit.

Equation (2) is valid only for test voltages with moderate waveform distortion. If waveform distortion in the test voltage causes the magnitude of the correction to be greater than 5%, the test voltage waveform shall be improved for an adequate determination of the no-load losses and currents.

8.4 Temperature correction of no-load losses

A reference temperature is required when stating no-load losses because the no-load losses vary with core temperature. The standard reference temperature T_r for transformer no-load losses is specified in 5.9 of IEEE Std C57.12.00-2010.

The observed decrease in no-load losses for an increase in temperature results from several mechanisms acting together. Changes in the core steel resistivity, changes in mechanical stress in the core structure, and variations in the temperature gradients in the core cause the no-load loss to change with temperature. Because these factors vary from design to design and between transformers of the same design, it is not practical to specify an exact formula to account for temperature variation throughout the operating temperature range of transformers.

However, ordinary variations of temperature encountered when performing the no-load loss test will not affect no-load losses materially, and no correction for temperature needs to be made, so long as the following conditions are met:

a) The average oil temperature is within ± 10 °C of the reference temperature T_r.

b) The difference between the top and bottom oil temperatures does not exceed 5 °C.

If conducting the test with temperatures outside the specified ranges is necessary, the empirical formula in Equation (3) may be used to correct the measured no-load losses to the reference temperature:

$$P_c(T_r) = P_c(T_m)\{1 + (T_m - T_r)K_T\} \tag{3}$$

where

$P_c\,(T_r)$ is the no-load losses, corrected to the standard reference temperature T_r
$P_c\,(T_m)$ is the no-load losses, corrected for waveform, at temperature T_m
T_r is the standard reference temperature (°C)
K_T is an empirically derived per-unit change in no-load loss per degrees Celsius

If the actual value of K_T is not available, a value of 0.000 65 per unit change per degrees Celsius should be used. This value is typical for cores constructed of grain-oriented silicon steel and is satisfactory as a correction for no-load losses when the transformer shall be tested outside the specified temperature range.

8.5 Determination of excitation (no-load) current

The excitation (no-load) current of a transformer is the current that maintains the rated magnetic flux excitation in the core of the transformer. The excitation current is usually expressed in per unit or in percent of the rated line current of the winding in which it is measured. (Where the cooling class of the transformer involves more than one kilovoltampere rating, the lowest kilovoltampere rating is used to determine the base current.) Measurement of excitation current is usually carried out in conjunction with the tests for no-load losses. Rms current is recorded simultaneously during the test for no-load losses using the average-voltage voltmeter method. This value is used in calculating the per-unit or percent excitation current. For a three-phase transformer, the excitation current is calculated by taking the average of the magnitudes of the three line currents.

8.6 Frequency conversion of no-load losses and excitation current

In the event that the no-load loss and excitation current test cannot be done at the rated power frequency, see Annex B for 50/60 Hz frequency conversions.

9. Load losses and impedance voltage

9.1 General

The load losses of a transformer are losses incident to a specified load carried by the transformer. Load losses include I^2R loss in the windings due to load current and stray losses due to eddy currents induced by leakage flux in the windings, core clamps, magnetic shields, tank walls, and other conducting parts. Stray losses may also be caused by circulating currents in parallel windings or strands. Load losses are measured by applying a short circuit across either the high-voltage winding or the low-voltage winding and applying sufficient voltage across the other winding to cause a specified current to flow in the windings. The power loss within the transformer under these conditions equals the load losses of the transformer at the temperature of test for the specified load current.

The impedance voltage of a transformer is the voltage required to circulate rated current through one of two specified windings when the other winding is short-circuited, with the windings connected as for rated voltage operation. Impedance voltage is usually expressed in per unit or in percent of the rated voltage of the winding across which the voltage is applied and measured. The impedance voltage comprises a resistive component and a reactive component. The resistive component of the impedance voltage, called the *resistance drop*, is in phase with the current and corresponds to the load losses. The reactive component of the impedance voltage, called the *reactance drop*, is in quadrature with the current and corresponds to the leakage-flux linkages of the windings. The impedance voltage is the phasor sum of the two components. The impedance voltage is measured during the load loss test by measuring the voltage required to circulate rated current in the windings. The measured voltage is the impedance voltage at the temperature of test, and the power loss dissipated within the transformer is equal to the load losses at the temperature of test and at rated load. The impedance voltage and the load losses are corrected to a reference temperature using the formulas specified in this standard.

The impedance kilovoltampere is the product of the impedance voltage across the energized winding in kilovolts times the winding current in amperes. The ratio of the load losses in kilowatts at the temperature of test to the impedance kilovoltampere at the temperature of test is the load loss power factor of the transformer during the test and is used for correction of phase-angle error as specified in this standard.

9.2 Factors affecting the values of load losses and impedance voltage

The magnitudes of the load losses and the impedance voltage will vary depending on the positions of tap changers, if any, in various windings. These changes are due to the changes in the magnitudes of load currents and associated leakage-flux linkages as well as to changes in stray flux and accompanying stray losses. In addition, several other factors affect the values of load losses and impedance voltage of a transformer. Considerations of these factors, partly, explain variations in load loss values and impedance voltage for the same transformer under different test conditions as well as variations between load loss values and impedance voltage of different transformers of the same design. These factors are discussed in 9.2.1 through 9.2.4.

9.2.1 Design

The design-related factors include conductor material, conductor dimensions, winding design, winding arrangement, shielding design, and selection of structural materials.

9.2.2 Process

The process-related factors that affect load loss values and impedance voltage are the dimensional tolerances of conductor materials, the final dimensions of completed windings, phase assemblies, metallic parts exposed to stray flux, and variations in properties of conductor material and other metallic parts.

9.2.3 Temperature

Load loss values are also a function of temperature. The I^2R component of the load losses increases with temperature, whereas the stray loss component decreases with temperature. Procedures for correcting the load losses and impedance voltage to the standard reference temperature are described in 9.4.2.

9.2.4 Measurements

At low power factors, such as those encountered while measuring load losses and impedance voltage of power transformers, judicious selection of measurement method and test system components is essential for accurate and repeatable test results. The phase-angle errors in the instrument transformers, measuring instruments, bridge networks, and accessories affect load loss test results. Procedures for correcting the load losses for metering phase-angle errors are described in 9.4.1.

9.3 Tests for measuring load losses and impedance voltage

Regardless of the test method selected, the following preparatory requirements shall be satisfied for accurate test results:

a) To determine the temperature of the windings with sufficient accuracy, the following conditions shall be met, except as stated in the note below:

   1) The temperature of the insulating liquid has stabilized, and the difference between top and bottom oil temperatures does not exceed 5 °C.

   2) The temperature of the windings shall be taken immediately before and after the load losses and impedance voltage test in a manner similar to that described in 5.1. The average shall be taken as the true temperature.

   3) The difference in winding temperature before and after the test shall not exceed 5 °C.

   NOTE—For distribution and pad-mounted transformers up to 2500 kVA, where it may not be practical to wait for thermal equilibrium, the method used to determine the winding temperature shall take into consideration the lack of thermal equilibrium and the effect of ohmic heating of the winding conductors by load current during the test. The method used can be verified by staging a repeated measurement of the load losses and impedance voltage at a later time when condition 1, condition 2, and condition 3 are met.

b) The conductors used to short-circuit the low-voltage high-current winding of a transformer shall have a cross-sectional area equal to or greater than the corresponding transformer leads.

c) The frequency of the test source used for measuring load losses and impedance voltage shall be within ± 0.5% of the nominal value.

d) The maximum value of correction to the measured load losses due to the test system phase-angle error is limited to ± 5% of measured losses. If more than 5% correction is required, test methods and/or test apparatus should be improved for an adequate determination of load losses.

9.3.1 Wattmeter-voltmeter-ammeter method

The connections and apparatus needed to determine load losses and impedance voltage of a single-phase transformer are shown in Figure 15 and Figure 16. Figure 15 applies when instrument transformers are not required. If instrument transformers are required (as is generally the case), then Figure 16 applies.

NOTE—Instrument transformers to be added when necessary.

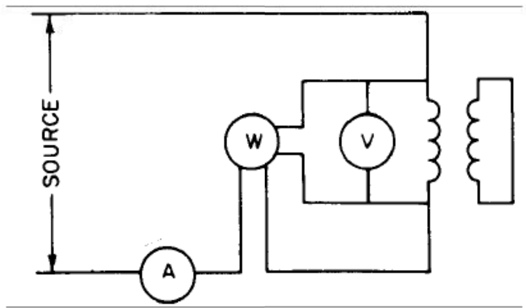

Figure 15—Single-phase transformer connections for load loss and impedance voltage tests without instrument transformers

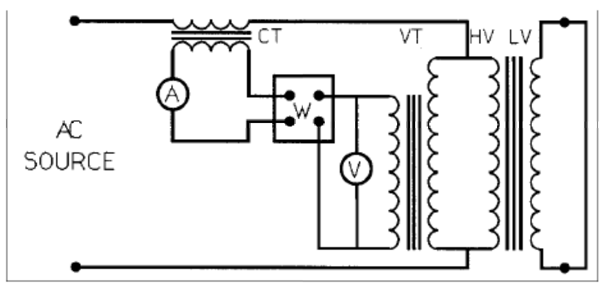

Figure 16—Single-phase transformer connections for load loss and impedance voltage tests with instrument transformers

For three-phase transformers, a three-phase power measurement using two wattmeters is possible, but it can result in very large errors at low power factors in load loss tests of transformers. The two-wattmeter method should not be used for loss tests on three-phase transformers.

For three-phase transformers, Figure 17 shows the apparatus and connections using the three-wattmeter method.

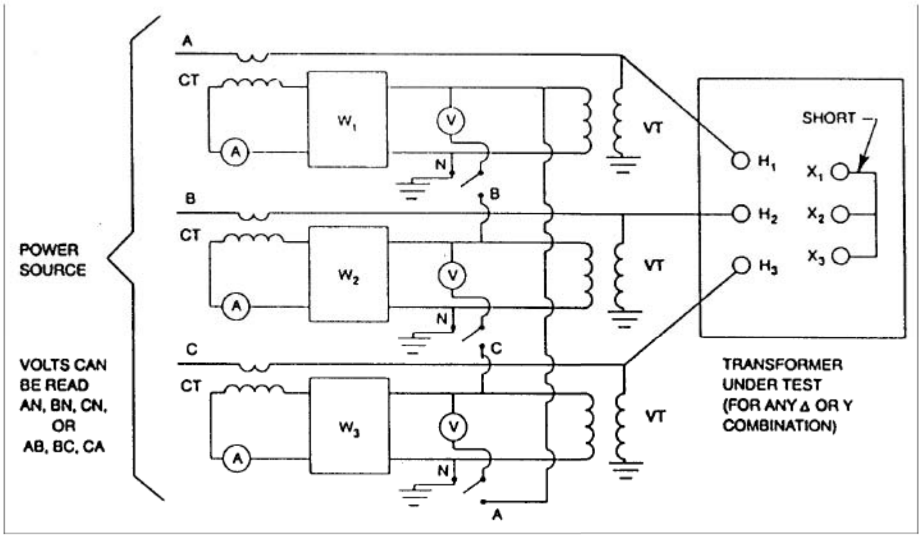

Figure 17—Three-phase transformer connections for load loss and impedance voltage tests using three-wattmeter method

The selection of test method and test system components should comply with accuracy requirements as specified in 9.4 of IEEE Std C57.12.00-2010.

9.3.2 Impedance bridge methods

Impedance bridge methods may be used as an alternative to the wattmeter-voltmeter-ammeter method for measurement of load losses and impedance voltage.

Although many configurations of impedance bridge networks are possible, the choice of a particular network is determined by considerations of the measurement environment and available test facility. The general form of the impedance bridge as shown in Figure 18 is an electrical network arranged so that a voltage proportional to the current through the transformer under test is compared with a reference voltage that is a function of the applied voltage E_T. The voltage comparison is made by adjusting one or more of the bridge arms (Z_1, Z_2, and Z_3) until the voltages across Z_2 and Z_3 are exactly equal in magnitude and phase. Voltage balance is indicated by a null reading of the detector DET. The impedance characteristics of the transformer under test can then be calculated from the values of Z_1, Z_2, and Z_3.

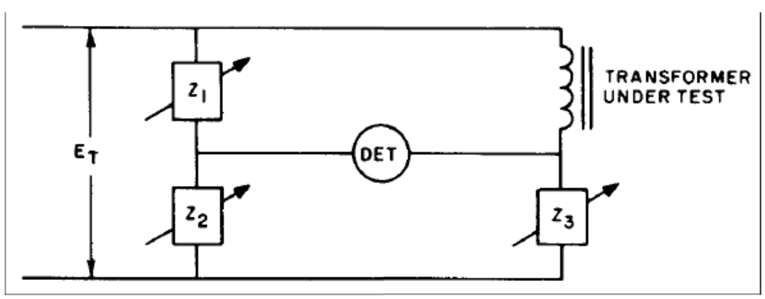

Figure 18—General impedance bridge network

Two of the most commonly used bridge networks for transformer testing are shown in Figure 19 and Figure 20. In Figure 19, a bridge technique employs a precision, low-loss, high-voltage capacitor and precision current transformer. It has some similarities to classic Schering and Maxwell bridges. In Figure 20, another bridge technique employs a high-voltage capacitor, precision current transformer, and transformer ratio arm bridge.

In general, the bridge network adjustments for voltage balance are frequency-dependent; therefore, excitation of the bridge shall be made with a power source that has low harmonic distortion and excellent frequency stability.

The factors that affect overall accuracy of test results by the wattmeter-voltmeter-ammeter method also impact the accuracy of test results by impedance bridge methods.

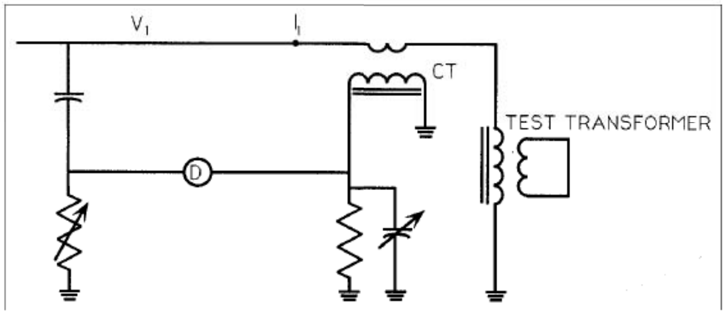

Figure 19—RC-type impedance bridge

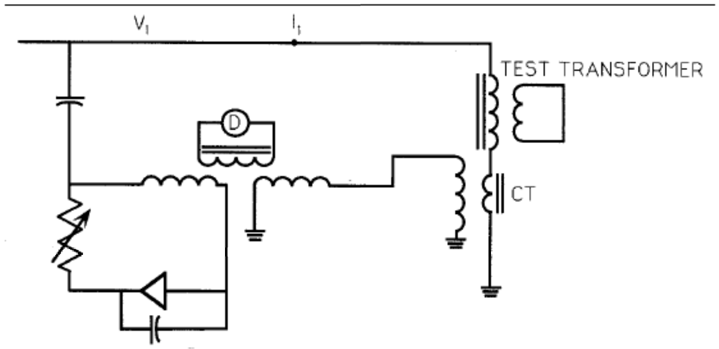

Figure 20—Transformer-ratio-arm bridge

Loss measurements on three-phase transformers using a three-phase source are made by connecting the bridge network to each phase in turn and calculating the total losses from the three single-phase measurements. This approach is analogous to the three-wattmeter method of measuring losses by switching a single wattmeter from phase to phase. To verify that switching the bridge from phase to phase does not affect the result on the remaining phases and to demonstrate that the time involved in switching the bridge does not result in undue heating of the transformer windings during the test, the losses can be monitored for stable readings by wattmeters in all phases.

9.3.3 Transformer test procedures

9.3.3.1 Two-winding transformers and autotransformers

Load loss and impedance voltage tests are carried out using the connections and apparatus shown in Figure 16 for single-phase transformers and Figure 17 for three-phase transformers.

With one winding short-circuited, a voltage of sufficient magnitude at rated frequency is applied to the other winding and adjusted to circulate rated current in the excited winding. Simultaneous readings of wattmeter, voltmeter, and ammeter are taken. If necessary, the corrections for losses in external connections and connected measuring instruments should be made.

The procedure for testing three-phase transformers is very similar, except that all connections and measurements are three-phase instead of single-phase and a balanced three-phase source of power is used for the tests. If the three line currents cannot be balanced, their average rms value should correspond to the desired value. Simultaneous readings of wattmeters, voltmeters, and ammeters should be recorded.

Single-phase and three-phase autotransformers may be tested with internal connections unchanged. The test is made using the autotransformer connection. The input (or output) terminals are shorted, and voltage (at rated frequency) is applied to the other terminals. The voltage is adjusted to cause rated line current to flow in the test circuit as shown in Figure 21. Simultaneous readings of wattmeter, voltmeter, and ammeter are recorded to determine load losses and impedance voltage.

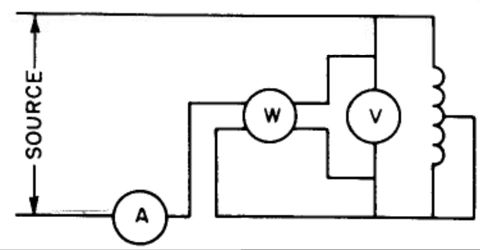

Figure 21 —Connections for impedance loss and impedance voltage tests of an autotransformer

For the purpose of measuring load losses and impedance voltage, the series and common windings of autotransformers may be treated as separate windings, one short-circuited and the other excited. When the transformer is connected in the two-winding connection for the test, the current held shall be the rated current of the excited winding, which may or may not be the same as rated line current. The load loss watts and applied voltamperes will be the same, regardless of whether series and common windings are treated as separate windings in the two-winding connection or are connected in the autotransformer connection, so long as rated winding current is held in the first case and rated line current in the second case.

9.3.3.2 Three-winding transformer

For a three-winding transformer, which may be either single-phase or three-phase, three sets of impedance measurements are made between pairs of windings, following the same procedure as for two-winding transformers. Measurements of the impedances Z_{12}, Z_{23}, and Z_{31} are obtained between windings 1, 2, and 3.

If the kilovoltampere capacities of the different windings are not alike, the current held for the impedance test should correspond to the capacity of the lower rated winding of the pair of windings under test. However, all data, when converted to percentage form, should be based on the same output kilovoltampere, preferably of the primary winding. An equivalent three-winding impedance network, as shown in Figure 22, can be derived from Equation (4), Equation (5), and Equation (6):

$$Z_1 = \frac{Z_{12} - Z_{23} + Z_{31}}{2} \tag{4}$$

$$Z_2 = \frac{Z_{23} - Z_{31} + Z_{12}}{2} = Z_{12} - Z_1 \tag{5}$$

$$Z_3 = \frac{Z_{31} - Z_{12} + Z_{23}}{2} = Z_{31} - Z_1 \tag{6}$$

where Z_{12}, Z_{23}, and Z_{31} are the measured impedance values between pairs of windings, as indicated, all expressed on the same kilovoltampere base.

These equations involve complex numbers, but they may be used for the resistance (in-phase) component or the reactance (quadrature) component of the impedance voltage or of the impedance voltamperes.

The treatment of the individual load losses and impedance voltages for temperature corrections, and so on, is the same as for two-winding single-phase transformers.

Total load losses of a three-winding transformer is the sum of losses in the branches of the equivalent circuit of Figure 22 for any specific terminal load conditions.

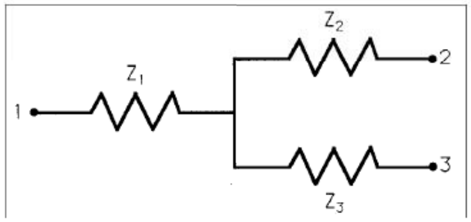

Figure 22—Equivalent three-winding impedance network

9.3.3.3 Interlacing impedance voltage of a Scott-connected transformer

The interlacing impedance voltage of Scott-connected transformers is the single-phase voltage applied from the midtap of the main transformer winding to both ends, connected together. The voltage is sufficient to circulate a current equal to the rated three-phase line current in the supply lines. The current in each half of the winding is 50% of this value.

The percent interlacing impedance is the measured voltage expressed as a percent of the teaser voltage. The percent resistance is the measured losses expressed as a percentage of the rated kilovoltampere of the teaser winding.

9.3.3.4 Test of three-phase transformer with single-phase voltage

To determine the load losses and impedance voltage of a three-phase transformer with single-phase voltage, the setup schematic shown in Figure 23 is recommended.

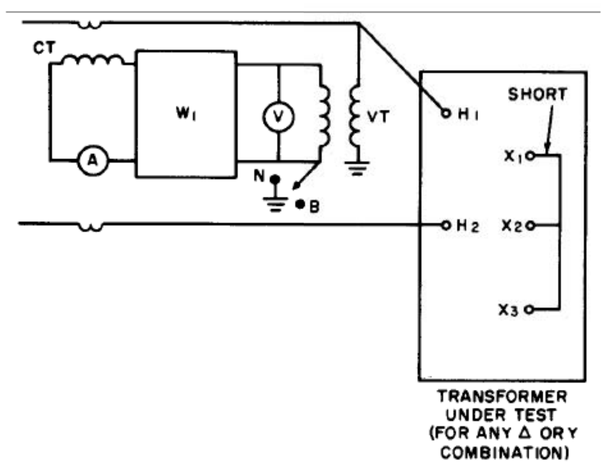

Figure 23—Test of three-phase transformer with single-phase voltage

The three line leads of one winding are short-circuited, and single-phase voltage at rated frequency is applied to two terminals of the other winding. The applied voltage is adjusted to circulate rated line current.

Three successive readings are taken on the three pairs of leads, for example, H_1 and H_2, H_2 and H_3, H_3 and H_1. Then

$$Measured\ load\ losses\ (W) = 1.5\left(\frac{P_{12}+P_{23}+P_{31}}{3}\right) \tag{7}$$

$$Measured\ impedance\ voltage = \frac{\sqrt{3}}{2}\left(\frac{E_{12}+E_{23}+E_{31}}{3}\right) \tag{8}$$

where

- P is the individual reading of measured load losses as indicated by subscripts
- E is the individual reading of measured impedance voltage as indicated by subscripts

The stray loss component shall be obtained by subtracting the I^2R losses from the measured load losses of the transformer. Let R_1 be the resistance measured between two high-voltage terminals and R_2 be the resistance between two low-voltage terminals; let I_1 and I_2 be the respective rated line currents. Then the total I^2R loss of all three phases will be as in Equation (9):

$$\text{Total } I^2R \text{ (watts)} = 1.5(I_1^2R_1 + I_2^2R_2) \tag{9}$$

This formula applies equally well to wye- or delta-connected windings.

Temperature correction shall be made as in 9.4.2.

9.4 Calculation of load losses and impedance voltage from test data

Load losses and impedance voltage measurements vary with temperature and, in general, shall be corrected to a reference temperature. In addition, load loss measurement values shall be corrected for metering phase-angle error.

9.4.1 Correction of load loss measurement due to metering phase-angle errors

Load loss error can be magnitude related, such as instrument transformer ratio errors and meter calibration. Correction of load loss measurement due to phase-angle errors in the wattmeters, voltage-measuring circuit, and current-measuring circuit shall be applied in accordance with Table 1 using the correction formula in Equation (10):

$$P_C = P_m - V_m A_m\left(-\varphi W_d - \varphi V_d + \varphi C_d\right) \tag{10}$$

where

- P_C is the wattmeter reading, corrected for phase-angle error (W)
- P_m is the actual wattmeter reading (W)
- V_m is the voltmeter reading across wattmeter voltage element (V)
- A_m is the ammeter reading in wattmeter current element (A)
- φW_d is the phase-angle error of wattmeter where applicable (rad)
- φV_d is the phase-angle error of voltage transformer (rad)
- φC_d is the phase-angle error of current transformer (rad)

Table 1—Requirements for phase-angle error correction

Apparent load loss power factor ($PF = P_m/VA$)	Comments
$PF \leq 0.03$	Apply phase-angle error correction
$0.03 < PF \leq 0.10$	Apply phase-angle error correction if $\left\lvert -\varphi W_d - \varphi V_d + \varphi C_d \right\rvert > 290$ µrad (1 min)
$PF > 0.10$	Apply phase-angle error correction if $\left\lvert -\varphi W_d - \varphi V_d + \varphi C_d \right\rvert > 870$ µrad (3 min)

In general, instrument transformer phase-angle errors are a function of burden and excitation. Likewise, wattmeter phase-angle errors are a function of the scale being used and the circuit power factor. Thus, the instrumentation phase-angle errors used in the correction formula shall be specific for the test conditions involved. Only instrument transformers meeting 0.3 metering accuracy class, or better, are acceptable for measurements.

Use of Equation (10) is limited to conditions of apparent power factor less than 0.20 and the total system phase-angle error less than 20 min. If corrections are required with apparent power factor or system phase error outside this range, the following exact formulas in Equation (11) apply:

$$\phi_a = \cos^{-1}\left(\frac{P_m}{V_m A_m}\right) \tag{11}$$

$$P_C = V_m A_m \cos\left(\phi_a - \varphi W_d - \varphi V_d + \varphi C_d\right)$$

For three-phase measurements, the corrections are applied to the reading of each wattmeter employed. The transformer load loss at temperature T_m is then calculated using Equation (12) as follows:

$$P(T_m) = \sum_{i=1}^{3} R_v R_a P_{ci} \tag{12}$$

where

$P(T_m)$ is the transformer load losses, corrected for phase-angle error at temperature T_m (W)
P_{ci} is the corrected wattmeter reading of the ith wattmeter (W)
R_v is the true voltage ratio of voltage-measuring circuit
R_a is the true current ratio of current-measuring circuit

9.4.2 Temperature correction of load losses

Both I^2R losses and stray losses of a transformer vary with temperature. The I^2R losses $P_r(T_m)$ of a transformer are calculated from the ohmic resistance measurements (corrected to the temperature T_m at which the measurement of load losses and impedance voltage was done) and the current that was used in the impedance measurement. These I^2R losses subtracted from the measured load loss watts $P(T_m)$ give the stray losses $P_s(T_m)$ of the transformer at the temperature at which the load loss test was made, as shown in Equation (13):

$$P_s(T_m) = P(T_m) - P_r(T_m) \tag{13}$$

where

$P_s(T_m)$ is the calculated stray losses at temperature T_m (W)

$P(T_m)$ is the transformer load losses corrected in accordance with 9.4.1, for phase-angle error at temperature T_m (W)

$P_r(T_m)$ is the calculated I^2R loss at temperature T_m (W)

The I^2R component of load losses increases with temperature. The stray loss component diminishes with temperature. Therefore, when it is desirable to convert the load losses from the temperature at which it is measured T_m to another temperature T, the two components of the load losses are corrected separately, as shown in Equation (14) and Equation (15):

$$P_r(T) = P_r(T_m)\left(\frac{T_k + T}{T_k + T_m}\right) \tag{14}$$

$$P_s(T) = P_s(T_m)\left(\frac{T_k + T_m}{T_k + T}\right) \tag{15}$$

and, then, as shown in Equation (16):

$$P(T) = P_r(T) + P_s(T) \tag{16}$$

where

$P_r(T)$ is I^2R loss (W) at temperature T (°C)

$P_s(T)$ is stray losses (W) at temperature T (°C)

$P(T)$ is transformer load losses (W) corrected to temperature T (°C)

T_k is 234.5 °C (copper) or 225 °C (aluminum; see note below)

NOTE—The temperature 225 °C applies for pure electrical conductor (EC) aluminum. T_k may be as high as 230 °C for alloyed aluminum. Where copper and aluminum windings are employed in the same transformer, a value for T_k of 229 °C should be applied for the correction of stray losses.

9.4.3 Impedance voltage

Impedance voltage and its resistive and reactive components are determined by the use of Equation (17) through Equation (20):

$$E_r(T_m) = \frac{P(T_m)}{I} \tag{17}$$

$$E_x = \sqrt{E_z(T_m)^2 - E_r(T_m)^2} \tag{18}$$

$$E_r(T) = \frac{P(T)}{I} \tag{19}$$

$$E_z(T) = \sqrt{E_r(T)^2 + E_x^2} \tag{20}$$

where

$E_r(T_m)$ is the resistance voltage drop of in-phase component at temperature T_m (V)

$E_r(T)$ is the resistance voltage drop of in-phase component corrected to temperature T (V)

E_x is the reactance voltage drop of quadrature component (V)

$E_z(T_m)$ is the impedance voltage at temperature T_m (V)
$E_z(T)$ is the impedance voltage at temperature T (V)
$P(T)$ is the transformer load losses corrected to temperature T (W)
$P(T_m)$ is transformer load losses measured at temperature T_m (W)
I is the current in excited winding (A)

Per-unit values of the resistance, reactance, and impedance voltage are obtained by dividing $E_r(T)$, E_x, and $E_z(T)$ by the rated voltage. Percentage values are obtained by multiplying per-unit values by 100.

9.4.4 Frequency conversion of load losses and impedance

In the event that the load loss and impedance test cannot be done at the rated power frequency, see Annex B for 50/60 Hz frequency conversions.

9.5 Zero-phase-sequence impedance

9.5.1 Zero-phase-sequence impedance tests of three-phase transformers

The zero-phase-sequence impedance characteristics of three-phase transformers depend on the winding connections and, in some cases, on the core construction. Zero-phase-sequence impedance tests described in this standard apply only to transformers having one or more windings with a physical neutral brought out for external connection. In all tests, one such winding shall be excited at rated frequency between the neutral and the three line terminals connected together. External connection of other windings shall be as described in zero-phase-sequence impedance for various transformer connections. Transformers with connections other than as described in zero-phase-sequence impedance shall be tested as determined by the individuals responsible for design and application.

The excitation voltage and current shall be established as follows:

a) If no delta connection is present on the transformer, the applied voltage should not exceed 30% of the rated line-to-neutral voltage of the winding being energized, nor should the phase current exceed its rated value.

b) If a delta connection is present, the applied voltage should be such that the rated phase current of any delta winding is not exceeded.

The percent excitation voltage at which the tests are made shall be shown on the test report. The time duration of the test shall be such that the thermal limits of any of the transformer parts are not exceeded.

Single-phase measurements of excitation voltage, total current, and power shall be similar to those described in 9.3. The zero-phase-sequence impedance, in percent, on kilovoltampere base of excited winding for the test connection is as follows in Equation (21):

$$Z_0(\%) = 300\left(\frac{E}{E_r} \times \frac{I_r}{I}\right) \tag{21}$$

where

Z_0 is the zero sequence impedance, in percent, on kilovoltampere base of excited winding for the test connection
E is measured excitation voltage (V)
E_r is rated phase-to-neutral voltage of excited winding (V)
I is measured total input current flowing in the three parallel-connected phases (A)

I_r is rated current per phase of the excited windings (A)

9.5.2 Transformers with one neutral externally available, excluding transformers with interconnected windings

The zero-phase sequence network, given the external characteristics for transformers of this type, is shown in Figure 24. Winding 1 has the available neutral, whereas windings 2, 3, and so forth do not.

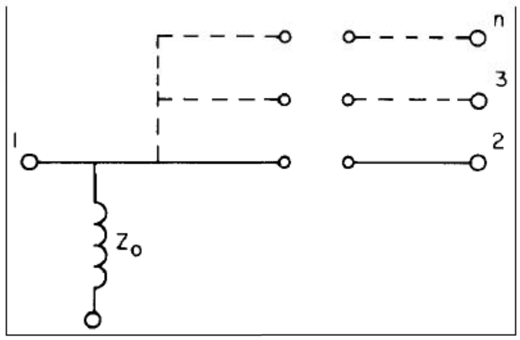

Figure 24—Equivalent zero-phase-sequence network for transformers with one externally available neutral

A zero-sequence test shall be made on the winding with the available neutral. A single-phase voltage shall be applied between the three shorted line terminals and the neutral. The external terminals of all other windings may be open-circuited or shorted and grounded.

The term *interconnected windings* shall be interpreted to mean windings in which one or more electrical phases are linked by more than one magnetic phase.

9.5.3 Transformers with two neutrals externally available, excluding transformers with interconnected windings

The zero-phase sequence network, given the external characteristics for transformers of this type, is shown in Figure 25. Windings 1 and 2 have the externally available neutrals, whereas windings 3, 4, and so forth do not. The diagram is drawn for the case of 0° phase shift between windings 1 and 2.

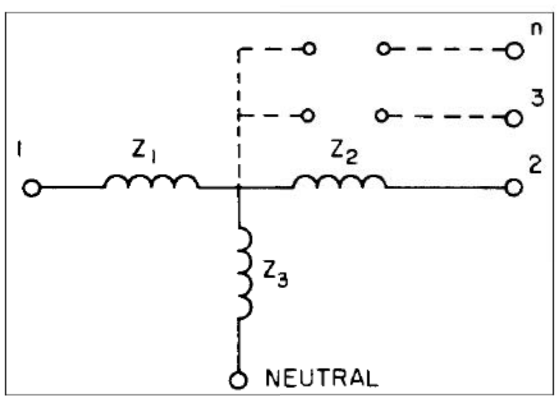

Figure 25—Equivalent zero-phase-sequence network for transformer with two externally available neutrals and 0° phase shift between windings 1 and 2

NOTE—Applies also to autotransformers.

Four tests may be made to determine the zero-phase-sequence equivalent network, one of which is redundant.

a) *Test 1*. Apply a single-phase voltage to winding 1 between the shorted line terminals of winding 1 and its neutral. All other windings are open-circuited. The measured zero-phase-sequence impedance is represented by Z_1N_o.

b) *Test 2*. Apply a single-phase voltage to winding 1 between the shorted line terminals of winding 1 and its neutral. Short the line terminals and neutral of winding 2. All other windings may be open-circuited or shorted. The measured zero-sequence impedance is represented by Z_1N_s.

c) *Test 3*. Apply a single-phase voltage to winding 2 between the shorted line terminals of winding 2 and its neutral. All other windings are open-circuited. The measured zero-phase-sequence impedance is represented by Z_2N_o.

d) *Test 4*. Apply a single-phase voltage to winding 2 between the shorted line terminals of winding 2 and its neutral. Short the line terminals and neutral of winding 1. All other windings may be open-circuited or shorted. The measured zero-phase-sequence impedance is represented by Z_2N_s.

Test 4 and Test 2 are redundant, and Test 4 need not be performed. If performed, however, it may be used as a check. All measured zero-phase-sequence impedances should be expressed in percent and placed on a common kilovoltampere base. The constants in the equivalent circuit are as shown in Equation (22) through Equation (24):

$$Z_3 = +\sqrt{Z_{2N_o}(Z_{1N_o} - Z_{1N_s})} = +\sqrt{Z_{1N_o}(Z_{2N_o} - Z_{2N_s})} \tag{22}$$

$$Z_2 = Z_{2N_o} - Z_3 \tag{23}$$

$$Z_1 = Z_{1N_o} - Z_3 \tag{24}$$

NOTE—These equations involve complex numbers. The plus sign before the radical in Equation (22) is appropriate for most common cases in which windings 1 and 2 are physically adjacent in the design and no delta winding (3, 4, etc.) is interleaved with them. A minus sign may be appropriate when a delta winding (3 or 4) is physically located within or between windings 1 and 2. The correctness of the sign can be checked by comparison with design calculations of zero-sequence impedance.

If Z_{1N_o} and Z_{2N_o} approach infinity, then Z_3 approaches infinity, and the equivalent circuit is that shown in Figure 26.

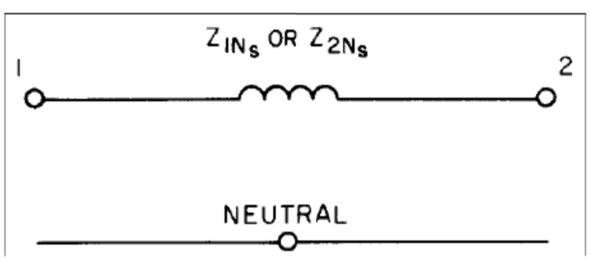

Figure 26—Equivalent zero-phase-sequence network for transformers with two externally available neutrals and 0° phase shift if Z_{1N_o} and Z_{2N_o} approach infinity

In the case of wye–wye connected transformers, the zero-sequence impedance, in general, is a nonlinear function of the applied voltage, which in turn may require more than one set of measurements to characterize the nonlinear behavior.

9.5.4 Autotransformers

The tests and equivalent circuits of 9.5.2 and 9.5.3 apply equally well for autotransformer connections, except that the externally available neutral of a common winding shall be considered as two externally available neutrals, one for the common winding and one for the series-common combination.

9.5.5 General test method for zero-phase-sequence impedance measurement on transformers with interconnected windings (see Rosselli [B13])

The zero-phase-sequence impedance test described in this subclause applies to transformers with interconnected windings, generally of zig-zag connections with and without delta winding and with and without external neutral(s) available. Typical phasor and zero-sequence impedance diagrams are shown in Figure 27(a) and Figure 27(b).

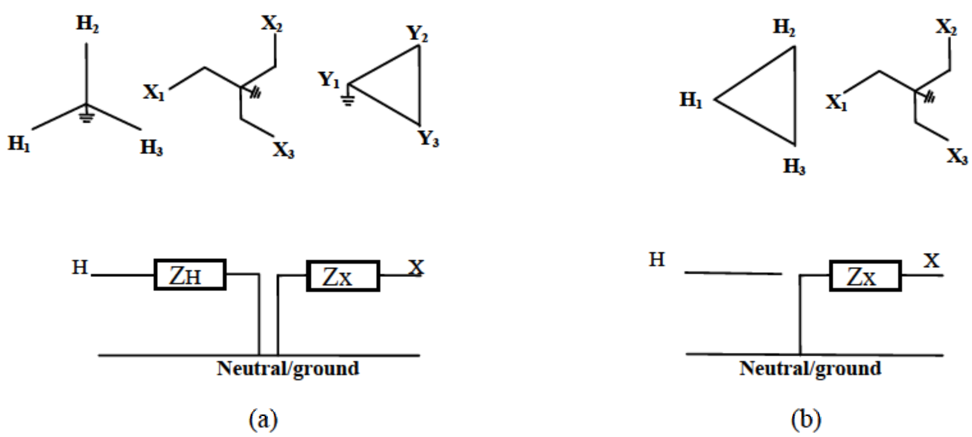

Figure 27—Typical phasor and zero-sequence impedance diagrams

Exciting voltage, current and voltage measurements, and terminal connections shall be established as follows:

a) Primary winding shall be excited with a three-phase voltage at rated frequency and with one phase of secondary interconnected winding shorted to its grounded neutral. If external neutral is not available, the phase should be shorted to ground. The other two secondary terminals shall be open-circuited. When no delta connection is present on the transformer, the applied voltage should not exceed 30% of the rated line-to-neutral voltage of the winding being excited, nor should the phase current exceed its rated value. When a delta winding is present, the applied voltage should be such that the rated phase current of any delta winding is not exceeded. The source must be ungrounded to eliminate any system zero-sequence impedance that could influence the final calculation.

b) Measure the primary voltage on each phase and the secondary voltages to ground of open-circuited phases.

c) Measure the applied current to each phase of the primary windings and current in the shorted phase of the secondary winding.

d) Repeat step a through step c for other two phases of the secondary winding, one at a time.

e) Calculate the zero-phase-sequence impedance for each phase using the equation in Equation (27). The final zero-phase-sequence impedance shall be the average of the calculated zero-sequence impedances for all phases, or if more conservative values are required, then the lowest Z_0 can be used. All values shall be included in the certified test report.

f) For simplifying calculations, resistance component impedance is considered negligible.

$$Z_0(\%) = 300\left(\frac{E_{AV}}{Er} \times \frac{Ir}{I}\right) - \left[2Z_+ + 3Z_N\right] \quad (25)$$

where

E_{AV} is the average of applied three-phase measured voltages divided by transformer ratio
E_r is the rated phase-to-neutral voltage of the shorted winding
I is the measured total current flowing in the shorted phase
I_r is the rated current per phase of the shorted winding at the megavoltampere rating of the transformer
Z_+ is the percent positive-phase-sequence impedance based on the megavoltampere rating
Z_N is the percent neutral impedance based on the megavoltampere rating (This value will be zero if no neutral impedance is used.)

10. Dielectric tests

10.1 General

10.1.1 Factory dielectric tests

The purpose of dielectric tests in the factory is to demonstrate that the transformer has been designed and constructed to withstand the specified insulation levels.

10.1.2 Test requirements

Test levels and other test parameters shall be as outlined in IEEE Std C57.12.00 or as otherwise specified.

10.1.3 Measurement of test voltages

Unless otherwise specified, the dielectric test voltages shall be measured or applied, or both, in accordance with IEEE Std 4, with the following exceptions:

a) A protective resistance may be used in series with sphere gaps, on either the live or the grounded sphere. When unnecessary to protect the spheres from arc damage, it may be omitted.

b) The bushing-type potential divider method shall be considered a standard method for transformer tests.

c) The rectified capacitor-current method shall be considered a standard method for transformer tests.

d) In conducting low-frequency tests for transformers of 100 kVA and less to be tested at 50 kV or less, it is permissible to depend on the ratio of the testing transformer to indicate the proper test voltage.

10.1.4 Type of power transformer

The terms *Class I* and *Class II* power transformers, as used in this standard, are defined in 5.10 of IEEE Std C57.12.00-2010.

10.1.5 Factory dielectric tests and conditions

10.1.5.1 Test sequence

Lightning impulse voltage tests, when required, shall precede the low-frequency tests. Switching impulse voltage tests, when required, shall also precede the low-frequency tests.

For Class II power transformers, the induced-voltage test shall be the final dielectric test performed.

10.1.5.2 Temperature

Dielectric tests may be made at temperatures assumed under normal operation or at the temperatures attained under conditions of routine test.

10.1.5.3 Assembly

Transformers, including bushings and terminal compartments when necessary to verify air clearances, shall be assembled prior to making dielectric tests. However, assembly of items that do not affect dielectric tests, such as radiators and cabinets, is not necessary. Bushings shall, unless otherwise authorized by the purchaser, be those to be supplied with the transformer.

10.1.5.4 Transformers for connection to gas-insulated equipment

During dielectric testing of transformers for direct connection to gas-insulated substations, testing with the in-service bushings is preferred, but substitute air-oil bushings may be used unless otherwise specified by the purchaser. Live part clearances and locations of the substitute bushings inside the transformer shall be identical, within normal manufacturing tolerances, to those of the in-service bushings. When required internal clearances, or external air clearances, and/or external air clearances cannot be achieved, suitable arrangements are required as determined by the manufacturer and purchaser in advance of the design of the transformer.

10.1.6 Tests on bushings

When tests are required on outdoor apparatus (air-to-oil) bushings separately from the transformers, the tests shall be made in accordance with IEEE Std C57.19.00 and IEEE Std C57.19.01.

Details of separate testing of bushings for use on transformers connected to gas-insulated equipment shall be agreed upon by the manufacturer and purchaser prior to the design of the transformer.

10.1.7 Dielectric tests in the field

Field dielectric tests may be warranted based on detection of combustible gas or other circumstances. However, periodic dielectric tests are not recommended because of the severe stress imposed on the insulation.

Where field dielectric tests are required, low-frequency applied-voltage and induced-voltage tests shall be used. For distribution transformers and Class I power transformers, the line-to-ground or line-to-line voltage stress imposed shall not exceed 150% of normal operating stress or 85% of full test voltage, whichever is lower. The duration of the tests shall be the same as that specified in 10.6 and 10.7 for applied and induced voltage, respectively.

For Class II power transformers, the line-to-ground or line-to-line voltage stress imposed shall not exceed 150% of maximum system operating voltage. The duration of the test shall not exceed the limits given in Table 2.

Table 2—Maximum test duration

Test voltage as a percentage of maximum system operating voltages	Allowable duration (min)
150	5
140	12
130	36
120	120

When inducing a transformer in excess of its rated voltage, the test frequency should be increased as necessary to avoid core saturation. Guidance in this area is provided in 10.7.2.

10.2 Switching impulse test procedures

The switching impulse test, when specified, shall consist of applying or inducing a switching impulse wave between each high-voltage line terminal and ground with a crest value equal to the specified test level.

10.2.1 Number of tests

The test series shall consist of one reduced voltage transient at 50% to 70% of specified test level followed by two full voltage transients at the specified test level.

10.2.2 Switching impulse waves

10.2.2.1 Polarity

Negative polarity waves shall be used.

NOTE 1—The transformer core may be pre-biased using either a dc supply or reduced switching impulse waves of positive polarity. Reduced switching impulse waves of positive polarity not exceeding 70% of the full test level may be applied prior to the first full wave and in between full-wave tests. The purpose is to bias the core in the opposite flux polarity to delay saturation during negative polarity full-wave test.

NOTE 2—Negative polarity waves are specified for the actual test to minimize the risk of erratic external flashover (in the gap forming the air clearance to ground or in between phases). Negative polarity waves are deemed to stress the internal insulation in a similar manner as positive polarity waves.

10.2.2.2 Wave shape

The switching impulse voltage wave shall have a crest value in accordance with the assigned insulation level, subject to a tolerance of ± 3%, and shall exceed 90% of the crest value for at least 200 µs. The actual time to crest shall be greater than 100 µs, and the time to the first voltage zero on the tail of the wave shall be at least 1000 µs.

Occasionally, core saturation will cause the time to the first voltage zero to be less than 1000 µs. Successive transients of the same polarity may cause the time to the first voltage zero to become even shorter. To increase the time to the first voltage zero, it may be necessary to magnetically bias the core in the direction opposite to that caused by the switching impulse transient. This goal can be accomplished by passing a small direct current through the winding between impulses, by reversing the switching impulse polarity on successive applications, or by applying reduced impulses of opposite polarity before each full switching impulse transient. If biasing cannot be accomplished to obtain 1000 µs to the first voltage zero, the shorter tail may be used because the duration of a switching impulse in actual service will similarly be reduced because of core saturation.

10.2.2.3 Time to crest

The actual time to crest shall be defined as the time interval from the start of the transient to the time when the maximum amplitude is reached.

10.2.2.4 Time to first voltage zero

The time to the first voltage zero on the tail of the wave shall be defined as the time interval from the start of the transient to the time when the first voltage zero occurs on the tail of the wave.

10.2.2.5 Ninety-percent time

A smooth wave sketched through any oscillations on the switching impulse voltage oscillogram may be used to determine the time that the applied wave is in excess of 90% of the specified crest value.

10.2.3 Failure detection

A voltage oscillogram shall be taken of each applied or induced transient. The test is successful if there is no sudden collapse of voltage indicated on the oscillograms. Successive oscillograms may differ, however, because of the influence of magnetic saturation on impulse duration.

10.2.4 Tap connections

The choice of tap connections for all windings shall be made by the manufacturer.

10.3 Lightning impulse test procedures

Lightning impulse tests, when required as a routine test or when otherwise specified, shall consist of and be applied in the following order: one reduced full wave, two chopped waves, and one full wave. The time interval between applications of the last chopped wave and the final full wave should be minimized, without intentional delays, to avoid recovery of dielectric strength if a failure were to occur prior to the final full wave.

When front-of-wave tests are also specified, impulse tests are generally applied in the following order: one reduced full wave, two front-of-waves, two chopped waves, and one full wave.

The order of the chopped-wave and front-of-wave tests is not mandatory. However, a reduced full wave shall be applied first, and the full wave shall be the last wave to be applied to the terminal under test. Other reduced full waves may be applied at any time during the intervening sequence.

For guide information on impulse testing techniques, interpretation of oscillograms, and failure detection criteria, see IEEE Std C57.98.

10.3.1 General

Impulse tests shall be made without excitation.

10.3.1.1 Full-wave test

The test wave rises to crest in 1.2 μs and decays to half of crest value in 50 μs from the virtual time zero. The crest value shall be in accordance with the assigned basic impulse insulation level (BIL), subject to a tolerance of ± 3%; and no flashover of the bushing or test gap shall occur. The tolerance on virtual front time should normally be ± 30%, and the tolerance on time to half of crest should normally be ± 20%. However, as a practical matter, the following shall be considered:

a) The virtual front time shall not exceed 2.5 μs except for windings of large impulse capacitance (low-voltage, high-kilovoltampere and some high-voltage, high-kilovoltampere windings). To demonstrate that the large capacitance of the winding causes the long front, the impulse generator series resistance may be reduced. The reduction should cause superimposed oscillations. Only the inherent generator and lead inductances should be in the circuit.

b) The impedance of some windings may be so low that the desired time to the 50% voltage point on the tail of the wave cannot be obtained with available test equipment. For such cases, shorter waves are considered acceptable provided that the optimum impulse generator connection is used (i.e., using parallel stages, if applicable, and the largest available capacitance). However, if by using the optimum impulse generator connection, the minimum tail time specified (40 μs) cannot still be achieved, the following alternative methods shall be used in the following preferred order:

    1) Use of resistor(s) on the nonimpulsed winding(s). The resistor value shall be the minimum necessary to achieve the required minimum tail time of 40 μs and shall not exceed the values given in Table 3 (in 10.3.2.1). If the transformer is to be connected to a cable or to a gas-insulated switchgear or line (GIS or GIL), the resistor value shall not exceed 30 Ω for cable-connected terminals or 75 Ω for GIS- or GIL-connected terminals.

    2) Use of resistor on the grounded terminal of the impulsed winding. Here also, the resistor value shall be the minimum necessary to achieve the required minimum tail time of 40 μs and shall not exceed the values given in Table 3. If the transformer is foreseen to be connected to a cable or to a GIS or GIL, the resistor value shall not exceed 30 Ω for cable-connected terminals or 75 Ω for GIS- or GIL-connected terminals.

NOTE 1—The impulse voltage applied to the resistor should not exceed 80% of the rated lightning impulse level of the terminal(s) on which the resistor(s) are connected, unless the manufacturer has consented. For delta-connected windings, the impulse voltage applied to the resistor, if used on nonimpulsed terminals of the delta, should not exceed 50% of the rated lightning impulse level of the terminal(s) on which the resistor(s) are connected.

NOTE 2—IEEE Std C57.98 and IEC 60076-4 [B8] give background information regarding the effect of added resistors to the dielectric stresses applied to the transformer.

NOTE 3—In general, the voltage peak appearing across the resistor is considerably delayed compared to the instant of the voltage peak of the applied lightning impulse. Thus, the resulting difference between the applied impulse and the voltage across the resistor (e.g., voltage across the winding) is similar to the one that would appear across the winding if the resistor were not used and the terminal were directly grounded. If the resistor applied voltage peak coincides within 10 μs of the voltage impulse peak, then the voltage drop across the winding is significantly reduced, and a special procedure should be agreed upon between the manufacturer and the purchaser.

NOTE 4—The use of the Glaninger circuit (see IEEE Std C57.98) is also an effective method to increase the tail time. If such circuit is used, care should be exercised on the overswing in the opposite polarity. Overswing in opposite polarity up to 75% is common.

NOTE 5—If the specific application (line, cable, GIS, or GIL) is not indicated at the time of order, the transformer is deemed to be overhead line-connected.

If the calculated tail time for a particular connection and transformer design is such that the minimum time to 50% (e.g., 40 μs) cannot be achieved, the manufacturer shall notify the purchaser of this possibility. The manufacturer shall also state the strategy to be taken to obtain the best achievable wave shape. Notification should be given during the bidding stage for cases where the minimum tail time cannot be obtained for a particular transformer design and/or because of test laboratory limitations. In such cases, shorter wave shapes may be agreed upon between manufacturer and purchaser.

NOTE—The minimum impulse generator energy required to meet the minimum tail time (40 μs) during an impulse test on a particular transformer design and connection can be estimated by using Equation (26):

$$E_{\min.} = \frac{2\pi f (t_2)^2}{zU^2} \left(\frac{U_{BIL}}{\eta} \right)^2 VA \tag{26}$$

where

- $E_{\min.}$ is the minimum energy required from the impulse generator (J)
- f is the power frequency, 60Hz (or 50 Hz)
- t_2 is the tail time (s) (t_2 equals 40 μs)
- z is the impedance (in per unit) seen from the impulsed terminal
- U is the winding rated voltage (V, phase-to-phase)
- U_{BIL} is the rated BIL of the tested winding (V)
- η is the impulse generator efficiency (in per unit) ($\eta = 1.0$)
- VA is the three-phase power rating (VA) for which the impedance z is defined

NOTE—This equation has been derived from the equations given in IEC 60076-4 [B8]. More information about wave shape control can be found in IEEE Std C57.98 and IEC 60076-4.

10.3.1.2 Reduced full-wave test

A reduced full wave is the same as a full wave, except that the crest value shall be between 50% and 70% of the full-wave value.

10.3.1.3 Chopped-wave test

A chopped wave is inherently a full lightning impulse wave, except that the crest value shall be at the required level and the voltage wave shall be chopped at or after the required time to flashover (time to chopping) but not later than 6 μs after virtual origin. The virtual front time of the chopped wave may be different than the virtual front during a full-wave test because of the presence of the chopping gap. Nevertheless, the tolerance on the virtual front time for the chopped-wave test should remain as defined for full-wave test.

The gap or other equivalent chopping device shall be located as close as possible to the terminals of the transformer without disrupting its electrical field distribution. The distance between the chopping device and the test object shall not exceed a lead length greater than the total height of the transformer (tank + bushing). The impedance between the tested terminal and the grounded end of the chopping device shall be limited to that of the necessary leads. The voltage zero following the instant of chopping shall occur within 1 μs. However, for some winding designs (particularly low-voltage windings of high stray capacitance and some layer windings), the circuit response after chopping may not be oscillatory; it may be overdamped. For such cases, the time interval to the first voltage zero after the instant of chopping may be significantly greater than 1 μs.

Only for cases where the overswing to the opposite polarity is greater than 30% is it permissible to add a series-connected resistor in the chopping circuit to limit the amount of overswing. When a resistor is added in the chopping circuit, the resistor shall not decrease the overswing below 30% of the amplitude of the chopped wave.

The use of a resistor in the chopping circuit may increase the time interval to the first voltage zero after the instant of chopping. If the use of a resistor in the chopping circuit does conflict with the above requirement of the maximum time interval to the first voltage zero after the instant of chopping, the priority shall be given to the maximum limit of the time interval. For such cases, it may not be possible to reduce the overswing to the opposite polarity to 30%.

NOTE 1—This method will ensure that the steepness of the voltage collapse (dv/dt) is as high as possible.

NOTE 2—The use of a chopping gap made of sphere gap(s) (single or multiple sphere gaps) is the preferred chopping method since it usually gives faster voltage collapse. The use of a rod-rod chopping gap is also permissible since this method more accurately replicates in-service flashover of an air insulator. Notably, the rod-rod gap requires a greater distance between its electrode for a given operating voltage than does a sphere gap. The extended arc length of the rod-rod gap provides more natural circuit damping than the shorter arc length of a sphere gap.

NOTE 3—If the above prescribed maximum lead length to the chopping gap cannot be achieved because of the presence of transformer accessories such as coolers or any other transformer accessories, then the shortest possible lead length should be used during tests.

10.3.1.4 Front-of-wave test

The wave to be used in a front-of-wave test is similar to a full wave, except that it is chopped on the front of the wave at the assigned crest level and time to sparkover. The time to sparkover for front-of-wave impulse tests shall be the time from virtual zero to the time of sparkover. As with the chopped-wave test, the manufacturer shall be permitted to add resistance in the circuit to limit the amount of overswing to the opposite polarity to 30% of the amplitude of the front-of-wave.

10.3.1.5 Wave polarity

For mineral-oil-immersed transformers, the test waves are normally of negative polarity to reduce the risk of erratic external flashover in the test circuit.

10.3.1.6 Impulse oscillograms

All impulses applied to a transformer shall be recorded by an oscilloscope or by a suitable digital transient recorder, unless their crest voltage is less than 40% of the full-wave level. These oscillograms shall include voltage oscillograms for all impulses and ground-current oscillograms for all full-wave and reduced full-wave impulses. Sweep times should be on the order of 2 μs to 5 μs for front-of-wave tests, 5 μs to 10 μs for chopped-wave tests, 50 μs to 100 μs for full-wave tests, and 100 μs to 600 μs for ground-current measurements.

When reports require oscillograms, those of the first reduced full-wave voltage and current, the last two chopped waves, and the last full wave of voltage and current shall represent a record of the successful application of the impulse test to the transformer.

When transformers receiving front-of-wave impulse tests require reports that include oscillograms, those of the first reduced full-wave voltage and current, the last two front-of-waves, the last two chopped waves, and the last full wave of voltage and current shall represent a record of the successful application of the front-of-wave impulse test to the transformer.

10.3.2 Connections for impulse tests of line terminals

In general, the tests shall be applied to each terminal, one at a time.

10.3.2.1 Terminals not being tested

Neutral terminals shall be solidly grounded. Line terminals, including those of autotransformers and regulating transformers, shall be either solidly grounded or grounded through a resistor with an ohmic value not in excess of the values given in Table 3.

Table 3—Grounding resistor values

Nominal system voltage (kV)	Resistance (Ω)
345 and below	450
500	350
765	300
NOTE—These values are representative of typical transmission-line surge impedances.	

The following factors shall be considered in the actual choice of grounding for each terminal:

a) The voltage to ground on any terminal that is not being tested should not exceed 80% of the full-wave impulse voltage level for that terminal.

b) When a terminal has been specified to be directly grounded in service, then that terminal shall be solidly grounded.

c) When a terminal is to be connected to a low-impedance cable connection in service, then that terminal shall be either directly grounded or grounded through a resistor with an ohmic value not in excess of the surge impedance of the cable.

d) Grounding through a low-impedance shunt for current measurements may be considered the equivalent of a solid ground.

10.3.2.2 Windings for series or multiple connections

When either connection is 25 kV nominal system voltage or above, the windings shall be tested on both series and multiple connections. The test voltage for the two conditions shall correspond to the BIL of the winding for that connection. For nominal system voltages of 15 kV and below, only the series connections shall be tested, unless tests on both connections are specified.

10.3.2.3 Windings for delta or wye connections

When either connection is 25 kV nominal system voltage or above, the three-phase transformer shall be tested on both delta and wye connections. The test voltage for each connection shall correspond to the BIL of the winding for that connection. For nominal system voltages of 15 kV and below, only the wye connection shall be tested, unless tests on both connections are specified.

10.3.2.4 Tap connections

Tap connections shall be made with minimum effective turns in the winding under test. The choice of tap connections of windings not being tested shall be made by the manufacturer. (Regulating transformers shall be set at maximum buck position.)

10.3.2.5 Protective devices that are an integral part of the transformer

Transformers and regulators may have, as an integral part of their design, nonlinear protective devices connected across whole or portions of windings. Operation of these protective devices during impulse testing may cause differences between the reduced full-wave and the full-wave and/or chopped-wave oscillograms. In order to demonstrate that these differences are solely caused by the operation of the protective devices and not by a transformer failure, additional reduced full-wave impulse tests at different voltage levels shall be applied to show the effect of the operation of the nonlinear devices on voltage and current oscillograms and its reproducibility.

The purpose of the nonlinear protective devices is to limit transient overvoltages, which may be impressed or induced across the windings during lightning impulse surges (high-frequency voltage surges). However, during the standardized switching impulse tests, because of the potentially high energy level contained in switching surges, provisions must be made so that these devices will not operate within any of the winding sections. If, during switching impulse tests, a flashover is observed across line bushings, the nonlinear devices may limit the resulting overvoltages produced within the winding sections after flashover.

Typical oscillograms depicting the operation of protective devices during impulse testing are shown in IEEE Std C57.98.

The following test sequence shall be performed:

- One reduced full wave between 50% and 70% of the required full-wave impulse level
- One or more intermediate reduced full waves between 75% and 100% of the required full-wave impulse level (see Note 1)
- One full wave at 100% of the required full-wave impulse level
- Two chopped waves at 100% of the required chopped-wave impulse level
- One full wave at 100% of the required full-wave impulse level
- One or more intermediate reduced full waves at the same voltage levels as used before the first full-wave test
- One reduced full wave between 50% and 70% of the required full-wave impulse level

With the exception of the special cases given below in Notes 2 and 3, the intermediate reduced full-wave impulse level shall show the operation of the nonlinear devices and its effect on the current and voltage oscillograms.

NOTE 1—The voltage level to be applied for the intermediate reduced full wave is not specifically given. Only a range is proposed because the threshold operating level of the nonlinear devices is transformer design dependent. Generally, a lightning impulse within that specified voltage range will cause the operation of the nonlinear devices. The specific number of intermediate full-wave tests and their voltage levels cannot be given here. The number of intermediate full-wave tests and their respective voltage level for a given transformer should be chosen by the manufacturer and agreed to by the purchaser.

NOTE 2—In some cases, tests at 100% of the required full-wave impulse level with the standardized lightning impulse wave shape will not show the operation of the nonlinear devices. In such cases, additional intermediate reduced full-wave tests are not necessary and may be waived.

NOTE 3—In some other special cases, the operation of the nonlinear devices can be observed only during the chopped-wave impulse tests. In such cases, the intermediate reduced full-wave tests are also not necessary and may be waived. As explained in 10.3.4.2a), comparison of the recorded oscillograms may be done by comparing the two chopped-wave tests together up to the time of chopping. Chopped-wave tests cannot be compared during and after chopping. For such cases, reduced chopped-wave impulses at a test level of approximately 75% of the required chopped-wave test level may be a useful tool to assess that the differences on the recorded oscillograms are solely caused by the operation of the nonlinear devices. If reduced chopped-wave tests are performed, they should, by agreement, be performed before and after the required chopped-wave tests.

Because of the operation of the nonlinear devices, the comparison of the voltage and current oscillograms shall be made only between two tests performed at the same voltage level, e.g., comparing, for example, the two 80% reduced full-wave tests. Because it is not possible to compare a single 100% full-wave test with other reduced full-wave tests (as is the case for transformers not having nonlinear devices), two 100% full-wave impulse tests need to be performed to compare them. Each reduced full-wave test performed after a full-wave test shall be compared with the corresponding reduced full-wave test performed prior to the full-wave test.

10.3.3 Impulse tests on transformer neutrals

Impulse tests on the neutral of a transformer or a separate regulator connected in the neutral of a transformer require one reduced full wave and two full waves to be applied directly to the neutral or regulator winding with an amplitude equal to the insulation level of the neutral. The winding being tested shall be either on the minimum voltage connection or on the maximum voltage connection. A wave having a front of not more than 10 μs and a tail of 50 μs to half-crest shall be used, except that, when the inductance of the winding is so low that the desired voltage magnitude and duration to the 50% point on the tail of the wave cannot be obtained, a shorter wave tail may be used.

10.3.4 Detection of failure during impulse test

Given the nature of impulse test failures, one of the most important matters to consider is the detection of such failures. Several indications of insulation failure exist.

10.3.4.1 Ground current oscillograms

In the ground current method of failure detection, the impulse current in the grounded end of the winding tested is measured by an oscilloscope or by a suitable digital transient recorder connected across a suitable shunt inserted between the normally grounded end of the winding and the ground. Any differences in the wave shape between the reduced full wave and the final full wave detected by comparison of the two current oscillograms may be indications of failure or deviations due to noninjurious causes. They should be fully investigated and explained by a new reduced full-wave test and full-wave test. Examples of probable causes of different wave shapes are operation of protective devices, core saturation, or conditions in the test circuit external to the transformer.

The ground current method of detection is not suitable for use with chopped-wave tests.

10.3.4.2 Other methods of failure detection

Other methods of detecting failure include the following:

a) Voltage oscillograms. Any unexplained differences between the reduced full wave and the final full wave detected by comparison of the two voltage oscillograms, or observed by comparing the chopped waves to each other and to the full wave up to the time of chopping, are indications of failure.

b) Failure of gap to sparkover. In making the chopped-wave test, failure of the chopping gap or any external part to sparkover, although the voltage oscillogram shows a chopped wave, is a definite indication of a failure either within the transformer or in the test circuit.

c) Noise. Unusual noise within the transformer at the instant of applying the impulse is an indication of trouble. Such noise should be investigated.

d) Measurement. Measurement of voltage and current induced in another winding may also be used for failure detection.

10.4 Routine impulse test for distribution transformers

For distribution transformers, the impulse tests specified in 10.3 are design tests. This subclause (i.e., 10.4) defines a routine quality control test that is suitable for high-volume production-line testing. The routine impulse test for distribution transformers applies to overhead, pad-mounted, and underground liquid-immersed distribution transformers with requirements specified in IEEE Std C57.12.20, IEEE Std C57.12.22, IEEE Std C57.12.23, IEEE Std C57.12.24, ANSI C57.12.25, IEEE Std C57.12.26, and IEEE Std C57.12.36.

10.4.1 Terminals to be tested

In routine testing, impulse tests are applied to all high-voltage line terminals. Impulse tests of the low-voltage terminals or the neutral terminal are not required. Line terminals rated more than 600 V are considered high voltage.

10.4.2 Procedure

The windings under test are connected to ground through a low-impedance shunt. The tank, the core, and either one of the low-voltage terminals or the neutral terminal are also connected to the shunt or are directly grounded. This shunt shall consist of either of the following:

a) Ground current method. A suitable resistance shunt or wide-band pulse current transformer is employed to examine the waveform of the ground current.

b) Neutral impedance method. A low-impedance shunt, consisting of a parallel combination of resistance and capacitance (RC), is employed. The voltage across this neutral impedance shunt is examined.

An impulse voltage with 1.2×50 µs wave shape and with specified crest magnitude shall be applied in each test. The tolerances, polarity, and method of determining the wave shape shall be as specified in 10.3.1.1 and 10.3.1.5. During each test, the waveform of the ground current or the voltage wave across the neutral impedance shall be examined.

The required impulse tests shall be applied using either of the test series in Method 1 or Method 2.

10.4.2.1 Method 1

One reduced full-wave test is performed, followed by one 100% magnitude full-wave test. The applied-voltage wave in the first test shall have a crest value of between 50% and 70% of the assigned BIL. The applied-voltage wave in the second test shall have a crest value of 100% of the assigned BIL. Failure detection is accomplished by comparing the reduced full-wave test with the 100% magnitude full-wave test, using either the ground current waveform or the neutral impedance voltage waveform. A dielectric breakdown will cause a difference in compared waveforms. Observed differences in the waveforms may be indications of failure, or they may be due to noninjurious causes. The criteria used to judge the magnitude of observed differences shall be based on the ability to detect a staged single-turn fault made by placing a loop of wire around the core leg and over the coil.

10.4.2.2 Method 2

Two full-wave tests, with crest magnitude equal to the assigned BIL, are applied to the transformer under test. A neutral impedance shunt, using suitable values of resistance and capacitance, is employed to record waveforms for comparison. The waveforms in both tests are compared with pre-established levels. A dielectric breakdown will cause a significant upturn and increase in magnitude of the voltage wave examined across the neutral impedance. The pre-established levels are based on a staged single-turn fault test, made by placing a loop of wire around the core leg and over the coil.

10.4.2.3 Failure detection

The failure detection methods described in 10.4.2.1 and 10.4.2.2 for the routine impulse test are based on the following two conditions:

a) The transformer connections during the test are such that no low-voltage windings are shorted.

b) Chopped-wave tests are not applied.

In addition to these methods of failure detection, other methods of failure detection, as described in 10.3.4.2, are also indications of failure and should be investigated.

When the test is complete and the process of failure detection is complete, the waveform records may be discarded.

The routine impulse test may be conducted either before or after the low-frequency dielectric tests; however, the preferred sequence is for the impulse test to precede the low-frequency dielectric tests.

10.4.3 Terminals not being tested

All high-voltage terminals not being tested shall be solidly grounded for impulse tests of the high-voltage windings. However, if two high-voltage terminals are grounded, causing a short circuit across one or more of the high-voltage windings, the failure detection sensitivity of the test may be impaired, and a single-turn fault may not be detectable. In such cases, only one high-voltage terminal should be grounded. Grounding through a low-impedance shunt for current measurements may be considered the equivalent of a solid ground. The low-voltage windings shall be solidly grounded for impulse tests of the high-voltage windings by applying the ground to only one low-voltage terminal in order to minimize the risk of a deliberate short circuit across any low-voltage winding. Selection of the low-voltage terminal to be grounded should be as follows:

a) For a single-phase three-wire connection, where X_2 would be grounded in service, terminal X_2 shall be solidly grounded; and terminals X_1 and X_3 shall be open, except as provided in the paragraph that follows this list.

b) For a single-phase two-wire connection, where either X_1 or X_2 may be grounded in service, then either terminal X_1 or X_2 shall be solidly grounded; and the remaining terminal shall be open, except as provided in the paragraph that follows this list.

c) For a three-phase four-wire connection, where X_0 would be grounded in service, terminal X_0 shall be grounded; and terminals X_1, X_2, and X_3 shall be open, except as provided in the paragraph that follows this list.

d) For a three-phase three-wire delta connection, only one of the low-voltage terminals X_1, X_2, or X_3 shall be solidly grounded; and the two remaining terminals shall be open, except as provided in the paragraph that follows this list.

For series multiple or other low-voltage connections not covered specifically above, the low-voltage windings shall be grounded in accordance with the principle of grounding the winding without causing a direct short circuit across any low-voltage winding and preferably selecting the terminal that will be grounded in service.

It is permissible to limit the voltage to ground of any low-voltage terminal by connecting a resistor across the low-voltage windings. This resistor shall be sized to limit the induced voltage to less than 80% of the BIL of the terminal. Current flowing in the limiting resistor shall not interfere with the ability to detect a staged single-turn fault.

10.4.4 Windings for series or multiple connections

For high-voltage windings with series or multiple connections, the routine impulse test shall be conducted on each connection at its assigned BIL.

10.4.5 Windings for delta or wye connections

For high-voltage windings with delta or wye connections, the routine impulse test shall be conducted on each connection at its assigned BIL.

10.4.6 Tap connections

For windings with taps, the routine impulse test shall be performed in the tap connection for shipment in accordance with Clause 10 of IEEE Std C57.12.00-2010.

10.5 Low-frequency tests

Low-frequency tests shall be performed in accordance with the requirements of 5.10, Table 4, and Table 5 of IEEE Std C57.12.00-2010.

For distribution transformers and Class I power transformers, the low-frequency test levels are developed by the applied-voltage and induced-voltage tests described in 10.6 and 10.7, or combinations thereof. The induced-voltage test may involve either single-phase or three-phase excitation.

For single-phase transformers with a BIL of 150 kV or less that have only one high-voltage bushing, the high-voltage neutral terminal permanently connected to ground, and no secondary windings permanently grounded, no applied-voltage test is required. These transformers shall receive an induced-voltage test between the high-voltage terminal and ground with duration of 7200 cycles but not less than 15 s. This voltage shall be 1000 V plus 3.46 times the rated transformer winding voltage, but in no case shall the line-to-ground voltage developed exceed 40 000 V for 125 kV BIL or 50 000 V for 150 kV BIL. An applied-potential test shall be applied to all windings that are not permanently grounded.

For Class II power transformers, the low-frequency tests involve a special induced test as described in 10.8 and applied-voltage tests as described in 10.6.

10.5.1 Induced-voltage test for transformers with series or multiple connections

Transformers with windings that have multiple connections (series-parallel or delta-wye) and whose connections each have a nominal system voltage of 25 kV or above shall receive two induced tests, one in each connection. If more than one winding has such multiple connections, then the connections in each of the windings shall change between the tests, and the manufacturer shall determine the relative connections for each test. The test voltage and duration (Class I—7200 cycle or Class II—1 h test) shall be contingent on the system voltage level of the high-voltage winding for the connection being tested. In all cases, the last induced test shall be for the connection with the highest test voltage.

10.6 Applied-voltage tests

10.6.1 Duration, frequency, and connections

The test shall be performed at low frequency (<500 Hz), and the duration of the test shall be 1 min.

The winding being tested shall have all its parts joined together and connected to the line terminal of the testing transformer.

All other terminals and parts (including core and tank) shall be connected to ground.

10.6.2 Relief gap

A relief gap set at a voltage 10% or more in excess of the specified test voltage may be connected during the applied-voltage test.

10.6.3 Application of test voltage

The voltage should be started at one quarter or less of the full value and be brought up gradually to full value. After being held for the time specified in 10.6.1, it should be reduced gradually before the circuit is opened.

10.6.4 Failure detection

Careful attention should be maintained for evidence of possible failure, such as an indication of smoke and bubbles rising in the oil, an audible sound such as a thump, or a sudden increase in test circuit current. Any such indication should be carefully investigated by observation, by repeating the test, or by other tests to determine whether a failure has occurred.

10.7 Induced-voltage tests for distribution and Class I power transformers

10.7.1 Test duration

The induced-voltage test shall be applied for 7200 cycles, or 60 s, whichever is shorter.

10.7.2 Test frequency

As an induced-voltage test applies greater-than-rated volts per turn to the transformer, the frequency of the impressed voltage shall be high enough to limit the flux density in the core to that permitted by 4.1.6.1 of IEEE Std C57.12.00-2010. The minimum test frequency to meet this condition is given in Equation (27):

$$\textit{Minimum test frequency} = \frac{E_t}{1.1 \times E_r} \times \textit{rated frequency} \tag{27}$$

where

E_t is the induced voltage across winding (V)

E_r is the rated voltage across winding (V)

10.7.3 Application of voltage

The voltage should be started at one quarter or less of full value and be brought up gradually to full value. After being held for the time specified in 10.7.1, it should be reduced gradually before the circuit is opened.

10.7.4 Grounding of windings

When a transformer has one end of the high-voltage winding grounded, the other windings should be grounded during the induced-voltage test. This ground on each winding may be made at a selected point of the winding itself or of the winding of a step-up transformer that is used to supply the voltage or that is connected for the purpose of furnishing the ground.

10.7.5 Need for additional induced tests

When the induced test on a winding results in a voltage between terminals of other windings in excess of the low-frequency test voltage specified in Table 4 or Table 5, as applicable, of IEEE Std C57.12.00-2010, the other winding may be sectionalized and grounded. Additional induced tests shall then be made to give the required test voltage between terminals of windings that were sectionalized.

10.7.6 Failure detection

Careful attention should be maintained for evidence of possible failure, such as an indication of smoke and bubbles rising in the oil, an audible sound such as a thump, a sudden increase in test circuit current, or an appreciable increase in partial discharge level. Any such indication should be carefully investigated by observation, by repeating the test, or by other tests to determine whether a failure has occurred.

10.8 Induced-voltage test for Class II power transformers

10.8.1 General

Each Class II power transformer shall receive an induced-voltage test with the required test levels induced in the high-voltage winding. The tap connections shall be chosen, when possible, so that test levels developed in the other windings during the 1 h test are x times their maximum operating voltages, as specified in ANSI C84.1, where x is the ratio of the test voltage on the high-voltage winding to the maximum operating voltage.

10.8.2 Test procedure

The voltage shall first be raised to the 1 h level and held for a minimum of 1 min or until a stable partial discharge level is obtained to verify that there are no partial discharge problems. The level of partial discharges shall be recorded just before raising the voltage to the enhancement level. The voltage shall then be raised to the enhancement level and held for 7200 cycles. The voltage shall then be reduced directly to the 1 h level and held for 1 h.

During this 1 h period, partial discharge measurements shall be made at 5 min intervals. Partial discharge acceptance criteria shall be based on each line terminal rated 115 kV and above. These measurements shall be made in accordance with 10.9.

10.8.3 Connections

The transformer shall be excited exactly as it will be in service. The voltage may be induced from any winding or from special windings or taps provided for test purposes. Single-phase transformers shall be excited from single-phase sources. Three-phase transformers shall be excited from three-phase sources. The neutral terminals and other terminals that are normally grounded in service shall be solidly grounded. This will stress all of the insulation at the same per unit of overstress.

10.8.4 Frequency

The test frequency shall be increased, relative to operating frequency, as required to avoid core saturation. The requirements in test frequency are also applicable in the case of this induced test.

10.8.5 Failure detection

Failure may be indicated by the presence of smoke and bubbles rising in the oil, an audible sound such as a thump, or a sudden increase in the test current. Any such indication shall be carefully investigated by observation, by repeating the test, and by other diagnostic tests to determine whether a failure has occurred. In terms of interpretation of partial discharge measurements, the results shall be considered acceptable and no further partial discharge tests required under the following conditions:

a) The magnitude of the partial discharge level does not exceed 500 pC during the 1 h test period.

b) The increase in partial discharge levels during the 1 h period does not exceed 150 pC.

c) The partial discharge levels during the 1 h period do not exhibit any steadily rising trend, and no sudden sustained increase in the levels occurs during the last 20 min of the test.

Judgment should be used on the 5 min readings so that momentary excursions of the partial discharge readings caused by cranes or other ambient sources are not recorded. Also, the test may be extended or repeated until acceptable results are obtained.

A failure to meet the partial discharge acceptance criterion shall not warrant immediate rejection, but it shall lead to consultation between purchaser and manufacturer about further investigations.

10.9 Partial discharge measurement

10.9.1 Internal partial discharges

Apparent internal partial discharges (apparent charge) shall be measured at the terminals of the transformer windings under test and reported in units of picocoulombs (pC).

Where agreed to by both the purchaser and the manufacturer, radio influence voltage (RIV) measurements may be used in lieu of, or in conjunction with, apparent charge measurements. The procedure for RIV measurements is included in Annex A.

10.9.2 Instrumentation

A partial discharge meter shall be used to measure the apparent charge generated by any internal partial discharges. The partial discharge detector, based on IEEE Std C57.113, is used to measure the partial discharge levels at the terminals. The partial discharge meter shall be coupled to the line terminal(s) of the winding(s) under test through the voltage tap of the bushing(s) or through a suitable coupling capacitor connected in parallel with the bushing. General principles and circuits are described in IEEE Std C57.113.

External shielding may be used to avoid air corona, such as may occur at the bushing terminals or grounded projections. Radio-frequency chokes or tuned filters may be used to isolate the transformer under test and the partial-discharge-measuring circuit from the remainder of the test circuit, including its energy source.

10.9.3 Calibration

The test circuit shall be calibrated according to IEEE Std C57.113.

10.10 Insulation power-factor tests

The insulation power factor is the ratio of the power dissipated in the insulation in watts to the product of the effective voltage and current in voltamperes when tested under a sinusoidal voltage and prescribed conditions.

The methods described in this standard are applicable to distribution and power transformers of present-day design that are immersed in an insulating liquid.

10.10.1 Preparation for tests

The test specimen shall have the following:

a) All windings immersed in insulating liquid

b) All windings short-circuited

c) All bushings in place

d) The average temperature of the windings and insulating liquid should be between 10 °C and 40 °C, but preferably as close to 20 °C as practical. The top liquid temperature shall be measured and recorded.

10.10.2 Instrumentation

The insulation power factor may be measured by special bridge circuits or by the voltampere-watt method. The accuracy of measurement should be within ± 0.25% insulation power factor, and the measurement should be made at or near a frequency of 60 Hz.

10.10.3 Voltage to be applied

The voltage to be applied for measuring insulation power factor shall not exceed half of the low-frequency test voltage given in Table 4 and Table 5 of IEEE Std C57.12.00-2010 for any part of the winding or 10 000 V, whichever is lower.

10.10.4 Procedure

Insulation power-factor tests shall be made from windings to ground and between windings as shown in Table 4.

Table 4—Measurements to be made in insulation power-factor tests

Method I **Test without guard circuit**[a]	**Method II** **Test with guard circuit**[a]
Two-winding transformers[b]	Two-winding transformers[b]
High to low and ground	High to low and ground
Low to high and ground	High to ground, guard on low
High and low to ground	Low to high and ground
—	Low to ground, guard on high
Three-winding transformers[b]	Three-winding transformers[b]
High to low, tertiary, and ground	High to low and ground, guard on tertiary
Low to high, tertiary, and ground	High to ground, guard on low and tertiary
Tertiary to high, low, and ground	Low to tertiary and ground, guard on high
High and low to tertiary and ground	Low to ground, guard on high and tertiary
High and tertiary to low and ground	Tertiary to high and ground, guard on low
Low and tertiary to high and ground	Tertiary to ground, guard on high and low
High, low, and tertiary to ground	High and low to tertiary and ground
	High and tertiary to low and ground

NOTE 1—Although the real significance that can be attached to the power factor of liquid-immersed transformers is still a matter of opinion, experience has shown that the power factor is helpful in assessing the probable condition of the insulation when good judgment is used.

NOTE 2—In interpreting the results of power-factor test values, the comparative values of tests taken at periodic intervals are useful in identifying potential problems rather than an absolute value of power factor.

NOTE 3—A factory power-factor test will be of value for comparison with field power-factor measurements to assess the probable condition of the insulation. It has not been feasible to establish standard power-factor values for liquid-immersed transformers for the following reasons:

a) Experience has indicated that little or no relation exists between power factor and the ability of the transformer to withstand the prescribed dielectric tests.
b) Experience has shown that the variation in power factor with temperature is substantial and erratic so that no single correction curve will fit all cases. The power factor shall be reported along with the top oil temperature measured and the bottom oil temperature if available. No temperature correction shall be applied. Temperature correction of the power factor results for trending basis may be applied by the purchaser.
c) The various liquids and insulating materials used in transformers result in large variations in insulation power-factor values.

[a] In this table, the term *guard* signifies one or more conducting elements arranged and connected on an electrical instrument or measuring circuit to divert unwanted currents from the measuring means.
[b] Permanently connected windings, such as in autotransformers and regulators, shall be considered as one winding.

10.11 Insulation resistance tests

Insulation resistance tests shall be made when specified. Insulation resistance tests are made to determine the insulation resistance from individual windings to ground or between individual windings. Insulation resistance tests are commonly measured in megohms or may be calculated from measurements of applied voltage and leakage current.

NOTE 1—The insulation resistance of electrical apparatus is of doubtful significance compared to the dielectric strength. It is subject to wide variation in design, temperature, dryness, and cleanliness of the parts. When the insulation resistance falls below prescribed values, it can, in most cases of good design and where no defect exists, be brought up to the required standard by cleaning and drying the apparatus. Therefore, the insulation resistance may be useful to indicate whether the apparatus is in suitable condition for application of dielectric test.

NOTE 2—The significance values of insulation-resistance tests generally require some interpretation, depending on the design and the dryness and cleanliness of the insulation involved. When a purchaser decides to make insulation resistance tests, it is recommended that insulation resistance values be measured periodically (during maintenance shutdown) and plotted. Substantial variations in the plotted insulation resistance values should be investigated for cause.

NOTE 3—Insulation resistances may vary with applied voltage, and any comparison shall be made with measurements at the same voltage.

NOTE 4—Under no circumstances should tests be made while the transformer is under vacuum.

10.11.1 Preparation for tests

The test specimen shall have the following:

a) All windings immersed in insulating liquid

b) All windings short-circuited

c) All bushings in place

d) Temperature of windings and insulating liquid near the reference temperature of 20 °C

10.11.2 Instrumentation

Insulation resistance may be measured using the following equipment:

a) A variable-voltage dc power supply with means to measure voltage and current (generally in microamperes or milliamperes)

b) A megohmeter

NOTE—Megohmeters are commonly available with nominal voltages of 500 V, 1000 V, and 2500 V; dc applied test equipment is available at higher voltages.

10.11.3 Voltage to be applied

The dc voltage applied for measuring insulation resistance to ground shall not exceed a value equal to the rms low-frequency applied voltage allowed in 10.6.

NOTE 1—Partial discharges should not be present during insulation resistance tests because they can damage a transformer and may also result in erroneous values of insulation resistance.

NOTE 2—When measurements are to be made using dc voltages exceeding the rms operating voltage of the winding involved (or 1000 V for a solidly grounded wye winding), a relief gap may be employed to protect the insulation.

10.11.4 Procedure

Insulation-resistance tests shall be made with all circuits of equal voltage above ground connected together. Circuits or groups of circuits of different voltage above ground shall be tested separately. Examples of procedures include the following:

a) High voltage to low voltage and ground, low voltage to high voltage and ground.

b) Voltage should be increased in increments, typically 1 kV to 5 kV, and held for 1 min while the current is read.

c) The test should be discontinued immediately if the current begins to increase without stabilizing.

d) After the test has been completed, all terminals should be grounded for enough time to allow any trapped charges to decay to a negligible value.

11. Temperature-rise tests

A temperature-rise test is defined as a test to determine the temperature rise above ambient of one or more of the transformer's windings, as measured at the terminals. The result for a given terminal pair or winding is the average value of the temperature of the entire circuit; it is not the temperature at any given point in a specific winding. The term *average temperature rise* refers to the value determined by measurements on a given terminal pair of the winding. It does not refer to the arithmetic average of results determined from different terminal pairs of the transformer.

See 4.1.2 and 5.11.2 of IEEE Std C57.12.00-2010 for conditions under which temperature limits apply. All temperature-rise tests shall be made under normal (or equivalent to normal) conditions for the means of cooling, as follows:

a) Temperature-rise tests shall be conducted on transformers that are completely assembled and filled to the proper liquid level.

b) Temperature-rise tests shall be made in a room that is as free from drafts as practicable.

c) When it is not possible or practical to test the transformer as a completed assembly, the transformer shall be tested with the components required to ensure normal means of cooling the transformer during temperature-rise tests. When the transformers are equipped with thermal indicators, bushing current transformers, or the like, such devices shall be assembled with the transformer.

11.1 Test methods

Tests shall be made by one of the following methods:

a) Actual loading

b) Simulated loading

   1) The short-circuit method, in which appropriate total losses are produced by the effect of short-circuit current

   2) The loading back (opposition) method, in which rated voltage and current are induced in the transformer under test

11.1.1 Actual loading

Actual loading is the most accurate method, but energy requirements are excessive for large transformers. Transformers of small output may be tested under actual load conditions by loading them on a rheostat, bank of lamps, water box, and so on.

11.1.2 Simulated loading

11.1.2.1 Short-circuit method

Conduct the short-circuit method as follows:

a) Prior to making the total loss run (see step b), measure load loss at rated current and frequency for the combination of connections and taps that give the highest average winding temperature rise. This process will generally involve those connections and taps resulting in the highest losses. This thermal connection load loss shall be measured in accordance with Clause 9 and referenced to a temperature equal to rated average winding rise plus 20 °C. The required total losses for the total loss run shall be the sum of thermal connection load loss plus no-load loss measured in accordance with Clause 8.

b) For the total loss run, short-circuit one or more windings and circulate sufficient current at rated frequency to produce the required total losses as determined in step a and in 11.4.2.

c) Determine liquid temperature rises as described in 11.3.2.

d) For the rated current run, reduce the current in the windings to the rated current (or reduced current according to 11.4.1) value for the connection and the loading used. Hold the current constant for 1 h. Measure the liquid temperatures, immediately shut down, and measure the hot resistances in accordance with 11.2.2.

e) Repeat the rated current run (step d) for hot-resistance measurements on additional terminal pairs if needed to meet the time limit criteria of 11.2.2.

f) Determine average winding rises in accordance with 11.3.3.

11.1.2.2 Loading back method

Duplicate transformers may be tested by connecting their respective high-voltage and low-voltage windings in parallel (see Figure 28 and Figure 29). Transformers shall be tested with the combination of connections and taps that give the highest average winding temperature rise. This process will generally involve those connections and taps resulting in the highest losses.

a) Apply rated voltage at rated frequency to one set of windings. Circulate load current by opening the connections of either pair of windings at one point and impress a voltage across the break just sufficient to circulate rated current at rated frequency for the connection and loading used. The total loss applied during this test shall be the same as the sum of the no-load loss and load loss measured according to Clause 8 and Clause 9.

b) Measure liquid temperatures, and determine liquid temperature rises as described in liquid temperature rise determination.

c) Immediately shut down, and measure the hot resistance in accordance with hot-resistance measurements.

d) When needed to meet the time limit criteria of hot-resistance measurements, resume the heat run for 1 h, holding rated voltage at rated frequency for the connection and loading used. Measure the liquid temperatures, immediately shut down, and measure the hot resistance of additional terminal pairs in accordance with hot-resistance measurements.

e) Determine average winding temperature rises in accordance with average winding temperature-rise determination.

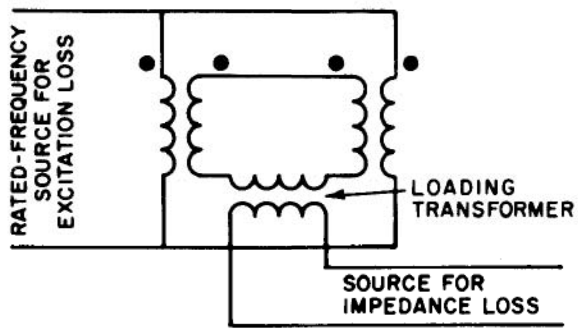

Figure 28—Example of loading back method: single phase

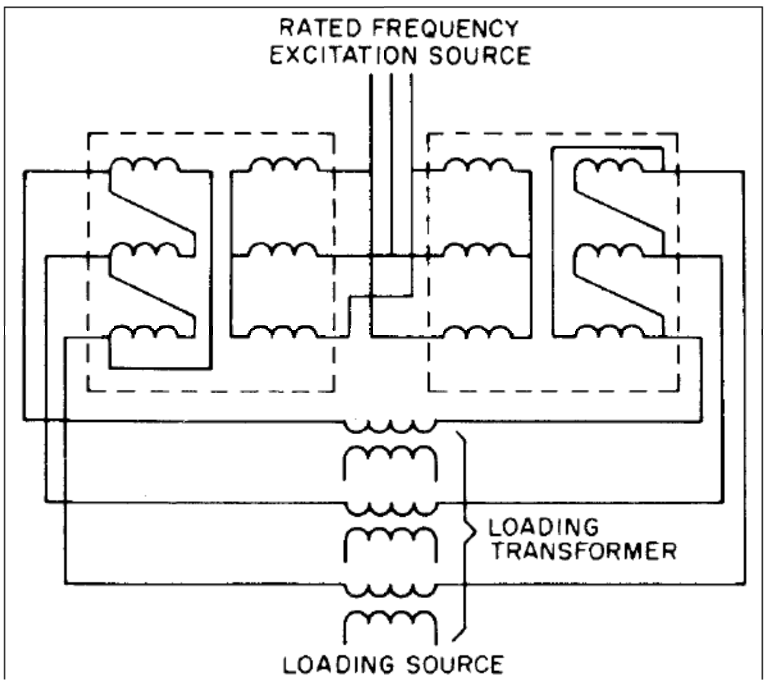

Figure 29—Example of loading back method: three phase

11.2 Resistance measurements

11.2.1 Cold-resistance measurements

Cold-resistance measurements shall be taken on all terminal pairs in accordance with Clause 5. The same test equipment shall be used for both cold-resistance and hot-resistance measurements. Normally, cold-resistance measurements are taken prior to loading the transformer for temperature-rise test. However, it is permissible to allow the transformer to cool to ambient temperature and perform cold-resistance measurements after the loading test. Whenever it is necessary to make cold-resistance measurements following the temperature-rise test, the cool-down time shall be sufficient to allow the criteria in 5.1 to be met.

11.2.2 Hot-resistance measurements

When the transformer is shut down for hot-resistance measurements, fans and cooling water shall be shut off. Oil pumps may be shut off or left running during shutdown. Hot-resistance measurements shall be taken as soon as possible after shutdown, allowing sufficient time for the inductive effects to disappear as indicated from the cold-resistance measurement. To minimize inductive effects when transferring measuring instrument leads from one terminal pair to another, the same relative polarity should be maintained between measuring leads and transformer terminals.

a) The time from instant of shutdown shall be recorded for each resistance measurement.

b) At least one resistance measurement shall be taken on all terminal pairs within 4 min after shutdown.

c) A series of at least four resistance measurements shall be made on one terminal pair corresponding to a phase of a winding.

d) Resistance-time measurements in accordance with item c shall be made on all windings.

e) The resistance-time data collected in item c shall be corrected to the instant of shutdown using a resistance-time cooling curve determined by plotting data on suitable coordinate paper or by using a curve fitting program.

f) The resistance-time data obtained on one phase of a winding shall be used to determine the correction to shutdown for the other phases of the same winding, provided the first measurement on each of the other phases has been taken within 4 min after shutdown.

11.3 Temperature measurements

11.3.1 Ambient temperature measurements

11.3.1.1 Air-cooled transformers

For air-cooled transformers, the ambient temperature shall be taken as that of the surrounding air, which should not be less than 10 °C nor more than 40 °C. For temperatures within this range, no correction factor shall be applied. Tests may be made at temperatures outside this range when suitable correction factors are available.

The temperature of the surrounding air shall be determined by at least three thermocouples or thermometers in containers spaced uniformly around the transformer under test. They shall be located about mid-height of the transformer and 1 m to 2 m (3 ft to 6 ft) from the transformer. They shall be protected from drafts and radiant heat from the transformer under test or other sources.

When the liquid time constant of the transformer (calculated according to Equation (14) of IEEE Std C57.91-1995) is 2 h or less, the time constant of the containers shall be between 50% and 150% of that of the transformer under test. When the liquid time constant of the transformer under test is more than 2 h, the time constant of the containers shall be within 1 h of the liquid time constant of the transformer under test.

The time constant of a container shall be taken as the time necessary for its temperature to change 6.3 °C when the ambient temperature is abruptly changed 10 °C.

11.3.1.2 Water-cooled transformers

For water-cooled transformers, the flow rate in liters per minute and the temperature of the incoming and outgoing water shall be measured.

The ambient temperature shall be taken as that of the incoming water and should not be less than 20 °C nor more than 30 °C. For temperatures within this range, no correction factor shall be applied. Tests may be made at temperatures outside this range when suitable correction factors are available.

11.3.2 Liquid temperature rise determination

Liquid temperature rise is the difference between liquid temperature and ambient temperature. The ultimate liquid temperature rise above ambient shall be considered to be reached when the top liquid temperature rise does not vary more than 2.5% or 1 °C, whichever is greater, during a consecutive 3 h period.

It is permissible to shorten the time required for the test by the use of initial overloads, restricted cooling, and so on.

The top liquid temperature shall be measured by a thermocouple or suitable thermometer immersed approximately 50 mm (2 in) below the top liquid surface.

The bottom liquid temperature shall be measured by one of the following methods:

a) Thermocouples may be attached to an insulated rod and located inside the tank so that the thermocouples are in the liquid flow path from the external cooling means to the bottom of the windings.

CAUTION

Exercise caution when employing this method.
This method may be hazardous for transformers with very high voltage windings.

b) If heat exchangers or radiators are mounted on a common manifold with a single entrance to the tank, the thermocouples may be located in the piping of the single entrance.

c) If heat exchangers or radiators have multiple entrances into the tank, thermocouples may be installed in the bottom of one radiator or heat exchanger. For accuracy, a radiator or heat exchanger located in the middle of the bank is preferred.

d) If it is not possible to measure the temperature of the liquid inside the tank, radiators, or heat exchangers, surface temperature measurements may be used with the results corrected to account for the temperature difference between the surface and the liquid inside the tank. If surface temperature measurements are made on radiator headers, choose headers one third or one half the way in from either end of a bank of radiators. For transformers without radiators, locate the thermocouples on the tank wall at the elevation of the bottom of the winding. Thermocouples located on external cooling surfaces, for the purpose of determining internal oil temperatures, shall be shielded and insulated so that their readings are not significantly affected by the air movement from fans or thermally induced air currents.

The average liquid temperature shall be determined as equal to top liquid temperature minus half the difference in temperature of the moving liquid at the top and bottom of the cooling means. When bottom liquid temperature cannot be measured directly, the temperature difference may be taken as the difference between the surface temperature of the liquid inlet and the outlet. A thermocouple is the preferred method of measuring surface temperature (see 11.3.4 for method of measurement). Infrared measurement devices may also be used to measure surface temperatures.

11.3.3 Average winding temperature-rise determination

The average winding temperature of a terminal pair corresponding to a winding phase shall be determined from the terminal pair's hot resistance at shutdown. When it is not possible to determine the hot resistance (e.g., with extremely low resistance windings), other methods may be used. The average winding temperature of a terminal pair shall be determined by Equation (28):

$$\theta_w = \frac{R_h}{R_c}\left(\theta_k + \theta_{rc}\right) - \theta_k \tag{28}$$

The average temperature rise of a terminal pair corresponding to a winding phase shall be determined by Equation (29):

$$\Delta\theta_w = \Delta\theta_l + \theta_w - \theta_l \tag{29}$$

where

$\Delta\theta_w$	is the average winding temperature rise of a terminal pair (°C)
$\Delta\theta_l = \theta_{l,\mathrm{TL}} - \theta_a$	is the average liquid temperature rise as determined from the total loss run (°C)
θ_w	is the average winding temperature of a terminal pair corresponding to hot resistance R_h (°C)
$\theta_{l,\mathrm{TL}}$	is the average liquid temperature at end of total loss run (°C)
θ_l	is the average liquid temperature at shutdown (°C)
θ_a	is the ambient temperature (°C)
θ_{rc}	is the temperature at which cold resistance R_c was measured (°C)
R_c	is the cold resistance, measured according to Clause 5 (Ω)
R_h	is the hot resistance of a terminal pair (Ω)
θ_k	is 234.5 °C for copper and 225.0 °C for aluminum

NOTE—The value for θ_k may be as high as 230 °C for alloyed aluminum.

Average winding rise shall be calculated by using either top liquid rise or average liquid rise. When other-than-rated winding current is used, the average liquid rise method shall be used to determine winding rises.

a) In the top liquid rise method, the average winding temperature rise is equal to the top liquid rise, measured during the total loss run, plus the quantity (average winding temperature at shutdown minus top liquid temperature at shutdown).

b) In the average liquid rise method, the average winding temperature rise is the average liquid rise, measured during the total loss run, plus the quantity (average winding temperature at shutdown minus average liquid temperature at shutdown).

The average winding temperature rise for each terminal pair corresponding to a winding phase shall be corrected for actual test currents, test losses, and altitude as prescribed in 11.4. The corrected average winding temperature rise shall be reported for each terminal pair of the transformer.

11.3.4 Other temperature measurements

When measured, the temperature rise of metal parts other than windings shall be determined by use of a thermocouple, suitable thermometer, fiber optic temperature sensor, or other appropriate temperature measurement techniques.

A thermocouple is the preferred method of measuring surface temperature. When used for this purpose, the thermocouple should be soldered to the surface. When this option is not practical, the thermocouple should be soldered to a thin metal plate or foil approximately 625 mm^2 (1 in^2). The plate should be held firmly and snugly against the surface. The thermocouple should be thoroughly insulated thermally from the surrounding medium.

The surface temperature of metal parts surrounding, or adjacent to, outlet leads or terminals carrying heavy current may be measured at intervals or immediately after shutdown.

11.4 Correction of temperature-rise test results

For any of the loading methods adopted, temperature-rise test results shall be corrected for the predictable effects caused by

a) Difference in winding rated current and the winding test current

b) Difference in required loss and test loss

c) Difference in altitude of operation

11.4.1 Correction for differences between winding rated current and test current

When test equipment limitations dictate, it is permissible to hold winding current at a value lower than rated current for the winding, but not less than 85% of rated winding current. When the current held in any of the windings under test differs from the rated current, the observed differences between the average winding temperature at shutdown and the average liquid temperature at shutdown shall be corrected to give the average temperature rise of the windings at the rated current by using Equation (30):

$$\Delta\theta_{w,c} = \Delta\theta_{w,o}\left(\frac{rated\ \ current}{test\ \ current}\right)^{2m} \tag{30}$$

where

$\Delta\theta_{w,c}$ is the corrected difference between average winding temperature corrected to shutdown, and the average liquid temperature at shutdown (°C)
$\Delta\theta_{w,o}$ is the observed difference between average winding temperature corrected to shut own, and the average liquid temperature at shutdown (°C)
m is 0.8 for Classes ONAN, ONAF, OFAF, and OFWF
is 1.0 for Classes ODAF and ODWF

The corrected average winding rise is the average liquid rise plus $\Delta\theta_{w,c}$.

11.4.2 Correction of liquid temperature rise for differences in required total loss and actual loss

This method may be used when actual loss is within 20% of the required total loss, as in Equation (31):

$$\Delta\theta_{l,c} = \Delta\theta_{l,o}\left[\left(\frac{P_r}{P_T}\right)^n - 1\right] \tag{31}$$

where

$\Delta\theta_{l,c}$ is the liquid temperature rise correction (°C)
$\Delta\theta_{l,o}$ is the observed liquid temperature rise (°C)
P_r is the required total loss (W)
P_T is the actual test total loss (W)
n is 0.8 for Class ONAN
is 0.9 for Classes ONAF, OFAF, and OFWF
is 1.0 for Classes ODAF and ODWF

Corrected liquid temperature rise = observed liquid temperature rise + $\Delta\theta_{l,c}$.

Corrected average winding temperature rise = observed winding temperature rise + $\Delta\theta_{l,c}$.

11.4.3 Correction of liquid temperature rises for differences in altitude

When tests are made at an altitude of 1000 m (3280 ft) or less, no altitude correction shall be applied to the temperature rises.

When a transformer tested at an altitude less than 1000 m (3280 ft) is to be operated at an altitude above 1000 m (3280 ft), it shall be assumed that the liquid temperature rise will increase in accordance with Equation (32):

$$\Delta\theta_A = \Delta\theta_o\left(\frac{A}{A_o} - 1\right)F \tag{32}$$

where

$\Delta\theta_A$ is the increase in liquid temperature rise (°C) at altitude A meters (ft)
$\Delta\theta_o$ is the observed liquid temperature rise (°C)
A is altitude meters (ft)
A_0 is 1000 m (3300 ft)
F is 0.04 for self-cooled mode or 0.06 for forced-air-cooled mode

NOTE—Winding temperature rise above liquid temperature is not affected by altitude.

11.4.4 Frequency conversion of temperature-rise test results

In the event that the temperature-rise test cannot be done at the rated power frequency, see Annex B for 50/60 Hz frequency conversions.

12. Short-circuit tests

12.1 General

This test code applies to liquid-immersed distribution and power transformers 5 kVA and above. Within this range, four categories shall be recognized as listed in Table 5.

Table 5—Transformer categories covered by this test code

Category	Single-phase (kVA)	Three-phase (kVA)
I[a]	5 to 500	15 to 500
II	501 to 1667	501 to 5000
III	1668 to 10 000	5001 to 30 000
IV	Above 10 000	Above 30 000

NOTE—All kilovoltampere ratings are minimum nameplate kilovoltampere for the principal windings.

[a] Category I shall include distribution transformers manufactured in accordance with IEEE Std C57.12.20 up through 500 kVA, single-phase or three-phase. In addition, autotransformers of 500 kVA-equivalent two-winding kilovoltampere or less that are manufactured as distribution transformers in accordance with IEEE Std C57.12.20 shall be included in Category I even though their nameplate kilovoltampere may exceed 500 kVA.

The code defines a procedure to demonstrate the mechanical capability of a transformer to withstand short-circuit stresses. The prescribed tests are not designed to verify thermal performance. Conformance to short-circuit thermal requirements shall be by calculation in accordance with Clause 7 of IEEE Std C57.12.00-2010.

The short-circuit test procedure described in this standard is intended principally for application to new transformers to verify design. Tests may be conducted at the manufacturer's facilities, at test laboratories, or in the field; but it shall be recognized that complete equipment is not usually available in the field for conducting tests and verifying results.

12.2 Test connections

12.2.1 Two-winding transformers and autotransformers without tertiary windings

12.2.1.1 Fault location

The short circuit may be applied on the transformer primary or secondary terminals as dictated by the available voltage source, but the secondary fault is preferred because it most closely represents the system fault condition. The short circuit shall be applied by means of suitable low-resistance connectors.

In order of preference, the tests may be conducted by either of the following:

a) Closing a breaker at the faulted terminal to apply a short circuit to the previously energized transformer.

b) Closing a breaker at the source terminal to apply energy to the previously short-circuited transformer.

12.2.1.2 Fault type

The type of fault to be applied will be dependent on the available energy source. Any of the following types may be used (given in order of preference for three-phase transformers):

a) Three-phase source: three-phase short circuit

b) Three-phase source: single phase-to-ground short circuit

c) Single-phase source: simulated three-phase short circuit

   NOTE—For wye-connected windings, apply source or fault between one line terminal and the other two connected together. For delta-connected windings, apply source or fault between two line terminals with no connection to the other line terminal (shall be repeated for each of three phases).

d) Single-phase source: single-phase short circuit on one phase at a time (applies to all single-phase transformers)

12.2.1.3 Tap connection for test

When the transformer is provided with taps in any winding, at least one test satisfying the asymmetrical current requirement shall be made on the tap connection that calculations predict will produce the most severe mechanical stresses. Extremes of the tap range (all taps out or all taps in) normally produce the most severe stresses, and they are recommended. Tests on other taps, or connections in the case of dual voltage windings, may be required to verify design adequacy.

12.2.2 Multiwinding transformers, including autotransformers

12.2.2.1 Fault location and type

Fault types and terminals to which they are to be applied shall be determined individually for each particular transformer. The maximum fault current for each winding shall be determined from calculations of fault types specified in Clause 7 of IEEE Std C57.12.00-2010 using various fault types, fault locations, and applicable system data. During testing, each winding shall be subjected to its maximum calculated fault current on at least one test. In general, a given fault type and location will not produce the maximum fault current in more than one winding; therefore, it will be necessary to make tests with several different connections to fully evaluate the capability of all windings. In order of preference, the tests may be conducted by either of the following methods:

a) Closing a breaker at the faulted terminal to apply a short circuit to the previously energized transformer.

b) Closing a breaker at the source terminal to apply energy to the previously short-circuited transformer.

12.3 Test requirements

12.3.1 Symmetrical current requirement, two-winding transformers

For two-winding transformers, the required value of symmetrical current for any test shall be determined from the equations in Clause 7 of IEEE Std C57.12.00-2010.

NOTE—For Categories I and II, calculate I_{SC} using transformer impedance only; except for Category I, the symmetrical current magnitude shall not exceed the values listed in 7.1.4.1 and Table 13 of IEEE Std C57.12.00-2010. For Categories III and IV, calculate I_{SC} using transformer plus system impedance.

See Clause 7 of IEEE Std C57.12.00-2010 for additional clarifying information on determining Z_S.

12.3.2 Symmetrical current requirement, multiwinding transformers and autotransformers

For multiwinding transformers and autotransformers, the required peak value of symmetrical current in each winding shall be determined by calculation based on applicable system conditions and fault types.

12.3.3 Asymmetrical current requirement

The required first cycle peak for asymmetrical current tests shall be calculated in accordance with the equations in Clause 7 of IEEE Std C57.12.00-2010.

12.3.4 Number of tests

Each phase of the transformer shall be subjected to a total of six tests satisfying the symmetrical current requirement specified in 12.3.1 or 12.3.2, as applicable. Two of these tests on each phase shall also satisfy the asymmetrical current requirements specified in 12.3.3.

12.3.5 Duration of tests

The duration of short-circuit tests shall be in accordance with Clause 7 of IEEE Std C57.12.00-2010.

12.4 Test procedure

12.4.1 Fault application

To produce the fully asymmetrical current wave specified in 12.3.3, a synchronous switch should be used to control the timing of fault application.

12.4.2 Calibration tests

Calibration tests to establish required source voltage or switch closing times should be made at voltage levels no greater than 50% of the voltage that would produce the specified symmetrical short-circuit current. For field testing, calibration tests should be made at reduced voltage levels, if possible. Tests with voltage equal to or greater than that required to produce 95% of the specified symmetrical short-circuit current may be counted toward fulfillment of the required number of tests.

12.4.3 Terminal voltage limits

When tests are to be made by applying a short circuit to energized transformers, the no-load source voltage shall not exceed 110% of the rated tap voltage, unless otherwise approved by the manufacturer.

Throughout the course of any test, the voltage at the transformer source terminals shall be maintained within a range of 95% to 105% of that necessary to produce the required symmetrical short-circuit current as determined in 12.3.1 or 12.3.2, as applicable.

12.4.4 Temperature limits

For liquid-filled transformers, top liquid temperature at the start of the test shall be between 0 °C and 40 °C.

12.4.5 Current measurements

Current magnitudes shall be measured on the transformer terminals connected to the energy source. The symmetrical peak current shall be established as half of the peak-to-peak envelope of the current wave, measured at the midpoint of the second cycle of test current. When the transformer winding connected to the energy source is wye-connected, the first cycle peak asymmetrical current in each phase of the winding shall be measured directly from the oscillogram of terminal currents. When the transformer winding connected to the energy source is delta-connected, the first cycle peak asymmetrical current cannot be determined directly from terminal measurements at the source terminals. The following alternatives exist:

a) When the faulted winding is wye-connected, measure first cycle peak asymmetrical current with oscillograms at the faulted terminals. Convert to source winding current by inverse turns ratio.

b) When all windings are delta-connected, connect metering accuracy current transformers having suitable current ratios inside the delta of the source winding, and measure first cycle peak asymmetrical current from oscillograms obtained from these current transformers.

c) When all windings are delta-connected, determine only symmetrical current in the external lines and time fault application for the instant that would produce peak asymmetrical current in the required phase winding. (Close breaker at a time close to voltage zero for the given phase winding, with appropriate timing adjustment to account for the R/X ratio of the test system plus transformer.)

12.4.6 Tolerances on required current

After the measured impedance is taken into account, the measured current (symmetrical or asymmetrical) in the tested phase(s) shall not be less than 95% of the required current.

12.4.7 Frequency conversion of short-circuit test

In the event that the short-circuit test cannot be done at the rated power frequency, see Annex B for 50/60 Hz frequency conversions.

12.5 Proof of satisfactory performance

The transformer under test shall be judged to have performed satisfactorily when the visual inspection (12.5.1) and dielectric test (12.5.2) criteria have been satisfactorily met. In 12.5.3 through 12.5.6, recommended terminal measurements listed can be made during the course of the tests, but they are not required unless specified. When the terminal measurements are made and the requirements of 12.5.3 through 12.5.6 have been met following all tests, it is probable that the transformer has sustained no mechanical damage during the test. A composite evaluation of the degree to which all criteria of 12.5.3 through 12.5.6 have been met may indicate the need for a greater or lesser degree of visual inspection to confirm satisfactory performance. The evidence may be sufficient to permit a judgment of satisfactory performance to be made without complete dielectric tests. A decision to waive all or part(s) of the visual inspection or dielectric test criteria shall be based on discussion and negotiation of all parties involved in specification and performance of short-circuit tests.

12.5.1 Visual inspection

Visual inspection of the core and coils shall give no indication that any change in mechanical condition has occurred that will impair the function of the transformer. The extent of the visual inspection shall be established on the basis of combined evidence obtained from the terminal measurements described in 12.5.3 through 12.5.6. When the terminal measurements give no indication of change in condition, external inspection of the core and coils removed from the tank may suffice. Any evidence of change in condition from more than one of the terminal measurements warrants disassembly of the windings from the core for a more detailed inspection.

12.5.2 Dielectric tests

The transformer shall the withstand standard dielectric tests of IEEE Std C57.12.00 at the full specification level following the short-circuit test series. Impulse tests shall be made following the short-circuit test series only when specified.

12.5.3 Wave shape of terminal voltage and current

No abrupt changes shall occur in the terminal voltage or short-circuit current wave shapes during any test.

12.5.4 Leakage impedance

Leakage impedance measured on a per-phase basis after the test series shall not differ from that measured before the test series by more than the following values:

— Category I: The allowable variation shall be a function of the transformer impedance Z_T as in Table 6.

Table 6—Leakage impedance variation for Category I

Z_T (per unit)	Percentage variation (Z_T)
0.0299 or less	$22.5 - (500) \times (Z_T)$
0.0300 or more	7.5

— Categories II and III: 7.5% allowable for noncircular concentric coils; 2% allowable variation for circular coils.

— Category IV: 2% allowable variation.

The measuring equipment shall have the demonstrated capability of giving reproducible readings within an accuracy of ± 0.2%.

12.5.5 Low-voltage impulse (LVI) tests

Comparison of oscilloscope traces of LVI current taken before and after each short circuit shall show no significant change in wave shape. Acceptable conditions and conditions requiring further investigation are defined in 12.5.5.1 and 12.5.5.2, respectively.

12.5.5.1 Acceptable conditions

For LVI tests, the following conditions are acceptable:

a) No LVI trace change occurs during the complete test series.

b) Small changes of amplitude or phase angle occur following one of the short-circuit tests, but no further changes occur on subsequent tests.

c) Small changes of amplitude or phase angle occur following one of the short-circuit tests, but the trace returns to its original shape on subsequent tests.

12.5.5.2 Conditions requiring further investigation

For LVI tests, the following conditions require further investigation:

a) Large LVI trace changes occur during the course of the test series.

b) Small changes of amplitude or phase angle occur after the first full amplitude short-circuit test, and these changes continue to grow with each subsequent test.

12.5.6 Excitation current

Excitation current measured after the test series shall not increase above that measured before the test series by more than 5% for stacked-type cores. For transformers with wound core construction, the increase shall not exceed 25%.

12.5.7 Other diagnostic measurements

Other diagnostic measurements may be made during the course of the tests to evaluate whether any sudden or progressive changes have occurred in the mechanical condition of the transformer. Such results may be useful to understand the response to short-circuit forces, but they shall not form part of the proof criteria.

13. Audible sound emissions

13.1 General

13.1.1 Introduction

Audible sound from transformers originates principally in the transformer core and transmits through the dielectric fluid and/or structural supports to the outer shell and/or other solid surface, where it radiates as airborne sound. In some situations, the windings may be a noise source under rated load conditions, but this noise is not included in this standard. The frequency spectra of the audible sound consists primarily of the even harmonics of the power frequency; thus, for a 60 Hz power system, the audible sound spectra consists of tones at 120 Hz, 240 Hz, 360 Hz, 480 Hz, and so on. The audible sound also contains the noise emitted by any dielectric fluid mechanical cooling system. Mechanical cooler sound consists of broadband fan noise, plus discrete tones at the fan blade passage frequency and its harmonics.

Described in this clause are methods for

- Measuring continuous transformer sound pressure levels in terms of A-weighted, one-third octave, or discrete frequency bands.
- Rating transformer sound emissions.
- Reporting the results in a standard manner.

13.1.2 Applicability

The procedures specified for measuring transformer sound pressure levels or for calculating transformer sound power levels are intended to be applicable to transformers being tested in an indoor or outdoor laboratory, to transformers being tested in a factory, or to transformers that have been installed in substations (either single or in combination, with other equipment).

13.2 Instrumentation

13.2.1 Sound level meter

Sound pressure level measurements shall be made with instrumentation meeting the requirements of ANSI S1.4 for Type 1 meters.

13.2.2 One-third octave filter

One-third octave band frequency measurements shall be made when specified with instrumentation meeting the requirements of ANSI S1.4 for Type 1 meters together with ANSI S1.11 for Type E, Class II performance, or their equal.

13.2.3 Narrowband filter

Discrete frequency measurements may be made when specified or when ambient noise test conditions required by the specification cannot be attained. Suitable analyzer bandwidth characteristics are one-tenth octave; a bandwidth of 10% of the selected frequency; or 3 Hz, 10 Hz, or 50 Hz bandwidths.

13.2.4 Wind screen

A suitable wind screen shall be used when measuring sound.

13.2.5 Calibration

Sound-measuring instrumentation shall be calibrated as recommended by the sound level meter manufacturer before and after each set of measurements. When calibration change is greater than 1 dB, sound measurements shall be declared invalid, and the test shall be repeated.

13.3 Test conditions

13.3.1 Environment

Measurements should be made in an environment having an ambient sound pressure level at least 5 dB below the combined transformer and ambient sound pressure level. When the ambient sound pressure level is 5 dB or more below the combined transformer and ambient sound pressure level, the corrections shown in Table 7 shall be applied to the combined transformer and ambient sound pressure level to obtain the transformer sound pressure level. When the difference between the ambient sound pressure level and the combined transformer and ambient sound pressure level is less than 5 dB and it is desired only to know the sound pressure level that the transformer does not exceed, a correction of –1.6 dB may be used. For one-third octave or narrowband measurements, the 5 dB difference shall apply to each frequency band in which measurements are being made.

When ambient sound conditions do not comply, suitable corrections may be feasible when the ambient sound conditions are steady and discrete frequency sound levels are measured. For this condition, the details and methods for making the measurements and the ambient corrections shall be agreed upon by the manufacturer and the purchaser of the transformer.

Table 7—Ambient sound corrections

Difference between the ambient sound pressure level and the combined transformer and ambient sound pressure level (dB)	Correction to be added to the combined transformer and ambient sound pressure level to obtain the ambient-corrected sound pressure level of the transformer (dB)
5	–1.6
6	–1.3
7	–1.0
8	–0.8
9	–0.6
10	–0.4
over 10	0.0

13.3.2 Transformer location

The transformer shall be located so that no acoustically reflecting surface is within 3 m (10 ft) of the measuring microphone, other than the floor or ground. When a transformer is to be tested within a semi-reverberant facility, it should be located in an asymmetrical manner with respect to the room geometry. If the specified conditions cannot be met, the transformer shall be no closer than 3 m (10 ft) from a sound-reflecting surface. When transformer sound emissions are measured in an enclosed space, sound reflections from walls or other large objects can influence the results because the sound contains discrete tones that are affected by room acoustics, room geometry, or reflecting objects. Thus, differences may exist in the sound measured in an indoor transformer installation and the sound measured in an acoustical laboratory or an outdoor installation.

13.3.3 Transformer operation

The transformer shall be connected and energized at rated voltage and rated frequency and shall be at no load with the tap changer, if any, on the principal tap. Pumps and fans shall be operated as appropriate for the rating being tested. When cooling equipment is not connected to the transformer, it should be so noted on the data sheet. When suitable cooling equipment sound emission data are available, the cooling equipment sound data may be appropriately added to the measured transformer sound if agreed to by the manufacturer and the purchaser. The addition of cooling equipment sound data to measured transformer sound data shall be clearly noted on the data sheet.

13.3.4 Tap changer

When the transformer is equipped with a tap changer, the transformer may on certain tap changer positions produce sound levels that are greater than the levels at the principal tap position. Sound measurements should be made with the transformer on the principal tap, unless otherwise specified. The excitation shall be appropriate to the tap in use.

13.3.5 Operating conditions

Sound measurements shall begin after the transformer being tested is energized and steady-state sound level conditions are established. Measurements may be made immediately on transformers in continuous operation.

13.3.6 Rated voltage

The rated voltage shall be measured line to line for delta-connected windings and line to neutral for wye-connected windings. The voltage shall be measured with a voltmeter responsive to the average value of the voltage but scaled to read the rms value of a sinusoidal wave having the same average value. The voltmeter should be connected between the terminals of the energized windings.

13.3.7 Frequency conversion of audible sound test

In the event that the audible sound test cannot be done at the rated power frequency, see Annex B for 50/60 Hz frequency conversions.

13.4 Microphone positions

13.4.1 Reference sound-producing surface

The reference sound-producing surface of a transformer is a vertical surface that follows the contour of a taut string stretched around the periphery of the transformer or integral enclosure (see Figure 30). The contour shall include radiators, coolers, tubes, switch compartments, and terminal chambers; but it shall exclude bushings and minor extensions, such as valves, oil gauges, thermometers, conduit terminal boxes, and projections at or above cover height.

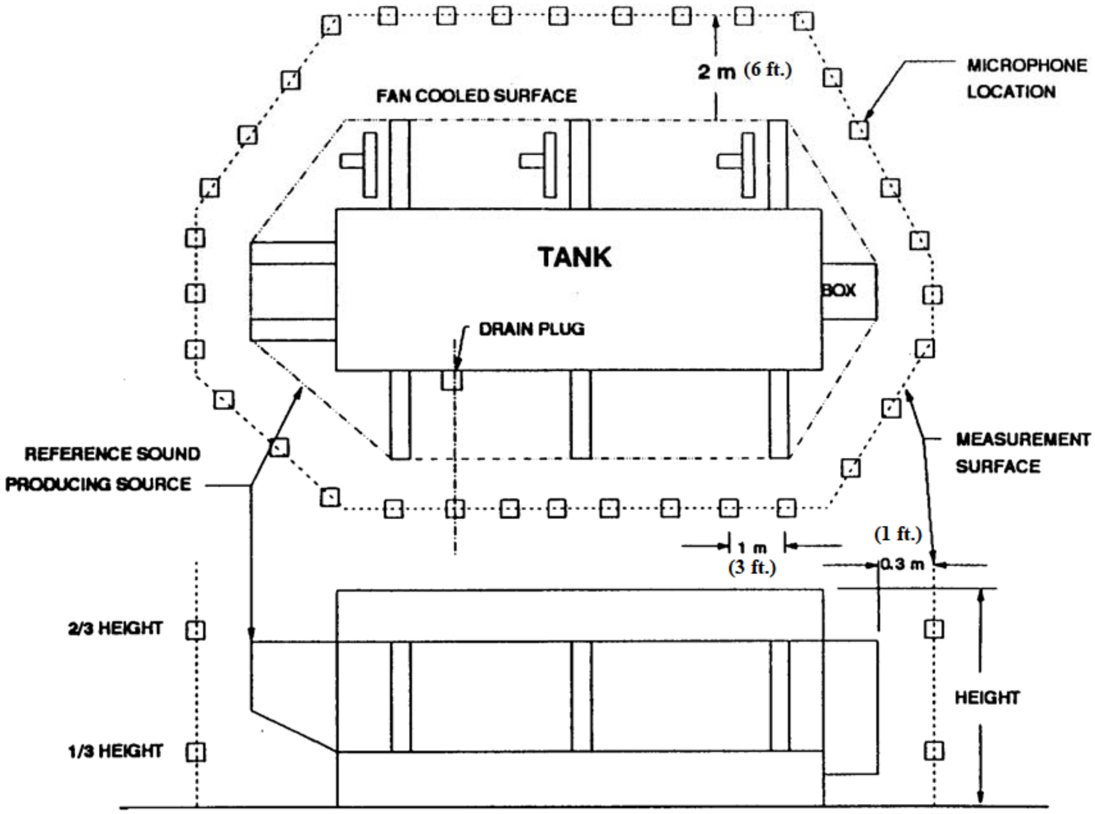

Figure 30—Microphone location for measuring audible sound from transformers

13.4.2 Safety considerations

In consideration of safety and consistency of measurement, the reference sound-producing surface near unenclosed live parts of field-assembled items (such as switches, switchgear, terminal compartments, wall-mounted bushings, and SF6 air-to-oil adapter bushings) shall be moved outward from the taut string contour to be consistent with safe working clearances as determined by the manufacturer for the voltage class of the live parts involved.

13.4.3 First measurement position

The first microphone locations shall coincide with the main drain valve. Additional microphone locations shall be at 1 m (3 ft) intervals in a horizontal direction, proceeding clockwise as viewed from above along the measurement surface defined in 13.4.1.

13.4.4 Number of microphone locations

No fewer than four microphone locations shall be used. Consequently, intervals of less than 1 m (3 ft) may result for small transformers. The microphone shall be located on the measurement surface. The microphone shall be spaced 0.3 m (1 ft) from the reference sound-producing surface. When fans are in operation, the microphone shall be located 2 m (6 ft) from any portion of the radiators, coolers, or cooling tubes cooled by forced air.

13.4.5 Height of microphone locations

For transformers having an overall tank or enclosure height of less than 2.4 m (7.9 ft), measurements shall be made at half height. For transformers having an overall tank or enclosure height of 2.4 m (7.9 ft) or more, measurements shall be made at one-third and at two-thirds height.

13.5 Sound power rating

The sound power rating of a transformer shall be determined using one of the three methods described in this clause. The sound power rating is determined using the following steps:

a) Measure ambient sound pressure levels.

b) Measure combined transformer and ambient sound pressure level.

c) Compute ambient-corrected sound pressure levels.

d) Compute average sound pressure levels.

e) Calculate sound power levels.

13.5.1 Ambient sound pressure level

The ambient sound pressure level shall be established by averaging (see 13.5.4) the ambient sound pressure levels measured immediately preceding and immediately following the sound measurements with the transformer energized. The ambient sound shall be measured at a minimum of four locations, and the instruments shall be in conformance with 13.2. However, additional measurements may be made if agreed to by the manufacturer and purchaser or if the ambient measurements vary by more than 3 dB around the transformer. At least one of the locations for measuring ambient sound pressure levels shall be on the center of each face of the measurement surface. Ambient sound pressure level corrections may be made at each microphone location before the average transformer sound pressure level is computed. Ambient sound pressure levels shall be measured using the same bandwidth (A-weighted, one-third octave, or discrete frequencies) specified for measuring the transformer sound. The ambient sound corrections shall be made with the identical frequency bandwidths that are used to measure the combined transformer and ambient sound pressure level.

13.5.2 Sound pressure level measurements

Transformer sound pressure levels shall be measured in conformance with 13.2, 13.3, and 13.4 using A-weighted sound level measurements. Furthermore, one-third octave band sound level measurements or narrowband sound level measurements may be made when specified. When specified, the sound pressure level shall also be measured using the sound level meter set to the C-weighting network. Discrete frequency sound emissions may be measured when agreed to by the purchaser and the manufacturer or when ambient sound pressure levels required by this specification (see 13.3.1) for either the A-weighted or the one-third octave band sound level measurements cannot be attained.

13.5.2.1 A-weighted sound pressure level measurements

The A-weighted sound pressure level shall be measured with a sound level meter set to the A-weighted network.

13.5.2.2 One-third octave sound pressure level measurements

The one-third octave band sound pressure levels shall be measured at the mid-band frequencies of 63 Hz through 4000 Hz, inclusive.

13.5.2.3 Narrowband sound pressure level measurements

Discrete frequency sound pressure levels shall be measured at the fundamental power frequency (60 Hz, for example) and at least at each of the next six even harmonics (120 Hz, 240 Hz, 360 Hz, 480 Hz, 600 Hz, and 720 Hz).

13.5.2.4 C-weighted sound pressure level measurements

The C-weighted sound pressure level shall be measured with a sound level meter set to the C-weighted network.

13.5.3 Ambient-corrected sound pressure levels

The ambient-corrected sound pressure level shall be computed using the procedure described in 13.3.1.

13.5.4 Average sound pressure level (L_p)

The energy average transformer sound pressure level shall be computed by averaging the ambient-corrected sound pressure levels measured at each microphone location and for each frequency band (A-weighted, one-third octave band, or discrete frequency) using Equation (33):

$$L_p = 10 \cdot \log_{10}\left\{\frac{1}{N}\sum_{i=1}^{N} 10^{(Li/10)}\right\} \tag{33}$$

where

L_i is the sound pressure level measured at the *i*th location for the A-weighted sound level, for a one-third octave frequency band, or for a discrete frequency (dB)

N is the total number of sound measurements

The arithmetic mean of the measured sound pressure levels may be used to determine the average transformer sound pressure level when the variation of the measured levels is 3 dB or less or when an approximate value of the average transformer sound level is desired.

13.5.5 Sound power level calculation (L_w)

The sound power level shall be computed for each frequency band (A-weighted, one-third octave band, or discrete frequency) using Equation (34):

$$L_w = L_p + 10 \cdot \log_{10}(S) \tag{34}$$

The measurement surface area S is the vertical area (in square meters or square feet) enveloping the transformer (measurement surface) on which the sound measurement points are located plus the horizontal plane bounded by the vertical measurement surface.

Alternatively, for large transformers, the measurement surface area is approximately equal to 125% of the vertical area enveloping the transformer (measurement surface).

13.5.6 Computation of A-weighted sound power level

A transformer A-weighted sound power level shall be computed using the procedures in 13.5.6.1 and 13.5.6.2 when the A-weighted sound level is not measured.

13.5.6.1 One-third octave sound pressure

When a transformer sound power level has been computed using one-third octave sound pressure measurements (see Table 8), the A-weighted sound power level can be computed using Equation (35):

$$L_w(A) = 10 \cdot \log_{10}\left\{\sum_{j=1}^{19} 10^{((Lw(fj)+Kj)/10)}\right\} \tag{35}$$

where

$L_w(f_j)$ is the sound power level in the f_j third octave frequency band (dB)

K_j is the A-weighted correction for the jth frequency band (see Table 8)

Table 8—A-weighted frequency corrections for one-third octave band sound levels

A-weighted frequency correction for one-third octave band sound levels	Corrections (K_j) (dB)
63	–26.2
80	–22.5
100	–19.1
125	–16.1
160	–13.4
200	–10.9
250	–8.6
315	–6.6
400	–4.8
500	–3.2
630	–1.9
800	–0.8
1000	0.0
1250	0.6
1600	1.0
2000	1.2
2500	1.3
3150	1.2
4000	1.0

13.5.6.2 Discrete frequencies

When a transformer sound power level has been computed using discrete frequencies (see Table 9), the estimated core/tank A-weighted sound power level shall be computed using Equation (36):

$$L_w(A) = 10 \cdot \log_{10}\left\{\sum_{k=1}^{7} 10^{((L_w(f_k)+K_k)/10)}\right\} \tag{36}$$

where

$L_w(A)$ is the estimated A-weighted sound power level (dB)

f_k is the seven discrete frequencies for measuring transformer sound (Hz)

K_k is the discrete frequency correction from Table 9

Discrete frequency measurements shall be used only for estimating transformer core/tank sound ratings because the sound is not measured over the entire audible frequency spectrum.

Table 9—A-weighted frequency corrections for discrete frequency sound levels

Discrete frequency (f_k) (Hz)	Correction (K_k)
60	–26.9
120	–16.6
240	–9.1
360	–5.6
480	–3.5
600	–2.2
720	–1.1

13.6 Presentation of results

Reports describing transformer sound ratings shall include, as a minimum, the following data and Figure 31 through Figure 34, as applicable:

a) A statement that the measurements were made and reported as described in this standard.

b) A detailed description of all deviations from this test code.

c) A description of the transformer being tested, including rated power, voltage, voltage ratio, and connections.

d) Measured voltage at the start of the sound tests.

e) The name of the transformer manufacturer, the location of manufacturer, the transformer type and serial number, the date and time of the test, and the name of the engineer approving the test.

f) A description of the sound-measuring instruments, the microphone, and the calibration method. Include the following information for the sound-measuring instruments: manufacturer, model, serial number, and calibration source.

g) A description of the test environment, including a dimensioned sketch. Show the position of the transformer with respect to other objects, and show the location of the measuring surface, the microphone positions, and sound reflecting or absorbing surfaces.

h) The descriptor specified by the purchaser and manufacturer for measuring one of the following sound pressure levels:

  1) A-weighted sound pressure level

  2) One-third octave band sound pressure level

  3) Narrowband sound level

i) Combined transformer and ambient sound pressure level measured at each location and the average sound pressure level.

j) Ambient sound pressure levels measured at each location.

k) Clear descriptions of the sound levels measured for any of the following operating conditions:

  1) Transformer fully equipped with its auxiliaries in service.

2) Transformer fully equipped with its auxiliaries not in service.

3) Cooling equipment in service with transformer not energized.

l) Average A-weighted transformer sound pressure levels corrected for background noise conditions and, when specified, the one-third octave band sound pressure levels or the narrowband sound pressure levels.

m) The measurement surface area and the distance between the measurement microphone locations and the transformer.

n) The A-weighted sound power level of the transformer and, when specified, the one-third octave band sound power level.

Sound level data shall be rounded to the nearest whole decibel with decimal values of 0.5 and above being rounded to the next higher integer.

A-weighted transformer sound pressure level, dB(A)				
Microphone		Ambient transformer sound pressure level (dBA)	Ambient sound level* (dBA)	Corrected A-weighted sound pressure level (dBA)
#	Height (m)			
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				
22				
23				
24				
25				
26				

A-weighted ambient level		
Microphone		Measured ambient level (dBA)
#	Height (m)	
A		
B		
C		
D		
E		
F		
G		
H		

*Use average ambient sound level to compute ambient corrected transformer sound level.

Average A-weighted sound pressure level:____________________ dBA
A-weighted sound power level: ____________________ dBA, re 10^{-12} W

Figure 31 —Weighted sound power calculation: test no. ____________

One-third octave frequency (Hz)	Measured ambient plus transformer sound pressure level (dB) — Microphone location																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
63																				
80																				
100																				
125																				
160																				
200																				
250																				
315																				
400																				
500																				
630																				
800																				
1000																				
1250																				
1600																				
2000																				
2500																				
3150																				
4000																				
Height (m)																				
A-weighted C-weighted																				

Measured ambient sound pressure level — Microphone location								
A	B	C	D	E	F	G	H	Average*
XXXXXXXXXXXXXXXXXXXX								XXXXX

*Use average ambient sound level to compute ambient corrected transformer sound level.

Figure 32—One-third octave sound power calculation: test no. ________________

One-third octave frequency (Hz)	Ambient corrected transformer sound pressure level (dB) — Microphone location																				Average sound pressure level (dB)	Sound power level (dB)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20		
63																						
80																						
100																						
125																						
160																						
200																						
250																						
315																						
400																						
500																						
630																						
800																						
1000																						
1250																						
1600																						
2000																						
2500																						
3150																						
4000																						
A-weighted C-weighted																						

Average A-weighted sound pressure level: ______________________ dB(A)
A-weighted sound pressure level: ______________________ dB(A), re: 10^{-12} W

Figure 33—A-weighted sound power level: test no. ________________

Microphone		Measured ambient plus transformer sound pressure level (dB)							Ambient corrected transformer sound pressure level (dB)						
		Frequency (Hz)							Frequency (Hz)						
Location	Height (m)	60	120	240	360	480	600	720	60	120	240	360	480	600	720
1															
2															
3															
4															
5															
6															
7															
8															
9															
10															
11															
12															
13															
14															
15															
16															
17															
18															
19															
20															

Measured ambient sound pressure level (dB)									Average sound pressure level (dB)							
		Frequency (Hz)							Frequency (Hz)							Estimated A-weighted
Location	Height (m)	60	120	240	360	480	600	720	60	120	240	360	480	600	720	
A																
B																
C																
D																
E																
F																
Average*																

*Use average ambient sound level to compute ambient corrected transformer sound level.

A-weighted sound pressure level: ________dB(A).
A-weighted sound power level: __________ dB(A), re: 10^{-12} W.

Figure 34—Discrete frequency sound power calculation: test no. ________________

14. Calculated data

14.1 Reference temperature

The reference temperature for determining load losses, voltage regulation, and efficiency shall be equal to the sum of the rated average winding temperature rise by resistance plus 20 °C.

14.2 Losses and excitation current

14.2.1 Determination of no-load losses and excitation current

No-load losses and excitation current shall be determined for the rated voltage and frequency on a sine-wave basis, unless a different form is inherent in the operation of the transformer.

14.2.2 Load losses

Load losses shall be determined for rated voltage, current, and frequency and shall be corrected to the reference temperature (see 14.1).

14.2.3 Total losses

Total losses are the sum of the no-load losses and the load losses.

14.3 Efficiency

The efficiency of a transformer is the ratio of its useful power output to its total power input as shown in Equation (37):

$$\eta = \frac{P_o}{P_i} = \frac{P_i - P_L}{P_i} = 1 - \frac{P_L}{P_i} = 1 - \frac{P_L}{P_o + P_L} \tag{37}$$

where

- η is efficiency
- P_o is output (W)
- P_i is input (W)
- P_L is losses (W)

When specified, efficiency shall be calculated on the basis of the reference temperature for the average winding temperature rise of the transformer.

14.4 Voltage regulation of a constant-voltage transformer

14.4.1 General

The voltage regulation of a constant-voltage transformer is defined in IEEE Std C57.12.80. The regulation may be expressed in percentage (or per unit) on the basis of the rated secondary voltage at full load.

14.4.2 Reference temperature

When specified, voltage regulation calculations shall be based on the reference temperature described in 14.1.

14.4.3 Load loss watts and impedance volts

The load loss watts and impedance volts used to compute voltage regulation are derived from the measurement of the factors described in 9.2 corrected to reference temperature described in 9.4.

14.4.4 Voltage regulation computation, two-winding transformers

When specified, the voltage regulation shall be computed according to exact formulae for the calculation of regulation through three-phase to two-phase transformers.

14.4.4.1 Exact formula for the calculation of regulation

The exact formulae for calculating regulation are shown in Equation (38) and Equation (39):

a) When the load is lagging:

$$reg = \sqrt{(R + F_p)^2 + (X + q)^2} - 1 \tag{38}$$

b) When the load is leading:

$$reg = \sqrt{(R+F_p)^2 + (X-q)^2} - 1 \tag{39}$$

where

F_p is power factor of load

q is + $\sqrt{1-F_p^2}$

R is resistance factor of transformer = $\dfrac{\text{load loss in kilowatts}}{\text{rated kilovoltamperes}}$

X is reactance factor of transformer = + $\sqrt{Z^2 - R^2}$ (Ω)

Z is impedance factor of transformer = $\dfrac{\text{impedance kilovoltamperes}}{\text{rated kilovoltamperes}}$

The quantities F_p, q, R, X, and Z are on a per-unit basis. Results shall be multiplied by 100 to obtain the percentage of regulation.

14.4.4.2 General expression for calculation of transformer regulation

A general expression for the calculation of transformer regulation permitting any degree of precision justified by the supporting data is Equation (40):

$$reg = a - \frac{1}{2}a^2 + \frac{1}{2}a^3 - \frac{5}{8}a^4 + \frac{7}{8}a^5 - \frac{21}{16}a^6 + \frac{33}{16}a^7 \tag{40}$$

where

reg is the regulation on a per-unit basis

a is a quantity depending on the angle and magnitude of the transformer impedance, the power factor of the load, and the number of windings in the transformer.

The quantity a for the calculation of the per-unit regulation of a two-winding transformer is determined by Equation (41):

$$a = Z\cos(\Phi + \theta) + \frac{Z^2}{2} \tag{41}$$

where

R is the resistance factor of transformer = $\dfrac{\text{load loss in kilowatts}}{\text{rated kilovoltamperes}}$

Z is the impedance factor of transformer = $\dfrac{\text{impedance kilovoltamperes}}{\text{rated kilovoltamperes}}$

X is reactance factor of transformer = + $\sqrt{Z^2 - R^2}$ (Ω)

ϕ is the impedance angle of transformer impedance

$\cos\phi$ is R/Z

F_p is the power factor of load $\cos\phi$

θ is the phase angle of load current; positive for leading current, negative for lagging current

14.4.4.3 Three-phase to two-phase transformers

For the calculation of the regulation for three-phase to two-phase transformation, proceed as follows:

a) For the per-unit regulation of main phase, use the impedance of the main transformer for substitution in the formula selected for use.
b) For the per-unit regulation of the teaser phase, use the sum of the impedance of the teaser transformer plus the interlacing impedance of the main transformer for substitution in the formula selected for use.
c) To determine the interlacing impedance, connect the two ends of the three-phase winding of the main transformer together and impress between this common connection and the 50% tap a voltage sufficient to pass three-phase line current in the supply lines.
d) The voltage thus determined is the interlacing impedance voltage and is to be put on a per-unit basis by reference to the rated voltage of the teaser transformer on the 86.6% tap.

Annex A

(informative)

Partial discharge measurement using radio-influence voltage instrumentation and its failure detection

A.1 Partial discharge measurement

A.1.1 Internal partial discharges

Apparent internal partial discharges shall be determined in terms of the RIV generated and measured at the line terminals of the winding under test.

A.1.2 Instrumentation

A radio noise and field strength meter conforming to ANSI Std C63.2 [B2] shall be used to measure the RIV generated by any internal partial discharges. The measurement shall be on a quasi-peak basis at a nominal frequency of 1 MHz; a frequency from 0.85 MHz to 1.15 MHz may be used to discriminate against local radio-station signal interference. The radio-noise meter shall be coupled to the line terminal(s) of the winding under test through the capacitance tap of the bushing(s). A suitable device shall be used to compensate for the capacitance dividing effect produced by the bushing tap-to-ground capacitance plus that of all elements between the bushing tap and the meter (e.g., coaxial cables, adapters). This device shall be tuned to minimize the dividing effect of the capacitances and to convey the RIV signal to the radio-noise meter with minimum attenuation. External shielding may be used to minimize the risk of air corona, which may occur at the bushing terminals or grounded projections. Radio-frequency chokes or tuned filters may be used to isolate the transformer under test and the RIV-measuring circuit from the remainder of the test circuit, including its energy source.

A.1.3 Calibration

The test circuit components connected to the winding under test may attenuate the generated RIV level and add to the measured RIV background level. Therefore, it is necessary to determine the relationship between the RIV at the terminal of the winding under test and the RIV reading of the radio-noise meter connected in typical location in the test circuit. The steps for this calibration ratio are as follows:

a) Apply a signal to the terminal under test of approximately 100 μV at the measuring frequency.

b) Measure the voltage at the terminal with the radio-noise meter connected directly to the terminal.

c) With the same radio-noise meter, measure the voltage provided by the test circuit at the location where the radio-noise meter will be connected during the partial discharge test on the transformer. A second radio-noise meter may be used for this measurement, provided its relationship to the first has been established at the measuring frequency.

d) Use the ratio of the calibration signal voltage measured at the transformer terminal to that measured at the normal meter location in the test circuit as a multiplier on the RIV at the terminal of the winding under test.

e) Establish that this calibration ratio remains valid over the RIV range of interest.

A.2 Failure detection

Failure may be indicated by the presence of smoke and bubbles rising in the oil, an audible sound such as a thump, or a sudden increase in test current. Any such indication shall be carefully investigated by observation, by repeated test, or by other tests to determine whether a failure has occurred.

In terms of interpretation of partial discharge measurements, the results shall be considered acceptable and no further partial discharge tests required under the following conditions:

a) The magnitude of the partial discharge level does not exceed 100 μV.

b) The increase in partial discharge levels during the 1 h does not exceed 30 μV.

Judgment should be used on the 5 min readings so that momentary excursions of the RIV meter caused by cranes or other ambient sources are not recorded. Also, the test may be extended or repeated until acceptable results are obtained.

A failure to meet the partial discharge acceptance criterion shall not warrant immediate rejection, but it shall lead to consultation between purchaser and manufacturer about further investigations.

Annex B

(normative)

50/60 Hz frequency conversion of measured performance parameters

It is preferred to perform tests at the rated frequency of the transformer to be tested. However, tests cannot always be done at the rated frequency. In such cases, upon agreement between the purchaser and the manufacturer at the tender stage, the conversion factors given in this annex shall be used to convert the tested values from the frequency used for test to the required rated frequency. The purpose of the frequency conversion factors is to have uniformity among manufacturers when such cases arise. These conversion factors are intended for 50-Hz-to-60-Hz conversion; however, the 60-Hz-to-50-Hz conversion factors are essentially the reciprocal of the 50-Hz-to-60-Hz factors as shown in this annex. See Girgis et al. [B6] for additional information.

B.1 No-load loss and excitation current

The following conversion factors shall be used to convert the values of measured no-load loss and excitation current at the design flux density from the frequency used for measurement to the required rated frequency. Voltage measured according to the average voltmeter method should be applied so that the resulting core flux density is equal to the flux density at the rated frequency of the transformer. For example, in the case of the test performed at 50 Hz on a 60 Hz transformer, the applied voltage should be 5/6 of the voltage corresponding to the 60 Hz operation.

No-Load Loss Conversion Factors (50 Hz to 60 Hz):

For Single-Phase Transformers:

$$B \leq 1.4T = 1.32 \tag{B.1}$$

$$B > 1.4T = 1.32 - 0.05 \times (B-1.4) \tag{B.2}$$

For Three-Phase Transformers:

$$B \leq 1.4T = 1.33 \tag{B.3}$$

$$B > 1.4T = 1.33 - 0.05 \times (B-1.4) \tag{B.4}$$

No-Load Loss Conversion Factors (60 Hz to 50 Hz):

For Single-Phase Transformers:

$$B \leq 1.4T = 1/1.32 \tag{B.5}$$

$$B > 1.4T = \frac{1}{1.32 - 0.05 \times (B - 1.4)} \tag{B.6}$$

For Three-Phase Transformers:

$$B \leq 1.4T = 1/1.33 \tag{B.7}$$

$$B > 1.4T = \frac{1}{1.33 - 0.05 \times (B - 1.4)} \tag{B.8}$$

Where B = flux density [T]

The value of each of these conversion factors is an average value for all core materials. This averaging translates into a maximum of 1% uncertainty of the corrected value.

The excitation current conversion factor is 1.00; thus the measured value of the excitation current does not need to be converted from one frequency to the other.

Numerical Example: 50-Hz-to-60-Hz Conversion for a Three-Phase Transformer:

Design Flux Density	= 1.7 T
Rated Voltage at 60 Hz	= 13.8 kV
Voltage Applied at 50 Hz = 13.8 × 5/6	= 11.5 kV
Conversion Factor = 1.33 – 0.05×(1.7-1.4)	= 1.315

Measured No-Load Loss at 50 Hz	= 22.8 kW
Converted No-Load Loss at 60 Hz	= 22.8 × 1.315 = 30 kW
Measured excitation current at 50 Hz	= 2.3 A
Excitation current at 60 Hz	= 2.3 A

B.2 Load loss

The following conversion factors shall be used to convert the values of load loss measured at 50 Hz to their corrected values at 60 Hz.

Conversion values are given below to convert the measured winding eddy and stray loss separately if a magnetic field program was available to calculate at least the winding eddy losses. Otherwise, a conversion factor is given below for the sum of winding eddy + stray losses.

Load Loss Conversion Factors (50 Hz to 60 Hz)

Winding Eddy Loss:	1.44
Stray Loss:	1.23
Winding Eddy + Stray loss:	1.34

Load Loss Conversion Factors (60 Hz to 50 Hz)

Winding Eddy Loss:	$1/1.44$
Stray Loss:	$1/1.23$
Winding Eddy + Stray loss:	$1/1.34$

The voltage to be applied on the transformer shall be such that the resulting current in the transformer is equal to the rated current. For transformers larger than approximately 10 MVA, the impedance voltage is nearly proportional to frequency. In the case of the test performed at 50 Hz on a 60 Hz transformer, the applied voltage would be nearly 5/6 of the impedance voltage of the transformer corresponding to the 60 Hz operation.

Since the value of each of the conversion factors is an average value for the different types of tank wall shielding, this averaging would represent an additional 1% uncertainty to the accuracy of the converted loss values.

Numerical Example; 50-Hz-to-60-Hz Conversion:

Measured Losses at 50 Hz:

Total Load Loss	= 142.4 kW
I^2R	= 124.6 kW
Winding Eddy + Stray	= 17.8 kW

Converted Losses for 60 Hz

Winding Eddy + Stray = 17.8 ×1.34	= 23.9 kW
Total Load Loss = 124.6 + 23.9	= 148.5 kW

B.3 Temperature-rise test

The following current multipliers shall be applied to achieve the correct rated frequency loss. The injected test currents for the initial estimate of the total losses shall be adjusted so that the ohmic I^2R loss is increased to offset the decreased winding eddy and stray loss at 50 Hz operation.

Multipliers for Heat Run Currents (50 Hz to 60 Hz):

Multiplier for Total Losses Heat Run Current: $$\sqrt{\frac{P_0 + (P_{I2R} + P_{e+s} \cdot 1.34)}{P_0 + (P_{I2R} + P_{e+s})}} \qquad \text{(B.9)}$$

Multiplier for Winding Rise Run Current: $$\sqrt{\frac{P_{I2R} + 1.44 \cdot P_e}{P_{I2R} + P_e}} \qquad \text{(B.10)}$$

where

P_0 is the converted no-load loss at 60 Hz (measured at 50 Hz and converted to 60 Hz)

P_{I2R} is the calculated I^2R losses at rated current from the dc resistance measurement

P_{e+s} is the measured (winding eddy + stray) loss at 50 Hz

P_e is the measured winding eddy loss at 50 Hz

Multipliers for Heat Run Currents (60 Hz to 50 Hz):

Multiplier for Total Losses Heat Run Current: $$\sqrt{\frac{P_0 + \left(P_{I2R} + P_{e+s}/1.34\right)}{P_0 + (P_{I2R} + P_{e+s})}} \qquad \text{(B.11)}$$

Multiplier for Winding Rise Run Current: $$\sqrt{\frac{P_{I2R} + P_e/1.44}{P_{I2R} + P_e}} \qquad \text{(B.12)}$$

where

P_0 is the converted no-load loss at 50 Hz (measured at 60 Hz and converted to 50 Hz)

P_{I2R} is the calculated I^2R losses at rated current from the dc resistance measurement

P_{e+s} is the measured (winding eddy + stray) loss at 60 Hz

P_e is the measured winding eddy loss at 60 Hz

Numerical Example: Temperature-Rise Test at 50 Hz for a 60 Hz Transformer:

Total Loss Heat Run Current for 60 Hz	= 272 A
Rated Current for 60 Hz	= 246.6 A
P_0 Measured at 50 Hz and Converted to 60Hz	= 14.4 kW
P_{I2R}	= 124.6 kW
P_{e+s} Measured at 50 Hz	= 17.8 kW
P_e Measured at 50 Hz	= 4.3 kW

Total Loss Run Current at 50 Hz $$= 272.0 \times \sqrt{\frac{14.4 + (124.6 + 17.8 \times 1.34)}{14.4 + (124.6 + 17.8)}} = 277.2A$$

Winding Rise Current at 50 Hz $$= 246.6 \times \sqrt{\frac{124.6 + 1.44 \times 4.3}{124.6 + 4.3}} = 248.4A$$

The manufacturer shall provide an adequate supply to operate the cooling equipment at the rated frequency.

The measured average oil and average winding rises will be considered accurate for rated frequency condition since the correct rated frequency losses are applied. It should be noted that direct hot spot temperature measurements (e.g., fiberoptic probes) would need to be corrected for winding eddy losses at the rated frequency.

The measured tank temperature rises could be in error by a few degrees Celsius since the stray losses will not be correct and should thus be noted on the certified test reports.

B.4 Short-circuit test

Voltage shall be applied so that the transformer is subjected to the calculated symmetrical and asymmetrical currents (calculated for the rated frequency). Thus, in the case of the test performed at 50 Hz on a 60 Hz transformer, the applied voltage would be nearly 5/6 of the voltage required for a 60 Hz operation test.

For large power transformers, it should be noted that mechanical winding resonance in the 100–120 Hz range may impact the short circuit response of the windings at one frequency versus the other.

B.5 Audible sound

B.5.1 A-weighted sound level conversion

The following conversion factors for both ONAN and ONAF stages shall be used to convert the value of A-weighted sound level measured at 50 Hz to the corrected values at 60 Hz and conversely from 60 Hz to 50 Hz. The manufacturer shall provide an adequate supply to operate the cooling equipment at the rated frequency.

Using these frequency conversion factors requires that the manufacturer verify that neither the core nor the windings or the tank plates/stiffeners will experience mechanical resonance at the rated frequency. In such a case, the purchaser and the manufacturer should agree on any other adjustments that should be applied to the tested values. If measurements, however, indicate core, tank, or winding resonance at the frequency at which the measurement is being performed, the purchaser and the manufacturer should agree on whether any other adjustment to the tested values would be allowed as these resonances may not be excited when the transformer is operating at the rated frequency.

The uncertainty is greater, and the possibility of resonance(s) exists when the transformer is operating at the rated frequency. Therefore, if the converted measured sound level is within 2 dB below the guaranteed value, then upon agreement with the purchaser, verification of the sound level at site may be required.

B.5.1.1 50/60 Hz conversion of ONAN (core) sound level

Voltage should be applied so that the resulting flux density in the core is equal to the design flux density at the rated frequency of the transformer. For example, in the case of the test performed at 50 Hz on a 60 Hz transformer, the applied voltage should be 5/6 of the voltage corresponding to the 60 Hz operation.

The corrected sound level for 60 Hz operation is obtained by adding 3.6 dB to the measured ONAN sound level at 50 Hz ($LP_{ONAN\text{-}50}$). Conversely, the corrected sound level for 50 Hz operation is obtained by subtracting 3.6 dB from the measured sound level at 60 Hz ($LP_{ONAN\text{-}60}$). The same approach can be used for transformers with OD and OF ratings.

B.5.1.2 50/60 Hz conversion of ONAF sound level

Conversion from 50 Hz Tested Sound Levels to Corresponding 60 Hz Levels:

First, the ONAF sound pressure level of the transformer ($LP_{ONAF\text{-}50/60}$) operating at 50 Hz with the cooling equipment operating at 60 Hz should be measured. Then the following conversion is to be made:

$LP_{ONAN\text{-}60}$: ONAN Sound Pressure Level at 60 Hz = $LP_{ONAN\text{-}50} + 3.6$

The corresponding ONAF sound pressure level at 60 Hz is

$$\mathrm{LP_{ONAF\text{-}60}} = 10 \cdot \log\left[10^{0.1 \cdot LP_{ONAF-50/60}} - 10^{0.1 \cdot LP_{ONAN-50}} + 10^{0.1 \cdot LP_{ONAN-60}}\right]$$

Conversion from 60 Hz Tested Sound Levels to the Corresponding 50 Hz Levels:

First, the ONAF sound pressure level of the transformer ($\mathrm{LP_{ONAF\text{-}60/50}}$) operating at 60 Hz with the cooling equipment operating at 50 Hz should be measured. Then the following conversion is to be made:

$\mathrm{LP_{ONAN\text{-}50}}$: ONAN Sound Pressure Level at 50 Hz = $\mathrm{LP_{ONAN\text{-}60}} - 3.6$

The corresponding ONAF sound pressure level at 50 Hz is

$$\mathrm{LP_{ONAF\text{-}50}} = 10 \cdot \log\left[10^{0.1 \cdot LP_{ONAF-60/50}} - 10^{0.1 \cdot LP_{ONAN-60}} + 10^{0.1 \cdot LP_{ONAN-50}}\right]$$

Numerical Example:

Measured Sound Levels:

$\mathrm{LP_{ONAN\text{-}50}}$ = 59.5 dBA
$\mathrm{LP_{ONAF\text{-}50/60}}$ = 66.1 dBA

Calculated Sound Levels:

$\mathrm{LP_{ONAN\text{-}60}}$ = 59.5 + 3.6 = 63.1 dBA
$\mathrm{LP_{ONAF\text{-}60}}$ $= 10 \cdot \log\left[10^{0.1 \cdot (66.1)} - 10^{0.1 \cdot (59.5)} + 10^{0.1 \cdot (63.1)}\right] = 67.2 dBA$

B.5.1.3 Load sound level conversion

NOTE—Load noise measurement is not presently covered in IEEE Std C57.12.00 or IEEE Std C57.12.90-2010.

For this test, impedance voltage should be applied so that the resulting current in the windings is equal to the rated current of the transformer. For example, in the case of the test performed at 50 Hz on a 60 Hz transformer, the applied voltage should be 5/6 of the impedance voltage for the 60 Hz operation.

The corrected sound level in dBA for 60 Hz operation (in the absence of current harmonics) is obtained by adding 4.6 dB to the load sound level measured at 50 Hz. Conversely, the corrected sound level for 50 Hz operation is obtained by subtracting 4.6 dB from the measured sound level at 60 Hz. The 4.6 dB conversion is the sum of the 1.6 dB difference in sound power produced at 60 Hz versus 50 Hz [20 Log (60/50)] and the 3.0 dB difference in the magnitude of the A-weighting attenuation at 100 Hz versus at 120 Hz.

B.5.2 Frequency spectrum conversion

The corrected sound levels at the main frequency components of the transformer sound in dBA, for 60 Hz operation, are obtained by adding the following values to the measured levels at 50 Hz:

Center frequency (Hz)	< 100/120	100/120	200/240	300/360	400/500	> 400/500
Adder (dB)	5.5	4.6	3.9	3.4	3.2	2.5

Conversely, the corrected sound levels at the main frequency components for 50 Hz operation is obtained by subtracting the values in the table above from the measured sound levels at 60 Hz.

For *linear* sound level values of the frequency spectrum, a constant value of 1.6 dB is to be added to all frequency components of the measured frequency spectrum at 50 Hz in order to obtain the corresponding frequency spectrum for the 60 Hz operation. Conversely, the frequency spectrum for 50 Hz operation is obtained by subtracting 1.6 dB from the measured spectrum at 60 Hz.

Annex C

(informative)

Bibliography

[B1] ANSI C57.12.10, American National Standard for Transformers 230 kV and Below, 833/958 through 8333/10 417 kVA, Single-Phase, and 750/862 through 60 000/80 000/100 000 kVA, Three-Phase without Load Tap Changing; and 3750/4687 through 60 000/80 000/100 000 kVA with Load Tap Changing—Safety Requirements.[8]

[B2] ANSI C63.2, American National Standard for Electromagnetic Noise and Field Strength Instrumentation, 10 kHz to 40 GHz—Specifications.

[B3] ASTM D117, Standard Guide for Sampling, Test Methods, and Specifications for Electrical Insulating Oils of Petroleum Origin.[9]

[B4] ASTM D877, Standard Test Method for Dielectric Breakdown Voltage of Insulating Liquids Using Disk Electrodes.

[B5] ASTM D1816, Standard Test Method for Dielectric Breakdown Voltage of Insulating Oils of Petroleum Origin Using VDE Electrodes.

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[B9] IEEE Std 454™-1973 (withdrawn), IEEE Recommended Practice for the Detection and Measurement of Partial Discharges (Corona) During Dielectric Tests.[11, 12]

[B10] IEEE Std C57.12.40™, IEEE Standard Requirements for Secondary Network Transformers, Subway and Vault Types (Liquid Immersed).

[B11] IEEE Std C57.12.70™, IEEE Standard Terminal Markings and Connections for Distribution and Power Transformers.

[B12] IEEE Std C57.106™, IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment.

[B13] Rosselli, Girolamo, "*Transformer Test to Calculate Z_0 for Interconnected Windings Transformers Using Symmetrical Sequence Components,*" IEEE proceedings paper O5GM0335 presented in 2005 at IEEE meeting in San Francisco.

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[8] ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).
[9] ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA (http://www.astm.org/).
[10] IEC standards are available from the International Electrotechnical Commission (http://www.iec.ch/).
[11] IEEE publications are available from the Institute of Electrical and Electronics Engineers Inc., 445 Hoes Lane, Piscataway, NJ 08854, USA (http://standards.ieee.org/).
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9.0 INTRODUCTION

The General Plan is an expression of the community's vision for the physical, social, cultural and economic development of Moreno Valley. It supports the City Council's vision for creating a positive future for Moreno Valley. Goals are general expressions of conditions that the City would like to attain. Objectives are specific conditions that the City would like to achieve. Policies are principles or guidelines intended to direct future activities and decisions in order to achieve the goals and objectives. Programs are plans of action to implement or advance the goals, objectives and policies.

9.1 ULTIMATE GOALS

The ultimate goals of the City of Moreno Valley General Plan are to achieve a community which:

I. Exhibits an orderly and balanced land use pattern that accommodates a range of residential, cultural, recreational, business and employment opportunities.

II. Is clean, attractive and free of blight and deteriorated conditions.

III. Provides public services and public facilities that are needed and desired by the community, including, but not limited to, a library(s) and library services.

IV. Enjoys a healthy economic climate that benefits both residents and businesses.

V. Provides recreational amenities, recreation services and open space, including, but not limited to, parks, multi-use trails, community centers and open space.

VI. Enjoys a circulation system that fosters traffic safety and the efficient movement of motor vehicles, bicycles and pedestrians.

VII. Emphasizes public health and safety, including, but not limited to, police, fire, emergency and animal services and protection from floods and other hazards.

VIII. Recognizes the need to conserve natural resources while accommodating growth and development.

9.2 COMMUNITY DEVELOPMENT ELEMENT GOALS, OBJECTIVES POLICIES AND PROGRAMS

9.2.1 COMMUNITY DEVELOPMENT ELEMENT GOALS

Goal 2.1

A pattern of land uses, which organizes future growth, minimizes conflicts between land uses, and which promotes the rational utilization of presently underdeveloped and undeveloped parcels.

Goal 2.2

An organized, well-designed, high quality, and functional balance of urban and rural land uses that will meet the needs of a diverse population, and promote the optimum degree of health, safety, well-being, and beauty for all areas of the community, while maintaining a sound economic base.

Goal 2.3

Achieves an overall design statement that will establish a visually unique image throughout the City.

Goal 2.4

A supply of housing in sufficient numbers suitable to meet the diverse needs of future residents and to support healthy economic development without creating an oversupply of any particular type of housing.

Goal 2.5

Maintenance of systems for water supply and distribution; wastewater collection, treatment, and disposal; solid waste collection and disposal; and energy distribution which are capable of meeting the present and future needs of all residential, commercial, and industrial customers within the City of Moreno Valley.

9.2.2 COMMUNITY DEVELOPMENT ELEMENT OBJECTIVES AND POLICIES

Objective 2.1

Balance the provision of urban and rural lands within Moreno Valley by providing adequate land for present and future urban and economic development needs, while retaining the significant natural features and the rural character and lifestyle of the northeastern portion of the community.

Objective 2.2

Provide a wide range of residential opportunities and dwelling types to meet the demands of present and future residents of all socioeconomic groups.

Policies:

2.2.1 In determining allowable density for residential parcels an "adjusted net acreage" shall be used. Adjusted net acres shall mean the land area that would remain after dedication of ultimate rights-of-ways for arterial streets, freeways and park dedications.

2.2.2 The primary purpose of areas designated ***Hillside Residential*** is to balance the preservation of hillside areas with the development of view-oriented residential uses.

a. Within the Hillside Residential category, appropriate residential uses include large lot residential uses. Lots smaller than one acre may only be permitted as clustered units to minimize grading, and other impacts on the environment, inclusive of the Multi-Species Habitat Conservation Plan.

b. The maximum residential density within Hillside Residential areas shall be determined by the steepness of slopes within the project. The maximum allowable density shall not exceed one dwelling unit per acre on sloping hillside property and shall decrease with increasing slope gradient.

c. Future development within Hillside Residential areas shall occur in such a manner as to maximize preservation of natural hillside contours, vegetation and other characteristics. Hillside area developments should minimize grading by following the natural contours as much as possible.

d. Development within Hillside Residential areas shall be evaluated to determine the precise boundaries of the area. If the Community Development Director determines that adequate slope information is not available, applicants requesting to develop within these areas shall complete a slope analysis for the proposed development site. Portions of the development that exceed an average slope of 10% shall adhere to the policies within the Hillside Residential category. Portions of the development where the slopes are less than 10% on average shall adhere to policies within the adjacent land use category.

2.2.3 The primary purpose of areas designated ***Rural Residential*** is to provide for and protect rural lifestyles, as well as to protect natural resources and hillsides in the rural portions of the City.

a. The maximum residential density within Rural Residential and areas shall be determined by the steepness of slopes within the individual project area. The maximum allowable density shall be 0.4 dwelling units per acre (an average lot size of 2.5 acres) on flat terrain and shall decrease with increasing slope gradient.

b. Within the Rural Residential category, appropriate residential uses include large lot residential uses. Lots smaller than 2.5 acres may only be permitted as clustered units to minimize grading and other impacts on the environment, inclusive of the Multi-Species Habitat Conservation Plan.

2.2.4 The primary purpose of areas designated ***Residential 1*** is to provide for and protect rural lifestyles. The maximum allowable density for projects within the Residential 1 areas shall be 1.0 dwelling unit per acre.

2.2.5 The primary purpose of areas designated ***Residential 2*** is to provide for suburban lifestyles on residential lots larger than commonly available in suburban subdivisions and to provide a rural atmosphere. The maximum allowable density shall be 2.0 dwelling units per acre.

2.2.6 The primary purpose of areas designated ***Residential 3*** is to provide a transition between rural and urban density development areas, and to provide for a suburban lifestyle on residential lots larger than those commonly found in suburban subdivisions. The maximum allowable density shall be 3.0 dwelling units per acre.

2.2.7 The primary purpose of areas designated ***Residential 5*** is to provide for single-family detached housing on standard sized suburban lots. The maximum allowable density shall be 5.0 dwelling units per acre.

2.2.8 The primary purpose of areas designated ***Residential 10*** is to provide for a variety of residential products and to encourage innovation in housing types. Developments within Residential 10 areas are typically expected to provide amenities not generally found in suburban subdivisions, such as common open space and recreational areas. The maximum allowable density shall be 10.0 dwelling units per acre.

2.2.9 The primary purpose of areas designated ***Residential 15*** is to provide a range of multi-family housing types for those not desiring dwellings on individual lots that include amenities such as common open space and recreational facilities. The maximum allowable density shall be 15.0 dwelling units per acre.

2.2.10 The primary purpose of areas designated ***Residential 20*** is to provide a range of high density multi-family housing types. Developments within Residential 20 areas shall also provide amenities, such as common open spaces and recreational facilities. The maximum density shall be 20 dwelling units per acre.

2.2.11 Densities in excess of the maximum allowable density for residential projects may be permitted pursuant to California density bonus law.

2.2.12 Planned Unit Developments (PUD) shall be encouraged for residential construction in order to provide housing that is varied by type, design, form of ownership, and size. PUD's shall also provide opportunities to cluster units to protect significant environmental features and/or provide unique recreational facilities.

2.2.13 Discourage costly "leap-frog" development patterns by encouraging in-fill development wherever feasible, thereby reducing overall housing costs. Development within an area designated as SP 212-1 (Moreno Highlands) is not considered to be leapfrog development.

2.2.14 Encourage a diversity of housing types, including conventional, factory built, mobile home, and multiple family dwelling units

2.2.15 Encourage the use of innovative and cost effective building materials, site design practices and energy and water conservation measures to conserve resources and reduce the cost of residential development.

2.2.16 Affordable housing developments should be compatible in visual design with surrounding development.

2.2.17 Discourage nonresidential uses on local residential streets that generate traffic, noise or other characteristics that would adversely affect nearby residents.

Objective 2.3

Promote a sense of community and pride within residential areas through increased neighborhood interaction and enhanced project design.

Policies:

2.3.1 Within individual residential projects, a variety of floor plans and elevations should be offered.

2.3.2 Encourage building placement variations, roofline variations, architectural projections, and other embellishments to enhance the visual interest along residential streets.

2.3.3 Discourage the development of single-family residences with a bulk (building mass) that is out of scale with the size of the parcels on which they are located.

2.3.4 Design large-scale small lot single family and multiple family residential projects to group dwellings around individual open space and/or recreational features.

2.3.5 Ensure that all multiple family housing is well-designed, attractive and livable by:

a. Ensuring all structures are architecturally compatible and include decorative architectural features and articulation in walls and roofs;

b. Providing adequate parking, walkways, lighting, landscaping, amenities and open space areas;

c. Providing private open space areas such as patios and balconies.

Objective 2.4

Provide commercial areas within the City that are conveniently located, efficient, attractive, and have safe and easy pedestrian and vehicular circulation in order to serve the retail and service commercial needs of Moreno Valley residents and businesses.

Policies:

2.4.1 The primary purpose of areas designated **Commercial** is to provide property for business purposes, including, but not limited to, retail stores, restaurants, banks, hotels, professional offices, personal services and repair services. The zoning regulations shall identify the particular uses permitted on each parcel of land, which could include compatible noncommercial uses. Commercial development intensity should not exceed a Floor Area Ratio of 1.00 and the average floor area ratio should be significantly less.

2.4.2 The commercial area located at the intersection of **Alessandro Boulevard and Redlands Boulevard** shall provide for commercial land uses that are compatible with the historical, small town nature of the original Moreno town site. The zoning regulations shall identify the particular uses permitted on each parcel of land, which could include compatible noncommercial uses.

2.4.3 The commercial area located on the **north side of State Route 60 at the intersection of Moreno Beach Drive** shall provide for the establishment of commercial land uses that serve the daily needs of the surrounding residential neighborhood and the traveling public. It is not intended to serve the needs of the region for goods, services, entertainment or recreation. The zoning regulations shall identify the particular uses and type of development permitted on each parcel, which could include office uses and compatible noncommercial uses.

2.4.4 An overlay district limiting land uses to those that are supportive and compatible with medical uses shall be established around the **Riverside County Regional Medical Center and the Moreno Valley Community Hospital**. The zoning regulations shall identify the particular uses and type of development permitted on each parcel.

2.4.5 The primary purpose of locations designated **Mixed-Use** on the Moreno Valley General Plan Land Use map is to provide for the establishment of commercial and office uses and/or residential developments of up to 20 dwelling units per acre. The zoning regulations shall identify the particular uses and type of development permitted on each parcel. Overall development intensity should not exceed a floor area ratio of 1.00.

2.4.6 The primary purpose of areas designated **Residential/Office** on the Moreno Valley General Plan Land Use map is to provide areas for the establishment of office-based working environments or residential developments of up to 15 dwelling units per acre. The zoning regulations shall identify the particular uses and type of residential development permitted on each parcel of land. Overall development intensity should not exceed a Floor Area Ratio of 1.00.

2.4.7 The primary purpose of areas designated **Office** is to provide for office uses, including, administrative, professional, legal, medical and financial offices. The zoning regulations shall identify the particular uses permitted on each parcel of land, which could include limited non-office uses that support and are compatible with office uses. Development intensity should not exceed a Floor Area Ratio of 2.00 and the average intensity should be significantly less.

2.4.8 Orient commercial development toward pedestrian use. Buildings should be designed and sited so as to present a human-scale environment, including convenient and comfortable pedestrian access, seating areas, courtyards, landscaping and convenient pedestrian access to the public sidewalk.

2.4.9 Require reciprocal parking and access agreements between individual parcels where practical.

2.4.10 Design internal roadways so that direct access is available to all structures visible from a particular parking area entrance in order to eliminate unnecessary vehicle travel, and to improve emergency response.

2.4.11 The commercial area located in the vicinity of the intersection of Gilman Springs Road and Jack Rabbit Trail shall provide those commercial support activities necessary and/or incidental to adjacent recreational uses and emphasize tourist-oriented activities and retail services. Recreation-oriented residential land use types may be appropriate to the extent that they are incidental to and complement the recreational character of the area. At such time as the area is annexed to the City, the zoning regulations shall identify the particular uses permitted on each parcel of land.

Objective 2.5

Promote a mix of industrial uses which provide a sound and diversified economic base and ample employment opportunities for the citizens of Moreno Valley with the establishment of industrial activities that have good access to the regional transportation system, accommodate the personal needs of workers and business visitors; and which meets the service needs of local businesses.

Policies:

2.5.1 The primary purpose of areas designated **Business Park/Industrial** is to provide for manufacturing, research and development, warehousing and distribution, as well as office and support commercial activities. The zoning regulations shall identify the particular uses permitted on each parcel of land. Development intensity should not exceed a Floor Area Ratio of 1.00 and the average floor area ratio should be significantly less.

2.5.2 Locate manufacturing and industrial uses to avoid adverse impacts on surrounding land uses.

2.5.3 Screen manufacturing and industrial uses where necessary to reduce glare, noise, dust, vibrations and unsightly views.

2.5.4 Design industrial developments to discourage access through residential areas.

Objective 2.6

Maintain an adequate inventory of lands for the conduct of public, quasi-public, and institutional activities, including protection of areas needed for future public, quasi-public, and institutional facilities.

Policies:

2.6.1 The primary purpose of areas designated ***Public/Quasi-Public*** is to provide property for civic, cultural and public utility uses, including, but not limited to schools, libraries, fire stations, museums, and government offices. The zoning regulations shall identify the particular uses permitted on each parcel of land. Development intensity should not exceed a Floor Area Ratio of 1.00 and the average Floor Area Ratio should be significantly less.

Objective 2.7

Encourage open space preservation through appropriate land use policies that recognize the valuable natural resources and areas required for protection of public safety that exist in the City.

Policies:

2.7.1 The primary purpose of areas designated ***Open Space***, is to provide areas that are substantially unimproved, including, but not limited to areas for outdoor recreation, the preservation of natural resources, the grazing of livestock and the production of crops. Development intensity should not exceed a Floor Area Ratio of 0.10 and the average Floor Area Ratio should be significantly less.

2.7.2 The primary purpose of areas designated ***Floodplain*** is to designate floodplain areas where permanent structures for human occupancy are prohibited to protect of the public health and safety. Development intensity should not exceed a Floor Area Ratio of 0.05.

Objective 2.8

The major purpose of specific plans is to encourage and promote the development of larger-scaled mixed-use developments for the purpose of providing adequate flexibility and innovation in residential building types, land use mixes, site design, and development concepts.

Policies:

2.8.1 In order to provide superior design solutions, reduce adverse environmental impacts, preserve scenic values, and enhance the provision of open space and other amenities, transfers of residential densities permitted under the General Plan may be accomplished in accordance with the following:

a. The transfer of residential densities may be accomplished only pursuant to approval of a planned unit development or hillside development.

b. Up to one hundred percent (100%) of the density indicated on the General Plan Land Use map may be transferred within a single hillside development or planned unit development project. Densities may not be transferred from one project to another.

c. The proposed transfer of densities shall be accomplished such that the project results in a superior use of land, increased sensitivity to the environment, and/or enhanced project amenities without an increased burden on public facilities and services.

2.8.2 To the extent that development policies, land use standards, design guidelines, and other provisions of the adopted specific plans are, by their content, intended to address issues contained in the objectives, policies, and implementation programs of the Moreno Valley General Plan, and are inconsistent with the provisions of the General Plan, then the provisions of those specific plans shall be controlling; otherwise, all other provisions of the Moreno Valley General Plan shall remain in effect.

Objective 2.9

Maintain City boundaries that are logical in terms of City service capabilities, economic development needs, social and economic interdependencies, citizen desires, and City costs and revenues.

Policies:

2.9.1 Support and encourage the annexation of unincorporated areas within the General Plan study area for which:

a. Long-term benefits will be derived by the City;

b. Adequate infrastructure and services have been or can be economically provided in accordance with current City standards;

c. The proposed annexation will generate sufficient revenues to adequately pay for the provision of City services within a reasonable period of time.

Objective 2.10

Ensure that all development within the City of Moreno Valley is of high quality, yields a pleasant living and working environment for existing and future residents, and attracts business as the result of consistent exemplary design.

Policies:

2.10.1 Encourage a design theme for each new development that is compatible with surrounding existing and planned developments.

2.10.2 Screen trash storage and loading areas, ground and roof mounted mechanical equipment, and outdoor storage areas from public view as appropriate.

2.10.3 Require exterior elevations of buildings to have architectural treatments that enhance their appearance.

a. A design theme, with compatible materials and styles should be evident within a development project;

b. Secondary accent materials, colors and lighting should be used to highlight building features;

c. Variations in roofline and setbacks (projections and recesses) should be used to break up the building mass.

d. Industrial buildings shall include architectural treatments on visible facades that are aesthetically pleasing.

2.10.4 Landscaping and open spaces should be provided as an integral part of project design to enhance building design, public views, and interior spaces; provide buffers and transitions as needed; and facilitate energy and resource conservation.

2.10.5 Development projects adjacent to freeways shall provide landscaped buffer strips along the ultimate freeway right-of-way.

2.10.6 Buildings should be designed with a plan for adequate signage. Signs should be highly compatible with the building and site design relative to size, color, material, and placement.

2.10.7 On-site lighting should not cause nuisance levels of light or glare on adjacent properties.

2.10.8 Lighting should improve the visual identification of structures. Within commercial areas, lighting should also help create a festive atmosphere by outlining buildings and encouraging nighttime use of areas by pedestrians.

2.10.9 Fences and walls should incorporate landscape elements and changes in materials or texture to deter graffiti and add visual interest.

2.10.10 Minimize the use and visibility of reverse frontage walls along streets and freeways by such treatments as landscaping, berming, and "side-on" cul-de-sacs.

2.10.11 Screen and buffer nonresidential projects from adjacent residential property and other sensitive land uses when necessary to mitigate noise, glare and other adverse effects on adjacent uses.

2.10.12 Screen parking areas from streets to the extent consistent with surveillance needs (e.g. mounding, landscaping, low profile walls, and/or grade separations).

2.10.13 Provide landscaping in automobile parking areas to reduce solar heat and glare.

2.10.14 Preserve or relocate existing mature trees and vegetation where practical. Mature trees shall be replaced when they cannot be preserved or relocated.

2.10.15 Emphasize the "gateway status" of lands in the vicinity of the intersection of I-215 and State Route 60, at the intersection of Alessandro Boulevard and I-215, at the intersection of Perris Boulevard and State Route 60, and at State Route 60 and Gilman Springs Road. In the vicinity of those areas designated as having "gateway status", the City shall encourage community identification signing.

Objective 2.11

Maintain a water system that is capable of meeting the daily and peak demands of Moreno Valley residents and businesses, including the provision of adequate fire flows.

Policies:

2.11.1 Permit new development only where and when adequate water services can be provided.

Objective 2.12

Maintain a wastewater collection, treatment, and disposal system that is capable of meeting the daily and peak demands of Moreno Valley residents and businesses.

Policies:

2.12.1 Prior to the approval of any new development application ensure that adequate septic or sewer service capacity exists or will be available in a timely manner.

Objective 2.13

Coordinate development activity with the provision of public infrastructure and services to eliminate possible gaps in service provision.

Policies:

2.13.1 Limit the amount of development to that which can be adequately served by public services and facilities, based upon current information concerning the capability of public services and facilities.

2.13.2 Unless otherwise approved by the City, public water, sewer, drainage and other backbone facilities needed for a project phase shall be constructed prior to or concurrent with initial development within that phase.

2.13.3 It shall be the ultimate responsibility of the sponsor of a development project to assure that all necessary infrastructure improvements (including system wide improvements) needed to support project development are available at the time that they are needed.

2.13.4 Encourage installation of advanced technology infrastructure, including, but not limited to, infrastructure for high speed internet access and solar energy.

Objective 2.14

Establish and implement comprehensive solutions to the financing of public facilities that adequately distribute costs based on the level of benefit received and the timing of development.

Policies:

2.14.1 Conduct periodic review of public facilities impact mitigation fees in accordance with state statutes to ensure that the charges are consistent with the costs of improvements. Utilize the service and mitigation standards contained in the Moreno Valley General Plan as the basis for determining improvement costs.

2.14.2 Promote the establishment of benefit assessment districts, Mello-Roos Community Facilities Districts, tax increment financing, and other financing mechanisms in combination with programmed capital improvements to eliminate existing public service and facility gaps, and to provide necessary facilities in advance of the impacts created by development.

2.14.3 Review development projects for their impacts on public services and facilities including, but not necessarily limited to, roadways, water, sewer, fire, police, parks, and libraries and require public services or facilities to be provided at the standards outlined in the Moreno Valley General Plan and the standards of applicable service agencies.

Objective 2.15

Ensure that all Moreno Valley residents have access to high-quality educational facilities, regardless of their socioeconomic status or location within the City.

Policies:

2.15.1 Encourage an ongoing open liaison with all school districts regarding proposed school design and siting to maximize access and minimize impacts to adjacent uses.

Objective 2.16

Maintain local library facilities and reserves in accordance with the following minimum standards: 0.5 square feet of library space and 1.2 volumes per capita.

Policies:

2.16.1 Encourage inter-library loan agreements with the County library system and those of surrounding cities to provide the widest possible variety of materials to library patrons.

2.16.2 Provide for the expansion of library facilities as needed to keep pace with the growing population of Moreno Valley.

Objective 2.17

Provide cultural facilities, including history (natural, cultural and children's) and art museums and performing arts facilities.

Policies:

2.17.1 Promote the development and construction of a civic/cultural center and museums.

Objective 2.18

Promote social services programs that meet the special needs for childcare, the elderly, and the disabled.

Policies:

2.18.1 Ensure that a full range of human service programs are available to meet the lifetime development needs of residents of all ages, including the special needs of seniors, families, children, disabled persons, and youth groups.

2.18.2 Encourage day care through zoning regulations by permitting such facilities in all compatible zoning classifications.

2.18.3 Work closely with local schools, private companies, churches, non-profit agencies, government social service agencies, and community groups to facilitate the provision of community services.

2.18.4 Encourage the development of senior citizens independent living and congregate care facilities in locations with convenient access to social, commercial, and medical services.

2.18.5 Promote volunteer involvement in all public programs and within the community as a whole.

9.2.3 COMMUNITY DEVELOPMENT ELEMENT PROGRAMS

2-1 Develop a community signing scheme for street corridors, public buildings and selected entrances to the community and its sub-communities.

2-2 Review and revise the Municipal Code to implement the goals, objectives and policies stated in the General Plan.

2-3 Conduct a detailed capital improvement program using the revised population projections and proposed land use characteristics of the General Plan.

2-4 Periodically study the feasibility of extending the sphere of influence north of the city limits and annexing unincorporated areas along the city boundary.

2-5 Disseminate local childcare resource information and provide referral service to residents and businesses.

2-6 Encourage demand-response public transportation facilities, such as the mini-bus or dial-a-ride systems in order facilitate the transportation needs of the elderly and the disabled.

2-7 Provide City information identifying available social services and facilities in a broad range of formats.

2-8 Evaluate existing social programs under the City's purview, and determine if they adequately address the needs of the aged, the disabled, low-income families and persons in crisis situations.

2-9 Work with other jurisdictions to seek changes in state law to allow reasonable controls on the location of community care facilities, foster homes and sober living facilities.

9.3 ECONOMIC DEVELOPMENT ELEMENT GOALS, OBJECTIVES, POLICIES AND PROGRAMS

9.3.1 ECONOMIC DEVELOPMENT ELEMENT GOALS

To be inserted after development of Economic Development Strategy.

9.3.2 ECONOMIC DEVELOPMENT ELEMENT POLICIES

To be inserted after development of Economic Development Strategy.

9.3.3 ECONOMIC DEVELOPMENT ELEMENT PROGRAMS

To be inserted after development of Economic Development Strategy.

9.4 PARKS, RECREATION AND OPEN SPACE ELEMENT GOALS, OBJECTIVES, POLICIES AND PROGRAMS

9.4.1 PARKS RECREATION AND OPEN SPACE ELEMENT GOALS

Goal 4.1

To enhance Moreno Valley as a desirable place in which to live, work, shop, and do business.

Goal 4.2

To retain an open space system that will conserve natural resources, preserve scenic beauty, promote a healthful atmosphere, provide space for outdoor recreation, and protect the public safety.

9.4.2 PARKS, RECREATION AND OPEN SPACE ELEMENT OBJECTIVES AND POLICIES

Objective 4.1

Retain agricultural open space as long as agricultural activities can be economically conducted, and are desired by agricultural interests, and provide for an orderly transition of agricultural lands to other urban and rural uses.

Policies:

4.1.1 Encourage grazing and crop production as a compatible part of a rural residential atmosphere.

Objective 4.2

Provide safe, affordable and accessible recreation facilities and programs to meet the current and future needs of Moreno Valley's various age and interest groups and promote the provision of private recreational facilities.

Policies:

4.2.1 Neighborhood parks shall serve as the day-to-day recreational areas of the City, Neighborhood parks should be within a reasonable walking distance of the population served. Community parks may also serve day-to-day recreation needs. That portion of the community and/or regional facilities that provide similar amenities to those found in neighborhood parks shall also be considered as meeting this objective.

4.2.2 Community parks shall provide opportunities for participation in sports and related athletic activities, water-oriented recreation and other special interest activities (e.g. golf, tennis, equestrian, etc).

4.2.3 Employ a multifaceted approach in the financing and acquisition, development and maintenance of parkland, including the financing of parklands through development fees, state and federal grant-in-aid programs, gifts and donations, and other sources.

4.2.4 Encourage special events (tournaments, festivals, celebrations) that reflect the uniqueness of Moreno Valley and contribute to community identity, cohesiveness and stability.

4.2.5 Work in conjunction with private and public school districts and other public agencies to facilitate the public use of school grounds and facilities for recreational activities. The City shall also encourage the development of park sites adjacent to school facilities to maximize recreational opportunities in Moreno Valley.

4.2.6 The City shall use cost effectiveness, demand and need for service and potential return on investment as criteria for the development and operation of future recreational facilities and programs.

4.2.7 The City level of service standard is 3 acres of developed parkland for every 1,000 new residents. Exceptions from this ratio may be made in exchange for extraordinary amenities of comparable economic value. Land not suitable for active recreation purposes may not be counted toward fulfilling parkland dedication requirements.

4.2.8 Encourage the development of recreational facilities within private developments, with appropriate mechanisms to ensure that such facilities are properly maintained and that they remain available to residents in perpetuity.

4.2.9 In conjunction with the school districts, civic organizations, and other private, civic-minded entities, encourage and participate in the provision of organized recreational activities for Moreno Valley residents of all ages.

4.2.10 Involve individuals and citizen groups reflecting a cross section of Moreno Valley citizens (including youth and adults) in the planning, design and maintenance of parks, recreation facilities and recreation programs.

4.2.11 Emphasize joint planning and cooperation with all public agencies as the preferred approach to meeting the parks and program needs of Moreno Valley citizens.

4.2.12 Include multi-functional spaces and facilities in parks to facilitate cultural events.

4.2.13 Provide recreation programs and access to facilities at reasonable costs.

4.2.14 Establish linear parks in agreement with public and private utilities, including the State of California along the California Aqueduct, for the use and maintenance of utility corridors and rights-of-way for recreational purposes.

4.2.15 Work closely with Riverside County Parks Department in its open space program to ensure that trail systems within Moreno Valley effectively link open space components.

4.2.16 Acquire land jointly with the local school districts for future school/park sites.

4.2.17 Require new development to contribute to the park needs of the City.

4.2.18 Provide lighted sports fields to increase availability and utilization of courts and playing field facilities.

Objective 4.3

Develop a hierarchical system of trails which contribute to environmental quality and energy conservation by providing alternatives to motorized vehicular travel and opportunities for recreational equestrian riding, bicycle riding, and hiking, and that connects with major regional trail systems.

Policies:

4.3.1 The City's network of multiuse trails, including regional trails, community trails, and local feeder trails, shall (1) be integrated with recreational, residential and commercial areas, schools and equestrian centers; (2) provide access to community resources and facilities, and (3) connect urban populations with passage to hillsides, ridgelines, and other scenic areas.

4.3.2 The City shall establish an agreement with public and private utilities for the use and maintenance of utility corridors and rights-of-way for trail purposes.

4.3.3 All new development approvals shall be contingent on trail right-of-way dedication and improvement in accordance with the Master Plan of Trails (Figure 4-5).

4.3.4 In conjunction with all development review, the City shall consider multiuse trail access and traditional travel routes through the property.

4.3.5 In conjunction with the review and approval of nonresidential developments, the City should consider the use of multiuse trail amenities such as hitching posts, benches, rest areas, and drinking facilities.

4.3.6 Wherever possible, development of residential areas conditioned for animal keeping on lots of ½ acre or larger, shall include a decomposed granite trail on one side of the street and traditional concrete sidewalk on the other.

4.3.7 Trail design and construction should take into consideration the safety and convenience of all trail users as the primary concern.

4.3.8 The City should facilitate the development of a multiuse regional trail system.

4.3.9 Unless otherwise specified due to fire department requirements, access or as established by a specific plan, city trails along roadways shall be ten (10) feet wide and shall be constructed with decomposed granite or equal material and shall provide appropriate fencing or other devices where needed to delineate trails from vehicular rights-of-way.

4.3.10 Where firefighting access is required, trails shall be 20' wide to meet the needs of the Fire Department and its equipment. Fire Department requirements shall be met in all conditions where access is required.

4.3.11 In unusual situations where legal or topographical barriers exist (e.g., excessive slope, the configuration of right-of-way, existing vegetation, etc.), the City shall have the discretion to amend the trail requirement as needed to accomplish the goals of this General Plan.

4.3.12 Local feeder trails shall connect residential lots in property zoned for horse keeping to the community trail system.

4.3.13 The City will encourage volunteer programs for the improvement of existing trails for the purpose of providing an integrated trail network that is safe, functional and readily accessible.

4.3.14 Where feasible, use drainage courses, utility rights-of-way and other such opportunities to incorporate trail and open space elements in the design of major development projects.

4.3.15 Utilize the Citizen's Advisory Board on Recreational Trails in making recommendations to City Council for the distribution of funds for the construction of new trails.

9.4.3 PARKS, RECREATION AND OPEN SPACE PROGRAMS

4-1 Develop a parks and recreation facilities master plan to implement the Parks and Recreation Element.

4-2 Develop policies and criteria for the establishment of trails and rest/picnic areas in natural open space areas.

4-3 Set policies and criteria for the establishment of greenbelt standards and design guidelines to allow flexibility in design of greenbelt/parks/open spaces areas within new development as long as non-auto circulation corridors (for equestrians, bicycles, pedestrians, etc.) are provided and the overall dedication requirement for greenbelt and park facilities is met.

4-4 Explore the feasibility of requiring new development to provide a percentage of the development in greenbelt area.

4-5 Provide on-going opportunities for public involvement and input into the park planning process.

4-6 Maintain advisory committees, such as the Parks and Recreation Advisory Committee, created by City Council in 1988, to serve in an advisory capacity on parks and recreation issues.

4-7 Work with coalitions of sports organizations to define mutually compatible facility needs and mechanisms for the development, construction, operation and maintenance of these facilities.

4-8 Investigate the feasibility of establishing a non-profit foundation to seek and receive donations from private sources for the support of Parks and Recreation programs and facilities.

4-9 Acquire land and develop neighborhood and community parks in the "Recommended Future Parkland Acquisition Areas" shown in Figure 4-4.

4-10 Prepare a comprehensive plan of trails that clearly defines the routing of city trails and is part of the General Plan.

4-11 Develop policies and criteria for the establishment of multiuse trails and rest/picnic areas in natural open space areas.

4-12 Periodically review the Master Plan of Trails to show existing and planned trails.

4-13 Enact ordinances requiring developers to incorporate trail corridors into their development plans in accordance with the Master Plan of Trails.

4-14 Develop standards for residential feeder trails to guide developers in locating and constructing trails and for the arrangement of on-going maintenance requirements of the trails.

4-15 Establish a fee system for the equitable distribution of the cost of developing and maintaining trails citywide.

4-16 Investigate the feasibility of creating a special district(s) for the purpose of acquiring and managing open space and trails.

4-17 Seek out and apply for grants sponsored by state and federal agencies, such as the Recreational Trails Program administered by the Federal Highways Administration and the State Department of Parks and Recreation.

9.5 CIRCULATION ELEMENT GOALS, OBJECTIVES, POLICIES AND PROGRAMS

9.5.1 CIRCULATION ELEMENT GOALS

Goal 5.1

Develop a safe, efficient, environmentally and financially sound, integrated vehicular circulation system consistent with the City General Plan Circulation Element Map, Figure 9-1, which provides access to development and supports mobility requirements of the system's users.

Goal 5.2

Maintain safe and adequate pedestrian, bicycle, and public transportation systems to provide alternatives to single occupant vehicular travel and to support planned land uses.

9.5.2 CIRCULATION ELEMENT OBJECTIVES AND POLICIES

Objective 5.1

Create a safe, efficient and neighborhood-friendly street system.

Policies:

5.1.1 Plan access and circulation of each development project to accommodate vehicles (including emergency vehicles and trash trucks), pedestrians, and bicycles.

5.1.2 Plan the circulation system to reduce conflicts between vehicular, pedestrian and bicycle traffic.

5.1.3 Require adequate off-street parking for all developments.

5.1.4 Driveway placement shall be designed for safety and to enhance circulation wherever possible.

5.1.5 Incorporate American Disability Act (ADA) and Title 24 requirements in roadway improvements as appropriate.

5.1.6 Design new developments to provide opportunity for access and circulation to future adjacent developments.

Objective 5.2

Implement access management policies.

Policies:

5.2.1 Locate residential units with access from local streets. Minimize direct residential access from collectors. Prohibit direct single-family driveway access on arterials and higher classification roadways.

5.2.2 Feed short local streets into collectors.

5.2.3 Encourage the incorporation of traffic calming design into local and collector streets to promote safe vehicle speeds.

5.2.4 Design new subdivisions to minimize the disruptive impact of motor vehicles on local streets. Long, broad and linear streets should be avoided. Residential streets should be no wider than 40 feet, and should have an uninterrupted length of less than one half mile. Curvilinear streets and cul-de-sacs are preferred. Streets within the subdivision should be designed to facilitate access to residences and to discourage through traffic.

Objective 5.3

Maintain Level of Service (LOS) “C” on roadway links, wherever possible, and LOS “D” in the vicinity of SR 60 and high employment centers. Figure 9-2 depicts the LOS standards that are applicable to all segments of the General Plan Circulation Element Map.

Policies:

5.3.1 Obtain right-of-way and construct roadways in accordance with the designations shown on the General Plan Circulation Element Map and the City street improvement standards.

5.3.2 Wherever feasible, promote the development of roadways in accordance with the City standard roadway cross-sections, as shown in Figure 9-3. Cross-sections range from two-lane undivided roadways to 8-lane divided facilities.

5.3.3 Create new roadway classifications to accommodate future traffic demand, including; Divided Major Arterial – Reduced Cross-Section, and Divided Arterial – 6-lane. These cross-sections are shown on Figure 9-3.

5.3.4 For planning purposes, utilize LOS standards shown on Table 5 –1 to determine recommended roadway widths.

5.3.5 Ensure that new development pays a fair share of costs to provide local and regional transportation improvements and to mitigate cumulative traffic impacts. For this purpose, require new developments to participate in Transportation Uniform Mitigation Fee Program (TUMF), the Development Impact Fee Program (DIF) and any other applicable transportation fee programs and benefit assessment districts.

5.3.6 Where new developments would increase traffic flows beyond the LOS C (or LOS D, where applicable), require appropriate and feasible mitigation measures as a condition of approval. Such measures may include extra right-of-way and improvements to accommodate left-turn and right-turn lanes at intersections, or other improvements.

5.3.7 Provide consideration to projects that have overriding regional or local benefits that would be desirable even though the LOS standards cannot be met. These projects would be required to analyze traffic impacts and mitigate such impacts to the extent that it is deemed feasible.

5.3.8 Pursue arterial improvements that link and/or cross the State route 60 (SR-60) Freeway, including an additional over-crossing at Graham Street.

5.3.9 Address additional widenings at arterials providing access to SR-60 at Day Street, Frederick Street/Pigeon Pass road and Perris Boulevard.

Objective 5.4

Maximize efficiency of the regional circulation system through close coordination with state and regional agencies and implementation of regional transportation policies.

Policies:

5.4.1 Coordinate with Caltrans and the Riverside County Transportation Commission (RCTC) to identify and protect ultimate rights-of-way, including those for freeways, regional arterial projects, transit, bikeways and interchange expansion.

5.4.2 Coordinate with Caltrans and RCTC regarding the integration of Intelligent Transportation Systems (ITS) consistent with the principles and recommendations of the Inland Empire Regional ITS Architecture Project.

5.4.3 Work with property owners, in

cooperation with RCTC, to reserve rights-of-way for potential Community and Environmental Transportation Acceptability Process (CETAP) corridors through site design, dedication, and land acquisition, as appropriate.

5.4.4 The City Council will commit to establishing ongoing relationships with all agencies that play a role in the development of the City's transportation system. Council members who are appointed to these agencies as City representatives shall seek out leadership roles to maximize their effectiveness on behalf of the City. Council will strive to maintain continuity in their appointments of representatives to promote effective representation.

5.4.5 Work with RCTC, WRCOG, and the TUMF Central Zone Committee to facilitate the expeditious construction of TUMF Network projects, especially projects that directly benefit Moreno Valley.

5.4.6 Cooperatively participate with SCAG, RCTC, and WRCOG in the planning for a transportation system that anticipates regional needs for the safe and efficient movement of goods and people.

5.4.7 Utilizing a combination of regional, state and federal funds, development impact fees, and other locally generated funds, provide needed improvements along SR 60 and the associated interchanges, including interchange and grade separation improvements.

5.4.8 Reserve rights-of-way to accomplish future improvements as specified in the Caltrans District 8 Route Concept Fact Sheet for SR-60. Specifically, SR-60 shall be built to six general purpose lanes and two High Occupancy Vehicle (HOV) lanes through Moreno Valley. Additional auxiliary lanes may be required between interchanges. The need for auxiliary lanes will be determined from future studies.

5.4.9 Lobby the State Legislature to keep triple trailer trucks off highways in developed areas of California.

Objective 5.5

Maximize efficiency of the local circulation system by using appropriate policies and standards to design, locate and size roadways.

5.5.1 Space Collectors between higher classification roadways within development areas at appropriate one-quarter mile intervals.

5.5.2 Provide dedicated left-turn lanes at all major intersections on minor arterials and higher classification roadways.

5.5.3 Prohibit points of access from conflicting with other existing or planned access points. Require points of access to roadways to be separated sufficiently to maintain capacity, efficiency, and safety of the traffic flow.

5.5.4 Wherever possible, minimize the frequency of access points along streets by the consolidation of access points between adjacent properties on all circulation element streets, excluding collectors.

5.5.5 Design streets and intersections in accordance with the Moreno Valley Municipal Code.

5.5.6 Consider the overall safety, efficiency and capacity of street designs as more important than the location of on-street parking.

5.5.7 For developments fronting both sides of a street, require that streets be constructed to full width. Where new developments front only one side of a street, require that streets be constructed to half width plus an additional 12-foot lane for opposing traffic, whenever possible. Additional width may be needed for medians or left and/or right turn lanes.

5.5.8 Whenever possible, require private and public land developments to provide on-site and off-site improvements necessary to mitigate any development-generated circulation impacts. A review of each proposed land development project shall be undertaken to identify project impacts to the circulation system. The City may require developers to provide traffic impact studies prepared by qualified professionals to identify the impacts of a development.

5.5.9 Design curves and grades to permit safe movement of vehicular traffic per applicable Caltrans and Moreno Valley standards.

5.5.10 Provide adequate sight distances for safe vehicular movement at all intersections and driveways.

5.5.11 Implement National Pollutant Discharge Elimination System Best Management Practices relating to construction of roadways to control runoff contamination from affecting water resources.

Objective 5.6

Support development of a ground access system to March Inland Port in accordance with its development plan as a major cargo airport.

Policies:

5.6.1 Ensure that City arterials that provide access to and from March Inland Port are properly designed to accommodate projected traffic volumes, including truck traffic.

5.6.2 Ensure that traffic routes to March Inland Port are planned to minimize impacts to City residential communities.

Objective 5.7

Design roads to meet the needs of the residents of the community without detracting from the “rural” atmosphere in designated portions of Moreno Valley. (Designated “rural” areas include those encompassed by the Residential Agriculture 2, Residential 1, Rural Residential and Hillside Residential zoning districts. “Urban” areas encompass all other zoning districts.)

Policies:

5.7.1 Pursue development of modified sidewalk standards for local and collector roads within low density areas to reflect the rural character of those areas.

5.7.2 Provide sidewalks on arterials in designated low density areas that provide access to schools and bus stops.

Objective 5.8

Encourage development of an efficient public transportation system for the entire community.

Policies:

5.8.1 Support the development of high-speed transit linkages, or express routes, that would benefit the citizens and employers of Moreno Valley.

5.8.2 Support the efforts of the March Joint Powers Authority in its pursuit of a Transit Center

5.8.3 Encourage public transportation opportunities that address the particular needs of transit dependent individuals in the City such as senior citizens, the disabled and low -income residents.

5.8.4 Ensure that all new developments make adequate provision for bus stops and turnout areas for both public transit and school bus service.

5.8.5 Continue on-going coordination with transit authorities toward the expansion of transit facilities into newly developed areas.

Objective 5.9

Support and encourage development of safe, efficient and aesthetic pedestrian facilities.

Policies:

5.9.1 Encourage walking as an alternative to single occupancy vehicle travel, and help ensure the safety of the pedestrian as follows:

(a) All new developments shall provide sidewalks in conformance with the City's streets cross-section standards, and applicable policies for designated urban and rural areas.

(b) The City shall actively pursue funding for the infill of sidewalks in developed areas. The highest priority shall be to provide sidewalks on designated school routes.

5.9.2 Walkways shall be designed to minimize conflicts between vehicles and pedestrians.

5.9.3 Where appropriate, provide amenities such as, but not limited to, enhanced paving, seating, and landscaping to enhance the pedestrian experience.

5.9.4 Require the provision of convenient and safe pedestrian access to buildings from the public sidewalk.

Objective 5.10

Encourage bicycling as an alternative to single occupant vehicle travel for the purpose of reducing fuel consumption, traffic congestion, and air pollution. The Moreno Bikeway Plan is shown in Figure 9-4.

Policies:

5.10.1 Bikeways shall link residential neighborhood areas with parks, employment centers, civic and commercial areas, and schools.

5.10.2 Integrate bikeways, consistent with the Bikeway Plan, with the circulation system and maintain Class II and III bikeways as part of the City's street system.

5.10.3 Support bicycle safety programs, and active enforcement of laws relating to the safe operation of bicycles on City streets.

5.10.4 Link local bikeways with existing and planned regional bikeways.

Objective 5.11

Eliminate obstructions that impede safe movement of vehicles, bicyclists, and pedestrians.

Policies:

5.11.1 Landscaping adjacent to City streets, sidewalks and bikeways shall be designed, installed and maintained so as not to physically or visually impede public use of these facilities.

(a) The removal or relocation of mature trees, street trees and landscaping may be necessary to construct safe pedestrian, bicycle and street facilities.

(b) New landscaping, especially street trees shall be planted in such a manner to avoid overhang into streets, obstruction of traffic control devices or sight distances, or creation of other safety hazards.

5.11.2 Driveways shall be designed to avoid conflicts with pedestrian and bicycle travel.

Objective 5.12

Promote efficient circulation planning for all school sites that will maximize pedestrian safety, and minimize traffic congestion and neighborhood impacts.

Policy:

5.12.1 Coordinate with school districts to identify suggested pedestrian routes within existing and new subdivisions for school children to walk to and from schools and/or bus stops.

9.5.3 CIRCULATION ELEMENT PROGRAMS

5-1 Periodically review current traffic volumes, traffic collision data, and the pattern of urban development to coordinate, program, and as necessary revise the planning and prioritization of road improvements.

5-2 Periodically, reassess the goals, objectives and policies statements of the Circulation Element and propose amendments, as necessary.

5-3 Develop a comprehensive strategy to ensure full funding of the circulation system. The strategy will include the DIF, TUMF, and other funding sources that may be available to the City. In addition, the creation of benefit assessment districts, and road and bridge fee districts may be considered where appropriate.

5-4 Develop a multi-year transportation infrastructure improvement program that, to the extent feasible, phases the construction of new projects in advance of new development.

5-5 The above referenced program will prioritize circulation improvement projects to be funded from DIF, TUMF and other sources. Prioritization to consider the following factors:

(a) Traffic safety;
(b) Congestion relief;
(c) Access to new development;
(d) Equitable benefit.

5-6 Conduct studies of specified arterial segments to determine if any additional improvements will be needed to maintain an acceptable LOS at General Plan build-out. Generally, these segments will be studied as new developments are proposed in their vicinity. Measures will be identified that are consistent with the Circulation Element designation of these roadway segments, such as additional turn lanes at intersections, signal optimization by coordination and enhanced phasing, and travel demand management measures.

The study of specified arterial segments will be required to identify measures to maintain an acceptable LOS at General Plan build-out for at least one of the reasons discussed below:

(a) Segments will need improvement, but their ultimate volumes slightly exceed design capabilities.
(b) Segments will need improvements but require inter-jurisdictional coordination.
(c) Segments would require significant encroachment on existing adjacent development if built-out to their Circulation Element designations.

5-7 Establish traffic study guidelines to deal with development projects in a consistent manner. The traffic study guidelines shall include criteria for projects that propose changes it the approved General Plan land uses.

5-8 Develop access guidelines for arterials with commercial frontage to facilitate access to development and preservation of safe flow of traffic. A component of guidelines shall address shared access.

5-9 Collaborate with all adjacent jurisdictions to implement and integrate right-of-way requirements and improvement standards for General Plan roads that cross-jurisdictional boundary.

5-10 Support regional projects that improve access to Moreno Valley. Examples of specific ongoing projects that should be supported include:

(a) CETAP Cajalco alignment and extension to State Route 241 in Orange County;

(b) CETAP Moreno Valley to San Bernardino alternative alignments including Reche Canyon Road / Reche Vista Road alignment and the Pigeon Pass Road to Pepper Avenue alignment;

(c) TUMF Backbone Network projects to widen Alessandro Boulevard and Van Buren Boulevard;

(d) Measure A projects to widen SR-60 through the Badlands, widen Interstate 215 (I-215) from Riverside interchange to Interstate 10, and extension of San Jacinto commuter rail line;

(e) Construction of commuter rail stations in Highgrove, and at the intersection of Alessandro at I-215;

(f) Construction of HOV ramp connector from westbound SR-60 to south bound I-215;

(g) Widen SR-60/I-215 from Moreno Valley interchange to Riverside interchange.

5-11 Work with RCTC, Caltrans, County of Riverside, adjacent jurisdictions and other affected agencies to plan and develop a multi-modal transportation system.

5-12 Coordinate with Caltrans to redesign and reconstruct the SR-60 interchanges with Day Street, Perris Boulevard, Nason Street, Moreno Beach Drive, Redlands Boulevard, Theodore Street and Gilman Springs Road.

5-13 Implement Transportation demand management (TDM) strategies that reduce congestion in the peak travel hours. Examples include carpooling, telecommuting, and flexible work hours.

5-14 Implement programs in support of the efforts of Riverside Transit Agency toward the expansion of the existing bus system within the City and the provision of future public transportation consistent with the Riverside County Transit Plan.

5-15 Work with Riverside County Transportation Commission and Riverside Transit Agency to implement the Transit Oasis system.

5-16 Implement programs that mitigate on-street hazards for bicyclists.

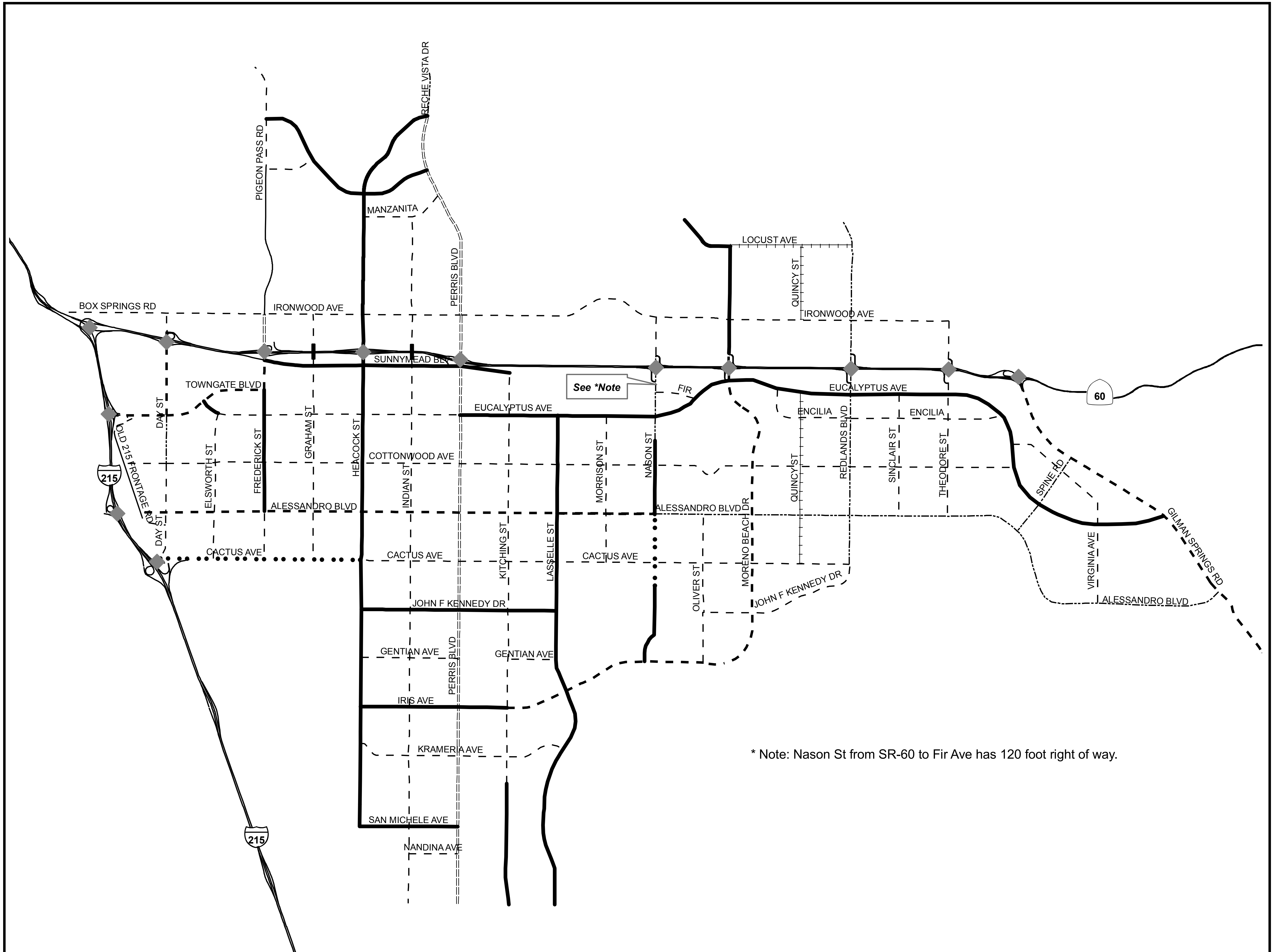
5-17 Pursue regional, state and federal grant opportunities to fund design and construction of the City bikeway system.

5-18 Pursue grant funding that supports traffic safety at and in the vicinity of school facilities.

5-19 Work with school districts and private schools to identify school site locations and designs that will minimize traffic impacts and promote traffic safety.

5-20 Work with school districts and private schools to identify suggested school routes and drop-off/pick-up plans for cars and buses.

5-21 Work with school districts and private schools to develop and promote traffic safety education programs.



MORENO VALLEY

FIGURE 9-1
CIRCULATION PLAN

Street Classification

- Freeway
- Divided Major Arterial
- Divided Major Arterial - Reduced Cross Section
- Divided Arterial - 6 lane
- Divided Arterial - 4 lane
- Arterial
- Minor Arterial
- Minor Arterial - Pigeon Pass Cross Section
- Collector
- Freeway Overpass
- Freeway Interchange

N

5,000 2,500 0 5,000 Feet

0.5 0.25 0 0.5 1 Miles

Date: July 11, 2006
State Plane NAD83 Zone 6
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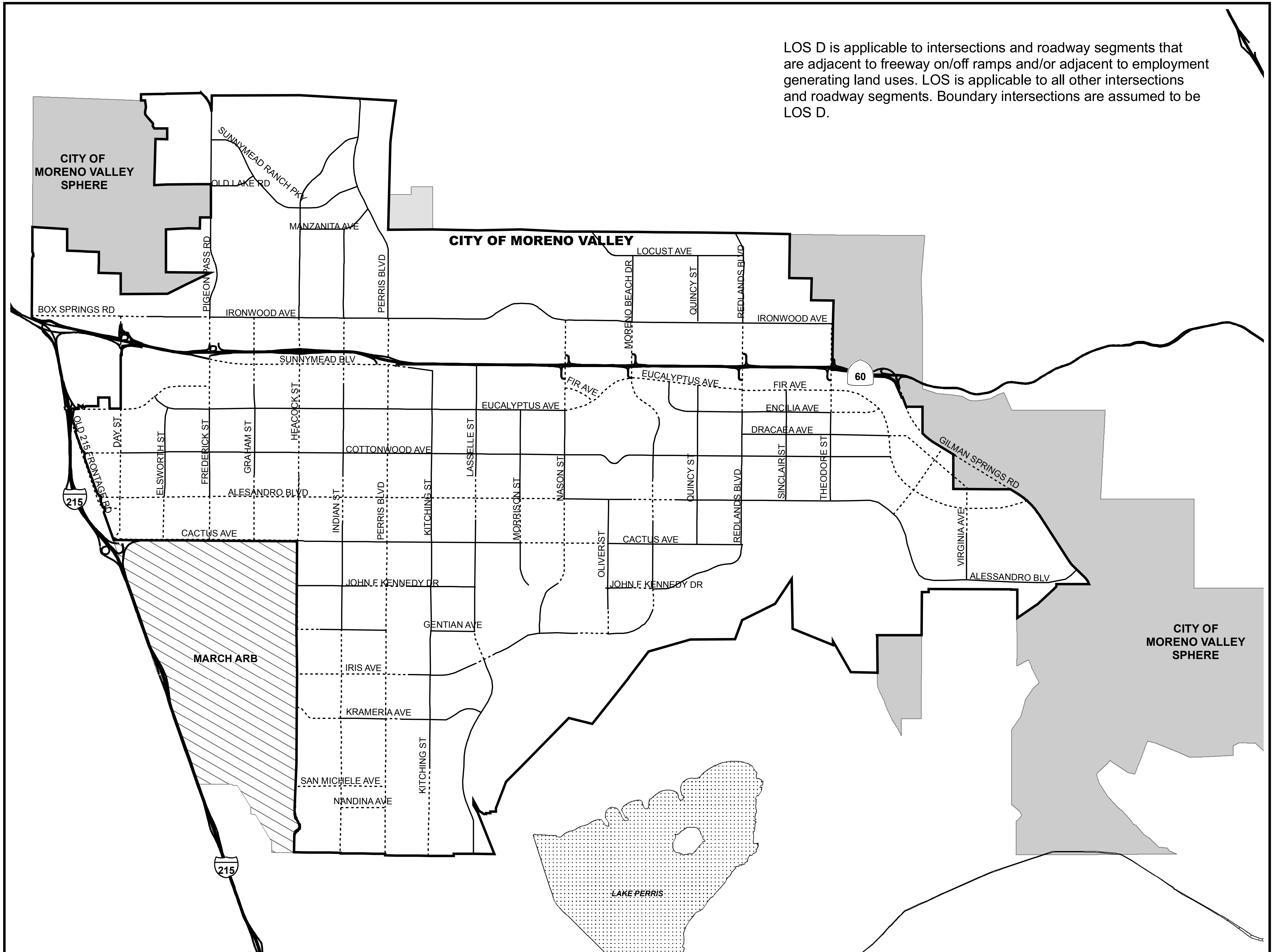
GEOGRAPHIC INFORMATION SYSTEMS



MORENO VALLEY

FIGURE 9-2
LOS STANDARDS

LOS C
LOS D
Highways
Moreno Valley
Moreno Valley Sphere
March ARB
Waterbodies

N

5,000 2,500 0 5,000 Feet
0.5 0.25 0 0.5 1 Miles

Date: July 11, 2006
State Plane NAD83 Zone 6
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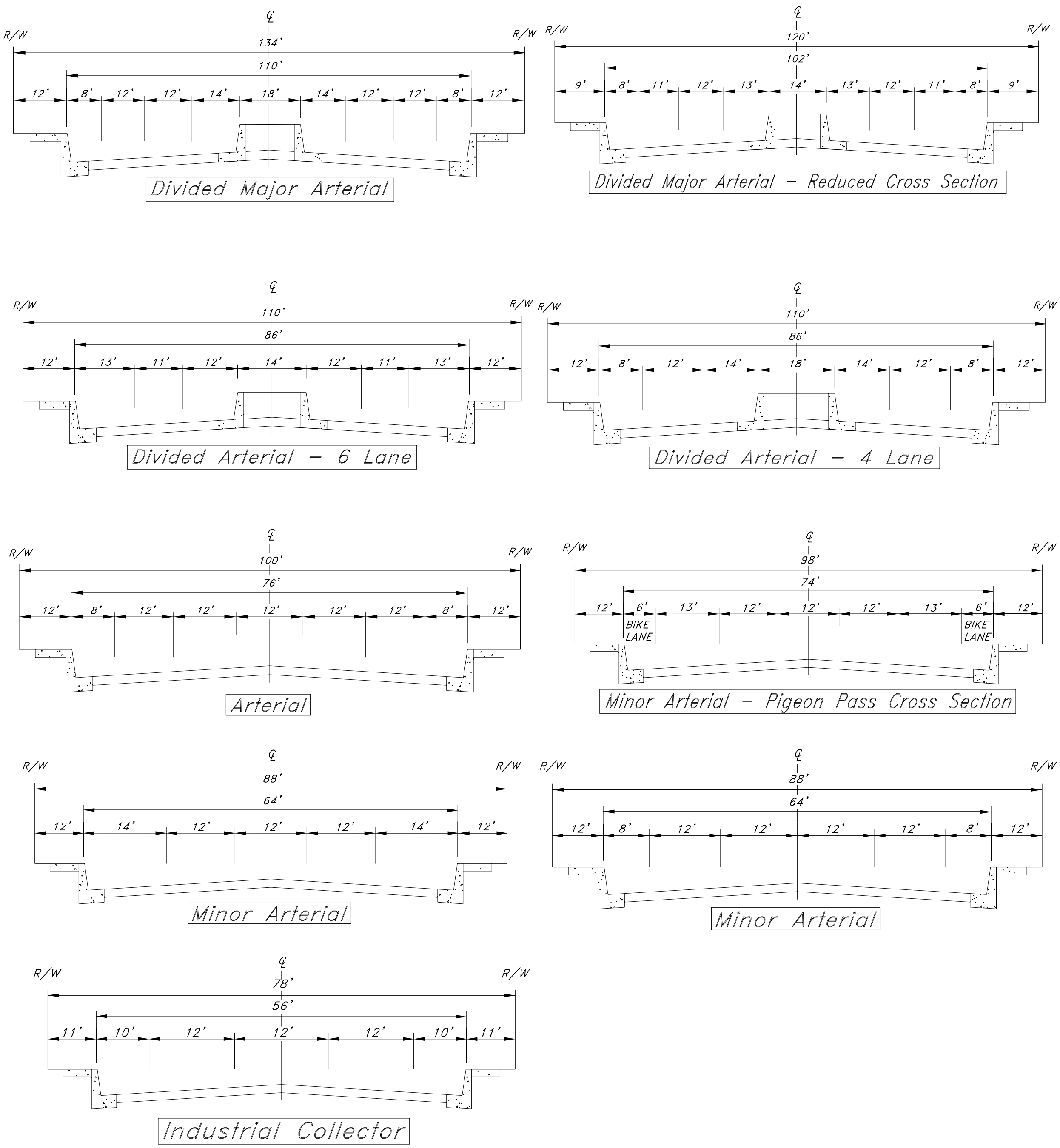
GEOGRAPHIC INFORMATION SYSTEMS

Figure 9-3

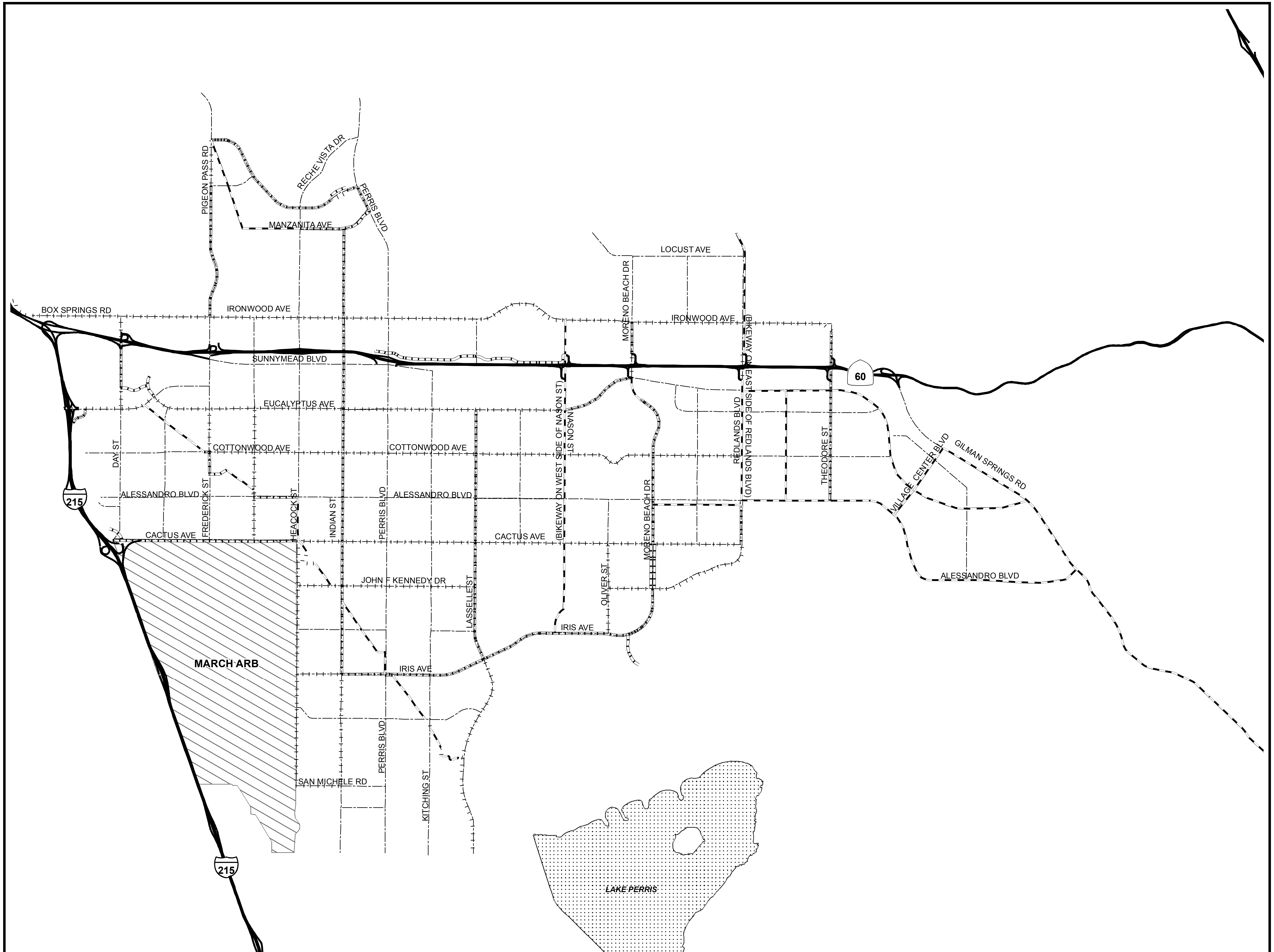
PROPOSED CITY OF MORENO VALLEY GENERAL PLAN ROADWAY CROSS-SECTIONS



NOT TO SCALE

MORENO VALLEY

FIGURE 9-4
BIKEWAY PLAN



Bikeway Classification

- Class I
- Class II
- Class III
- Roads
- Highways
- March ARB
- Waterbodies

N

5,000 2,500 0 5,000 Feet

0.5 0.25 0 0.5 1 Miles

Date: July 11, 2006
State Plane NAD83 Zone 6
File: G:\arcmap\planning\gen_plan_updates\bikeway.mxd

GEOGRAPHIC INFORMATION SYSTEMS

9.6 SAFETY ELEMENT GOALS, OBJECTIVES, POLICIES AND PROGRAMS

9.6.1 SAFETY ELEMENT GOALS

Goal 6.1

To achieve acceptable levels of protection from natural and man-made hazards to life, health, and property

Goal 6.2

To have emergency services which are adequate to meet minor emergency and major catastrophic situations.

9.6.2 SAFETY ELEMENT OBJECTIVES AND POLICIES

Objective 6.1

Minimize the potential for loss of life and protect residents, workers, and visitors to the City from physical injury and property damage due to seismic ground shaking and secondary effects.

Policies:

6.1.1 Reduce fault rupture and liquefaction hazards through the identification and recognition of potentially hazardous conditions and areas as they relate to the San Jacinto fault zone and the high and very high liquefaction hazard zones. During the review of future development projects, the City shall require geologic studies and mitigation for fault rupture hazards in accordance with the Alquist-Priolo Special Study Zones Act. Additionally, future geotechnical studies shall contain calculations for seismic settlement on all alluvial sites identified as having high or very high liquefaction potential. Should the calculations show a potential for liquefaction, appropriate mitigation shall be identified and implemented.

6.1.2 Require all new developments, existing critical and essential facilities and structures to comply with the most recent Uniform Building Code seismic design standards.

Objective 6.2

Minimize the potential for loss of life and protect residents, workers, and visitors to the City from physical injury and property damage, and to minimize nuisances due to flooding.

Policies:

6.2.1 Permit only that development in 100-year floodplain that represents an acceptable use of the land in relation to the hazards involved and the costs of providing flood control facilities. Locate critical facilities, such as hospitals, fire stations, police stations, public administration buildings, and schools outside of flood hazard areas.

6.2.2 Storm drains and catch basins owned and operated by the City shall be inspected, cleaned and maintained pursuant to an approved clean out schedule.

6.2.3 Maximize pervious areas in order to reduce increases in downstream runoff resulting from new development.

6.2.4 Design, construct and maintain street and storm drain flood control systems to accommodate 10 year and 100 year storm flows respectively.

6.2.5 The storm drain system shall conform to Riverside County Flood Control and Water Conservation District master drainage plans and the requirements of the Federal Emergency Management Agency.

Objective 6.3

Provide noise compatible land use relationships by establishing noise standards utilized for design and siting purposes.

Policies:

6.3.1 The following uses shall require mitigation to reduce noise exposure where current or future exterior noise levels exceed 20 CNEL above the desired interior noise level:

a. Single and multiple family residential buildings shall achieve an interior noise level of 45 CNEL or less. Such buildings shall include sound-insulating windows, walls, roofs and ventilation systems. Sound barriers shall also be installed (e.g. masonry walls or walls with berms) between single-family residences and major roadways.

b. New libraries, hospitals and extended medical care facilities, places of worship and office uses shall be insulated to achieve interior noise levels of 50 CNEL or less.

c. New schools shall be insulated to achieve interior noise levels of 45 CNEL or less.

6.3.2 Discourage residential uses where current or projected exterior noise due to aircraft over flights will exceed 65 CNEL.

6.3.3 Where the future noise environment is likely to exceed 70 CNEL due to overflights from the joint-use airport at March, new buildings containing uses that are not addressed under Policy 6.3.1 shall require insulation to achieve interior noise levels recommended in the March Air Reserve Base Air Installation Compatible Use Zone Report.

6.3.4 Encourage residential development heavily impacted by aircraft over flight noise, to transition to uses that are more noise compatible.

6.3.5 Enforce the California Administrative Code, Title 24 noise insulation standards for new multi-family housing developments, motels and hotels.

6.3.6 Building shall be limited in areas of sensitive receptors.

Objective 6.4

Review noise issues during the planning process and require noise attenuation measures to minimize acoustic impacts to existing and future surrounding land uses.

Policies:

6.4.1 Site, landscape and architectural design features shall be encouraged to mitigate noise impacts for new developments, with a preference for noise barriers that avoid freeway sound barrier walls.

Objective 6.5

Minimize noise impacts from significant noise generators such as, but not limited to, motor vehicles, trains, aircraft, commercial, industrial, construction, and other activities.

Policies:

6.5.1 New commercial and industrial activities (including the placement of mechanical equipment) shall be evaluated and designed to mitigate noise impacts on adjacent uses.

6.5.2 Construction activities shall be operated in a manner that limits noise impacts on surrounding uses.

Objective 6.6

Promote land use patterns that reduce daily automotive trips and reduce trip distance for work, shopping, school, and recreation.

Policies:

6.6.1 Provide sites for new neighborhood commercial facilities within close proximity to the residential areas they serve.

6.6.2 Provide multi-family residential development sites in close proximity to neighborhood commercial centers in order to encourage pedestrian instead of vehicular travel.

6.6.3 Locate neighborhood parks in close proximity to the appropriate concentration of residents in order to encourage pedestrian and bicycle travel to local recreation areas.

Objective 6.7

Reduce mobile and stationary source air pollutant emissions.

Policies:

6.7.1 Cooperate with regional efforts to establish and implement regional air quality strategies and tactics.

6.7.2 Encourage the financing and construction of park-and-ride facilities.

6.7.3 Encourage express transit service from Moreno Valley to the greater metropolitan areas of Riverside, San Bernardino, Orange and Los Angeles Counties.

6.7.4 Locate heavy industrial and extraction facilities away from residential areas and sensitive receptors.

6.7.5 Require grading activities to comply with South Coast Air Quality Management District's Rule 403 regarding the control of fugitive dust.

6.7.6 Require building construction to comply with the energy conservation requirements of Title 24 of the California Administrative Code.

Objective 6.8

As feasible given budget constraints, strive to maintain a police force with a ratio of one sworn officer for each 1,000 residents.

Policies:

6.8.1 Explore the most effective and economical means of providing responsive and adequate law enforcement protection in the future.

Objective 6.9

Reduce the risk and fear of crime through physical planning strategies that maximize surveillance opportunities and minimize opportunities for crime found in the present and future built environment, and by creating and maintaining a high level of community awareness and support of crime prevention.

Policies:

6.9.1 Promote the establishment of neighborhood and business watch programs to encourage community participation in the patrol of neighborhood areas, and increased awareness of any suspicious activity.

6.9.2 Require well-lighted entrances, walkways and parking lots, street lighting in all commercial, industrial areas and multiple-family residential areas to facilitate nighttime surveillance and discourage crime.

6.9.3 Incorporate "defensible space" concepts into the design of dwellings and nonresidential structures, including, but not limited to configuration of lots, buildings, fences, walls and other features that facilitate surveillance and reinforce a sense of territorial control.

Objective 6.10

Protect life and property from the potential short-term and long-term deleterious effects of the necessary transportation, use, storage treatment and disposal and hazardous materials and waste within the City of Moreno Valley.

Policies:

6.10.1 Require all land use applications and approvals to be consistent with the siting criteria and other applicable provisions of the adopted Hazardous Waste Management Plan, which is also incorporated into and as part of the General Plan.

6.10.2 Manage the generation, collection, storage, processing, treatment, transport and disposal of hazardous waste in accordance with provisions of the City of Moreno Valley's adopted Hazardous Waste Management Plan, which is also incorporated into and as part of the General Plan.

Objective 6.11

Maintain an integrated emergency management program that is properly staffed, trained, and equipped for receiving emergency calls, providing initial response, providing for key support to major incidents.

Policies:

6.11.1 Respond to any disaster situation in the City to provide necessary initial response and providing for key support to major incidents.

6.11.2 Provide emergency first aid treatment when necessary.

6.11.3 Support the maintenance of a trauma center within the City.

6.11.4 Aggressively attack uncontrolled fires and hold losses to a minimum.

6.11.5 Minimize uncontrolled fires through support of weed abatement programs.

Objective 6.12

Coordinate with Federal, State and County agencies and neighboring communities in developing a regional system to respond to emergencies and major catastrophes.

Policies:

6.12.1 Support mutual aid agreements and communication links with the County of Riverside and other local participating jurisdictions.

Objective 6.13

Maintain fire prevention, fire-related law enforcement, and public education and information programs to prevent fires.

Policies:

6.13.1 Provide fire safety education to residents of appropriate age.

Objective 6.14

Maintain the capacity to respond rapidly to emergency situations.

Policies:

6.14.1 Locate fire stations in accordance with the Fire Station Master Plan as shown in Figure 6-1. The exact location of each fire station may be modified based on availability of land and other factors.

6.14.2 Relate the timing of fire station construction to the rise of service demand in surrounding areas.

Objective 6.15

Ensure that property in or adjacent to wildland areas is reasonably protected from wildland fire hazard, consistent with the maintenance of a viable natural ecology.

Policies:

6.15.1 Encourage programs to minimize the fire hazard, including but not limited to the prevention of fuel build-up where wildland areas are adjacent to urban development.

6.15.2 Tailor fire prevention measures implemented in wildland areas to both the aesthetic and functional needs of the natural environment.

Objective 6.16

Ensure that uses within urbanized areas are planned and designed consistent with accepted safety.

Policies:

6.16.1 Ensure that ordinances, resolutions and policies relating to urban development are consistent with the requirements of acceptable fire safety, including requirements for smoke detectors, emergency water supply and automatic fire sprinkler systems.

6.16.2 Encourage the systematic mitigation of existing fire hazards related to land urban development or patterns of urban development as they are identified and as resources permit.

6.16.3 Ensure that adequate emergency ingress and egress is provided for each development.

6.16.4 Within the safety zones (e.g. Air Crash Hazard Zones and Clear Zones) shown in Figure 6-5, residential uses shall not be permitted, and business uses shall be restricted to low intensity uses as defined in the March Air Reserve Base Air Installation Compatible Use Zone Report, as amended from time to time.

Objective 6.17

Provide non-emergency public services provided that such demands do not interfere with fire protection and other emergency services.

9.6.3 SAFETY ELEMENT PROGRAMS

6-1 Request that public utility companies inspect their facilities and distribution networks to determine the potential impact of earthquake damage.

6-2 Evaluate historic buildings relative to the need for mitigation of geologic hazards, while weighing their historical value against the potential hazard of their collapse.

6-3 Reevaluate designated truck routes in terms of noise impact on existing land uses to determine if those established routes and the hours of their use should be adjusted to minimize exposure to truck noise.

6-4 Review existing ordinances to ensure that building and site design standards specifically address crime prevention utilizing defensible space criteria. Incorporate security standards into the Municipal Code.

6-5 Seek state and federal grants to offset any required additions in law enforcement staffing and/or equipment.

6-6 Update the Fire Protection Master Plan as conditions warrant.

6-7 Establish regulations for development along the urban-wildland interface.

6-8 Establish criteria for the design, maintenance, modification and replacement of fire facilities.

6-9 Establish criteria for weed abatement programs.

9.7 CONSERVATION ELEMENT GOALS, OBJECTIVES, POLICIES AND PROGRAMS

9.7.1 CONSERVATION ELEMENT GOALS

Goal 7.1

To achieve the wise use of natural resources within the City of Moreno Valley, its sphere of influence and planning area.

9.7.2 CONSERVATION ELEMENT OBJECTIVES AND POLICIES

Objective 7.1

Minimize erosion problems resulting from development activities.

Policies:

7.1.1 Require that grading plans include appropriate and feasible measures to minimize erosion, sedimentation, wind erosion and fugitive dust.

7.1.2 Circulation patterns within newly developing portions of Moreno Valley, particularly in hillside areas, should follow natural contours to minimize grading.

Objective 7.2

Maintain surface water quality and the supply and quality of groundwater.

Policies:

7.2.1 New development may use individual wells only where an adequate supply of good quality groundwater is available.

7.2.2 The City shall comply with the provisions of its permit(s) issued by the Regional Water Quality Control Board for the protection of water quality pursuant to the National Pollutant Discharge Elimination System.

7.2.3 In concert with the water purveyor identify aquifer recharge areas and establish regulations to protect recharge areas and regulate new individual wells.

Objective 7.3

Minimize the consumption of water through a combination of water conservation and reuse.

Policies:

7.3.1 Require water conserving landscape and irrigation systems through development review. Minimize the use of lawn within private developments, and within parkway areas. The use of mulch and native and drought tolerant landscaping shall be encouraged.

7.3.2 Encourage the use of reclaimed wastewater, stored rainwater, or other legally acceptable non-potable water supply for irrigation.

Objective 7.4

Maintain, protect, and preserve biologically significant habitats where practical, including the San Jacinto Wildlife Area, riparian areas, habitats of rare and endangered species, and other areas of natural significance.

Policies:

7.4.1 Require all development, including roads, proposed adjacent to riparian and other biologically sensitive habitats to provide adequate buffers to mitigate impacts to such areas.

7.4.2 Limit the removal of natural vegetation in hillside areas when retaining natural habitat does not pose threats to public safety.

7.4.3 Preserve natural drainage courses in their natural state and the natural hydrology, unless the protection of life and property necessitate improvement as concrete channels.

7.4.4 Incorporate significant rock formations into the design of hillside developments.

7.4.5 The City shall fulfill its obligations set forth within any agreement(s) and permit(s) that the City may enter into for the purpose of implementing the Western Riverside County Multi-species Habitat Conservation Plan.

Objective 7.5

Encourage efficient use of energy resources.

Policies:

7.5.1 Encourage building, site design, and landscaping techniques that provide passive heating and cooling to reduce energy demand.

7.5.2 Encourage energy efficient modes of transportation and fixed facilities, including transit, bicycle, equestrian, and pedestrian transportation. Emphasize fuel efficiency in the acquisition and use of City-owned vehicles.

7.5.3 Locate areas planned for commercial, industrial and multiple family density residential development within areas of high transit potential and access.

7.5.4 Encourage efficient energy usage in all city public buildings.

7.5.5 Encourage the use of solar power and other renewable energy systems.

Objective 7.6

Identify and preserve Moreno Valley's unique historical and archaeological resources for future generations.

Policies:

7.6.1 Historical, cultural and archaeological resources shall be located and preserved, or mitigated consistent with their intrinsic value.

7.6.2 Implement appropriate mitigation measures to conserve cultural resources that are uncovered during excavation and construction activities.

7.6.3 Minimize damage to the integrity of historic structures when they are altered.

7.6.4 Encourage restoration and adaptive reuse of historical buildings worthy of preservation.

7.6.5 Encourage documentation of historic buildings when such buildings must be demolished.

Objective 7.7

Where practical, preserve significant visual features significant views and vistas.

Policies:

7.7.1 Discourage development directly upon a prominent ridgeline.

7.7.2 Require new electrical and communication lines to be placed underground.

7.7.3 Implement reasonable controls on the size, number and design of signs to minimize degradation of visual quality.

7.7.4 Gilman Springs Road, Moreno Beach Drive, and State Route 60 shall be designated as local scenic roads.

7.7.5 Require development along scenic roadways to be visually attractive and to allow for scenic views of the surrounding mountains and Mystic Lake.

7.7.6 Minimize the visibility of wireless communication facilities by the public. Encourage "stealth" designs and encourage new antennas to be located on existing poles, buildings and other structures.

Objective 7.8

Maintain an adequate system of solid waste collection and disposal to meet existing and future needs.

Policies:

7.8.1 Encourage recycling projects by individuals, non-profit organizations, or corporations and local businesses, as well as programs sponsored through government agencies.

9.7.3 CONSERVATION ELEMENT PROGRAMS

7-1 Support regional solid waste disposal efforts by the County of Riverside.

7-2 Advocate for natural drainage channels to the Riverside County Flood Control District, in order to assure the maximum recovery of local water, and to protect riparian habitats and wildlife.

7-3 Maintain a close working relationship with EMWD to ensure that EMWD plans for and is aware of opportunities to use reclaimed water in the City.

7-4 Provide guidelines for preferred planting schemes and specific species to encourage aesthetically pleasing landscape statements that minimize water use.

7-5 Develop incentives where appropriate, for the maintenance and sensitive rehabilitation of historic structures and properties.

7-6 In areas where archaeological or paleontological resources are known or reasonably expected to exist, based upon the citywide survey conducted by the UCR Archaeological Research Unit, incorporate the recommendations and determinations of that report to reduce potential impacts to levels of insignificance.

9.8 HOUSING ELEMENT GOALS, OBJECTIVES, POLICES AND PROGRAMS

9.8.1 HOUSING ELEMENT GOALS

Goal 8.1

Improve and maintain decent, sanitary and affordable housing.

Goal 8.2

Improve and maintain decent, sanitary and affordable housing for very-low income households and seniors.

Goal 8.3

Reduce substandard housing and health and safety violations.

Goal 8.4

Assist in the revitalization of older neighborhoods.

Goal 8.5

Improve and maintain decent and affordable rental housing.

Goal 8.6

Assist very low, low and moderate-income first time buyers to purchase homes.

Goal 8.7

Add to the number of affordable rental units for very low and low-income households.

Goal 8.8

Create affordable housing units for senior households.

9.8.2 HOUSING ELEMENT OBJECTIVES AND POLICIES

Objective 8.1

Rehabilitate a minimum of fifteen single-family homes under the Home Improvement Loan Program (HILP).

Objective 8.2

Rehabilitate a minimum of fifteen single-family homes under the Homeowner Assistance for Minor Rehabilitation loan program (HAMR).

Policies:

8.2.1 Rehabilitate single-family homes to correct substandard conditions, improve handicap accessibility, and improve the aesthetics of older neighborhoods, thereby contributing to their preservation and revitalization.

Objective 8.3

Rehabilitate a minimum of ninety mobile homes, for very low-income homeowners, in mobile home parks citywide, under the Mobile Home Grant Program.

Policies:

8.3.1 Correct substandard conditions in mobile home parks.

Objective 8.4

Obtain code compliance from a minimum of twenty-five very low and moderate-income property owners, citywide, with emphasis on focus neighborhoods.

Policies:

8.4.1 Enforce correction by property owners of identified housing and code violations in rental properties occupied by very low to moderate-income households.

Objective 8.5

Conduct five neighborhood clean-ups annually; provide related services to Community Development Block Grant (CDBG) areas in conjunction with other projects, and assist in clean up of 360 housing units.

Policies:

8.5.1 Provide neighborhood improvement programs to CDBG target areas.

Objective 8.6

Assist 300 households citywide.

Policies:

8.6.1 Provide fair housing and landlord/tenant education services to very low to moderate-income households.

Objective 8.7

Rehabilitate fifty multi-family units, citywide, through utilization of the Rental Rehabilitation Program.

Policies:

8.7.1 To eliminate substandard housing conditions for low-income renters, while enhancing the appearance of multi-family developments.

Objective 8.8

Assist households with down payment and closing costs.

Policies:

8.8.1 Provide assistance to facilitate homeownership for very low to moderate-income households

Objective 8.9

Create a minimum of 126 affordable rental units, citywide.

Policies:

8.9.1 Facilitate the creation of affordable rental units.

Objective 8.10

Create a minimum of seventy senior units.

Policies:

8.10.1 Create decent and affordable housing opportunities for low and very-low income seniors.

9.8.3 HOUSING ELEMENT PROGRAMS

8-1 Utilize the Home Improvement Loan Program (HILP) that provides a 3% loan for up to $15,000 deferred for 20 years. Available citywide for very low to lower income homeowners.

8-2 Utilize the Homeowner Assistance for Minor Rehabilitation (HAMR) loan program that provides a 3% to 5% loan for up to $7,500 amortized over a 10-year term.

8-3 Utilize the Mobile Home Grant Program that provides grants up to $10,000 for owner-occupants of mobile homes.

8-4 Provide enhanced code compliance services and referrals to City housing rehabilitation programs.

8-5 Utilize the City Neighborhood Clean-up Program to provide volunteers and equipment to neighborhoods for clean up activities.

8-6 Contract with a fair housing agency to mediate between landlords and tenants and educate them on their rights and responsibilities.

8-7 Update the City's Analysis of Impediments to Fair Housing.

8-8 Provide rehabilitation loans through the City's Rental Rehabilitation Program that offers 5% loans with the first year deferred and amortized over a 19-year period.

8-9 Through the Homebuyer Assistance Program, provide 30-year deferred silent second loans, with no interest, up to 20% or $200,000 of the purchase price of resale homes.

8-10 Work with local CHDO to construct and/or rehabilitate houses for very low-income households.

8-11 Purchase HUD homes for resale to first time homebuyers.

8-12 Administer new construction home ownership program and youth job training.

8-13 Work with housing developers by providing Agency assistance to write-down the costs of units via loans.

8-14 Provide financial assistance for the development of affordable rental units for larger families.

8-15 Revise General Plan.

8-16 Continue to implement permit streamlining.

8-17 Develop standards for mobile home parks and mobile home subdivisions.

8-18 Review parking standards for multi-family 3 and 4 bedroom units, including covered parking requirements to determine if reductions are appropriate.

8-19 Review second unit regulations to determine if expansion is merited to additional districts.

8-20 Continue to pay the development fees for projects, on a case-by-case basis, that have received State or Federal funds, such as Section 202 and Tax Credits.

8-21 Utilize Redevelopment Agency funds, where appropriate and necessary, to facilitate infrastructure for affordable projects.

8-22 Propose general plan changes for rezoning areas in the city to housing uses or mixed uses that include housing.

8-23 Facilitate the construction of a sixty-nine unit multi-family senior complex.

Chapter 11.80 NOISE REGULATION

11.80.010 Legislative findings.

It is found and declared that:

A. Excessive sound within the limits of the city is a condition which has existed for some time, and the amount and intensity of such sound is increasing.

B. Such excessive sound is a detriment to the public health, safety, and welfare and quality of life of the residents of the city.

C. The necessity in the public interest for the provisions and prohibitions hereinafter contained and enacted is declared as a matter of legislative determination and public policy, and it is further declared that the provisions and prohibitions hereinafter contained and enacted are in pursuance of and for the purpose of securing and promoting the public health, safety, welfare and quality of life of the city and its inhabitants. (Ord. 740 § 1.2, 2007)

11.80.020 Definitions.

For purposes of this chapter, certain words and phrases used herein are defined as follows:

"A-weighted sound level" means the sound pressure level in decibels as measured with a sound level meter using the A-weighting network. The unit of measurement is the dB(A).

"Commercial" means all uses of land not otherwise classified as residential, as defined in this section.

"Construction" means any site preparation, and/or any assembly, erection, repair, or alteration, excluding demolition, of any structure, or improvements to real property.

"Continuous airborne sound" means sound that is measured by the slow-response setting of a meter manufactured to the specifications of ANSI Section 1.4-1983 (R2006) "Specification for Sound Level Meters," or its successor.

"Daytime" means eight a.m. to ten p.m. the same day.

"Decibel" (dB) means a unit for measuring the amplitude of sound, equal to twenty (20) times the logarithm to the base ten (10) of the ratio of the pressure of the sound measured to the reference pressure, which is twenty (20) micropascals (twenty (20) micronewtons per square meter.)

"Demolition" means any dismantling, intentional destruction or removal of structures or other improvements to real property.

"Disturb" means to interrupt, interfere with, or hinder the enjoyment of peace or quiet or the normal listening activities or the sleep, rest or mental concentration of the hearer.

"Emergency" means any occurrence or set of circumstances involving actual or imminent physical trauma or significant property damage which necessitates immediate action. Economic loss alone shall not constitute an emergency. It shall be the burden of an alleged violator to prove an "emergency."

"Emergency work" means any work made necessary to restore property to a safe condition following an emergency, or to protect persons or property threatened by an imminent emergency, to the extent such work is, in fact, necessary to protect persons or property from exposure to imminent danger or damage.

"Frequency" means the number of complete oscillation cycles per unit of time.

"Impulsive sound" means sound of short duration, usually less than one second, with an abrupt onset and rapid decay. Examples of sources of impulsive sound include explosions, drop forge impacts, and discharge of firearms.

"Nighttime" means 10:01 p.m. to 7:59 a.m. the following day.

"Noise disturbance" means any sound which:

1. Disturbs a reasonable person of normal sensitivities;

2. Exceeds the sound level limits set forth in this chapter; or

3. Is plainly audible as defined in this section. Where no specific distance is set forth for the determination of audibility, references to noise disturbance shall be deemed to mean plainly audible at a distance of two hundred (200) feet from the real property line of the source of the sound, if the sound occurs on privately owned property, or from the source of the sound, if the sound occurs on public right of way, public space or other publicly owned property.

"Person" means any person, person's firm, association, copartnership, joint venture, corporation, or any entity public or private in nature.

"Plainly audible" means that the sound or noise produced or reproduced by any particular source, can be clearly distinguished from ambient noise by a person using his/her normal hearing faculties.

"Public right-of-way" means any street, avenue, boulevard, sidewalk, bike path or alley, or similar place normally accessible to the public which is owned or controlled by a governmental entity.

"Public space" means any park, recreational or community facility, or lot which contains at least one building that is open to the general public during its hours of operation.

"Residential" means all uses of land primarily for dwelling units, as well as hospitals, schools, colleges and universities, and places of religious assembly.

"Sound" means an oscillation in pressure, particle displacement, particle velocity or other physical parameter, in a medium with internal forces that causes compression and rarefaction of that medium capable of producing an auditory impression. The description of sound may include any characteristic of such sound, including duration, intensity and frequency.

"Sound level" means the weighted sound pressure level as measured in dB(A) by a sound level meter and as specified in American National Standards Institute (ANSI) specifications for sound-level meters (ANSI Section 1.4-1971 (R1976)). If the frequency weighting employed is not indicated, the A-weighting shall apply.

"Sound level meter" means an instrument, demonstrably capable of accurately measuring sound levels as defined above.

All technical definitions not defined above shall be in accordance with applicable publications and standards of the American National Standards Institute (ANSI). (Ord. 740 § 1.2, 2007)

11.80.030 Prohibited acts.

A. General Prohibition. It is unlawful and a violation of this chapter to maintain, make, cause, or allow the making of any sound that causes a noise disturbance, as defined in Section 11.80.020.

B. Sound causing permanent hearing loss.

1. Sound level limits. Based on statistics from the Center for Disease Control and Prevention and the National Institute for Occupational Safety and Health, Table 1 and Table 1-A specify sound level limits which, if exceeded, will have a high probability of producing permanent hearing loss in anyone in the area where the sound levels are being exceeded. No sound shall be permitted within the city which exceeds the parameters set forth in Tables 11.80.030-1 and 11.80.030-1-A of this chapter:

Table 11.80.030-1

MAXIMUM CONTINUOUS SOUND LEVELS*

Duration per Day Continuous Hours	Sound level [db(A)]
8	90
6	92
4	95
3	97
2	100
1.5	102
1	105
0.5	110
0.25	115

* When the daily sound exposure is composed of two or more periods of sound exposure at different levels, the combined effect of all such periods shall constitute a violation of this section if the sum of the percent of allowed period of sound exposure at each level exceeds 100 percent

Table 11.80.030-1A

MAXIMUM IMPULSIVE SOUND LEVELS

Number of Repetitions per 24-Hour Period	Sound level [dB (A)]
1	145
10	135
100	125

2. Exemptions. No violation shall exist if the only persons exposed to sound levels in excess of those listed in Tables 11.80.030-1 and 11.80.030-1A are exposed as a result of:

a. Trespass;

b. Invitation upon private property by the person causing or permitting the sound; or

c. Employment by the person or a contractor of the person causing or permitting the sound.

C. Nonimpulsive Sound Decibel Limits. No person shall maintain, create, operate or cause to be operated on private property any source of sound in such a manner as to create any nonimplusive sound which exceeds the limits set forth for the source land use category (as defined in Section 11.80.020) in Table 11.80.030-2 when measured at a distance of two hundred (200) feet or more from the real property line of the source of the sound, if the sound occurs on privately owned property, or from the source of the sound, if the sound occurs on public right-of-way, public space or other publicly owned property. Any source of sound in violation of this subsection shall be deemed prima facie to be a noise disturbance.

Table 11.80.030-2

MAXIMUM SOUND LEVELS (IN dB(A)) FOR SOURCE LAND USES

Residential		Commercial	
Daytime	**Nighttime**	**Daytime**	**Nighttime**
60	55	65	60

D. Specific Prohibitions. In addition to the general prohibitions set out in subsection A of this section, and unless otherwise exempted by this chapter, the following specific acts, or the causing or permitting thereof, are regulated as follows:

1. Motor Vehicles. No person shall operate or cause to be operated a public or private motor vehicle, or combination of vehicles towed by a motor vehicle, that creates a sound exceeding the sound level limits in Table 11.80.030-2 when the vehicle(s) are not otherwise subject to noise regulations provided for by the California Vehicle Code.

2. Radios, Televisions, Electronic Audio Equipment, Musical Instruments or Similar Devices from a Stationary Source. No person shall operate, play or permit the operation or playing of any radio, tape player, television, electronic audio equipment, musical instrument, sound amplifier or other mechanical or electronic sound making device that produces, reproduces or amplifies sound in such a manner as to create a noise disturbance. However, this subsection shall not apply to any use or activity exempted in subsection E of this section and any use or activity for which a special permit has been issued pursuant to Section 11.80.040.

3. Radios, Electronic Audio Equipment, or Similar Devices from a Mobile Source Such as a Motor Vehicle. Sound amplification or reproduction equipment on or in a motor vehicle is subject to regulation in accordance with the California Vehicle Code when upon the public right-of-way. When upon public space or publicly owned property other than the public right-of-way or upon private property open to the public, sound amplification or reproduction equipment shall not be operated in such a manner that it is plainly audible at a distance of fifty (50) feet in any direction from the vehicle.

4. Portable, Hand-Held Music or Sound Amplification or Reproduction Equipment. Such equipment shall not be operated on a public right-of-way, public space or other publicly owned property in such a manner as to be plainly audible at a distance of fifty (50) feet in any direction from the operator.

5. Loudspeakers and Public Address Systems.

a. Except as permitted by Section 11.80.040, no person shall operate, or permit the operation of, any loudspeaker, public address system or similar device, for any commercial purpose:

1. Which produces, reproduces or amplifies sound in such a manner as to create a noise disturbance; or

2. During nighttime hours on a public right-of-way, public space or other publicly owned property.

b. No person shall operate, or permit the operation of, any loudspeaker, public address system or similar device, for any noncommercial purpose, during nighttime hours in such a manner as to create a noise disturbance.

6. Animals. No person shall own, possess or harbor an animal or bird that howls, barks, meows, squawks, or makes other sounds that:

a. Create a noise disturbance;

b. Are of frequent or continued duration for ten (10) or more consecutive minutes and are plainly audible at a distance of fifty (50) feet from the real property line of the source of the sound; or

c. Are intermittent for a period of thirty (30) or more minutes and are plainly audible at a distance of fifty (50) feet from the real property line of the source of the sound.

7. Construction and Demolition. No person shall operate or cause the operation of any tools or equipment used in construction, drilling, repair, alteration or demolition work between the hours of eight p.m. and seven a.m. the following day such that the sound there from creates a noise disturbance, except for emergency work by public service utilities or for other work approved by the city manager or designee. This section shall not apply to the use of power tools as provided in subsection (D)(9) of this section.

8. Emergency Signaling Devices. No person shall intentionally sound or permit the sounding outdoors of any fire, burglar or civil defense alarm, siren or whistle, or similar stationary emergency signaling device, except for emergency purposes or for testing as follows:

a. Testing of a stationary emergency signaling device shall not occur between seven p.m. and seven a.m. the following day;

b. Testing of a stationary emergency signaling device shall use only the minimum cycle test time, in no case to exceed sixty (60) seconds;

c. Testing of a complete emergency signaling system, including the functioning of the signaling device and the personnel response to the signaling device, shall not occur more than once in each calendar month. Such testing shall only occur only on weekdays between seven a.m. and seven p.m. and shall be exempt from the time limit specified in subsection (D)(8)(2) of this section.

9. Power Tools. No person shall operate or permit the operation of any mechanically, electrically or gasoline motor-driven tool during nighttime hours so as to cause a noise disturbance across a residential real property boundary.

10. Pumps, Air Conditioners, Air-Handling Equipment and Other Continuously Operating Equipment. Notwithstanding the general prohibitions of subsection a of this section, no person shall operate or permit the operation of any pump, air conditioning, air-handling or other continuously operating motorized equipment in a state of disrepair or in a manner which otherwise creates a noise disturbance distinguishable from normal operating sounds.

E. Exemptions. The following uses and activities shall be exempt from the sound level regulations except the maximum sound levels provided in Tables 11.80.030-1 and 11.80.030-1A:

1. Sounds resulting from any authorized emergency vehicle when responding to an emergency call or acting in time of an emergency.

2. Sounds resulting from emergency work as defined in Section 11.80.020

3. Any aircraft operated in conformity with, or pursuant to, federal law, federal air regulations and air traffic control instruction used pursuant to and within the duly adopted federal air regulations; and any aircraft operating under technical difficulties in any kind of distress, under emergency orders of air traffic control, or being operated pursuant to and subsequent to the declaration of an emergency under federal air regulations.

4. All sounds coming from the normal operations of interstate motor and rail carriers, to the extent that local regulation of sound levels of such vehicles has been preempted by the Noise Control Act of 1972 (42 U.S.C. § 4901 et seq.) or other applicable federal laws or regulations

5. Sounds from the operation of motor vehicles, to the extent they are regulated by the California Vehicle Code.

6. Any constitutionally protected noncommercial speech or expression conducted within or upon a any public right-of-way, public space or other publicly owned property constituting an open or a designated public forum in compliance with any applicable reasonable time, place and manner restrictions on such speech or expression or otherwise pursuant to legal authority.

7. Sounds produced at otherwise lawful and permitted city-sponsored events, organized sporting events, school assemblies, school playground activities, by permitted fireworks, and by permitted parades on public

right-of-way, public space or other publicly owned property.

8. An event for which a temporary use permit or special event permit has been issued under other provisions of this code, where the provisions of Section 11.80.040 are met, the permit granted expressly grants an exemption from specific standards contained in this chapter, and the permittee and all persons under the permittee's reasonable control actually comply with all conditions of such permit. Violation of any condition of such a permit related to sound or sound equipment shall be a violation of this chapter and punishable as such.

F. Nothing in this chapter shall be construed to limit, modify or repeal any other regulation elsewhere in this code relating to the regulation of noise sources, nor shall any such other regulation be read to permit the emission of noise in violation of any provision of this chapter. (Ord. 740 § 1.2, 2007)

11.80.040 Special provisions for temporary use and special event permits.

The exemption by permit set forth in Section 11.80.030(E)(8) shall be subject to the following requirements and conditions:

A. The permit application shall include the name, address and telephone number of the permit applicant; the date, hours and location for which the permit is requested; and the nature of the event or activity. It shall also specify the types of sounds and/or sound equipment to be permitted, the proposed duration of such sound, the specific standards from which the sound is to be exempted, and the reasons for each requested exemption.

B. The permit shall be issued provided the proposed activity meets the requirements of this section and the issuing official determines that the sound to be emitted at the event as proposed would not be detrimental to the public health, safety or welfare, that the event cannot reasonably achieve its legitimate aims and purposes without the exemption and that the sound levels proposed will not unreasonably damage the peace and quiet enjoyment of the lawful users of surrounding properties, nor constitute a public nuisance.

C. The official issuing the permit may prescribe any reasonable conditions or requirements he/she deems necessary to minimize noise disturbances upon the community or the surrounding neighborhood, and/or to protect the health, safety or welfare of the public, including participants in the permitted event, including use of mufflers, screens or other sound-attenuating devices.

D. Any permit granted must be in writing and shall contain all conditions upon which the permit shall be effective.

E. No more than six events requiring a sound limit exemption may be held at any particular location upon privately owned or controlled property per calendar year, provided further that the number of events shall not exceed the number permitted under the regulations for the type of permit issued. For purposes of this subsection, "location" means a legal parcel of real property or a complete shopping or commercial center or mall sharing common parking and access even if comprised of multiple legal parcels.

F. The exemption from sound limits under such permit shall not exceed maximum period of four hours in one twenty-four (24) hour day.

G. The permit will only be granted for hours between nine a.m. and ten p.m. on all days other than Friday and Saturday; and, on Friday and Saturday, between the hours of nine a.m. and one a.m. of the following day, except in the following circumstances:

1. A permit may be granted for hours between nine a.m. on New Year's Eve and one a.m. the following day (New Year's Day).

2. A permit may be granted for hours between nine a.m. and two a.m. the following day if there are no residences, hospitals, or nursing homes within a 0.5 mile radius of the property where the function is taking place.

H. Functions for which the permits are issued shall be limited to a continuous airborne sound level not to exceed seventy (70) dB(A), as measured two hundred (200) feet from the real property boundary of the source property if on private property, or from the source if on public right of way, public space or other publicly owned property. (Ord. 740 § 1.2, 2007)

11.80.050 Measurement or assessment of sound.

A. Measurement With Sound Meter.

1. The measurement of sound shall be made with a sound level meter meeting the standards prescribed by ANSI Section 1.4-1983 (R2006). The instruments shall be maintained in calibration and good working order. A calibration check shall be made of the system at the time of any sound level measurement. Measurements recorded shall be taken so as to provide a proper representation of the source of the sound. The microphone during measurement shall be positioned so as not to create any unnatural enhancement or diminution of the measured sound. A windscreen for the microphone shall be used at all times. However, a violation of this chapter may occur without the occasion of the measurements being made as otherwise provided.

2. The slow meter response of the sound level meter shall be used in order to best determine the average amplitude.

3. The measurement shall be made at any point on the property into which the sound is being transmitted and shall be made at least three feet away from any ground, wall, floor, ceiling, roof and other plane surface.

4. In case of multiple occupancy of a property, the measurement may be made at any point inside the premises to which any complainant has right of legal private occupancy; provided that the measurement shall not be made within three feet of any ground, wall, floor, ceiling, roof or other plane surface.

5. All measurements of sound provided for in this chapter will be made by qualified officials of the city who are designated by the city manger or designee to operate the apparatus used to make the measurements.

B. Assessment Without Sound Level Meter. Any police officer, code enforcement officer, or other official designated by the city manager or designee who hears a noise or sound that is plainly audible, as defined in Section 11.80.020, in violation of this chapter, may enforce this chapter and shall assess the noise or sound according to the following standards:

1. The primary means of detection shall be by means of the official’s normal hearing faculties, not artificially enhanced.

2. The official shall first attempt to have a direct line of sight and hearing to the vehicle or real property from which the sound or noise emanates so that the official can readily identify the offending source of the sound or noise and the distance involved. If the official is unable to have a direct line of sight and hearing to the vehicle or real property from which the sound or noise emanates, then the official shall confirm the source of the sound or noise by approaching the suspected vehicle or real property until the official is able to obtain a direct line of sight and hearing, and confirm the source of the sound or noise that was heard at the place of the original assessment of the sound or noise.

3. The official need not be required to identify song titles, artists, or lyrics in order to establish a violation. (Ord. 740 § 1.2, 2007)

11.80.060 Violation.

A. Violation of Sound Level Limits. Any person violating any of the provisions of this chapter shall be deemed guilty of a misdemeanor, and upon conviction thereof shall be punishable by a fine not to exceed one thousand dollars ($1,000.00) and/or six months in the county jail, or both. Notwithstanding the foregoing, any violation of the provisions of this chapter may, in the discretion of the citing officer or the city attorney, be cited and/or prosecuted as an infraction or be subject to civil citation pursuant to Chapter 1.10.

B. Joint and Several Responsibility. In addition to the person causing the offending sound, the owner, tenant or lessee of property, or a manager, overseer or agent, or any other person lawfully entitled to possess the property from which the offending sound is emitted at the time the offending sound is emitted, shall be responsible for compliance with this chapter if the additionally responsible party knows or should have known of the offending noise disturbance. It shall not be a lawful defense to assert that some other person caused the sound. The lawful possessor or operator of the premises shall be responsible for operating or maintaining the premises in compliance with this chapter and may be cited regardless of whether or not the person actually causing the sound is also cited.

C. Violation May be Declared a Public Nuisance. The operation or maintenance of any device, equipment, instrument, vehicle or machinery in violation of any provisions of this chapter which endangers the public health, safety and quality of life of residents in the area is declared to be a public nuisance, and may be subject to abatement summarily or by a restraining order or injunction issued

by a court of competent jurisdiction. (Ord. 824 § 1.2, 2011; Ord. 740 § 1.2, 2007)

Chapter 9.52 NOISE REGULATION

Sections:

9.52.010 Intent.
9.52.020 Exemptions.
9.52.030 Definitions.
9.52.040 General sound level standards.
9.52.050 Sound level measurement methodology.
9.52.060 Special sound sources standards.
9.52.070 Exceptions.
9.52.080 Enforcement.
9.52.090 Duty to cooperate.
9.52.100 Violations and penalties.

9.52.010 Intent.

At certain levels, sound becomes noise and may jeopardize the health, safety or general welfare of Riverside County residents and degrade their quality of life. Pursuant to its police power, the board of supervisors declares that noise shall be regulated in the manner described in this chapter. This chapter is intended to establish county-wide standards regulating noise. This chapter is not intended to establish thresholds of significance for the purpose of any analysis required by the California Environmental Quality Act and no such thresholds are established.

(Ord. 847 § 1, 2006)

9.52.020 Exemptions.

Sound emanating from the following sources is exempt from the provisions of this chapter:

A. Facilities owned or operated by or for a governmental agency;

B. Capital improvement projects of a governmental agency;

C. The maintenance or repair of public properties;

D. Public safety personnel in the course of executing their official duties, including, but not limited to, sworn peace officers, emergency personnel and public utility personnel. This exemption includes, without limitation, sound emanating from all equipment used by such personnel, whether stationary or mobile;

E. Public or private schools and school-sponsored activities;

F. Agricultural operations on land designated "Agriculture" in the Riverside County general plan, or land zoned A-l (light agriculture), A-P (light agriculture with poultry), A-2 (heavy agriculture), A-D (agriculture-dairy) or C/V (citrus/vineyard), provided such operations are carried out in a manner consistent with accepted industry standards. This exemption includes, without limitation, sound emanating from all equipment used during such operations, whether stationary or mobile;

G. Wind energy conversion systems (WECS), provided such systems comply with the WECS noise provisions of Riverside County Ordinance No. 348;

H. Private construction projects located one-quarter of a mile or more from an inhabited dwelling;

I. Private construction projects located within one-quarter of a mile from an inhabited dwelling, provided that:

1. Construction does not occur between the hours of six p.m. and six a.m. during the months of June through September, and

2. Construction does not occur between the hours of six p.m. and seven a.m. during the months of October through May;

J. Property maintenance, including, but not limited to, the operation of lawnmowers, leaf blowers, etc., provided such maintenance occurs between the hours of seven a.m. and eight p.m.;

K. Motor vehicles, other than off-highway vehicles. This exemption does not include sound emanating from motor vehicle sound systems;

L. Heating and air conditioning equipment;

M. Safety, warning and alarm devices, including, but not limited to, house and car alarms, and other warning devices that are designed to protect the public health, safety, and welfare;

N. The discharge of firearms consistent with all state laws.

(Ord. 847 § 2, 2006)

9.52.030 Definitions.

As used in this chapter, the following terms shall have the following meanings:

"Audio equipment" means a television, stereo, radio, tape player, compact disc player, mp3 player, I-POD or other similar device.

"Decibel (dB)" means a unit for measuring the relative amplitude of a sound equal approximately to the smallest difference normally detectable by the human ear, the range of which includes approximately one hundred thirty (130) decibels on a scale beginning with zero decibels for the faintest detectable sound. Decibels are measured with a sound level meter using different methodologies as defined below:

1. "A-weighting (dBA)" means the standard A-weighted frequency response of a sound level meter, which de-emphasizes low and high frequencies of sound in a manner similar to the human ear for moderate sounds.

2. "Maximum sound level (Lmax)" means the maximum sound level measured on a sound level meter.

"Governmental agency" means the United States, the state of California, Riverside County, any city within Riverside County, any special district within Riverside County or any combination of these agencies.

"Land use permit" means a discretionary permit issued by Riverside County pursuant to Riverside County Ordinance No. 348.

"Motor vehicle" means a vehicle that is self-propelled.

"Motor vehicle sound system" means a stereo, radio, tape player, compact disc player, mp3 player, I-POD or other similar device.

"Noise" means any loud, discordant or disagreeable sound.

"Occupied property" means property upon which is located a residence, business or industrial or manufacturing use.

"Off-highway vehicle" means a motor vehicle designed to travel over any terrain.

"Public or private school" means an institution conducting academic instruction at the preschool, elementary school, junior high school, high school, or college level.

"Public property" means property owned by a governmental agency or held open to the public, including, but not limited to, parks, streets, sidewalks, and alleys.

"Sensitive receptor" means a land use that is identified as sensitive to noise in the noise element of the Riverside County general plan, including, but not limited to, residences, schools, hospitals, churches, rest homes, cemeteries or public libraries.

"Sound-amplifying equipment" means a loudspeaker, microphone, megaphone or other similar device.

"Sound level meter" means an instrument meeting the standards of the American National Standards Institute for Type 1 or Type 2 sound level meters or an instrument that provides equivalent data.

(Ord. 847 § 3, 2006)

9.52.040 General sound level standards.

No person shall create any sound, or allow the creation of any sound, on any property that causes the exterior sound level on any other occupied property to exceed the sound level standards set forth in Table 1.

TABLE 1

Sound Level Standards (Db Lmax)

TABLE INSET:

GENERAL PLAN	GENERAL PLAN	GENERAL PLAN LAND USE	DENSITY	MAXIMUM DECIBEL LEVEL	

FOUNDATION COMPONENT	LAND USE DESIGNATION	DESIGNATION NAME		7 am--10 pm	10 pm--7 am
Community Development	EDR	Estate Density Residential	2 AC	55	45
	VLDR	Very Low Density Residential	1 AC	55	45
	LDR	Low Density Residential	1/2 AC	55	45
	MDR	Medium Density Residential	2--5	55	45
	MHDR	Medium High Density Residential	5--8	55	45
	HDR	High Density Residential	8--14	55	45
	VHDR	Very High Density Residential	14--20	55	45
	H'TDR	Highest Density Residential	20+	55	45
	CR	Retail Commercial		65	55
	CO	Office Commercial		65	55
	CT	Tourist Commercial		65	55
	CC	Community Center		65	55
	LI	Light Industrial		75	55
	HI	Heavy Industrial		75	75
	BP	Business Park		65	45
	PF	Public Facility		65	45
		Specific Plan-Residential		55	45

	SP	Specific Plan-Commercial		65	55
		Specific Plan-Light Industrial		75	55
		Specific Plan-Heavy Industrial		75	75
Rural Community	EDR	Estate Density Residential	2 AC	55	45
	VLDR	Very Low Density Residential	1 AC	55	45
	LDR	Low Density Residential	1/2 AC	55	45
Rural	RR	Rural Residential	5 AC	45	45
	RM	Rural Mountainous	10 AC	45	45
	RD	Rural Desert	10 AC	45	45
Agriculture	AG	Agriculture	10 AC	45	45
Open Space	C	Conservation		45	45
	CH	Conservation Habitat		45	45
	REC	Recreation		45	45
	RUR	Rural	20 AC	45	45
	W	Watershed		45	45
	MR	Mineral Resources		75	45

(Ord. 847 § 4, 2006)

9.52.050 Sound level measurement methodology.

Sound level measurements may be made anywhere within the boundaries of an occupied property. The actual location of a sound level measurement shall be at the discretion of the enforcement officials identified in Section 9.52.080 of this chapter. Sound level measurements shall be made with a sound level meter. Immediately before a measurement is made, the sound level meter shall be calibrated utilizing an acoustical calibrator meeting the standards of the American National Standards Institute. Following a sound level measurement, the calibration of the sound level meter shall be re-verified. Sound level meters and calibration equipment shall be certified annually.

(Ord. 847 § 5, 2006)

9.52.060 Special sound sources standards.

The general sound level standards set forth in Section 9.52.040 of this chapter apply to sound emanating from all sources, including the following special sound sources, and the person creating, or allowing the creation of, the sound is subject to the requirements of that section. The following special sound sources are also subject to the following additional standards, the failure to comply with which constitutes separate violations of this chapter:

A. Motor Vehicles.

1. Off-Highway Vehicles.

a. No person shall operate an off-highway vehicle unless it is equipped with a USDA-qualified spark arrester and a constantly operating and properly maintained muffler. A muffler is not considered constantly operating and properly maintained if it is equipped with a cutout, bypass or similar device.

b. No person shall operate an off-highway vehicle unless the noise emitted by the vehicle is not more than ninety-six (96) dBA if the vehicle was manufactured on or after January 1, 1986 or is not more than one hundred one (101) dBA if the vehicle was manufactured before January 1, 1986. For purposes of this subsection, emitted noise shall be measured a distance of twenty (20) inches from the vehicle tailpipe using test procedures established by the Society of Automotive Engineers under Standard J-1287.

2. Sound Systems. No person shall operate a motor vehicle sound system, whether affixed to the vehicle or not, between the hours of ten p.m. and eight a.m., such that the sound system is audible to the human ear inside any inhabited dwelling. No person shall operate a motor vehicle sound system, whether affixed to the vehicle or not, at any other time such that the sound system is audible to the human ear at a distance greater than one hundred (100) feet from the vehicle.

B. Power Tools and Equipment. No person shall operate any power tools or equipment between the hours of ten p.m. and eight a.m. such that the power tools or equipment are audible to the human ear inside an inhabited dwelling other than a dwelling in which the power tools or equipment may be located. No person shall operate any power tools or equipment at any other time such that the power tools or equipment are audible to the human ear at a distance greater than one hundred (100) feet from the power tools or equipment.

C. Audio Equipment. No person shall operate any audio equipment, whether portable or not, between the hours of ten p.m. and eight a.m. such that the equipment is audible to the human ear inside an inhabited dwelling other than a dwelling in which the equipment may be located. No person shall operate any audio equipment, whether portable or not, at any other time such that the equipment is audible to the human ear at a distance greater than one hundred (100) feet from the equipment.

D. Sound-Amplifying Equipment and Live Music. No person shall install, use or operate sound-amplifying equipment, or perform, or allow to be performed, live music unless such activities comply with the following requirements. To the extent that these requirements conflict with any conditions of approval attached to an underlying land use permit, these requirements shall control:

1. Sound-amplifying equipment or live music is prohibited between the hours of ten p.m. and eight a.m.

2. Sound emanating from sound-amplifying equipment or live music at any other time shall not be audible to the human ear at a distance greater than two hundred (200) feet from the equipment or music.

(Ord. 847 § 6, 2006)

9.52.070 Exceptions.

Exceptions may be requested from the standards set forth in Section 9.52.040 or 9.52.060 of this chapter and may be characterized as construction-related, single-event or continuous-events exceptions.

A. Application and Processing.

1. Construction-Related Exceptions. An application for a construction-related exception shall be made to and considered by the director of building and safety on forms provided by the building and safety department and shall be accompanied by the appropriate filing fee. No public hearing is required.

2. Single-Event Exceptions. An application for a single-event exception shall be made to and considered by the planning director on forms provided by the planning department and shall be accompanied by the appropriate filing fee. No public hearing is required.

3. Continuous-Events Exceptions. An application for a continuous-events exception shall be made to the planning director on forms provided by the planning department and shall be accompanied by the appropriate filing fee. Upon receipt of an application for a continuous-events exception, the planning director shall set the matter for public hearing before the planning commission, notice of which shall be given as provided in Section 18.26c of Riverside County Ordinance No. 348. Notwithstanding the above, an application for a continuous-events exception that is associated with an application for a land use permit shall be processed concurrently with the land use permit in the same manner that the land use permit is required to be processed.

B. Requirements for Approval. The appropriate decisionmaking body or officer shall not approve an exception application unless the applicant demonstrates that the activities described in the application would not be detrimental to the health, safety or general welfare of the community. In determining whether activities are detrimental to the health, safety or general welfare of the community, the appropriate decisionmaking body or officer shall consider such factors as the proposed duration of the activities and their location in relation to sensitive receptors. If an exception application is approved, reasonable conditions may be imposed to minimize the public detriment, including, but not limited to, restrictions on sound level, sound duration and operating hours.

C. Appeals. The director of building and safety's decision on an application for a construction-related exception is considered final. The planning director's decision on an application for a single-event exception is considered final. After making a decision on an application for a continuous-events exception, the appropriate decisionmaking body or officer shall mail notice of the decision to the applicant. Within ten (10) calendar days after the mailing of such notice, the applicant or an interested person may appeal the decision to the board of supervisors. Upon receipt of an appeal and payment of the appropriate appeal fee, the clerk of the board shall set the matter for hearing not less than five days nor more than thirty (30) days thereafter and shall give written notice of the hearing in the same manner as notice of the hearing was given by the appropriate hearing officer or body. The board of supervisors shall render its decision within thirty (30) days after the appeal hearing is closed.

D. Effect of a Pending Continuous-Events Exception Application. For a period of one hundred eighty (180) days from the effective date of this chapter, no person creating any sound prohibited by this chapter shall be considered in violation of this chapter if the sound is related to a use that is operating pursuant to an approved land use permit, if an application for a continuous-events exception has been filed to sanction the sound and if a decision on the application is pending.

(Ord. 847 § 7, 2006)

9.52.080 Enforcement.

The Riverside County sheriff and code enforcement shall have the primary responsibility for enforcing this chapter; provided, however, the sheriff and code enforcement may be assisted by the public health department. Violations shall be prosecuted as described in Section 9.52.100 of this chapter, but nothing in this chapter shall prevent the sheriff, code enforcement or the department of public health from engaging in efforts to obtain voluntary compliance by means of warnings, notices, or educational programs.

(Ord. 847.1 § 1, 2007: Ord. 847 § 8, 2006)

9.52.090 Duty to cooperate.

No person shall refuse to cooperate with, or obstruct, the enforcement officials identified in Section 9.52.080 of this chapter when they are engaged in the process of enforcing the provisions of this chapter. This duty to cooperate may require a person to extinguish a sound source so that it can be determined whether sound emanating from the source violates the provisions of this chapter.

(Ord. 847 § 9, 2006)

9.52.100 Violations and penalties.

Any person who violates any provision of this chapter once or twice within a one hundred eighty (180) day period shall be guilty of an infraction. Any person who violates any provision of this chapter more than twice within a one hundred eighty (180) day period shall be guilty of a misdemeanor. Each day a violation is committed or permitted to continue shall constitute a separate offense and shall be punishable as such. Penalties shall not exceed the following amounts:

A. For the first violation within a one hundred eighty (180) day period, the minimum mandatory fine shall be five hundred dollars ($500.00).

B. For the second violation within a one hundred eighty (180) day period, the minimum mandatory fine shall be seven hundred fifty dollars ($750.00).

C. For any further violations within a one hundred eighty (180) day period, the minimum mandatory fine shall be one thousand dollars ($1,000.00) or imprisonment in the county jail for a period not exceeding six months, or both.

(Ord. 847 § 10, 2006)

Chapter 9.55 RESERVED*

* Editor's note--Ord. 889, § 1, adopted February 24, 2009, repealed ch. 9.55, which pertained to targeted residential picketing and derived from Ord. 888, §§ 1--5, 1-6-09; Ord. 884, §§ 1--5, 3-3-09.

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Chapter 7: Noise Element

Definitions

Following is a list of commonly used terms and abbreviations that may be found within this element or when discussing the topic of noise. This is an abbreviated glossary to be reviewed prior to reading the element. It is important to become familiar with the definitions listed in order to better understand the importance of the Noise Element within the County of Riverside General Plan. Since the disbanding of the State Office of Noise Control in the mid-1990, the State of California Office of Planning and Research General Plan Guidelines can offer further information on other noise-related resources.

Ambient Noise: The composite of noise from all sources near and far. In this context, the ambient noise level constitutes the normal or existing level of environmental noise at a given location.

CNEL (Community Noise Equivalent Level): The average equivalent A-weighted sound level during a 24-hour day, obtained after addition of five decibels to sound levels in the evening from 7:00 p.m. to 10:00 p.m. and after the addition of 10 decibels to sound levels in the night from 10:00 p.m. to 7:00 a.m.

dB (Decibel): The unit of measure that denotes the ratio between two quantities that are proportional to power; the number of decibels corresponding to the ratio of the two amounts of power is based on a logarithmic scale.

dBA (A-weighted decibel): The A-weighted decibel scale discriminates upper and lower frequencies in a manner approximating the sensitivity of the human ear. The scale is based on a reference pressure level of 20 micropascals.

Intrusive Noise: That noise which intrudes over and above the existing ambient noise at a given location. The relative intrusiveness of a sound depends upon its amplitude, duration, frequency and time of occurrence, and tonal or informational content as well as the prevailing noise level.

L_{10}: The A-weighted sound level exceeded ten percent of the sample time. Similarly, L_{50}, L_{90}, etc.

L_{eq} (Equivalent energy level): The average acoustic energy content of noise during the time it lasts. The L_{eq} of a time-varying noise and that of a steady noise are the same if they deliver the same acoustic energy to the ear during exposure, no matter what time of day they occur. The County of Riverside uses a 10-minute L_{eq} measurement.

L_{dn} (Day-Night Average Level): The average equivalent A-weighted sound level during a 24-hour day, obtained after addition of 10 decibels to sound levels in the night from 10:00 p.m. to 7:00 a.m. Note: CNEL and Ldn represent daily levels of noise exposure averaged on an annual or daily basis, while Leq represents the equivalent energy noise exposure for a shorter time period, typically one hour.

★

The level of sound that impacts a property varies greatly during the day. As an example, the sound near an airport may be relatively quiet when no airplane is taking off or landing, but will be extremely loud as a plane takes off. In order to deal with these variations, several noise indices have been developed, which measure how loud each sound is, how long it lasts, and how often the sound occurs. The indices express all the sound occurring during the day as a single average level, which if it occurred all day would convey the same sound energy to the site.

Micropascal: The international unit for pressure, similar to pounds per square inch. 20 micropascals is the human hearing threshold. The scale ranges from zero for the average least perceptible sound to about 130 for the average pain level

Noise Contours: Lines drawn around a noise source indicating equal levels of noise exposure. CNEL and Ldn are the metrics used in this document to describe annoyance due to noise and to establish land use planning criteria for noise.

Introduction

> It is the policy of the United States to promote an environment for all Americans free from noise that jeopardizes their health or welfare.
>
> -Noise Control Act of 1972

Before the alarm clock sounds, the lawn mower next door begins to roar. Then, while listening to the morning news on the radio, an airplane flies overhead and deadens all sound in the neighborhood. Once outside, the neighbor's stereo can be heard a block away. And during the morning commute, car horns, rumbling mufflers, and whirring motorcycles serenade motorists on the highway. Even in the most rural areas of Riverside County, the eternal battle between the efficiency of technology, and the noise it can create cannot be avoided.

As modern transportation systems continue to develop and human dependence upon machines continues to increase, the general level of noise in our day to day living environment rises. In Riverside County, residential areas near airports, freeways, and railroads are being adversely affected by annoying or hazardous noise levels. Other activities such as construction, operation of household power tools and appliances, and industry, also contribute to increasing background noise.

Sound refers to anything that is or may be perceived by the ear. Noise is defined as "unwanted sound" because of its potential to disrupt sleep, rest, work, communication, and recreation, to interfere with speech communication, to produce physiological or psychological damage, and to damage hearing.

ADDRESSING NOISE ISSUES

The Noise Element is a mandatory component of the General Plan pursuant to the California Planning and Zoning Law, Section 65302(f). The element must recognize the guidelines adopted by the Office of Planning and Research pursuant to Section 46050.1 of the Health and Safety Code. It also can be utilized as a tool for compliance with the state's noise insulation standards.

The General Plan Noise Element provides a systematic approach to identifying and appraising noise problems in the community; quantifying existing and projected noise levels; addressing excessive noise exposure; and community planning for the regulation of noise. This element includes policies, standards, criteria, programs, diagrams, a reference to action items, and maps related to protecting public health and welfare from noise.

Tinnitus: The perception of ringing, hissing, or other sound in the ears or head when no external sound is present. For some people, tinnitus is just a nuisance. For others, it is a life-altering condition. In the United States, an estimated 12 million people have tinnitus to a distressing degree.

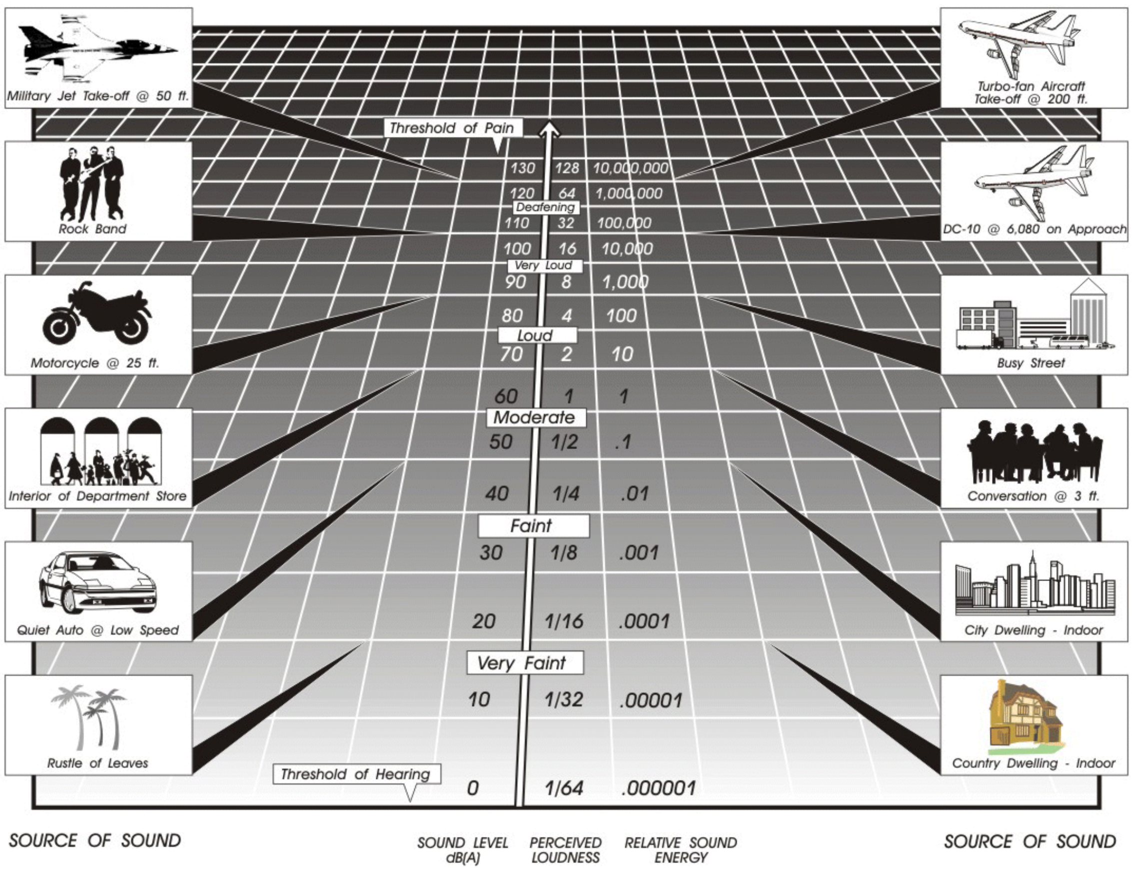
SETTING

Riverside County is a continuously evolving group of communities that relies heavily upon the modern technological conveniences of American society to thrive and succeed as a pleasant and desirable place to live and work. Without such necessities as air-conditioning, heating, generators, and cars, living in an urban, suburban, rural, desert, or mountainous environment becomes difficult, if not impossible. Fortunately, these amenities are available to the residents of Riverside County and are used everyday, often all day long. Unfortunately, these technological advances can come at a high price to residents' and visitors' ears.

The philosophical view commonly held by Riverside County staff and residents is that noise, which may be perceived by some to be annoying, may not be noticed at all by others. It is also important to note that people who move into an area where a noise source already exists (such as near an existing highway) are often more tolerant of that noise source than when a new noise generator locates itself in an established area that may be noise-sensitive (such as a stadium that is constructed near an established community).

Noise within Riverside County is generated by numerous sources found near places where people live and work. These sources are of particular concern when the noise they generate reaches levels above the prevailing background noise. There are many different types of noise, including mobile, stationary, and construction-related, that affect noise-sensitive receptors such as residences, schools, and hospitals. Figure 1, Common Noise Sources and Noise Levels, illustrates some noise producers that can be found within Riverside County, as well as their corresponding noise measurement. The following sections contain policies that address the issues of noise producers and their effects on noise-sensitive land uses.

Figure N- 1: Common Noise Sources and Noise Levels



Noise Sensitive Land Uses

A series of land uses have been deemed sensitive by the State of California. These land uses require a serene environment as part of the overall facility or residential experience. Many of these facilities depend on low levels of sound to promote the well being of the occupants. These uses include, but are not necessarily limited to; schools, hospitals, rest homes, long term care facilities, mental care facilities, residential uses, places of worship, libraries, and passive recreation areas. Activities conducted in proximity to these facilities must consider the noise output, and ensure that they don't create unacceptable noise levels that may unduly affect the noise-sensitive uses. The following policies address issues related to noise-sensitive land uses.

NOISE COMPATIBILITY

> ☞ *The General Plan policy and implementation item reference system:*
>
> *Identifies which element contains the Policy, in this case the Land Use Element, and the sequential number.*
>
> ***LU 1.3***
>
> Neighborhood Commercial uses should be located near residential uses.
>
> ***(AI 1 and AI 4)***
>
> *Reference to the relevant Action Items contained in the implementation Program*

The Noise Element of the General Plan is closely related to the Land Use Element because of the effects that noise has on sensitive land uses. Noise-producing land uses must be compatible with adjacent land uses in order for the Land Use Plan to be successful. Land uses that emit noise are measured in A-weighted decibels (dBA) or Community Noise Equivalent Level (CNEL). If existing land uses emit noise above a certain level, they are not compatible with one another, and therefore noise attenuation devices must be used to mitigate the noise to acceptable levels indoors and outdoors. In cases of new development, the placement of noise-sensitive land uses is integral to a successful community. Table 1, Land Use Compatibility for Community Noise Exposure, reveals the noise acceptability levels for different land uses. Areas around airports may have different or more restrictive noise standards than those cited in Table 1 (See Policy N 1.3 below).The following policies protect noise-sensitive land uses from noise emitted by outside sources, and prevent new projects from generating adverse noise levels on adjacent properties.

Policies:

N 1.1 Protect noise-sensitive land uses from high levels of noise by restricting noise-producing land uses from these areas. If the noise-producing land use cannot be relocated, then noise buffers such as setbacks, landscaping, or blockwalls shall be used. (AI 107)

N 1.2 Guide noise-tolerant land uses into areas irrevocably committed to land uses that are noise-producing, such as transportation corridors or within the projected noise contours of any adjacent airports. (AI 107)

N 1.3 Consider the following uses noise-sensitive and discourage these uses in areas in excess of 65 CNEL:

- Schools;
- Hospitals;
- Rest Homes;
- Long Term Care Facilities;
- Mental Care Facilities;
- Residential Uses;
- Libraries;
- Passive Recreation Uses; and

- Places of worship

According to the State of California Office of Planning and Research General Plan Guidelines, an acoustical study may be required in cases where these noise-sensitive land uses are located in an area of 60 CNEL or greater. Any land use that is exposed to levels higher than 65 CNEL will require noise attenuation measures.

Areas around airports may have different noise standards than those cited above. Each Area Plan affected by a public-use airport includes one or more Airport Influence Areas, one for each airport. The applicable noise compatibility criteria are fully set forth in Appendix L and summarized in the Policy Area section of the affected Area Plan. (AI 105)

Unregulated noise sources such as household power tools often emit more noise then regulated noise producers.

N 1.4 Determine if existing land uses will present noise compatibility issues with proposed projects by undertaking site surveys. (AI 106, 109)

N 1.5 Prevent and mitigate the adverse impacts of excessive noise exposure on the residents, employees, visitors, and noise-sensitive uses of Riverside County. (AI 105, 106, 108)

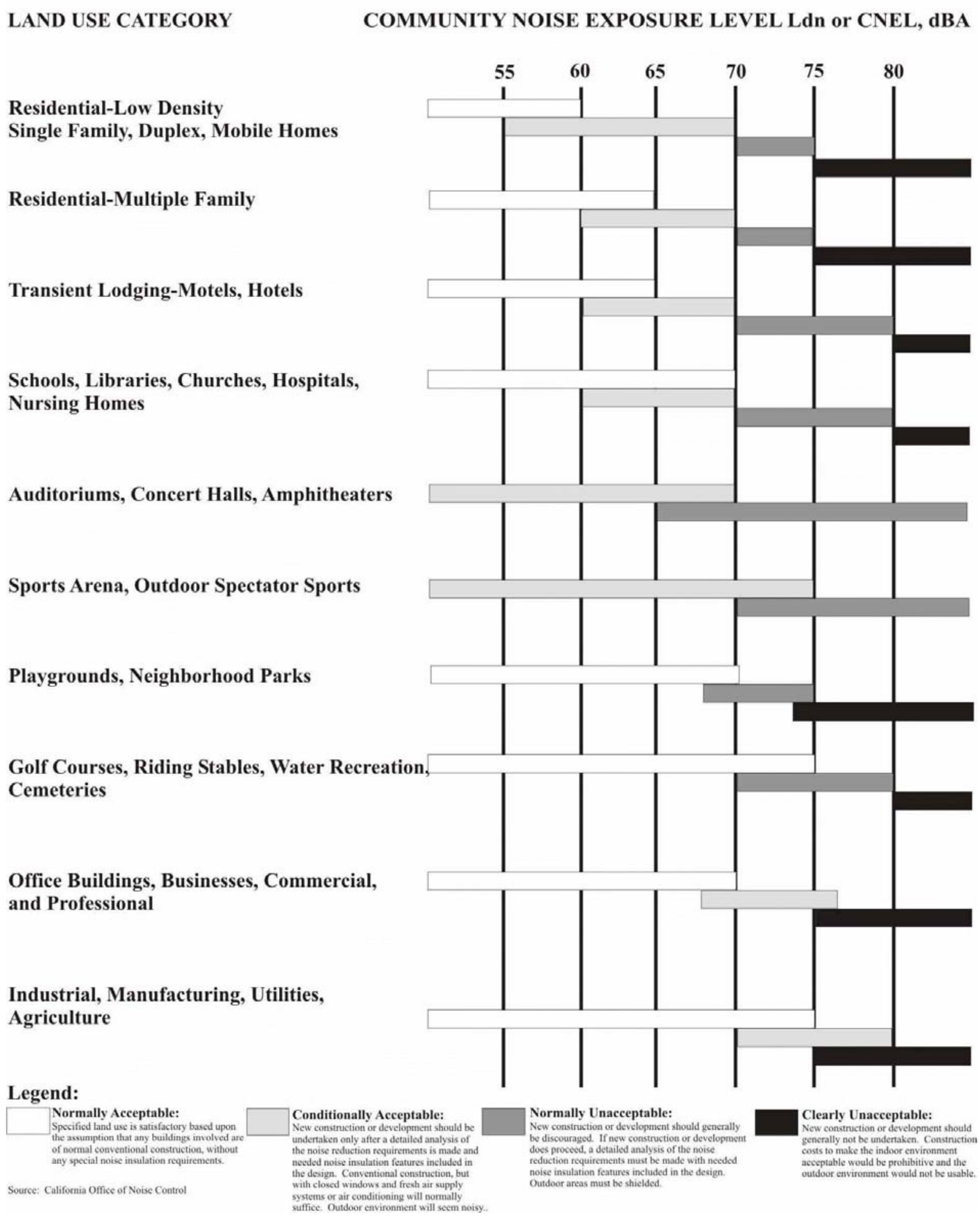
N 1.6 Minimize noise spillover or encroachment from commercial and industrial land uses into adjoining residential neighborhoods or noise-sensitive uses. (AI 107)

N 1.7 Require proposed land uses, affected by unacceptably high noise levels, to have an acoustical specialist prepare a study of the noise problems and recommend structural and site design features that will adequately mitigate the noise problem. (AI 106, 107)

N 1.8 Limit the maximum permitted noise levels that cross property lines and impact adjacent land uses, except when dealing with noise emissions from wind turbines. Please see the Wind Energy Conversion Systems section for more information. (AI 108)

Please contact the Office of Industrial Hygiene for more information on acoustical specialists.

Table N-1:
Land Use Compatibility for Community Noise Exposure



NOISE MITIGATION STRATEGIES

Many land uses emit noise above state-mandated acceptable levels. The noise emitted from a land use must be mitigated to acceptable levels indoors and outdoors in order for other, more noise-sensitive land uses to locate in proximity to these noise producers. There are a number of ways to mitigate noise and the following policies suggest some possible solutions to noise problems.

Policies:

N 2.1 Create a County Noise Inventory to identify major noise generators and noise-sensitive land uses, and to establish appropriate noise mitigation strategies. (AI 105)

N 2.2 Require a qualified acoustical specialist to prepare acoustical studies for proposed noise-sensitive projects within noise impacted areas to mitigate existing noise. (AI 105, 107)

N 2.3 Mitigate exterior and interior noises to the levels listed in the table below to the extent feasible, for stationary sources: (AI 105)

Table N-2:
Stationary Source Land Use Noise Standards [1]

Land Use	Interior Standards	Exterior Standards
Residential		
10:00 p.m. to 7:00 a.m.	40 L_{eq} (10 minute)	45 L_{eq} (10 minute)
7:00 a.m. to 10:00 p.m.	55 L_{eq} (10 minute)	65 L_{eq} (10 minute)

[1]These are only preferred standards; final decision will be made by the Riverside County Planning Department and Office of Public Health.

Noise Producers

LOCATION OF NOISE PRODUCERS

> *Good neighbors keep their noise to themselves.*

The communities of Riverside County need a variety of land uses in order to thrive and succeed. These land uses may provide jobs, clean water, ensure safety, ship goods, and ease transportation woes. But they may also emit high levels of noise throughout the day. These noise-producing land uses can complement a community when the noise they emit is properly mitigated. The following policies suggest a series of surveys and analyses to correctly identify the proper noise mitigating procedures in order to promote the continued success of the communities of Riverside County.

Agriculture

One of the major economic thrusts of Riverside County is the agricultural industry. The Riverside County Right-to-Farm Ordinance conserves, protects, and encourages the development, improvement, and continued viability of agricultural land and industries for the long-term production of food and other agricultural products, and for the economic well-being of the County's residents. The Right-to-Farm Ordinance also attempts to balance the rights of farmers to produce food and other agricultural products with the rights of non-farmers who own, occupy, or use land within or adjacent to agricultural areas. The Riverside County Right-to-Farm Ordinance also works to reduce the burden of the County's agricultural resources by limiting the circumstances under which agricultural operations may be deemed a nuisance. Policies within this section address the potential noise issues that may be raised in regards to agricultural production.

Policies:

N 3.1 Protect Riverside County's agricultural resources from noise complaints that may result from routine farming practices, through the enforcement of the Riverside County Right-to-Farm Ordinance. (AI 105, 107)

N 3.2 Require acoustical studies and subsequent approval by the Planning Department and the Office of Industrial Hygiene, to help determine effective noise mitigation strategies in noise-producing areas. (AI 105)

N 3.3 Ensure compatibility between industrial development and adjacent land uses. To achieve compatibility, industrial development projects may be required to include noise mitigation measures to avoid or minimize project impacts on adjacent uses. (AI 107)

N 3.4 Identify point-source noise producers such as manufacturing plants, truck transfer stations, and commercial development by conducting a survey of individual sites. (AI 106)

N 3.5 Require that a noise analysis be conducted by an acoustical specialist for all proposed projects that are noise producers. Include recommendations for design mitigation if the project is to be located either within proximity of a noise-sensitive land use, or land designated for noise-sensitive land uses. (AI 109)

N 3.6 Discourage projects that are incapable of successfully mitigating excessive noise. (AI 107)

N 3.7 Encourage noise-tolerant land uses such as commercial or industrial, to locate in areas already committed to land uses that are noise-producing. (AI 107)

STATIONARY NOISE

A stationary noise producer is any entity in a fixed location that emits noise. Stationary noise producers are common in many noise-sensitive areas. Motors, appliances, air conditioners, lawn and garden equipment, power tools, and generators are often found in residential neighborhoods, as well as on or near the properties of schools, hospitals, and parks. These structures are often a permanent fixture and are required for the particular land use. Industrial and manufacturing facilities are also stationary noise producers that may affect sensitive land uses. Furthermore, while noise generated by the use of motor vehicles over public roads is preempted from local regulation, the County considers the use of these vehicles to be a stationary noise source when operated on private property such as at a truck terminal or warehousing facility. The emitted noise from the producer can be mitigated to acceptable levels either at the source or on the adjacent property through the use of proper planning, setbacks, blockwalls, acoustic-rated windows, dense landscaping, or by changing the location of the noise producer. The following policies identify mechanisms to measure and mitigate the noise emitted from stationary noise producers.

The cumulative noise created by truck transfer stations can reach excessive levels when noise sensitive uses are located nearby.

Community Noise Inventory

There are a series of noise producers within Riverside County that bear special recognition. These uses may be important parts of the economic health of the County, but they still emit noise from time to time. Some of the special noise producers within the County include, but are not limited to the Riverside Raceway, surface mining, truck transfer stations in the Mira Loma area, manufacturing facilities, and natural gas transmission pipelines.

Three high pressure natural gas transmission pipelines are located in the community of Cabazon (within the Pass Area Plan), and a series of valve stations are placed along the pipeline throughout the community. The pipelines supply a major portion of the non-transportation energy supply for southern California. The depressurization of mainline valves at the valve stations for emergency or maintenance reasons can result in noise levels exceeding 140 dB L_{eq} at a distance of 50 feet from the source for more than an hour at a time. The pipelines are not located in heavily populated areas; however, should higher-intensity uses be approved in the area in the future, possible relocation of one or more pipelines or valves may be necessary.

A **pure tone** is a single frequency tone with no harmonic content (e.g. hum).

Policies:

N 4.1 Prohibit facility-related noise, received by any sensitive use, from exceeding the following worst-case noise levels: (AI 105)
a. 45 dBA-10-minute L_{eq} between 10:00 p.m. and 7:00 a.m.
b. 65 dBA-10-minute L_{eq} between 7:00 a.m. and 10:00 p.m.

N 4.2 Develop measures to control non-transportation noise impacts. (AI 105)

N 4.3 Ensure any use determined to be a potential generator of significant stationary noise impacts be properly analyzed, and ensure that the recommended mitigation measures are implemented. (AI 105, 106, 109)

N 4.4 Require that detailed and independent acoustical studies be conducted for any new or renovated land uses or structures determined to be potential major stationary noise sources. (AI 105)

N 4.5 Encourage major stationary noise-generating sources throughout the County of Riverside to install additional noise buffering or reduction mechanisms within their facilities to reduce noise generation levels to the lowest extent practicable prior to the renewal of Conditional Use Permits or business licenses or prior to the approval and/or issuance of new Conditional Use Permits for said facilities. (AI 105, 107)

N 4.6 Establish acceptable standards for residential noise sources such as, but not limited to, leaf blowers, mobile vendors, mobile stereos and stationary noise sources such as home appliances, air conditioners, and swimming pool equipment. (AI 105)

N 4.7 Evaluate noise producers for the possibility of pure-tone producing noises. Mitigate any pure tones that may be emitted from a noise source. (AI 106, 107)

N 4.8 Require that the parking structures, terminals, and loading docks of commercial or industrial land uses be designed to minimize the potential noise impacts of vehicles on the site as well as on adjacent land uses. (AI 106, 107)

Wind Energy Conversion Systems (WECS)

Wind energy is a unique resource found only in a portion of Riverside County. Wind Energy Conversion Systems (WECS) are used to harness the energy found in strong gusts of wind. In order to fully capitalize on this special commodity, a large number of wind turbines have been placed in a portion of the Coachella Valley and San Gorgonio Pass within Riverside County. There are some residential areas spread throughout the County that may also capitalize on wind-generated power. Though there is minimal residential development in the immediate areas where these windmills are located, the potential for noise and ground-borne vibration in neighboring developed areas may occur. The Wind Implementation Monitoring Program, designed and implemented by Riverside County, guides the policy direction for this area.

Policies:

N 5.1 Enforce the Wind Implementation Monitoring Program (WIMP).

N 5.2 Encourage the replacement of outdated technology with more efficient technology with less noise impacts. (AI 105)

MOBILE NOISE

Please see the ***Circulation Element*** *for further policies regarding transportation and noise related issues.*

Mobile noise sources may be one of the most annoying noise producers in a community because they are louder than background noises and more intense than many acceptable stationary noise sources. Though the noise emitted from mobile sources is temporary, it is often more disturbing because of its abruptness, especially single noise-producing events such as vehicle backfires. Common mobile noise sources include on-road vehicles, aircraft, and trains. The policies in this section identify common mobile noise sources, and suggest mitigation techniques to reduce the annoyance and burden of mobile noise sources on noise-sensitive receptors.

Policies:

N 6.1 Consider noise reduction as a factor in the purchase of County maintenance equipment and their use by County contractors and permittees. (AI 108)

N 6.2 Investigate the feasibility of retrofitting current County-owned vehicles and mechanical equipment to comply with noise performance standards consistent with the best available noise reduction technology. (AI 108)

Commercial Airliners are mobile noise sources that contribute to noise pollution

N 6.3 Require commercial or industrial truck delivery hours be limited when adjacent to noise-sensitive land uses unless there is no feasible alternative or there are overriding transportation benefits. (AI 105, 107)

N 6.4 Restrict the use of motorized trail bikes, mini-bikes, and other off-road vehicles in areas of the County except where designated for that purpose. Enforce strict operating hours for these vehicles in order to minimize noise impacts on sensitive land uses adjacent to public trails and parks. (AI 105, 108)

Transportation

The most common mobile noise sources in the County are transportation-related. Motor vehicle noise is of concern because it is characterized by a high number of individual events, which often create a higher sustained noise level in proximity to areas sensitive to noise exposure. Rail and aircraft operations, though less frequent, may generate extremely high noise levels that can be disruptive to daily activities. Though mass transit has not yet been developed within Riverside County, it is important to consider the noise that may be generated from transit service.

> The following airports are located within or have a direct effect on Riverside County. Please see Appendix I for a map with each airport's noise contours. Also see the area plans and airport land use plans for more specific airport-related policies:
>
> - *Banning Municipal Airport*
> - *Bermuda Dunes Airport*
> - *Blythe Airport*
> - *Chino Airport*
> - *Corona Municipal Airport*
> - *Chiriaco Summit Airport*
> - *Desert Center Airport*
> - *Desert Resorts Regional Airport*
> - *Flabob Airport*
> - *French Valley Airport*
> - *Hemet-Ryan Airport*
> - *March Inland Port*
> - *Palm Springs Regional Airport*
> - *Perris Valley Airport*
> - *Riverside Municipal Airport*
> - *Skylark Airport*

Airports

With the dynamic growth in aviation, aircraft noise will remain a challenging environmental problem and one that will affect an increasing number people as air traffic routes and procedures change in the future. Aircraft noise appears to produce the greatest community anti-noise response, although the duration of the noise from a single airplane is much less, for example, than that from a freight train. There is great economic benefit to gain from airports of any size, although living in proximity to an airport may bring about expected aircraft noise.

There are 15 (fifteen) airports that are located within or have a direct effect on Riverside County. The land under the flight paths of each airport was monitored to determine the amount of noise emitted by common aircraft taking-off and landing at any given airport. Noise contours were created based on the measurements from the monitoring program. The CNEL noise contour(s) for the following airports have been depicted in the applicable Area Plan's Airport Influence Area section:

- Banning Municipal Airport
- Bermuda Dunes Airport
- Blythe Airport
- Chino Airport
- Chiriaco Summit Airport
- Corona Municipal Airport
- Desert Center Airport
- Desert Resorts Regional Airport
- Flabob Airport
- French Valley Airport
- Hemet Ryan Airport
- Riverside Municipal Airport

An Airport Land Use Plan has been created for each airport within Riverside County, and it should be referenced for further information regarding airports. Helicopters and heliports are also potential sources of noise, but due to the relatively low frequency and short duration of their operation in most circumstances, these operations do not significantly affect average noise levels within the County. The following general policies address the noise that comes from airports and the aircraft they service.

Policies:

N 7.1 New land use development within Airport Influence Areas shall comply with airport land use noise compatibility criteria contained in the corresponding airport land use compatibility plan for the area. Each Area Plan affected by a public-use airport includes one or more Airport Influence Areas, one for each airport. The applicable noise compatibility criteria are fully set forth in Appendix L and summarized in the Policy Area section of the affected Area Plan.

N 7.2 Adhere to applicable noise compatibility criteria when making decisions regarding land uses adjacent to airports. Refer to the Airports section of the Land Use Element (Page LU-32) and the Airport Influence Area sections of the corresponding Area Plans.

N 7.3 Prohibit new residential land uses, except construction of a single-family dwelling on a legal residential lot of record, within the current 60 dB CNEL contours of any currently operating public-use, or military airports. The applicable noise contours are as defined by the Riverside County Airport Land Use Commission and depicted in Appendix L, as well as in the applicable Area Plan's Airport Influence Area section.

N 7.4 Check each development proposal to determine if it is located within an airport noise impact area as depicted in the applicable Area Plan's Policy Area section regarding Airport Influence Areas. Development proposals within a noise impact area shall comply with applicable airport land use noise compatibility criteria.

N 7.5 Revise the Riverside County Zoning Code to reflect aircraft noise-impacted areas around the County's major airports. (AI 109)

*Please see the **Circulation Element** for more in-depth information regarding Level of Service Standards, Average Daily Trips, and other information related to vehicular circulation.*

Vehicular

Roadway traffic is one of the most pervasive sources of noise within Riverside County. Traffic noise varies in how it affects land uses depending upon the type of roadway, and the distance of the land use from that roadway. Some variables that affect the amount of noise emitted from a road are speed of traffic, flow of traffic, and type of traffic (e.g. tractor trailers versus cars). Another variable affecting the overall measure of noise is a perceived increase in sensitivity to vehicular noise at night. Appendix I contains tables and figures that illustrate existing and forecasted noise from roadways throughout the County. The existing noise measurements were obtained by measuring noise at different points adjacent to the roadway. The future noise contours along freeways and major highways, also located in Appendix I, were created from the results of traffic modeling to project the noise of major roadways in the future. The following policies address the issues of roadway traffic noise, and suggest methods to reduce the noise impact of roads on adjacent and nearby land uses.

Policies:

N 8.1 Enforce all noise sections of the State Motor Vehicle Code.

N 8.2 Ensure the inclusion of noise mitigation measures in the design of new roadway projects in the County. (AI 105)


Off-road and all-terrain vehicles must obey strict operating hours when noise-sensitive land uses are nearby or adjacent to trails and open space.

N 8.3 Require development that generates increased traffic and subsequent increases in the ambient noise level adjacent to noise-sensitive land uses to provide for appropriate mitigation measures. (AI 106)

N 8.4 Require that the loading and shipping facilities of commercial and industrial land uses, which abut residential parcels be located and designed to minimize the potential noise impacts upon residential parcels. (AI 105)

N 8.5 Employ noise mitigation practices when designing all future streets and highways, and when improvements occur along existing highway segments. These mitigation measures will emphasize the establishment of natural buffers or setbacks between the arterial roadways and adjoining noise-sensitive areas. (AI 105)

"Calling noise a nuisance is like calling smog an inconvenience. Noise must be considered a hazard to the health of people everywhere."

-The Surgeon General

Please see the *Circulation Element* for additional policies related to transit development and rail systems.

An *at-grade railroad crossing* is one where the street and the rail line form an intersection, and physically cross one-another.

N 8.6 Require that all future exterior noise forecasts use Level of Service C, and be based on designed road capacity or 20-year projection of development (whichever is less) for future noise forecasts. (AI 106)

N 8.7 Require that field noise monitoring be performed prior to siting to any sensitive land uses along arterial roadways. Noise level measurements should be of at least 10 minutes in duration and should include simultaneous vehicle counts so that more accurate vehicle ratios may be used in modeling ambient noise levels. (AI 106)

Mass Transit

Currently, the County does not participate in or provide any rail transit services though public transportation is becoming a more desirable option for many travelers and commuters in Riverside County. Transit can be an alternative to driving a car through congested Riverside County freeways. Currently, the noise generated by public transportation within Riverside County affects only a very small percentage of the total residential population. As years pass, and the need for public transportation increases, there will be a greater number of residents affected by the noise that buses, transit oases shuttles, light rail, and trains will produce. The following policies address the issues of noise related to public transit.

Policies:

N 9.1 Encourage local and regional public transit providers to ensure that the equipment they operate and purchase is state-of-the-art and does not generate excessive noise impacts on the community. (AI 108)

N 9.2 Encourage the use of quieter electric-powered vehicles. (AI 108)

N 9.3 Encourage the development and use of alternative transportation modes including bicycle paths and pedestrian walkways to minimize vehicular noise within sensitive receptor areas.

N 9.4 Actively participate in the development of noise abatement plans for freeways and rapid transit. (AI 108)

Rail

The rail system within Riverside County criss-crosses its way through communities, industrial areas, rural areas, and urban centers. Trains carry passengers, freight, and cargo to local and regional destinations day and night. Rail transportation may become more popular in the future if a mass public transportation system is implemented within Riverside County. Currently, daily train traffic produces noise that may disrupt activities in proximity to railroad tracks. For instance, trains are required to sound their horns at all at-grade crossings, and they may also be required to slow their speed through residential areas. These types of noise disturbances can interfere with activities conducted on noise-sensitive land uses. Exhibits showing existing railroad noise contours can be found in Appendix I. These exhibits provide purely illustrative contours along rail lines throughout the County. The following policies suggest actions that could minimize the impacts of train noise on noise-sensitive land uses.

Policies:

N 10.1 Check all proposed projects for possible location within railroad noise contours using typical noise contour diagrams. (AI 106, 109)

N 10.2 Minimize the noise effect of rail transit (freight and passenger) on residential uses and other sensitive land uses through the land use planning process. (AI 106, 109)

N 10.3 Locate light rail and fixed rail routes and design rail stations in areas that are accessible to both residential and commercial areas, but also minimize noise impacts on surrounding residential and sensitive land uses. (AI 106, 109)

N 10.4 Install noise mitigation features where rail operations impact existing adjacent residential or other noise-sensitive uses. (AI 108)

N 10.5 Restrict the development of new sensitive land uses to beyond the 65 decibel CNEL contour along railroad rights-of-way. (AI 106, 109)

Building and Design

One of the most effective means of reducing noise in a sensitive area is to construct and design buildings in such a way that the noise is deflected in such a way that it does not affect the occupants. If the building has already been constructed, then landscaping and design techniques can be used to tastefully absorb the noise emitted from mobile or stationary sources. These building and design techniques should serve two purposes; to mitigate noise to acceptable indoor and outdoor levels, and to enhance the community character rather than detract from its surroundings. The following policies have been included in the Noise Element to ensure that the character of each community within Riverside County is preserved while minimizing noise to acceptable levels.

Natural Barriers and Landscaping

Policies:

N 11.1 Utilize natural barriers such as hills, berms, boulders, and dense vegetation to assist in noise reduction. (AI 108)

N 11.2 Utilize dense landscaping to effectively reduce noise. However, when there is a long initial period where the immaturity of new landscaping makes this approach only marginally effective, utilize a large number of highly dense species planted in a fairly mature state, at close intervals, in conjunction with earthen berms, setbacks, or block walls. (AI 108)

Temporary Construction

Policies:

N 12.1 Minimize the impacts of construction noise on adjacent uses within acceptable practices. (AI 105, 108)

N 12.2 Ensure that construction activities are regulated to establish hours of operation in order to prevent and/or mitigate the generation of excessive or adverse noise impacts on surrounding areas. (AI 105, 108)

N 12.3 Condition subdivision approval adjacent to developed/occupied noise-sensitive land uses (see policy N 1.3) by requiring the developer to submit a construction-related noise mitigation plan to the County for review and approval prior to issuance of a grading permit. The plan must depict the location of construction equipment and how the noise from this equipment will be mitigated during construction of this project, through the use of such methods as

a. Temporary noise attenuation fences;
b. Preferential location of equipment; and
c. Use of current noise suppression technology and equipment. (AI 107)

N 12.4 Require that all construction equipment utilizes noise reduction features (e.g. mufflers and engine shrouds) that are no less effective than those originally installed by the manufacturer. (AI 105, 108)

Building and Design Techniques

Policies:

N 13.1 Enforce the California Building Standards that sets standards for building construction to mitigate interior noise levels to the tolerable 45 CNEL limit. These standards are utilized in conjunction with the Uniform Building Code by the County's Building Department to ensure that noise protection is provided to the public. Some design features may include extra-dense insulation, double-paned windows, and dense construction materials.

★

Non-habitable areas within a home include:

- *kitchens*
- *bathrooms*
- *hallways*
- *garages*
- *closets*
- *utility rooms*
- *laundry rooms*

N 13.2 Continue to develop effective strategies and mitigation measures for the abatement of noise hazards reflecting effective site design approaches and state-of-the-art building technologies. (AI 108)

N 13.3 Incorporate acoustic site planning into the design of new development, particularly large scale, mixed-use, or master-planned development, through measures which may include:

- separation of noise-sensitive buildings from noise-generating sources;
- use of natural topography and intervening structure to shield noise-sensitive land uses; and
- adequate sound proofing within the receiving structure. (AI 106)

N 13.4 Consider and, when necessary to lower noise to acceptable limits, require noise barriers and landscaped berms. (AI 108)

N 13.5 Consider the issue of adjacent residential land uses when designing and configuring all new, non-residential development. Design and configure on-site ingress and egress points that divert traffic away from nearby noise-sensitive land uses to the greatest degree practicable. (AI 106, 107)

N 13.6 Prevent the transmission of excessive and unacceptable noise levels between individual tenants and businesses in commercial structures and between individual dwelling units in multi-family residential structures. (AI 105, 108)

N 13.7 Assist the efforts of local homeowners living in high noise areas to noise attenuate their homes through funding assistance and retrofitting program development, as feasible. (AI 105, 108)

N 13.8 Review all development applications for consistency with the standards and policies of the Noise Element of the General Plan.

N 13.9 Mitigate 600 square feet of exterior space to 65 dB CNEL when new development is proposed on residential parcels of 1 acre or greater.

Mixed Use

Policies:

N 14.1 Minimize the potential adverse noise impacts associated with the development of mixed-use structures where residential units are located above or adjacent to commercial uses. (AI 106, 107, 108)

N 14.2 Require that commercial and residential mixed-use structures minimize the transfer or transmission of noise and vibration from the commercial land use to the residential land use. (AI 105)

N 14.3 Minimize the generation of excessive noise level impacts from entertainment and restaurant/bar establishments into adjacent residential or noise-sensitive uses. (AI 105, 107)

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Vibration

> **Amplitude**-the distance that a vibrating particle travels from a fixed point.
>
> **Frequency**-the number of wave cycles that occur in 1 second.
>
> **Hertz (Hz)**-the unit by which frequency is measured.
>
> **Displacement**-a measure of the distance that a vibrated particle travels from its original position.
>
> **Velocity**-the rate of speed at which particles move in inches per second or millimeters per second.
>
> **Acceleration**-the rate of change in velocity with respect to time.

Another community annoyance related to noise is vibration. As with noise, vibration can be described by both its amplitude and frequency. Amplitude may be characterized by displacement, velocity, and/or acceleration. Typically, particle velocity (measured in inches or millimeters per second) and/or acceleration (measured in gravities) are used to describe vibration.

Vibration can be felt outdoors, but the perceived intensity of vibration impacts are much greater indoors, due to the shaking of the structure. Some of the most common sources of vibration come from trains and/or transit vehicles, construction equipment, airplanes, and large vehicles. Several land uses are especially sensitive to vibration, and therefore have a lower vibration threshold. These uses include, but are not limited to, concert halls, hospitals, libraries, vibration-sensitive research operations, residential areas, schools, and offices.

Table 3, Human Reaction to Typical Vibration Levels, presents the human reaction to various levels of peak particle velocity. Typical construction vibrations fall in the 10 to 30 Hz range and usually occur around 15 Hz. Traffic vibrations exhibit a similar range of frequencies. However, due to their suspension systems, city buses often generate frequencies around 30 Hz at high vehicle speeds. It is more uncommon, but possible, to measure traffic frequencies above 30 Hz.

Table N-3:
Human Reaction to Typical Vibration Levels

Vibration Level Peak Particle Velocity (inches/second)	Human Reaction
0.0059-0.0188	Threshold of perception, possibility of intrusion
0.0787	Vibrations readily perceptible
0.0984	Continuous vibration begins to annoy people
0.1968	Vibrations annoying to people in buildings
0.3937-0.5905	Vibrations considered unpleasant when continuously subjected and unacceptable by some walking on bridges.

Source: Caltrans, 1992

Policies:

N 15.1 Restrict the placement of sensitive land uses in proximity to vibration-producing land uses. (AI 105)

N 15.2 Consider the following land uses sensitive to vibration:
- Hospitals;
- Residential Areas;
- Concert Halls;
- Libraries;

- Sensitive Research Operations;
- Schools; and
- Offices

N 15.3 Prohibit exposure of residential dwellings to perceptible ground vibration from passing trains as perceived at the ground or second floor. Perceptible motion shall be presumed to be a motion velocity of 0.01 inches/second over a range of 1 to 100 Hz.

Noise Information Management

Current and projected noise data and maps for Riverside County require constant updating and review in order for the information to remain correct as well as accurate. Currently, there is no central noise information database available for the County staff or residents to reference when noise inquiries arise. This information is necessary and should be easily accessible when reviewing potential development plans, building a new home, siting an industrial area, evaluating circulation routes, or conducting other advanced planning activities. The following policies guide the County to create a database, or central location, where up-to-date information can be accessed by County Staff or residents.

Please see Table N-1 for more information in order to determine a noise threshold necessary for creating a noise database.

Mapping

Policies:

N 16.1 Identify, quantify, and map noise producers and provide noise contour diagrams as is practical. (AI 109)

N 16.2 Identify and map noise-sensitive land uses throughout the County. (AI 109)

N 16.3 Identify and map point-source noise producers such as surface mines, wind turbines, manufacturing plants, truck transfer stations, active recreational facilities, and amphitheaters. (AI 109)

Noise Data Management

Policies:

N 17.1 Maintain baseline information, on an ongoing basis, regarding ambient and stationary noise sources. (AI 105)

N 17.2 Monitor and update available data regarding the community's existing and projected ambient stationary noise levels.

N 17.3 Assure that areas subject to noise hazards are identified, quantified, and mapped in a form that is available to decisionmakers. (AI 109)

N 17.4 Develop and maintain a detailed, comprehensive noise data base. (AI 106)

N 17.5 Develop and update County Noise Inventories using the following steps.

a. Identify Noise Sources and Noise-sensitive Land Uses
b. Continue to identify various agency responsibilities; review noise complaint files; and conduct noise surveys and monitoring as needed.

N 17.6 Identify those areas of the County affected by high noise levels. (AI 106, 107, 109)

N 17.7 Evaluate current land uses to identify potential noise conflict areas. (AI 106, 107, 109)

N 17.8 Gather activity operations' data of noise sources; prepare analytical noise exposure models to develop existing and projected noise contours around major noise sources down to 50 CNEL. (AI 109)

N 17.9 Encourage greater involvement of other County departments in the identification, measurement, and reduction of noise hazards throughout the County, including: Building and Safety Department, Aviation Department, and the Department of Public Health-Office of Industrial Hygiene.

Public Noise Information

Policies:

N 18.1 Provide information to the public regarding the health effects of high noise levels and means of mitigating such levels. (AI 109)

N 18.2 Cooperate with industry to develop public information programs on noise abatement. (AI 108)

☞ N 18.3 Condition that prospective purchasers or end users of property be notified of overflight, sight, and sound of routine aircraft operations by all effective means, including:

a. requiring new residential subdivisions that are located within the 60 CNEL contour or are subject to overflight, sight, and sound of aircraft from any airport, to have such information included in the State of California Final Subdivision Public Report.
b. requiring that Declaration and Notification of Aircraft Noise and Environmental Impacts be recorded and made available to prospective purchasers or end users of property located within the 60 CNEL noise contour for any airport or air station or is subject to routine aircraft overflight. (AI 109)

N 18.4 Promote increased awareness concerning the effects of noise and suggest methods by which the public can be of assistance in reducing noise.

N 18.5 Require new developments that have the potential to generate significant noise impacts to inform impacted users on the effects of these impacts during the environmental review process. (AI 106, 107)

Lakeview Substation Project Noise Inquiries

- On page 4.12-13 and in Table 4.12-4 of the PEA for the Lakeview Substation Project ("Proposed Project"), SCE explains that a 138 kV Transmission Line has an audible noise level of approximately 33.5 dBA directly below the conductor. This information was derived from Figure 7.17 of the EPRI Transmission Line Reference Book (see attachment A).

  Please strike the citation to "(CPUC, 2009)" and replace it with the following:

  Electrical Power Research Institute (EPRI). 1978. Transmission Line Reference Book, 115-138 kV Compact Line Design.

- On Page 4.12-14 of the PEA, SCE states: "With all auxiliary cooling fans operating, the worst-case noise level from the transformers at full load is predicted to be no more than 66 dBA at three feet away from the equipment (CPUC 2009)."

  According to the manufacturer's sound level information (see attachment B), the noise level of each transformer bank planned for the Proposed Project would be 62.4 dB. This would result in a total noise level of 65.4 dBA for the two transformers simultaneously operating under full load conditions. SCE staff recently conducted 24-hour duration noise level measurements at the Concho Substation in Rancho Mirage, for transformer banks of the same make, type, and capacity as planned for the Proposed Project (see attachment C). The results of the 24-hour noise survey indicate hourly equivalent noise levels monitored between two transformer banks will not exceed 63.1 dBA. For the purpose of the Proposed Project noise analysis, the worst-case noise level from the transformers at full load is assumed to be 66 dBA at a distance of three feet from the equipment.

  References:

  Kuhlman. (2006). Load Tap Changing Transformer: Transformer Name Plate.
  Overweg, C. (2010). 115/12 kV Transformer Bank Noise Levels: Monitored at Concho Substation.

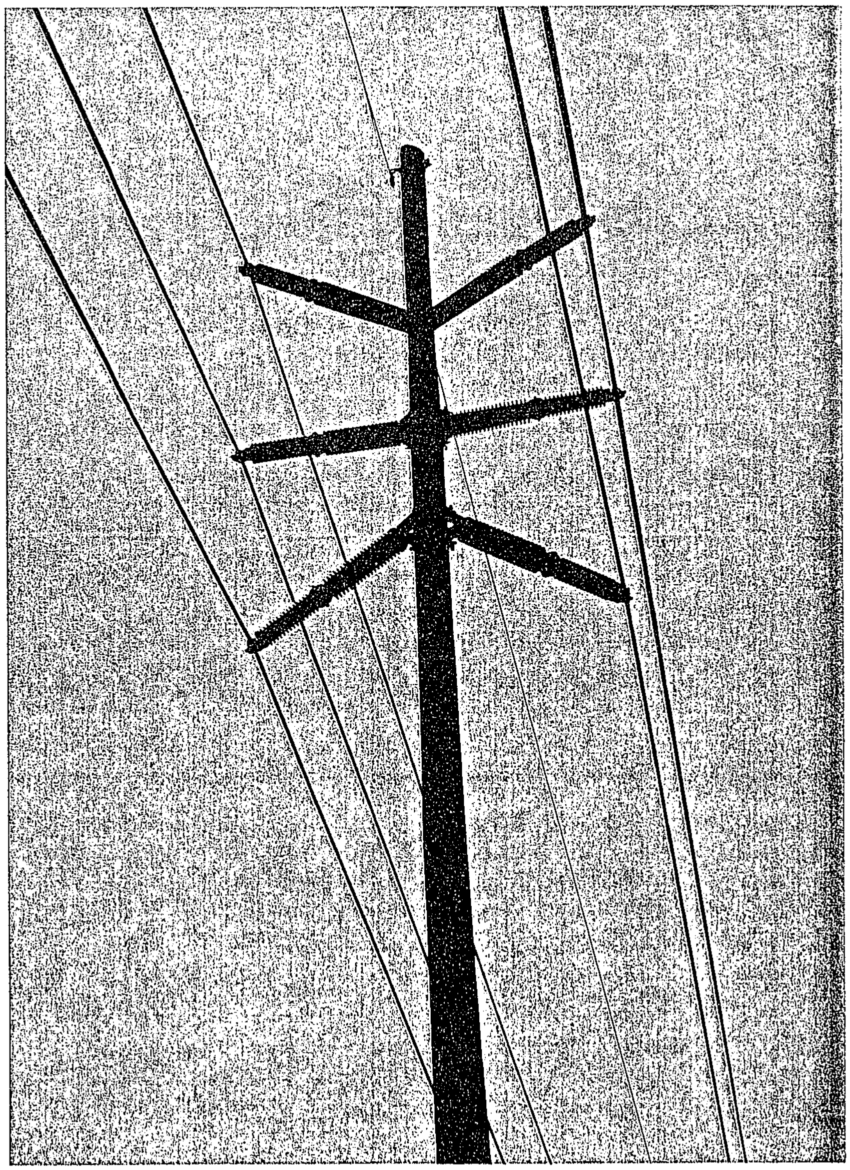
- On Page 4.12-14 of the PEA, SCE states: "Noise levels would be below 45 dBA during nighttime hours (10:00 p.m. to 7:00 a.m.) and below 55 dBA during daytime hours (7:00 a.m. to 10:00 p.m.)." The following information is provided to further clarify the conclusion made in that statement:

  The nearest noise-sensitive receptors are residences located approximately 150 feet or more from the transformer banks. Based on a distance sound attenuation of 6 dBA per distance doubling, the distance sound attenuation for 150 feet would be 34 dBA, resulting in a noise level of 32 dBA noise level at the nearest noise-sensitive receptor location. Furthermore, the 8-foot-high block wall around the

Proposed Project's perimeter is expected to further reduce transformer banks noise levels at the nearest receptor locations.

Transmission Line Reference Book

115-138 kV Compact Line Design



Electric Power Research Institute

Transmission Line Reference Book

115-138 kV Compact Line Design

Based on
EPRI Research Project 260

Prepared by
Power Technologies, Inc.
Schenectady, New York

Electric Power Research Institute
3412 Hillview Avenue, Palo Alto, California

AUDIBLE NOISE

Audible noise is due to point source corona, as are RI and TVI, and is a function of conductor voltage gradient and the number of irregularities on the conductor or on energized hardware. The major cause of irregularities is water droplets on the underside of the conductor. These droplets deform to point sources under the influence of the electric field, producing high local gradients and corona. Since water droplets are requisite to the primary mechanism, audible noise is generally limited to periods of heavy fog, rain, or immediately following rain.

The noise manifests itself as a sizzle, crackle, or hiss and a low-frequency hum. The first three are "white" noise, extending over the entire aural range (20 Hz to 2 × 10^4 Hz) and are caused by random point source discharges. The low-frequency hum is caused by space charge movement around the conductor at a frequency of 120 Hz and harmonics of 120 Hz. Unlike RI and TVI, audible noise is more localized; the noise is propagated via air and discharges a few spans away do not affect local measurements. This allows local remedial action, if necessary.

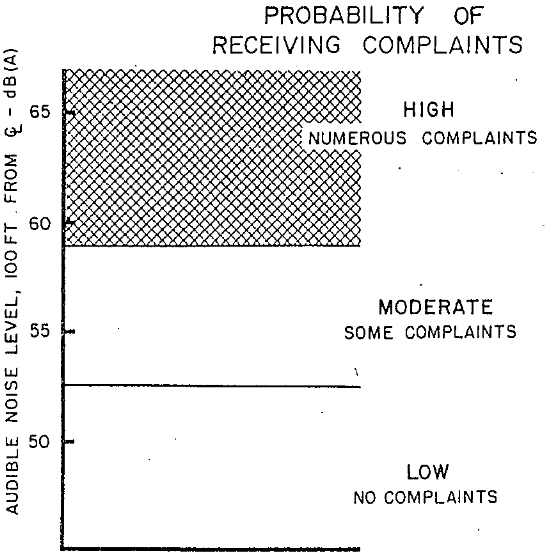
Annoyance caused by the audible noise depends on a number of qualitative factors, resulting in difficulty in specifying design levels. Such general factors as land use characteristics and ambient noise, together with individual activity and duration of exposure, must be recognized. For example, it would be unreasonable to use the same criteria for a line adjacent to an industrial facility as one near a hospital. Similarly, a line in a populous area has more potential for annoyance than one in an unpopulated area.

Audible noise is generally measured by the dB(A) scale (the "A" suffix refers to the weighting network used in the measurement). The dB(B) weighting network gives a better correlation with juror annoyance ratings of transmission line noise than the "A" network, probably because of the lower attenuation of the low-frequency noise with the "B" network (*7-11*). However, the dB(A) scale is in universal use for general noise ordinances, with excellent results.

Criteria for audible noise (AN) design is based on experience with other lines, present noise regulations, and typical ambient levels in the different areas of land usage. These criteria should recognize the statistical nature of the noise generation (*7-12*). Audible noise varies from being imperceptible in fair weather, to being noticeable over ambient during wet conditions, to higher but imperceptible over ambient during rain conditions. The line noise during heavy rain may be 6 dB(A) higher than when the conductor is merely wet (as after rain, during heavy fog, etc.). However, it is unlikely that heavy rain would cause annoyance because of the high ambient noise level and low exposure. Therefore it is more appropriate to consider the wet-conductor level because of its higher exposure probability.

A general guideline to acceptability is given in Reference *7-13* and is reproduced in Figure 7.16. It is based on public response to noise from existing lines at 100 feet from the center of the ROW and shows that less than 52.5 dB(A) resulted in no complaints. This is supported by other experience (*7-14*).

The method of calculation used on the compact line project is similar to that reported in Reference *7-15*. From single-phase cage tests, the generated acoustic power can be measured as a function of the conductor gradient. These can be summed for the three phases to give a lateral audible noise profile. Comparison with measured results indicates an accuracy to within ±3 dB. The results are presented in Figure 7.17 for Dove conductors (556.5 kcmil) at 30 feet effective height, with 3-foot phase-to-phase spacing (horizontal configuration), operating at 145 kV. This represents the most compact 138-kV design and a small conductor and therefore has the highest AN to be expected in practice. Noise levels are calculated at approximately 5 feet above the ground.



SOURCE: "An Analysis of Transmission Line Audible Noise Levels Based upon Field and Three-Phase Test Line Measurements," D. E. Perry, *IEEE Transactions on Power Apparatus and Systems*, 1972.

Figure 7.16 Probability of complaints about audible noise.

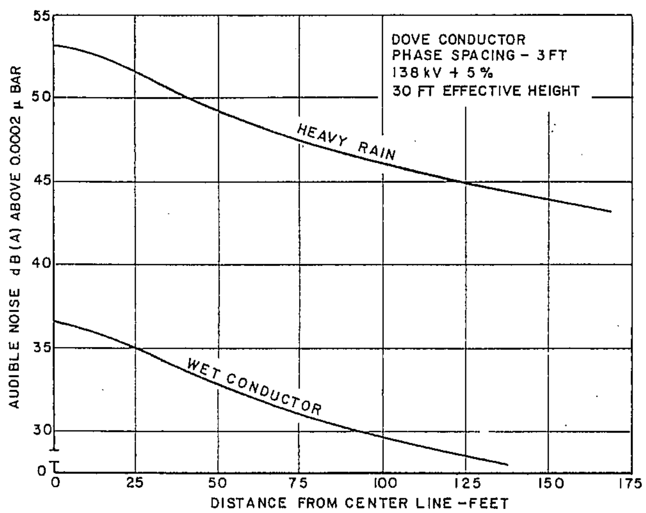


Figure 7.17. Audible noise for 3-phase compact line.

11.75
10.75

KUHLMAN CORPORATION
CRYSTAL SPRINGS, MS

KUHLMAN

LOAD TAP CHANGING TRANSFORMER

MVA 15.0/20.0/25.0 AT 55°C RISE
MVA 16.8/22.4/28.0 AT 65°C RISE
HV 115000Y/66395 VOLTS 450 KV BIL, HVN 450 KV BIL
LV 12470Y/7200 VOLTS 110 KV BIL
TV 7200 VOLTS 110 KV BIL
IMPEDANCE 7.30 % AT 115000Y–12470Y VOLTS AND 15.0 MVA
ZERO SEQUENCE IMPEDANCE 7.00 % AT 15.0 MVA

COOLING CLASS ONAN/ONAF/ONAF
THREE PHASE, 60 HERTZ

MFG. DATE: 05/07
SERIAL NO.: 362745-06-9

SOUND LEVEL 60/61.7/62.4 dB

LIQUID LEVEL BELOW TOP OF MANHOLE FLANGE AT 25°C IS 13.2 INCHES
LIQUID LEVEL CHANGES 0.88 INCHES PER 10°C CHANGE IN LIQUID TEMPERATURE.
OPERATING PRESSURE OF OIL PRESERVATION SYSTEM: 7.0 PSIG POSITIVE 8.0 PSIG NEGATIVE
TANK IS DESIGNED FOR 14.7 PSIG VACUUM AND 15.0 PSIG POSITIVE PRESSURE.
PRESSURE RELIEF DEVICE OPERATES AT 10.0 PSIG.
LTC: REINHAUSEN RMV–II RATED: 2000 AMPS
CIRCULAR COIL CONSTRUCTION, 3–LEGGED MITRED CORE.

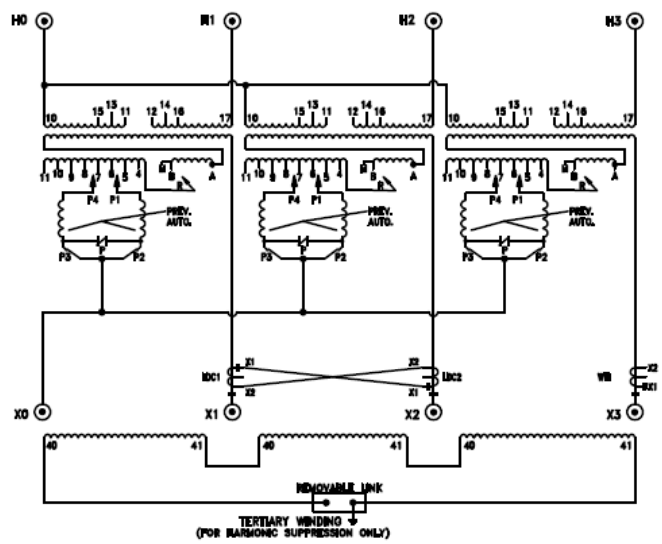
APPROXIMATE WEIGHT (POUNDS)			
CORE AND COILS			60816
TANK AND FITTINGS			17979
RADIATORS			9480
TANK OIL	5527	GALS.	41453
RADIATOR OIL	342	GALS.	2567
LTC OIL	345	GALS.	2588
TOTAL WEIGHT			134883

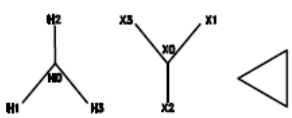
CAUTION

READ IM–3.010 AND TL 7002.06 BEFORE OPERATING TRANSFORMER.
DE–ENERGIZE TRANSFORMER BEFORE OPERATING H.V. TAP CHANGER.
FILLED AT TIME OF MANUFACTURE WITH MINERAL OIL THAT CONTAINED LESS THAN 1 PPM PCB. 362745-06

OIL IS TYPE II INHIBITED

LDC1, LDC2—1400:5 S.R. C100
WTI—1400:5 S.R. C100





VECTOR DIAGRAM

NOTE:
THIS UNIT CONTAINS EXTRA KEY SPACERS IN THE TOP OF THE CENTER WINDING FOR REMOVAL BY CUSTOMER FOR DEGREE OF POLYMERIZATION TESTING.

H.V. CONNECTIONS (COPPER CONDUCTORS)			
VOLTS H1–H2–H3	AMPS AT 28 MVA, 65°C	TAP CHANGER FOR DE–ENERGIZED OPERATION	
		POS	CONNECTS
120750	134	A	11 TO 12
117875	137	B	12 TO 13
115000	141	C	13 TO 14
112125	144	D	14 TO 15
109250	148	E	15 TO 16

L.V. CONNECTIONS (COPPER CONDUCTORS)					
VOLTS X1–X2–X3	AMPS AT 28 MVA, 65°C	POS NO.	LOAD TAP TAP CHANGER		
			P1 ON	P4 ON	R ON
13776	1173	16R	11	11	B
13658	1184	15R	10	11	
13539	1194	14R	10	10	
13479	1199	13R	9	10	
13420	1205	12R	9	9	
13361	1210	11R	8	9	
13301	1215	10R	8	8	
13183	1226	9R	7	8	
13064	1237	8R	7	7	
13004	1243	7R	6	7	
12945	1249	6R	6	6	
12886	1255	5R	5	6	
12826	1260	4R	5	5	
12708	1272	3R	4	5	
12589	1284	2R	4	4	
12529	1290	1R	M	4	
12470	1296	N	M	M	
12411	1303	1L	11	M	A
12351	1309	2L	11	11	
12232	1322	3L	10	11	
12114	1335	4L	10	10	
12054	1341	5L	9	10	
11995	1348	6L	9	9	
11936	1354	7L	8	9	
11876	1361	8L	8	8	
11757	1375	9L	7	8	
11639	1389	10L	7	7	
11579	1396	11L	6	7	
11520	1403	12L	6	6	
11461	1411	13L	5	6	
11401	1418	14L	5	5	
11282	1433	15L	4	5	
11164	1448	16L	4	4	
FOR STEP DOWN OPERATION					

0.50
9.81
20.63
0.50

.15625 DIA (6) HOLES

CUT LINE

NOTE:
SERIAL NO., MFG. DATE, AND IMPEDANCE WILL BE ENGRAVED AFTER FINAL TESTING AT KUHLMAN ELECTRIC.
22 GA. STAINLESS STEEL NAMEPLATE MATERIAL

DWN SCA DATED 07–24–06	CKD DATED
APR SLS DATED 07–24–06	PAGE 1 OF 1
TRANSFORMER NAMEPLATE	
KUHLMAN CORPORATION POWER TRANSFORMER DIV. CRYSTAL SPRINGS, MS	DWG. NO. 362745–3802
ISSUE	03
01	07–24–06, SCA
KCR# 13252 CHANGED TANK OIL AND TOTAL WEIGHT	
02	10/31/06, JDW
SEE KCR #13408	
03	12/13/06, MW

SOUTHERN CALIFORNIA EDISON
An EDISON INTERNATIONAL℠ Company

EMF & Energy Department
Corporate Environment, Health & Safety
2131 Walnut Grove Avenue
Rosemead, CA 91770

115/12 kV TRANSFORMER BANKS NOISE LEVELS

MONITORED at CONCHO SUBSTATION

Prepared By:

Cornelis Overweg, P.E., LEED® AP, INCE Bd. Cert.
Senior Environmental Noise Specialist
EMF & Energy Department / Corporate Environment, Health & Safety
Southern California Edison

October 2010

115/12 kV TRANSFORMER BANK NOISE LEVEL
MONITORED AT CONCHO SUBSTATION

1. INTRODUCTION

This report provides a summary of the 115/12 kV transformer bank noise levels monitored on September 20 and 21, 2010 at the SCE Concho Substation in Rancho Mirage. The body of the report provides the transformer banks nameplate information and a summary of the monitored average hourly equivalent noise levels ($Leq_{1\text{-}hr}$). Appendix A includes all hourly equivalent noise levels ($Leq_{1\text{-}hr}$) monitored during a 21-hour period.

2. FINDINGS

The noise measurement results presented in this report indicate the average hourly equivalent noise levels ($Leq_{1\text{-}hr}$) for the monitored transformers to range between 62.9 and 63.1 dBA. The monitored noise levels are consistent with the sound level data provided by the Kuhlman manufacturer (60 – 62.4 dBA).

3. TRANSFORMER DATA

An overview of the monitored transformers at the Concho Substation site, including an inventory of transformers and cooling fans name plate data, is presented in *Table 1*.

4. NOISE MEASUREMENTS

Noise measurements were conducted during a 21-hour period on 20 and 21 September 2010. The measurements were taken with a calibrated Bruel & Kjaer Model 2250 integrating sound level meter, equipped with a ½-inch pre-polarized condenser microphone with pre-amplifier. This sound level meter meets the current American National Standards Institute standard for a Type 1 precision sound level meter. The sound level meter was positioned between the two transformer banks, at a height of 5 feet above the ground and at a distance of 3 feet from the transformer banks surfaces.

The transformer banks cooling fans were observed to be operating on full capacity during the start-up and completion of the noise measurements. The weather conditions during the measurements were clear skies, temperatures ranging between 80 and 103 degrees Fahrenheit, the relative humidity ranging between 20 and 25 percent, and wind velocities between 1 and 3 mph.

A summary of the monitored average hourly equivalent noise levels ($Leq_{1\text{-}hr}$) is presented in *Table 2.* An overview of all hourly equivalent noise levels ($Leq_{1\text{-}hr}$) monitored during a 21-hour period is shown in Appendix A.

Southern California Edison

115/12 kV TRANSFORMER BANK NOISE LEVEL
MONITORED AT CONCHO SUBSTATION

TABLE 1
CONCHO SUBSTATION
TRANSFORMER BANKS - NAMEPLATE DATA

Substation		Transformer Bank	Transformer Bank
Concho	Transformer	No. 2 – South	No. 2 – North
	Manufacturer	Kuhlman	Kuhlman
	Serial No.	362745-06-7	362745-06-8
	MVA	28.0	28.0
	kV	115-12	115-12
	MFG Date	4/07	4/07
	Sound Level	60/61.7/62.4	60/61.7/62.4
	Cooling Fans		
	Manufacturer	Krenz	Krenz
	Model	A4P11NB1N	A4P11NB1N
	RPM	1140	1140
	HP	1/6	1/6
	Number of Fans	9 – HAF [1]	9 – HAF

TABLE 2
CONCHO SUBSTATION
MONITORED NOISE LEVELS - TRANSFORMER BANKS

Substation		Transformer Bank	Transformer Bank
Concho	Transformer	No. 2 – South + No. 2 - North	
	MFG	Kuhlman	
	MFG Sound Level	60/61.7/62.4	
	Monitored Noise Levels	SLM between No. 2 South and No. 2 North Bank	
	$Leq_{1\text{-}hr}$ - 24 $hours_{AVG}$	63.1 dBA	
	$Leq_{1\text{-}hr}$ - Day_{AVG}	63.1 dBA	
	$Leq_{1\text{-}hr}$ - $Evening_{AVG}$	62.9 dBA	
	$Leq_{1\text{-}hr}$ - $Night_{AVG}$	63.1 dBA	

[1] HAF = Horizontal Air Flow; VAF = Vertical Air Flow

115/12 kV TRANSFORMER BANK NOISE LEVEL
MONITORED AT CONCHO SUBSTATION

The data shown in above *Table 2* indicate the average hourly equivalent noise levels ($Leq_{1\text{-}hr}$) for the monitored transformers to range between 62.9 and 63.1 dBA. The monitored noise levels are consistent with the sound level data provided by the Kuhlman manufacturer (60 – 62.4 dBA).

Report Prepared By:

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Senior Environmental Noise Specialist
EMF & Energy Department / Corporate Environment, Health & Safety
Southern California Edison

Attachment: Appendix A

APPENDIX “A”
CONCHO SUBSTATION - NOISE LEVEL DATA
No. 2 - South and North Transformer Banks

Start Time	Substation	Transformer	LAeq
9/20/2010 10:00	Concho	No. 2 S + N	63.4
9/20/2010 11:00	Concho	No. 2 S + N	62.9
9/20/2010 12:00	Concho	No. 2 S + N	62.9
9/20/2010 13:00	Concho	No. 2 S + N	63.1
9/20/2010 14:00	Concho	No. 2 S + N	62.6
9/20/2010 15:00	Concho	No. 2 S + N	62.6
9/20/2010 16:00	Concho	No. 2 S + N	62.4
9/20/2010 17:00	Concho	No. 2 S + N	62.8
9/20/2010 18:00	Concho	No. 2 S + N	62.9
9/20/2010 19:00	Concho	No. 2 S + N	63.1
9/20/2010 20:00	Concho	No. 2 S + N	63.1
9/20/2010 21:00	Concho	No. 2 S + N	63.0
9/20/2010 22:00	Concho	No. 2 S + N	63.4
9/20/2010 23:00	Concho	No. 2 S + N	63.2
9/21/2010	Concho	No. 2 S + N	63.1
9/21/2010 1:00	Concho	No. 2 S + N	63.0
9/21/2010 2:00	Concho	No. 2 S + N	62.9
9/21/2010 3:00	Concho	No. 2 S + N	63.0
9/21/2010 4:00	Concho	No. 2 S + N	63.2
9/21/2010 5:00	Concho	No. 2 S + N	63.4
9/21/2010 6:00	Concho	No. 2 S + N	64.4
9/21/2010 7:00	Concho	No. 2 S + N	construction 1)
9/21/2010 8:00	Concho	No. 2 S + N	construction 1)
9/21/2010 9:00	Concho	No. 2 S + N	construction 1)
LAeq	7 am - 7 pm	AVG DAY	63.1
	7 pm - 10 pm	AVG EVE	62.9
	10 pm - 7 am	AVG NIGHT	63.1
			LAeq AVG
			63.1

1) - Due to loud construction activities at the site, the noise levels monitored during these hours have not been included in the results.