Technical Noise Supplement

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Acronyms and Abbreviations

AC	asphalt concrete
ADT	average daily traffic
ANSI	American National Institute of Standards
B	bel
Caltrans	California Department of Transportation
Calveno	California Vehicle Noise
CEQA	California Environmental Quality Act
CFR	Code of Federal Regulations
CNEL	community noise equivalent level
CWC	crosswind component
DAT	digital audio tape
dB	decibel
DGAC	dense-graded asphalt concrete
E/B	eastbound
EAG	Extraordinary Abatement Guidelines
EWNR	Exterior Wall Noise Rating
FFT	fast Fourier transform
TNM	Traffic Noise Model
ft/s	feet per second
GLR	graphic level recorder
Guidance Manual	Technical Guidance Manual on the Effects on the Assessment and Mitigation of Hydroacoustic Effects of Pile Driving Sound on Fish
HOV	high-occupancy vehicle
HTNPM	Highway Traffic Noise Prediction Model
Hz	hertz
I-	Interstate
kg/m^3	kilograms of mass per cubic meter
kHz	kilohertz
km/hr	kilometers per hour
L_{dn}	day-night noise level

L_{max}	maximum noise level
m/s	meters per second
N/m^2	newtons per square meter
NAC	noise abatement criteria
NADR	noise abatement design report
NEPA	National Environmental Policy Act
NIST	National Institute of Standards and Technology
Nm	newton meter
NRC	noise reduction coefficient
OGAC	open-graded asphalt concrete
OILR	outside to inside noise level reduction
OSHA	Occupational Safety and Health Administration
PCC	Portland cement concrete
PLD	path length difference
Protocol	Traffic Noise Analysis Protocol
pW	picowatt
R.Az.N.	right azimuth from north
REMEL	Reference Energy Mean Emission Level
rms	root mean square
SEL	sound exposure level
SFOBB	San Francisco–Oakland Bay Bridge
SLM	sound level meter
SPL	sound pressure level
SR	State Route
STC	Sound Transmission Class
TeNS	Technical Noise Supplement
TL	Transmission Loss
VNTSC	Volpe National Transportation Systems Center
vph	vehicles per hour
W	watt
W/B	westbound
W/m^2	watts per square meter
$\mu N/m^2$	micronewtons per square meter
μPa	micropascals

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Section 1
Introduction and Overview

1.1 Introduction

This 2009 Technical Noise Supplement (TeNS) to the California Department of Transportation (Caltrans) Traffic Noise Analysis Protocol (Protocol) (California Department of Transportation 2006) is an updated version of the 1998 TeNS. This version of the TeNS is compatible with applicable sections of the updated 2006 Protocol and contains corrections, additions, clarifications, and reorganization.

The purpose of the 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 Protocol. The contents of the TeNS are for informational purposes; *unless they are referenced in the Protocol, the contents of this document are not official policy, standard, or regulation*. Except for some Caltrans-specific methods and procedures, most methods and procedures recommended in TeNS are in conformance with industry standards and practices.

This document can 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.

1.2 Overview

The TeNS consists of nine sections. Except for Section 1, each covers a specific subject of highway noise. A brief description of the subjects follows.

- Section 1, “Introduction and Overview,” summarizes the subjects covered in the TeNS.

- Section 2, “Basics of Highway Noise,” covers the physics of sound as it pertains to characteristics and propagation of highway noise, effects of noise on humans, and ways of describing noise.
- Section 3, “Measurements and Instrumentation,” provides background information on noise measurements, and discusses various noise-measuring instruments and operating procedures.
- Section 4, “Traffic Noise Impact Screening Procedure,” was developed to assist in determining whether a highway project has the potential to cause a traffic noise impact. If the project does not pass the screening procedure, a detailed noise analysis should be performed. If the project passes the screening procedure, prudent engineering judgment should still be exercised to determine whether a detailed analysis is warranted.
- Section 5, “Detailed Analysis for Traffic Noise Impacts,” provides guidance for studying those projects failing the screening procedure, projects that are controversial or sensitive, or projects where the net effects of topography and shielding are complex or ambiguous. This section includes identifying land use, selecting receivers, determining existing noise levels, predicting future noise levels, and determining impacts.
- Section 6, “Detailed Analysis for Noise Barrier Design Considerations,” outlines the major aspects that affect the acoustical design of noise barriers, including the dimensions, location, and material; optimization of noise barriers; possible noise reflections; 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 difficulties and cautions.
- Section 7, “Noise Study Reports,” discusses the contents of noise study reports.
- Section 8, “Non-Routine Considerations and Issues,” covers non-routine and sometimes controversial issues involving the effects of noise on distant receivers, use of sound intensity and sound power as tools in characterizing sound sources, pavement noise, noise monitoring for insulating homes, construction noise, earthborne vibrations, California Occupational Safety and Health Administration (OSHA) noise standards, and effects and abatement of transportation-related noise on marine and wildlife.
- Section 9, “Glossary,” provides terminology and definitions common in transportation noise.
- Appendix A, “References Cited,” provide a listing of literature directly cited or used for reference in the TeNS.

Section 2
Basics of Highway Noise

The following sections introduce the fundamentals of sound and provide sufficient detail 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 to acquire a deeper understanding of the subject.

2.1 Physics of Sound

2.1.1 Sound, Noise, and Acoustics

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

Noise is defined as sound that is loud, unpleasant, unexpected, or undesired. It therefore may be classified as a more specific group of sounds. Although the terms *sound* and *noise* are often used synonymously, perceptions of sound and noise are highly subjective.

Sound is actually a process that consists of three components: source, path, and receiver. All three components must be present for sound to exist. Without a source, no sound pressure waves would be produced. Similarly, without a medium, sound pressure waves would not be transmitted. Finally, sound must be received—a hearing organ, sensor, or other object must be present to perceive, register, or be affected by sound. In most situations, there are many different sound sources, paths, and receivers.

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 abatement covers only a small, specialized part of acoustics.

2.1.2 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 pressure 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, approximately 1,126 feet per second (ft/s) in air of 20°C. The speed of sound can be calculated from the following formula:

$$c = \sqrt{1.401\left(\frac{P}{\rho}\right)} \quad \textbf{(2-1)}$$

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 = 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. Therefore, the speed of sound in the atmosphere is independent of air pressure. When air temperature changes, ρ changes, but *P* does not. Therefore, the speed of sound is temperature-dependent, as well as somewhat humidity-dependent because humidity affects the density of air. The effects of the latter with regard to the speed of sound, however, can be ignored for the purposes of the TeNS. The fact that the 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 0ºC, ρ is 1.2929 kg/m^3. At a standard air pressure of 760 millimeters Hg, pressure is 101,329 Pa. Using Equation 2-1, the speed of sound for standard pressure and temperature can be calculated as follows:

$$\mathbf{c} = \sqrt{(1.401)(\frac{101,329}{1.2929})} = 331.4 \text{ m/s, or } 1,087.3 \text{ ft/s.}$$

From this base value, the variation with temperature is described by the following equations:

$$\text{Metric units (m/s):} \quad c = 331.4\sqrt{1 + \frac{Tc}{273.2}} \qquad \textbf{(2-2)}$$

$$\text{English units (ft/s):} \quad c = 1051.3\sqrt{1 + \frac{Tf}{459.7}} \qquad \textbf{(2-3)}$$

Where:

c = speed of sound

T_c = temperature in degrees Celsius (include minus sign for less than 0ºC)

T_f = temperature in degrees Fahrenheit (include minus sign for less than 0ºF)

The above equations show that the speed of sound increases or decreases as the air temperature increases or decreases, respectively. This phenomenon plays an important role in the atmospheric effects on noise propagation, specifically through the process of refraction, which is discussed in Section 2.1.4.3.

2.1.3 Sound Characteristics

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

2.1.3.1 Frequency, Wavelength, and Hertz

For a given single pitch, the sound pressure waves are characterized by a sinusoidal periodic (i.e., recurring with regular intervals) wave, as shown in Figure 2-1. The upper curve shows how sound pressure varies above and below the ambient atmospheric pressure with distance at a given time. The lower curve shows how particle velocity varies above 0 (molecules moving right) and below 0 (molecules moving left). Please note that when the pressure fluctuation is at 0, the particle velocity is at its maximum, either in the positive or negative direction; when the pressure is at its positive or negative peak, the particle velocity is at 0. 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.

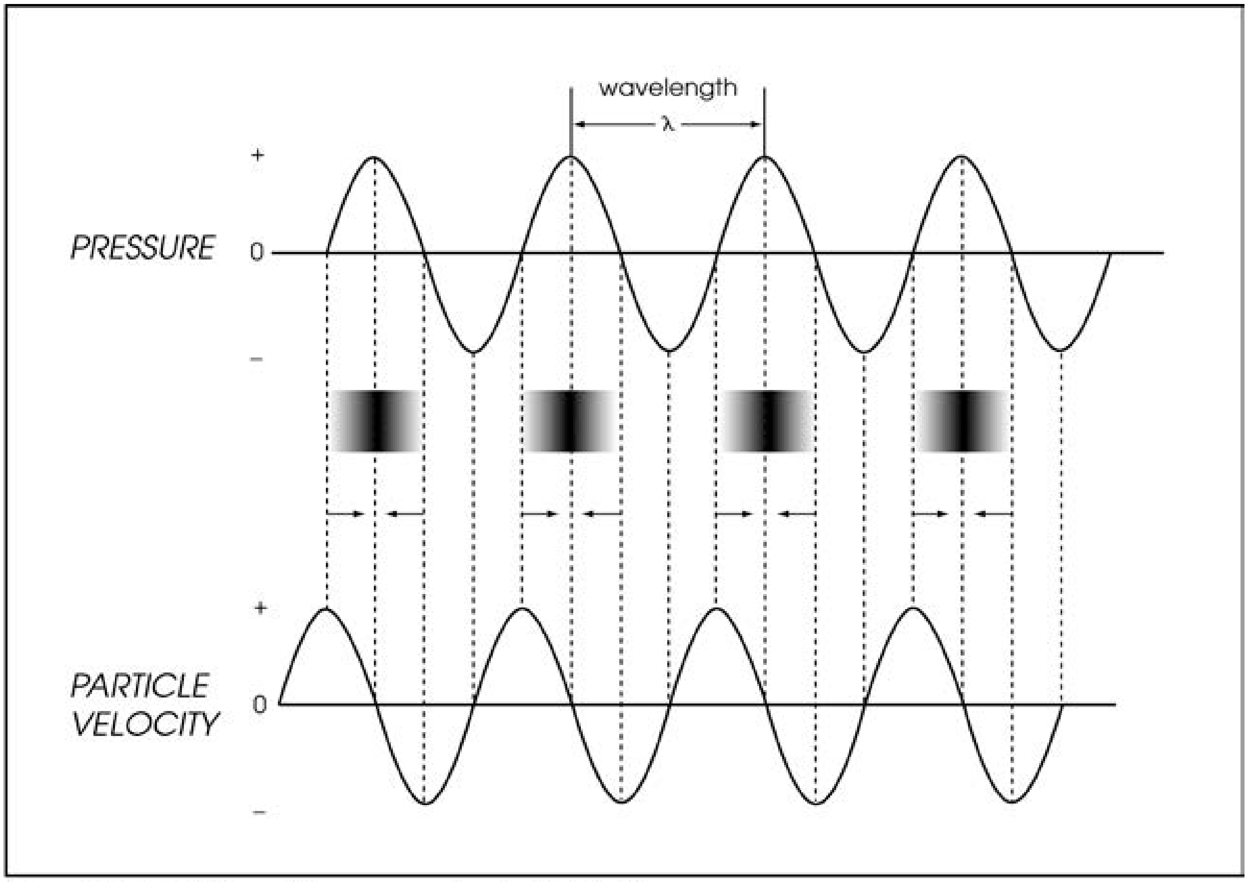

Figure 2-1. Sound Pressure vs. Particle Velocity

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 (Figure 2-2). Frequency is expressed in cycles per second, or hertz (Hz): 1 Hz equals one cycle per second. High frequencies are sometimes more conveniently expressed in units of kilohertz (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 20,000 Hz (20 kHz) on the high end. Frequencies are heard as the pitch or tone of sound. High-pitched sounds produce high frequencies, and 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 less than 16 Hz is referred to as infrasound, while high frequency sound above 20,000 Hz is called ultrasound. Both infrasound and ultrasound are not audible to humans, but 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 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 example, the frequency of a series of waves with periods of 0.05 (1/20) second is 20 Hz; a period of 0.001 (1/1000) second is 1,000 Hz or 1 kHz. Although low frequency earthborne vibrations (e.g., earthquakes and swaying of bridges or other structures) often are referred to by period, the term rarely is used in expressing airborne sound characteristics.

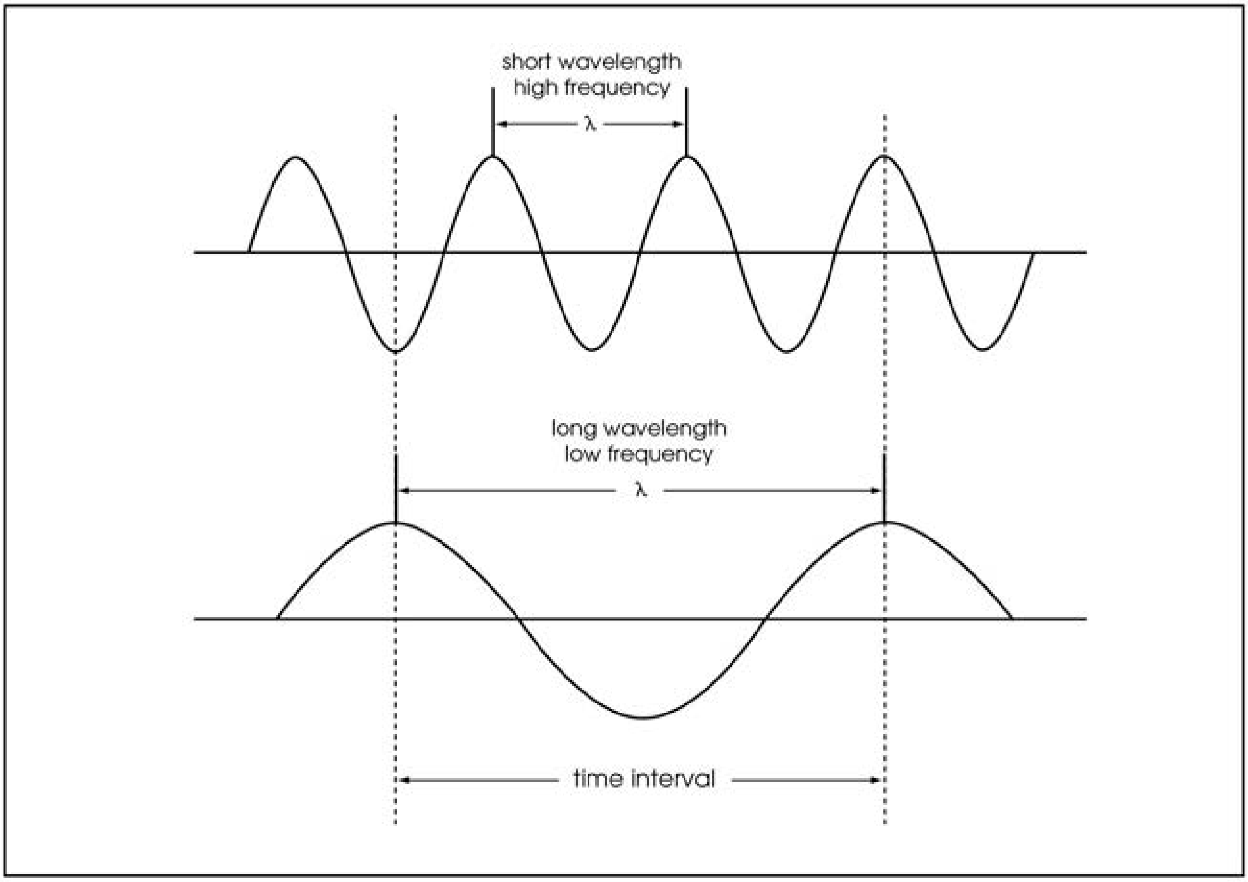

Figure 2-2. Frequency and Wavelength

Figure 2-2 shows that as the frequency of a sound pressure wave increases, its wavelength decreases, and vice versa. The relationship between frequency and wavelength is linked by the speed of sound, as shown in the following equations:

$$\lambda = \frac{c}{f} \qquad \textbf{(2-4)}$$

$$f = \frac{c}{\lambda} \qquad \textbf{(2-5)}$$

$$c = f\lambda \qquad \textbf{(2-6)}$$

Where:

λ = wavelength (meters or feet)

c = speed of sound (343.3 m/s at 20ºC, or 1,126.5 ft/s at 68º F)

f = frequency (Hz)

In these 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, it has been shown that it actually varies with temperature. These mathematical relationships hold true for any value of the speed of sound. Frequency normally is generated by mechanical processes at the source (e.g., wheel rotation, back and forth movement of pistons) and therefore is 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 be visualized easily 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 individual boxcars) is analogous to the speed of sound, while the length of each boxcar is the wavelength. The number of boxcars passing a stationary observer each second depicts the frequency (f). If the value of the latter is 2, and the speed of the train (c) is 108 kilometers per hour (km/hr), or 30 m/s, the length of each boxcar (λ) must be: c/f = 30/2 = 15 m.

Using Equation 2-4, a table can be developed showing frequency and associated wavelength. Table 2-1 shows the frequency and wavelength relationship at an air temperature of 20ºC (68ºF).

Table 2-1. Wavelength of Various Frequencies

Frequency (Hz)	Wavelength at 20ºC (68ºF) [Meters (Feet)]	
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)
1,000	0.34	(1.1)
2,000	0.17	(0.56)
4,000	0.09	(0.28)
8,000	0.04	(0.14)
16,000	0.02	(0.07)

The validity of Table 2-1 can be checked by multiplying each frequency by its wavelength, which should equal the speed of sound. Please notice that because of rounding, multiplying frequency and wavelength gives varying results for the speed of sound in air, which for 20ºC should be constant at 343.3 m/s (1,126.5 ft/s).

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 2.1.3.5 and 2.1.3.6.

2.1.3.2 Sound Pressure Levels and Decibels

As indicated in Figure 2-1, 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 referred to as the amplitude of the pressure waves. Whereas the frequency of the sound waves is responsible 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 microNewtons per square meter ($\mu N/m^2$), also called micro Pascals (μPa): 1 μPa is approximately one-hundred-billionth (1/100,000,000,000) of the normal atmospheric pressure. The pressure of a very loud sound may be 200 million μPa, or 10 million 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. Therefore, sound pressure levels

(SPLs) are described in logarithmic units of ratios of actual sound pressures to a reference pressure squared called bels. To provide a finer resolution, a bel is divided into tenths, or decibels (dB). In its simplest form, SPL in decibels is expressed as follows:

$$\text{Sound pressure level (SPL)} = 10\log_{10}\left(\frac{p_1}{p_0}\right)^2 \text{ dB} \qquad \textbf{(2-7)}$$

Where:

P_1 = sound pressure

P_0 = 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 is equal to the reference pressure, the expression results in a sound level of 0 dB:

$$10\log_{10}\left(\frac{p_1}{p_0}\right)^2 = 10\log_{10}(1) = 0 \text{ dB}$$

Please note that 0 dB does not represent an absence of any sound pressure. Instead, it is an extreme value that only those with the most sensitive ears can detect. Therefore, 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 most people, the threshold of hearing is probably close to 10 dB.

2.1.3.3 Root Mean Square and Relative Energy

Figure 2-1 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 decreasing 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 then can 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 peak SPL and root mean square (rms) SPL.

Peak SPL simply uses the maximum or peak amplitude (pressure deviation) for the value of P_1 in Equation 2-7. Therefore, peak SPL only uses one value (absolute value of peak pressure deviation) of the continuously changing amplitudes. The rms value of the wave amplitudes (pressure deviations) uses all 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; the square root of this mean value is the rms value. Figure 2-3 shows the peak and rms relationship for sinusoidal or single-frequency waves. The rms is 0.707 times the peak value.

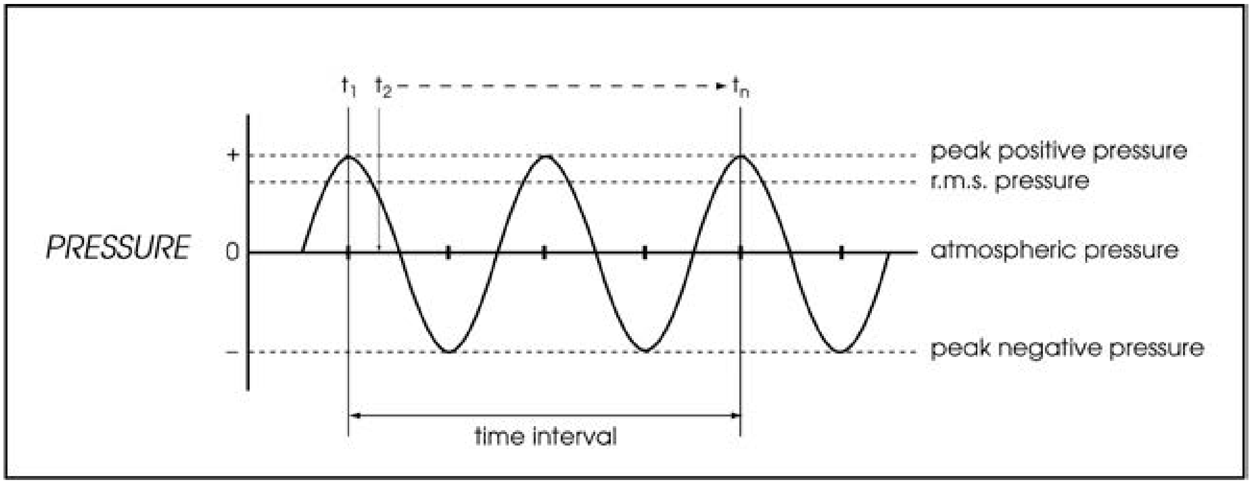

Figure 2-3. Peak and Root Mean Square Sound Pressure

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

$$\text{rms} = \sqrt{\left({}_1\Sigma^n(t_1^2 + t_2^2 + \ldots t_n^2)/n\right)} \qquad \textbf{(2-8)}$$

Where:

$t_1, t_2, \ldots t_n$ = discrete pressure values at times t_1 through t_n above (positive) and below (negative) the local atmospheric pressure

Sound pressures expressed in rms 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 SPLs are expressed as rms values.

2.1.3.4 Relationship between Sound Pressure Level, Relative Energy, Relative Pressure, and Pressure

Table 2-2 shows the relationship between rms SPL, relative sound energy, relative sound pressure, and pressure. Please note that SPL, 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 rms pressure deviations from local ambient atmospheric pressure.

The most useful relationship is that of SPL (dB) and relative energy. Relative energy is unitless. Table 2-2 shows that for each 10 dB increase in SPL the acoustic energy increases tenfold (e.g., 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, at a certain distance. For example, if one heavy truck passing by an observer at a given speed and distance produces an SPL of 80 dBA, the SPL of 10 heavy trucks identical to the single truck would be 90 dBA if they all could simultaneously occupy the same space and travel at the same speed and distance from the observer.

Because SPL is computed using $10\log_{10}(P_1/P_2)^2$, the acoustic energy is related to SPL as follows:

$$(P_1/P_2)^2 = 10^{SPL/10} \tag{2-9}$$

Table 2-2. Relationship between Sound Pressure Level, Relative Energy, Relative Pressure, and Sound Pressure

Sound Pressure Level (dB) $10\log_{10}\left(\frac{p_1}{p_0}\right)^2$		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		10^{20}	10^{10}	
	154			10^9 (1,000 Pa)
150		10^{15}		
140		10^{14}	10^7	
	134			10^8 (100 Pa)
130		10^{13}		
120		10^{12}	10^6	
	114			10^7 (10 Pa)
110		10^{11}		
100		10^{10}	10^5	
	94			10^6 (1 Pa)
90		10^9		
80		10^8	10^4	
	74			10^5 μPa
70		10^7		
60		10^6	10^3	
	54			10^4 μPa
50		10^5		
40		10^4	10^2	
	34			10^3 μPa
30		10^3		
20		10^2	10^1	
	14			10^2 μPa
10		10^1		
0		**10^0 = 1 = Ref.**	**10^0 = 1 = Ref.**	**$P_1 = P_0$ = 20** μPa

2.1.3.5 Adding, Subtracting, and Averaging Sound Pressure Levels

Because decibels are logarithmic units, SPL cannot be added or subtracted by ordinary arithmetic means. For example, if one automobile produces an SPL of 70 dB when it passes an observer, two cars passing simultaneously would not produce 140 dB; they would combine to produce 73 dB. The following discussion provides additional explanation of this concept. The SPL from any source observed at a given distance from the source may be expressed as $10\log_{10}(P_1/P_0)^2$ (see Equation 2-7). Therefore, the SPL from two equal sources at the same distance would be calculated as follows:

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

This 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 more than the sound level of one source. The total SPL of the two automobiles therefore would be 70 + 3 = 73 dB.

Adding and Subtracting Equal Sound Pressure Levels

The previous example of adding the noise levels of two cars may be expanded to any number of sources. The previous section described 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. It may be stated that *N* identical automobiles or other noise sources would yield an SPL calculated as follows:

$$SPL_{Total} = SPL_1 + 10\log_{10}(N) \quad \textbf{(2-10)}$$

Where:

SPL_1 = SPL of one source

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

Example

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

Solution

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

Equation 2-10 also may be rewritten as follows. This form is useful for subtracting equal SPLs:

$$SPL_1 = SPL_{Total} - 10\log_{10}(N) \quad \textbf{(2-11)}$$

Example

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

Solution

$SPL_1 = 68\text{ dB} - 10\log_{10}(6) = 68 - 7.8 = 60.2\text{ dB}$

In these 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, Equation 2-10 could have been written 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.

These exercises can be further expanded to include other useful applications in highway noise. For example, if one were to ask what the respective SPL increases would be along a highway if existing traffic were doubled, tripled, or quadrupled (assuming traffic mix, distribution, and speeds would not change), a reasonable prediction could be made using Equation 2-10. In this case, N would be the existing traffic ($N = 1$); $N = 2$ would be doubling, $N = 3$ would be tripling, and $N = 4$ would be quadrupling the existing traffic. Because $10\log_{10}(N)$ in Equation 2-10 represents the increase in SPL, the above values for N would yield +3, +4.8, and +6 dB, respectively.

Similarly, one might ask what the SPL decrease would be if traffic were reduced by a factor of 2, 3, or 4 (i.e., $N = 1/2$, $N = 1/3$, and $N = 1/4$, respectively). Applying $10\log_{10}(N)$ to these values would yield -3, -5, and -6 dB, respectively.

The same problem also may arise in a different form. For example, the traffic flow on a given facility is 5,000 vehicles per hour, and the SPL is 65 dB at a given location next to the facility. One might ask what the expected SPL would be if future traffic increased to 8,000 vehicles per hour. The solution would be:

$$65 + 10\log_{10}(8{,}000/5{,}000) = 65 + 2 = 67\text{ dB.}$$

Therefore, N may represent an integer, fraction, or ratio. However, N always must be more than 0. Taking the logarithm of 0 or a negative value is not possible.

In Equations 2-10 and 2-11, $10\log_{10}(N)$ was the increase from SPL_1 to SPL_{Total} and equals the change in noise levels from an increase or decrease in equal noise sources. Letting the change in SPLs be referred to as ΔSPL, Equations 2-10 and 2-11 can be rewritten as follows:

$$\Delta SPL = 10\log_{10}(N) \quad \textbf{(2-12)}$$

This equation is useful for calculating the number of equal source increments (*N*) that must be added or subtracted to change noise levels by ΔSPL. For example, if it is known that an increase in traffic volumes increases SPL by 7 dB, the factor change in traffic (assuming that traffic mix and speeds did not change) can be calculated as follows:

$7\text{ dB} = 10\log_{10}(N)$

$0.7\text{ dB} = \log_{10}(N)$

$10^{0.7} = N$

$N = 5.0$

Therefore, the traffic volume increased by a factor of 5.

Adding and Subtracting Unequal Sound Pressure Levels

If noise sources are not equal or equal noise sources are at different distances, $10\log_{10}(N)$ cannot be used. Instead, SPLs must be added or subtracted individually using the SPL and relative energy relationship in Equation 2-9. If the number of SPLs to be added is *N*, and SPL_1, SPL_2, and … SPL_n represent the first, second, and *n*th SPL, respectively, the addition is accomplished as follows:

$$SPL_{Total} = 10\log_{10}[10^{SPL_1/10} + 10^{SPL_2/10} + \ldots\ 10^{SPL_n/10}] \quad \textbf{(2-13)}$$

The above equation is the general equation for adding SPLs. The equation also may be used for subtraction (simply change "+" to "–"). However, the result between the brackets must always be more than 0. For example, determining the total SPL of 82, 75, 88, 68, and 79 dB would use Equation 2-13 as follows:

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

Adding Sound Pressure Levels Using a Simple Table

When combining sound levels, a table such as the following may be used as an approximation.

Table 2-3. 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 dB
2 or 3 dB	2 dB	74 + 71 = 76 dB
4 to 9 dB	1 dB	66 + 60 = 67 dB
10 dB or more	0 dB	65 + 55 = 65 dB

This table yields results within about 1 dB of the mathematically exact value and can be memorized easily. The table can also be used to add more than two SPLs. First, the list of values should be sorted, from lowest to highest. Then, starting with the lowest values, the first two should be combined, the result should be added to the third value, and so on until only the answer remains. For example, to determine the sum of the sound levels used in the preceding example using Table 2-3, the first step would be to rank the values from low to high: 68, 75, 79, 82, and 88 dB.

Using Table 2-3, the first two noise levels then should be added. The result then would be added to the next noise level, etc., as follows:

68 + 75 = 76,
76 + 79 = 81,
81 + 82 = 85,
85 + 88 = 90 dB
For comparison, using Equation 2-13, total SPL was 89.6 dB.

Two decibel-addition rules are important. First, when adding a noise level to an approximately equal noise level, the total noise level increases 3 dB. For example, doubling the traffic on a highway would result in an increase of 3 dB. Conversely, reducing traffic by one half would reduce the noise level by 3 dB. Second, when two noise levels are 10 dB or more apart, the lower value does not contribute significantly (less than 0.5 dB) to the total noise level. For example, 60 + 70 dB ≈ 70 dB. This means that if a noise level measured from a source is at least 70 dB, the background noise level (without the target source) must not be more than 60 dB to avoid risking contamination.

Averaging Sound Pressure Levels

There are two ways of averaging SPLs: arithmetic averaging and energy-averaging. Arithmetic averaging is simply averaging the decibel values. For example, the arithmetic average (mean) of 60 and 70 dB is:

$$(60 + 70)/2 = 65 \text{ dB}$$

Energy averaging is averaging of the energy values. Using the previous example, the energy average (mean) of 60 and 70 dB is:

$$10\log[(10^{6.0} + 10^{7.0})/2] = 67.4 \text{ dB}$$

Please notice that the energy average is always equal to or more than the arithmetic average. It is only equal to the arithmetic average if all values are the same. Averaging the values 60, 60, 60, and 60 dB yields equal results of 60 dB in both cases. The following discussion shows some examples of when each method is appropriate.

Energy Averaging

Energy averaging is the most widely used method of averaging noise levels. Sound energy relates directly to the sound source. For example, at a given distance the sound energy from six equal noise sources is three times that of two of the same sources at that same distance. If for some reason one wishes to average the number of sources and calculate the associated noise level, the correct way to do this is with energy averaging. Examples of applications of energy averaging are provided below.

Example 1

Assume that one is interested in the average noise level at a specific receiver along a highway between 6 a.m. and 7 a.m., and it is decided to take five 1-hour measurements on random days during that hour. The energy-averaged measurement results are 68, 67, 71, 70, and 71 dB. What is a good estimate of the noise level at that receiver? Because the main reason for the fluctuations in noise levels is probably the differences in source strength (vehicle mix, volumes, and speeds), energy averaging would be appropriate. Therefore, the result would be: $10\log[(10^{6.8} + 10^{6.7} + 10^{7.1} + 10^{7.0} + 10^{7.1})/5] = 69.6$ dB, or 70 dB.

Example 2

Noise is measured at a location along a highway. Assume that all vehicles on that highway are distributed equally, are traveling at the same speed, and are of the same type (e.g., automobiles). Such traffic characteristics would produce a near steady-state noise level. For example, one wants to measure the traffic noise for an hour. After 15 minutes, the traffic volume suddenly increases sharply, but speeds remain the same and the vehicles, although closer together, are still equally distributed for the remaining 45 minutes. The noise level during the first 15 minutes was 70 dB and during the last 45 minutes was 75 dB. What was the energy-averaged noise level? Because the time periods were not the same, the energy average must be time-weighted by using the following equation:

$$\text{Energy-averaged noise level} = 10\log[(15 * 10^{7.0} + 45 * 10^{7.5})/60] = 74.2\text{ dB}$$

In this example, the time was weighted in units of minutes. This also could have been accomplished using fractions of 1 hour, as follows:

$$\text{Energy-averaged noise level} = 10\log[(0.25 * 10^{7.0} + 0.75 * 10^{7.5})/1] = 74.2\text{ dB}$$

Arithmetic Averaging

Arithmetic averaging is used less frequently, but it is used in situations such as the following. For example, one wants to measure the noise of a machine with great accuracy. For simplicity, assume that the machine produces a steady noise level, which is expected to be constant, each time the machine is turned on. Because accuracy is of great importance, it is chosen to take repeat measurements with different sound level meters and to calculate the average noise level. In this case, it is appropriate to calculate the arithmetic mean by adding the measured decibel values and dividing by the number of measurements. Because the same source is measured repeatedly, any measured noise fluctuations are mainly from errors inherent in the instrumentation; method of measurement; environmental conditions; and, to a certain extent, source strength. Because the errors are distributed randomly, the expected value of the measurements is the arithmetic mean.

It is also appropriate to use arithmetic means for statistical comparisons of noise levels, or hypothesis testing, whether the noise levels were obtained by energy averaging or arithmetic means. Examples of applications of arithmetic averaging are provided below.

<u>Example 1</u>

One wants to compare the noise levels from Compressors A and B. It is decided to take five independent noise measurements at 25 feet from each compressor. Between each measurement, the compressors will be shut off and restarted. The following data are collected:

Compressor	Measured Noise Levels (dB)	Arithmetic Average (dB)
A	75, 76, 73, 74, 75	(75+76+73+74+75)/5 = 74.6
B	77, 75, 76, 78, 75	(77+75+76+78+75)/5 = 76.2

In addition, the hypothesis that Compressors A and B emit the same noise can be tested by calculating the standard deviations and using appropriate statistical tests assuming a certain level of significance. However, this is not the subject of discussion in this case.

Example 2
Residents A and B live next to the same highway. Resident A complains about the noise at night, while Resident B does not. One wishes to determine whether the nighttime noise level is higher at Residence A than Residence B. Four hours at night are randomly selected, and simultaneous energy-averaged noise measurements are taken at Residences A and B during the 4 hours. The measurement results are:

Hour	Residence A (dB)	Residence B (dB)
1	65	62
2	62	58
3	63	59
4	66	63
Arithmetic mean	64.0	60.5

The goal is a statistical comparison of noise levels at Residences A and B for the same randomly selected time periods, as well as the same traffic and environmental conditions. Although the 1-hour noise levels represent energy averages for each hour, arithmetic means should be calculated for the statistical comparison, as shown in the preceding measurement results.

The hypothesis that noise levels at Residence A equal noise levels at Residence B can be tested using the standard deviations, as well as the appropriate tests and significance levels. Please note, however, that statistical significance has no relationship to human significance. In this example, the noise level at Residence A is probably significantly higher statistically than at Residence B. In terms of human perception, however, the difference may be barely perceptible.

A good rule to remember is that whenever measurements or calculations must relate to the number of sources or source strength, energy averaging should be used. However, if improving accuracy in measurements or calculations of the same events or making statistical comparisons is the goal, the arithmetic means will be appropriate. Additional details about averaging and time-weighting are covered in the Section 2.2.2.

2.1.3.6 A-Weighting and Noise Levels.

SPL alone is not a reliable indicator of loudness. Frequency or pitch 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, 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 SPL in that range. In general, the healthy human ear is most sensitive to sounds between 1,000 and 5,000 Hz and perceives both higher and lower frequency sounds of the same magnitude with less intensity. To approximate the frequency response of the human ear, a series of SPL 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 everyday sounds. When people make relative judgments of the loudness or annoyance of a sound, their judgments 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 (e.g., B-, C-, D-scales), but these scales rarely, if ever, are used in conjunction with highway traffic noise. Noise levels for traffic noise reports should be reported as dBA. In environmental noise studies, A-weighted SPLs commonly are referred to as noise levels.

Figure 2-4 shows the A-scale weighting network that is normally used to approximate human response. The 0-dB line represents a reference line; the curve represents frequency-dependent attenuations provided by the ear's response. Table 2-4 shows the standardized values (American National Standards Institute 1983). The use of this weighting network is signified by appending an "A" to the SPL as dBA or dB(A).

The A-weighted curve was developed from averaging the statistics of many psychoacoustic tests involving large groups of people with normal hearing in the age group of 18 to 25 years. The internationally standardized curve is used worldwide to address environmental noise and is incorporated in virtually all environmental noise descriptors and standards. Section 2.2.2 covers the most common descriptors, applicable to transportation noise.

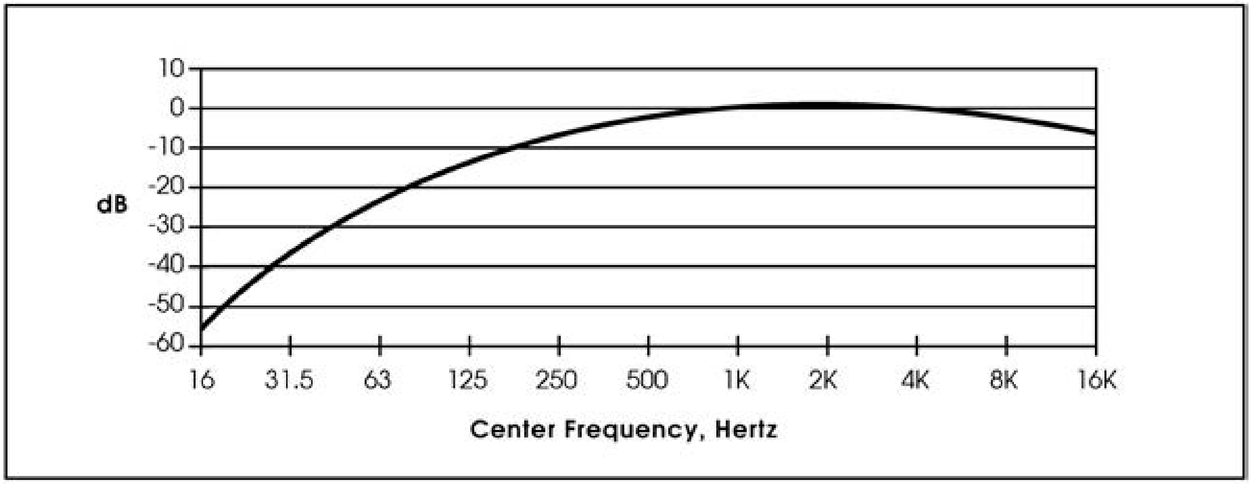

Figure 2-4. A-Weighting Network

Table 2-4. A-Weighting Adjustments for One-Third-Octave Center Frequencies

Frequency (Hz)	A-Weighting (dB)	Frequency (Hz)	A-Weighting (dB)	Frequency (Hz)	A-Weighting (dB)	Frequency (Hz)	A-Weighting (dB)
16	-56.7	100	-19.1	630	-1.9	4,000	+1.0
20	-50.5	125	-16.1	800	-0.8	5,000	+0.5
25	-44.7	160	-13.4	1,000	0	6,300	-0.1
31.5	-39.4	200	-10.9	1,250	+0.6	8,000	-1.1
40	-34.6	250	-8.6	1,600	+1.0	10,000	-2.5
50	-30.6	315	-6.6	2,000	+1.2	12,500	-4.3
63	-26.2	400	-4.8	2,500	+1.3	16,000	-6.6
80	-22.5	500	-3.2	3,150	+1.2	20,000	-9.3

Source: American National Standards Institute 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. Each filter allows the passage of a selected range (band) of frequencies only and attenuates its SPL to modify the frequency response of the sound level meter to about that of the A-weighted curve and the human ear.

A range of noise levels associated with common indoor and outdoor activities is shown in Table 2-5. The decibel scale is open-ended. As discussed, 0 dB or 0 dBA should not be construed as the absence of sound.

Instead, it is the generally accepted threshold of the best human hearing. SPLs in negative decibel ranges are inaudible to humans. On the other extreme, the decibel scale can go much higher than shown in Table 2-5. For example, gunshots, 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 2.2.1.1 discusses the human response to changes in noise levels.

Table 2-5. Typical Noise Levels

Common Outdoor Activities	Noise Level (dBA)	Common Indoor Activities
	110	Rock band
Jet flyover at 1,000 feet		
	100	
Gas lawnmower at 3 feet		
	90	
Diesel truck at 50 feet at 50 mph		Food blender at 3 feet
	80	Garbage disposal at 3 feet
Noisy urban area, daytime		
Gas lawnmower, 100 feet	**70**	Vacuum cleaner at 10 feet
Commercial area		Normal speech at 3 feet
Heavy traffic at 300 feet	**60**	
		Large business office
Quiet urban daytime	**50**	Dishwasher in next room
Quiet urban nighttime	**40**	Theater, large conference room (background)
Quiet suburban nighttime		
	30	Library
Quiet rural nighttime		Bedroom at night, concert hall (background)
	20	
		Broadcast/recording studio
	10	
	0	

2.1.3.7 Octave and One-Third-Octave Bands and Frequency Spectra

Very few sounds are pure tones (i.e., consisting of a single frequency). To represent the complete characteristics of a sound properly, it is necessary to divide the total sound into its frequency components (i.e., determine how much sound [SPL] comes from each of the multiple frequencies that make up the sound). This representation of frequency vs. SPL is called a frequency spectrum. Spectra usually consist of 8- to 10-octave bands, more or less spanning the frequency range of human hearing (20 to 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" (geometric means).

Because octave bands are rather broad, they are frequently subdivided into thirds to create one-third-octave bands. These are also standardized. For convenience, one-third-octave bands are sometimes numbered from 1 (1.25-Hz one-third-octave center frequency, which cannot be heard by humans) to 43 (20,000-Hz one-third-octave center frequency). Within the extreme range of human hearing there are 30 one-third-octave bands ranging from band 13 (20-Hz one-third-octave center frequency) to band 42 (16,000-Hz one-third-octave center frequency). Table 2-6 shows the ranges of the standardized octave and one-third-octave bands, as well as band numbers.

Frequency spectra are used in many aspects of sound analysis, from studying sound propagation to designing effective noise control measures. Sound is affected by many frequency-dependent physical and environmental factors. Atmospheric conditions, site characteristics, and materials and their dimensions used for sound reduction are some of the most 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. Effectiveness of different materials at transmitting noise will depend on the frequency of the noise. See Section 6.1.1 for a discussion of transmission loss and sound transmission class.

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 70 feet will tend to pass over a 16-foot-high noise barrier. Fortunately, A-weighted traffic noise tends to dominate in the 250- to 2,000-Hz range with wavelengths of about 0.6 to 4.5 feet. As discussed later, noise barriers are less effective at lower frequencies and more effective at higher ones.

Table 2-6. Standardized Band Numbers, Center Frequencies, One-Third-Octave and Octave Bands, and Octave Band Ranges

Band	Center Frequency (Hz)	One-Third-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	**1,000**	891–1,120	**708–1,410**
31	1,250	1,120–1,410	
32	1,600	1,410–1,780	
33	**2,000**	1,780–2,240	**1,410–2,820**
34	2,500	2,240–2,820	
35	3,150	2,820–3,550	
36	**4,000**	3,550–4,470	**2,820–5,620**
37	5,000	4,470–5,620	
38	6,300	5,620–7,080	

Band	Center Frequency (Hz)	One-Third-Octave Band Range (Hz)	Octave Band Range (Hz)
39	**8,000**	7,080–8,910	**5,620–11,200**
40	10,000	8,910–11,200	
41	12,500	11,200–14,100	
42	**16,000**	14,100–17,800	**11,200–22,400**
43	20,000	17,800–22,400	

Source: Bruel & Kjaer 1986.

Figure 2-5 shows a conventional graphical representation of a typical octave-band frequency spectrum. The octave bands are depicted as having the same width, although each successive band should increase by a factor of 2 when expressed linearly in terms of 1-Hz increments.

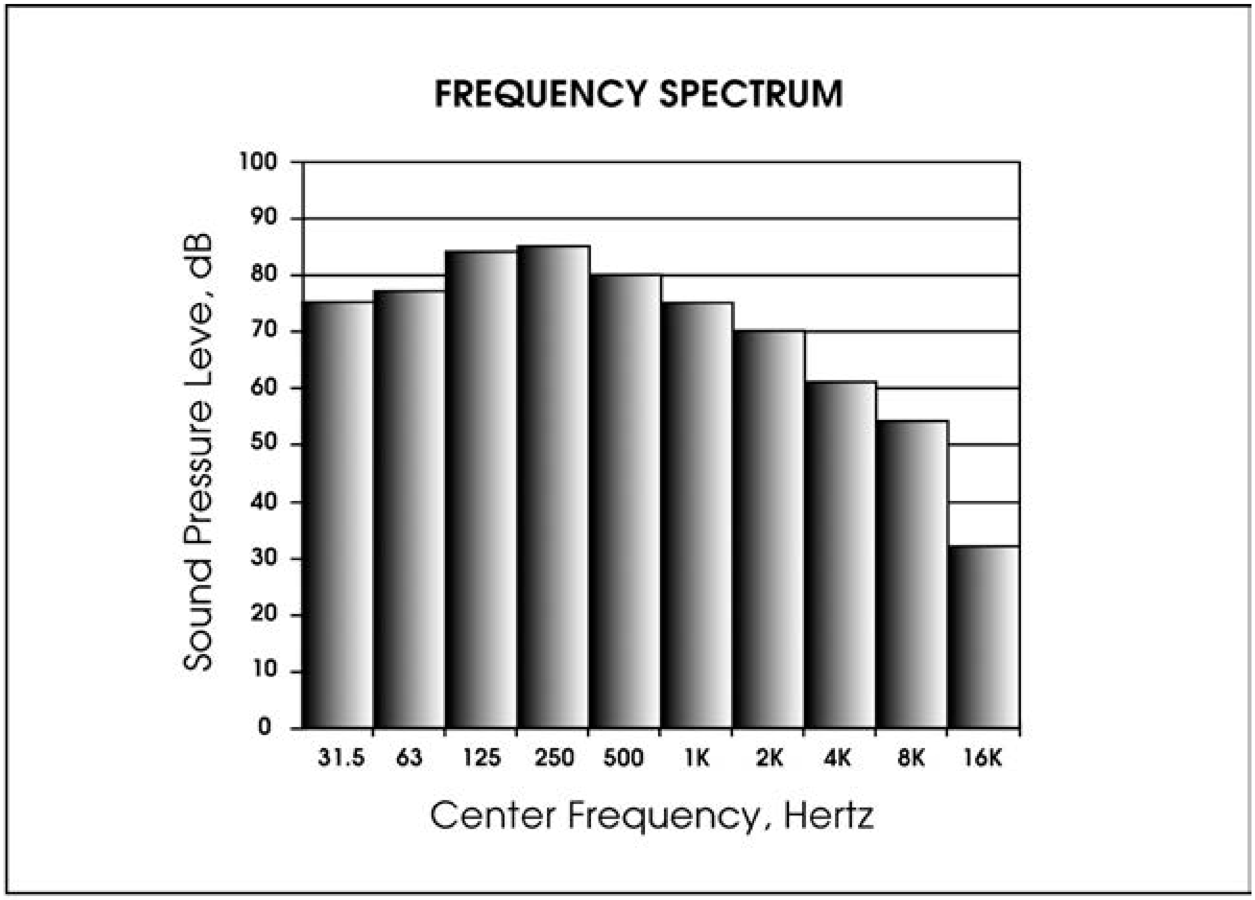

Figure 2-5. Typical Octave Band Frequency Spectrum

A frequency spectrum can also be presented in tabular form. For example, the data used to generate Figure 2-5 is illustrated in tabular form in Table 2-7.

Table 2-7. 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
1,000	75
2,000	70
4,000	61
8,000	54
16,000	32
Total sound pressure level = 89 dB	

Often, one is interested in the total noise level, or the summation of all octave bands. Using the data shown in Table 2-8, one may simply add all the SPLs, as was explained in Section 2.1.3.5. The total noise level for the above octave band frequency spectrum is 89 dB.

The same sorts of charts and tables can be compiled from one-third-octave band information. For example, if one had more detailed one-third-octave information for the above spectrum, a one-third-octave band spectrum could be constructed as shown in Figure 2-6 and Table 2-8. Please note that the total noise level does not change, and that each subdivision of three one-third-octave bands adds up to the total octave band shown in the previous example.

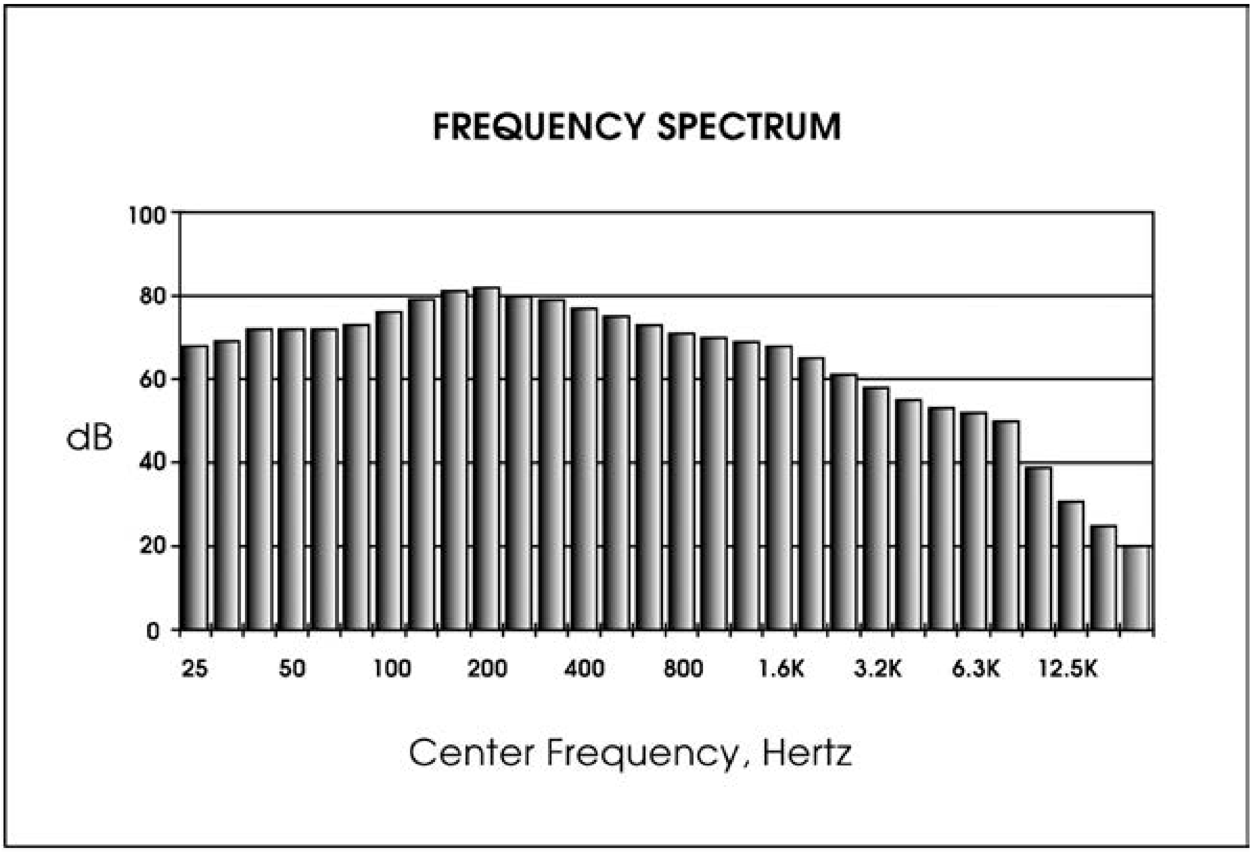

Figure 2-6. Typical One-Third-Octave Band Frequency Spectrum

Frequency spectrums are usually expressed in linear, unweighted SPLs (dB). However, they may also be A-weighted by applying the adjustments from Table 2-4. For example, the data in Table 2-8 can be A-weighted (rounded to nearest dB) as shown in Table 2-9.

Table 2-8. Tabular Form of Octave Band Spectrum

One-Third-Octave Band Center Frequency (Hz)	Sound Pressure Level (dB)	One-Third-Octave Band Center Frequency (Hz)	Sound Pressure Level (dB)	One-Third-Octave Band Center Frequency (Hz)	Sound Pressure Level (dB)
25	68	**250**	80	2,500	61
31.5	69	315	79	3,200	58
40	72	400	77	**4,000**	55
50	72	**500**	75	5,000	53
63	72	630	73	6,300	52
80	73	800	71	**8,000**	50
100	76	**1,000**	70	10,000	39
125	79	1,250	69	12,500	31
160	81	1,600	68	**16,000**	25
200	82	**2,000**	65	20,000	20
Total sound pressure level = 89 dB					

Table 2-9. 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
1,000	75 – 0 = 75
2,000	70 + 1 = 71
4,000	61 + 1 = 62
8,000	54 – 1 = 53
16,000	32 – 7 = 25
Total sound pressure level = 89 dB (linear) 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.

A linear noise level of 89 dB with a different frequency spectrum, however, could have produced a different A-weighted noise level, either higher or lower. The reverse may also be true. Theoretically, an infinite number of frequency spectrums 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 example, some evidence suggests that changes in frequencies are sometimes perceived as changes in noise levels, although the total A-weighted noise levels do not change significantly. Section 8 deals with some of these phenomena.

2.1.3.8 White and Pink Noise

White noise is noise with a special frequency spectrum that has the same amplitude (level) for each frequency interval 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 one-third-octave band spectrum of white noise would be a straight line, but this is 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 one-third-octave band.

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

2.1.4 Sound Propagation

From the source to 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; and

- shielding by natural and manmade features, noise barriers, diffraction, and reflection.

2.1.4.1 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, resulting from 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 2-7, from a^2 to $4a^2$.

Because the same amount of energy passes through both squares, the energy per unit area at 2D is reduced four times from that at distance D. Therefore, 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/DD reduction. This is the point source attenuation rate for geometric spreading.

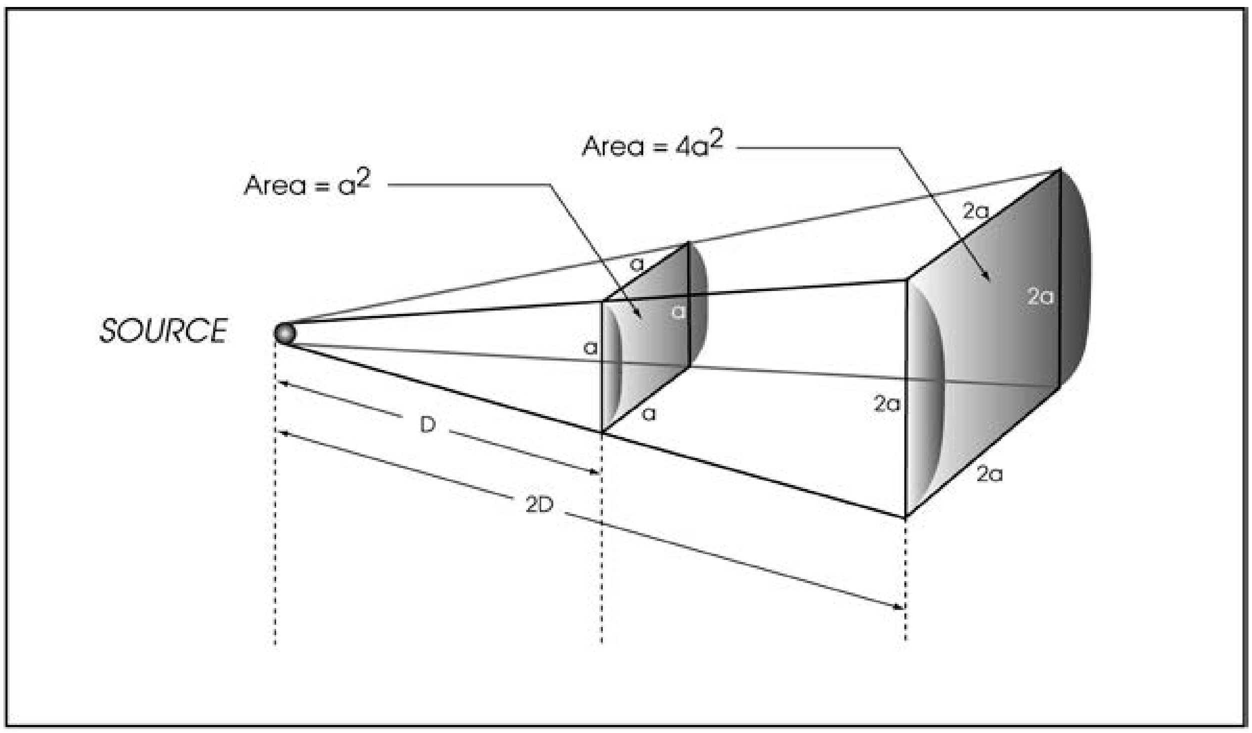

Figure 2-7. Point Source Propagation (Spherical Spreading)

As seen in Figure 2-8, based on the inverse square law the change in noise level between any two distances because of spherical spreading can be found using the following equation:

$$dBA_2 = dBA_1 + 10\log_{10}[(D_1/D_2)]^2 = dBA_1 + 20\log_{10}(D_1/D_2) \qquad \textbf{(2-14)}$$

Where:

dBA_1 = noise level at distance D_1

dBA_2 = noise level at distance D_2

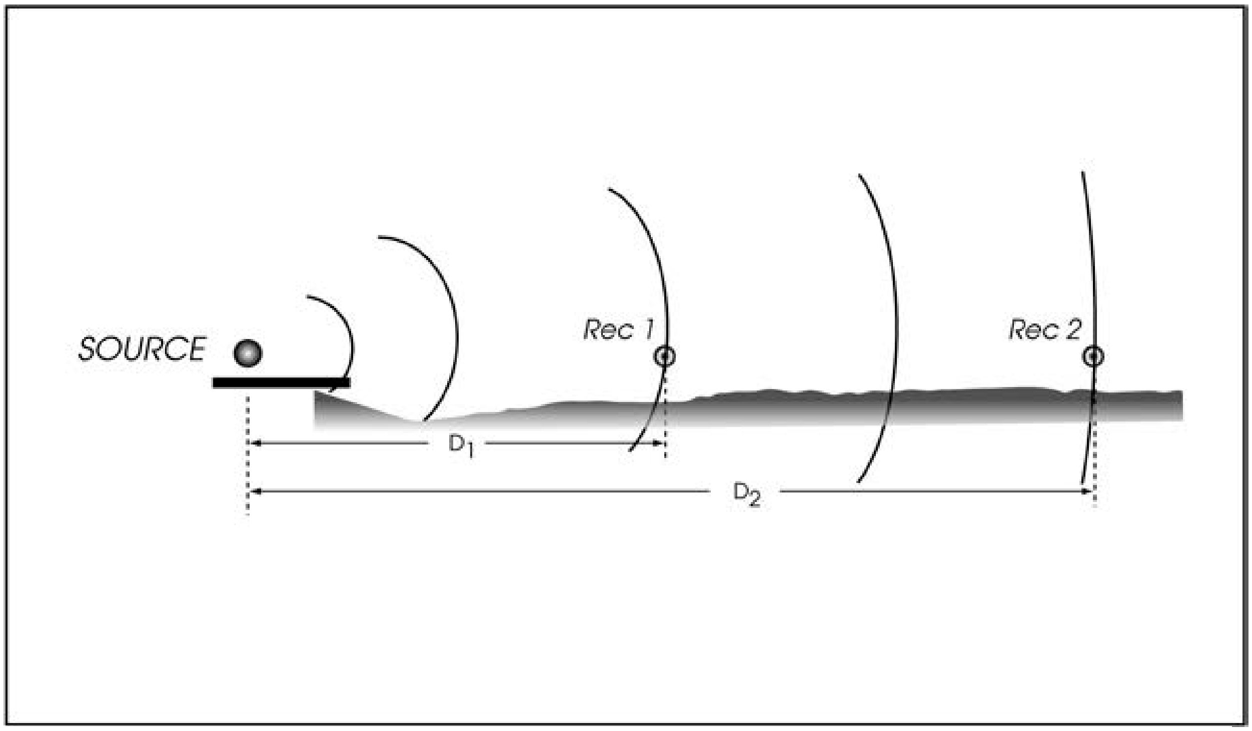

Figure 2-8. Change in Noise Level with Distance from Spherical Spreading

However, highway traffic noise is not a single, stationary point source. 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 a time interval (Figure 2-9). This results in cylindrical spreading rather than spherical spreading. Because 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/DD. The change in noise levels for a line source at any two different distances from cylindrical spreading is determined using the following equation:

$$dBA_2 = dBA_1 + 10\log_{10}(D_1/D_2) \quad \textbf{(2-15)}$$

Where:

dBA_1 = noise level at distance D_1 and conventionally the known noise level

dBA_2 = 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 more than D_1 and positive when D_1 is more than D_2. Therefore, the equation automatically accounts for the receiver being farther or closer with respect to the source—$\log_{10}$ of a number less than 1 gives a negative result, $\log_{10}$ of a number more than 1 is positive, and $\log_{10}(1) = 0$.

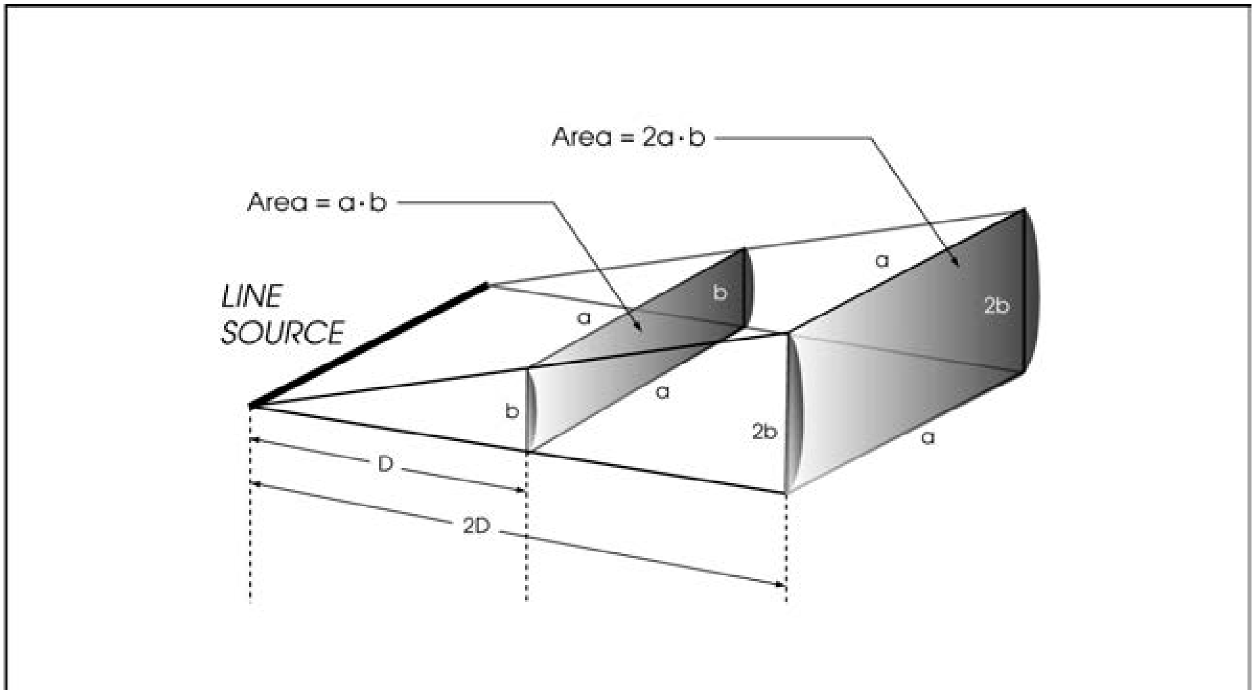

Figure 2-9. Line Source Propagation (Cylindrical Spreading)

2.1.4.2 Ground Absorption

Most often, the noise path between the highway and observer is very close to the ground. Noise attenuation from ground absorption and reflective wave cancellation adds to the attenuation from geometric spreading. Traditionally, this excess attenuation has been expressed in terms of decibels of attenuation per doubling of distance. This approximation is done for simplification only; for distances of less than 200 feet, the prediction results based on this scheme are sufficiently accurate. The sum of the geometric spreading attenuation and excess ground attenuation (if any) is referred to as the attenuation or dropoff rate. For distances of 200 feet or more, the approximation causes excessive inaccuracies in predictions. The amount of excess ground attenuation depends on the height of the noise path and characteristics of the intervening ground or site. In practice, excess ground attenuation may vary from 0 to 8–10 dBA/DD or more. In fact, it varies as the noise path height changes from the source to receiver and with vehicle type because the source heights are different. The complexity of terrain also influences the propagation of sound by potentially increasing the number of ground reflections.

The Federal Highway Administration (FHWA) Traffic Noise Model (TNM) Version 2.5 is the model that is currently approved by FHWA for use in noise impact studies. The TNM has complex algorithms that directly calculate excess ground attenuation based on ground type and site geometry. The earlier and now superceded FHWA noise model called the FHWA Highway Traffic Noise Prediction Model (HTNPM), which is described in FHWA Report FHWA-RD-77-108, used simplifying assumptions for calculating excess ground attenuation. Although not directly applicable to current noise impact studies, the method used by the HTNPM to calculate geometric and excess ground attenuation is discussed here for general reference.

The HTNPM categorizes project site conditions as follows:

- **Hard Sites:** These are sites with a reflective surface between the source and receiver, such as parking lots or smooth bodies of water. No excess ground attenuation is assumed for these sites. With hard sites, changes in noise levels with distance (dropoff rate) are related to geometric spreading only (3 dBA/DD for a line source and 6 dBA/DD for a point source).
- **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, this results in an overall dropoff rate of 4.5 dBA/DD for a line source and 7.5 dBA/DD for a point source.

The combined distance attenuation of noise from geometric spreading and ground absorption in the preceding scheme can be generalized with the following formulas:

$$\text{Line Source} = dBA_2 = dBA_1 + 10\log_{10}(D_1/D_2)^{1+\alpha} \quad \textbf{(2-16)}$$

$$\text{Point Source} = dBA_2 = dBA_1 + 10\log_{10}(D_1/D_2)^{2+\alpha} \quad \textbf{(2-17)}$$

Where:

α = site parameter that takes on the value of 0 for hard site and 0.5 for soft site

These formulas calculate the noise level at one distance if the noise level at another distance is known. The "α" scheme is just an approximation. Caltrans research has shown that for average traffic and soft-site characteristics, the α scheme is fairly accurate within 100 feet of a typical highway. Between 100 and 200 feet of a highway, the algorithm results in average overpredictions (model-predicted noise levels higher than actual) of 2 dBA. At 200 to 500 feet, overpredictions average about 4 dBA. Some typical examples of distance adjustment calculations using Equations 2-16 and 2-17 are provided below.

Example 1

The maximum noise level of a truck passing by an observer is measured to be 83 dBA at a distance of 25 meters. What is the maximum noise level at 62 meters if the terrain is considered a soft site? The truck is a point source; α for a soft site = 0.5. Therefore, at 62 meters the noise level is calculated as follows:

$$83 + 10\log_{10}(25/62)^{2+0.5} = 83 + (-9.9) = 73.1 \text{ dBA}$$

Example 2

The energy average noise level from a two-lane highway is 65 dBA at a receiver located 50 meters from the centerline. The ground between the highway and receiver is a grassy field. What noise level can be expected for a receiver 20 meters from the centerline of the same highway? The two-lane highway may be considered a line source (a series of moving point sources). The site parameter α is 0.5 (the grassy field is a soft site). Therefore, at 20 meters the estimated noise level is calculated as follows:

$$65 + 10\log_{10}(50/20)^{1+0.5} = 65 + (+6.0) = 71 \text{ dBA}$$

Please 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 is true.

Example 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 its noise falls below ambient noise, is 62 dBA at a distance of 35 meters. What is the energy average noise level of the truck at 50 meters if the site is hard? In this case the line source formula should be used. The difference between Examples 1 and 3 is that the maximum noise level was measured in Example 1. 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; 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. Therefore, Equation 2-16 should be used with $\alpha = 0$. The answer is 60.5 dBA at 50 meters.

Table 2-10 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. Section 5.5 contains additional discussions on how to use the appropriate dropoff rate in the noise prediction models.

Table 2-10. 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 Equation 2-17 (point source)	Use Equation 2-17 (point source)
Single moving point source (e.g., moving truck)	Use Equation 2-17 (point source)	Use Equation 2-16 (line source)
Series of point sources on a line, stationary or moving (e.g., highway traffic)	Use Equation 2-16 (line source)	Use Equation 2-16 (line source)

2.1.4.3 Atmospheric Effects and Refraction

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

Wind

The effects of wind on noise are mostly confined to noise paths close to the ground because of the wind shear phenomenon. Wind shear is caused by the slowing of wind in the vicinity of a ground plane because of 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 with decreasing heights, it creates a sound velocity gradient (because of 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 of the source and a noise concentration (increase) downwind of the source. Figure 2-10 shows the effects of wind on noise. Wind effects on noise levels along a highway depend very much on wind angle, receiver distance, and site characteristics. A 6-mph cross wind can increase noise levels at 250 feet 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 wind. 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 wind screen 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 0.5-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 analysis. FHWA's *Sound Procedures for Measuring Highway Noise: Final Report* (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 is provided in Section 3.

Wind Turbulence

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

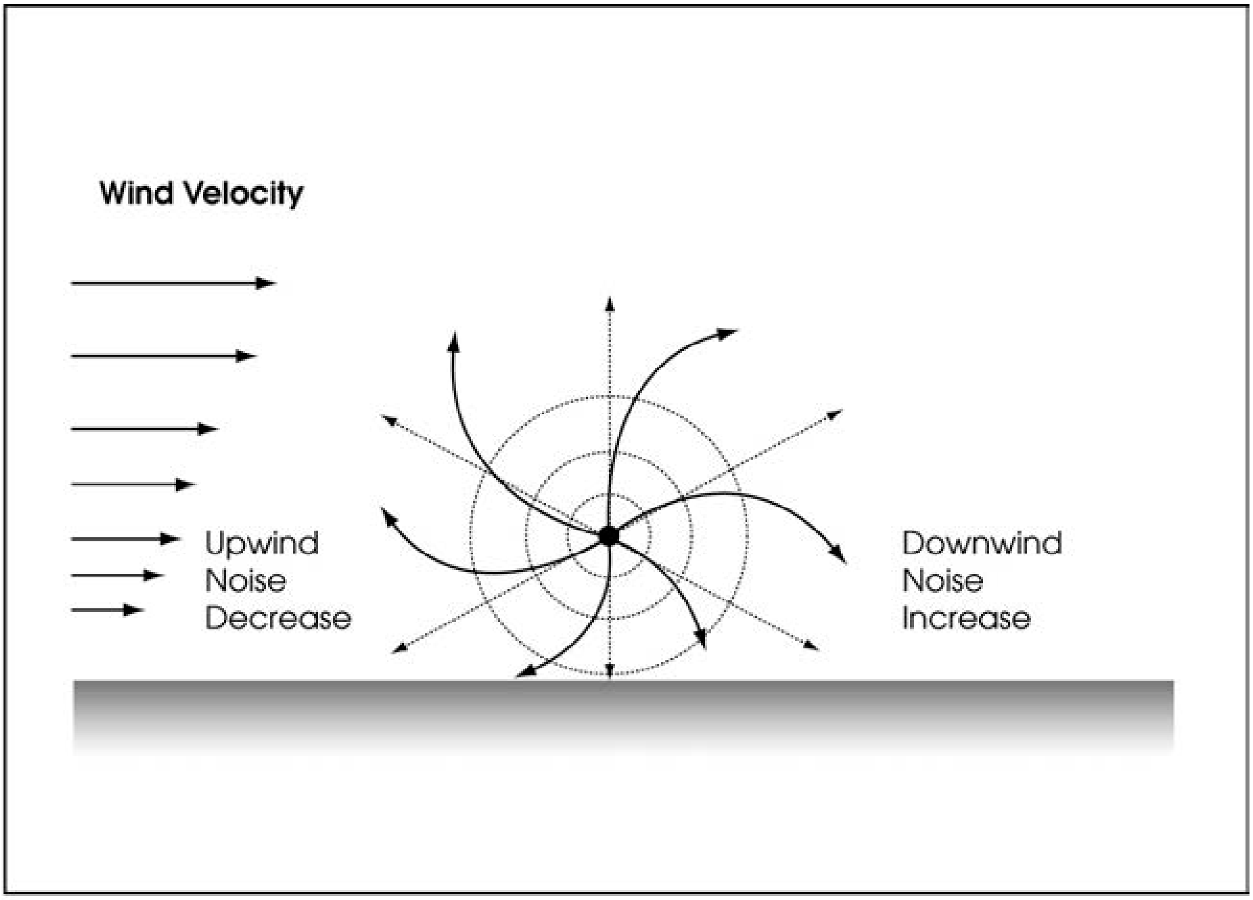

Figure 2-10. Wind Effects on Noise Levels

Temperature Gradients

Figure 2-11 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 -1ºC per 100 m. Because 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 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. Also, 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.

Temperature and Humidity

Molecular absorption in air also reduces noise levels with distance. Although this process only accounts for about 1 dBA per 1,000 feet 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 corresponding increase in frequencies of noise at the source. Because the propagation of noise is frequency-dependent, rain may also affect distance attenuation rates. However, 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. Therefore, no noise measurements or predictions are made for rainy conditions. Noise abatement criteria (NAC) and standards do not address rain.

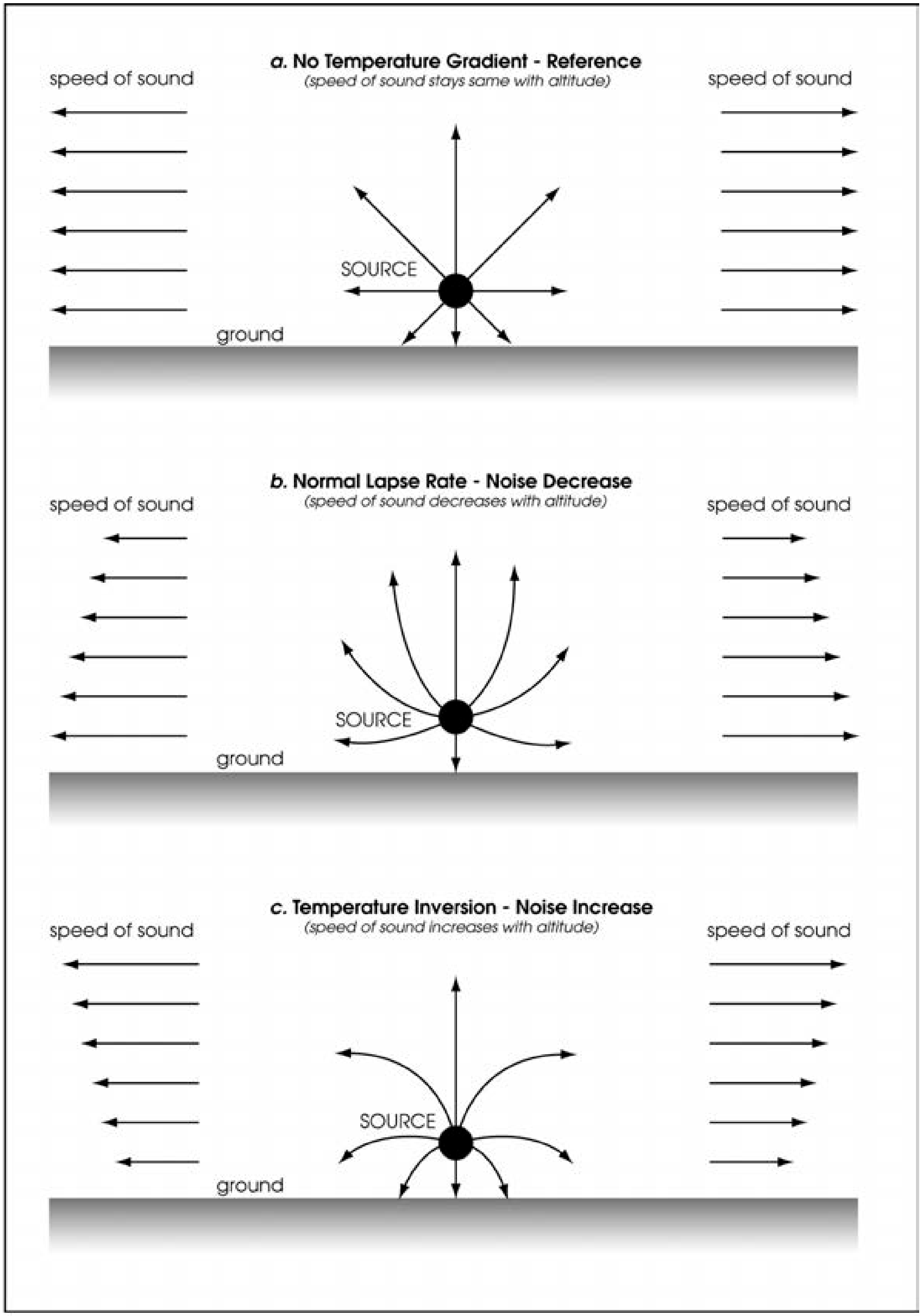

Figure 2-11. Effects of Temperature Gradients on Noise

2.1.4.4 Shielding by Natural and Manmade Features, Noise Barriers, Diffraction, and Reflection

A large object in the path between a noise source and receiver can significantly attenuate noise levels at the 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, and manmade features, such as buildings and walls, can significantly alter noise levels. Walls are often used specifically 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 16 feet above the line of sight between source and receiver must be at least 100 feet 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 200-foot-wide stand of trees would reduce noise by an additional 5 dBA). However, the limit is generally a total reduction of 10 dBA because sound waves passing over the tree tops (sky waves) are frequently refracted back to the surface because of 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 of reduction. Claims of increases in noise from removal of vegetation along highways are mostly spurred by the sudden visibility of the traffic source. There is evidence of a psychological effect (“out of sight, out of mind”) of vegetation on noise.

Buildings

Depending on site geometry, the first row of houses or buildings next to a highway may shield the successive rows. This often occurs where the facility is at-grade or depressed. The amount of noise reduction varies with building sizes, spacing of 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 to be 3 dBA, with 1.5 dBA for each additional row. For example, one may expect a 3-

dBA noise reduction behind the first row, 4.5 dBA behind the second row, and 6 dBA behind the third row. For houses or buildings spaced tightly (covering about 65% to 90% of the area, with 10 to 35% open space), the first row provides about 5 dBA of reduction. Successive rows still reduce noise by 1.5 dBA per row. However, for the reason mentioned in the preceding discussion, the limit is 10 dBA. For these assumptions to be true, the first row of houses or buildings 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 any natural or manmade feature between source and receiver that reduces noise is technically a noise barrier, the term is generally reserved for a wall or berm specifically constructed for noise reduction. The acoustical design of noise barriers is covered in Sections 4 and 6. However, it is appropriate at this time to introduce the acoustical concepts associated with noise barriers. These principles apply loosely to any obstacle between the source and receiver.

As shown in Figure 2-12, 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, although at a reduced level. The amount of this reduction depends on the material's mass and rigidity, and is called the transmission loss (TL), which is expressed in decibels. Its mathematical expression is:

$$TL = 10\log_{10}(E_f/E_b) \qquad \textbf{(2-18)}$$

Where:

E_f = relative noise energy immediately in front of barrier (source side)

E_b = relative noise energy immediately behind barrier (receiver side)

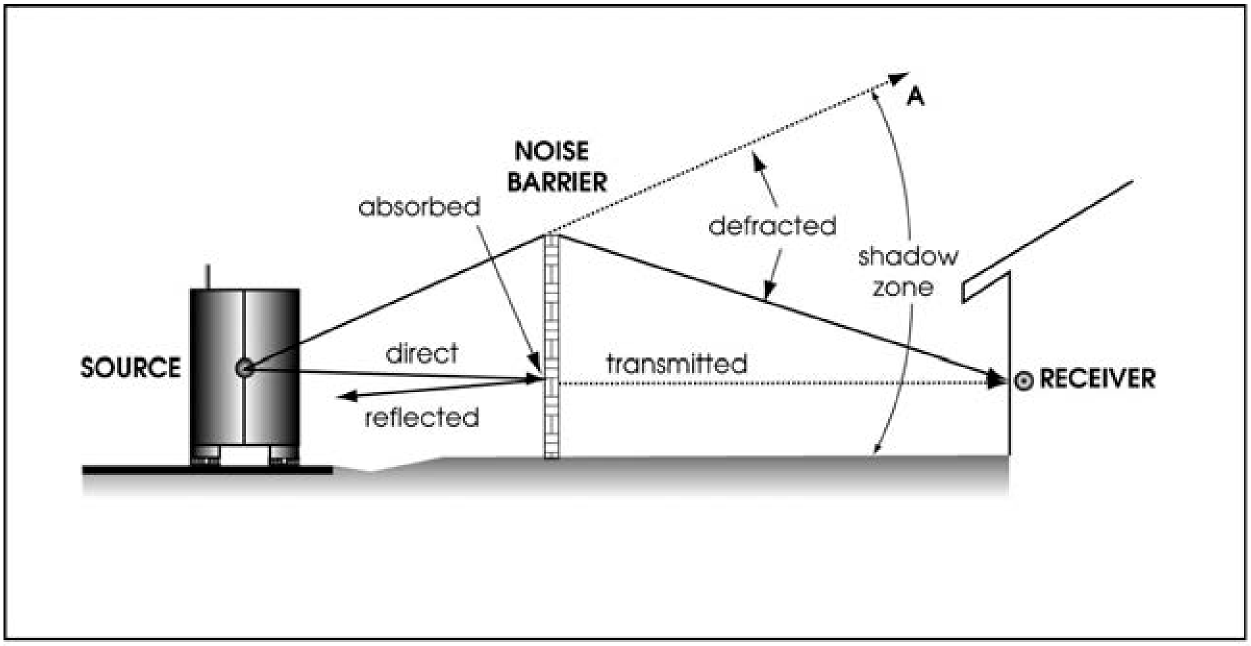

Figure 2-12. Alteration of Sound Paths after Inserting a Noise Barrier between Source and Receiver

Please note that E_f and E_b are relative energies (i.e., energies with reference to the energy of 0 dB [Section 2.1.3.4]). As relative energies, they may be expressed as any ratio (fractional or percentage) that represents their relationship. For example, if 1% of the noise energy striking a barrier is transmitted, TL = $10\log_{10}(100/1)$ = 20 dBA. Most noise barriers have TLs of 30 dBA or more. This means that only 0.1% of the noise energy is transmitted.

The remaining direct noise (usually close to 100%) is either partially or entirely absorbed by the noise barrier material (if sound absorptive) and/or partially or entirely reflected by it (if 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 almost perfectly reflective (i.e., almost all 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 ($\alpha = 0$) will reflect back virtually all noise energy (assuming a transmission loss of 30 dBA or more) toward the opposite side of a highway. If the difference in path length between the direct and reflected noise paths to the opposite (unprotected) side of a highway is ignored, the maximum expected increase in noise will be 3 dBA.

If one wishes to calculate the noise increase from a partially absorptive wall, Equation 2-18 may be used. E_f is the noise energy striking the barrier, but E_b 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, slightly less than 66.5 dBA. The reflected noise caused an increase of 1.5 dBA at the receiver.

The direct, transmitted, absorbed, and reflected noise paths (Figure 2-12) that have been discussed represent all variations of the direct noise path that result from insertion of the barrier. Of those, only transmitted noise reaches the receiver behind the barrier. However, there is one more path that reaches the receiver, which is the most important path. This is the noise path that was directed toward point A before the barrier insertion. With the barrier in place, sound energy traveling along this path is diffracted downward toward the receiver.

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 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 about six orders of magnitude) the noise shadows are not very well defined and amount to a noise reduction, not 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, the more frequencies will be attenuated. In Figure 2-12, 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. Please 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 of the barrier. The diffraction angle is defined by the top of the shadow zone and the line from the top of the barrier to receiver. Therefore, 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 determining the diffraction angle.

From the previous discussion, three conclusions are clear. First, the diffraction phenomenon depends on three critical locations: source, top of barrier, and receiver. Second, for a given source, top of barrier, and receiver configuration, a barrier is more effective in attenuating higher frequencies than lower frequencies (Figure 2-13). Third, the greater the angle of diffraction, the greater the noise attenuation.

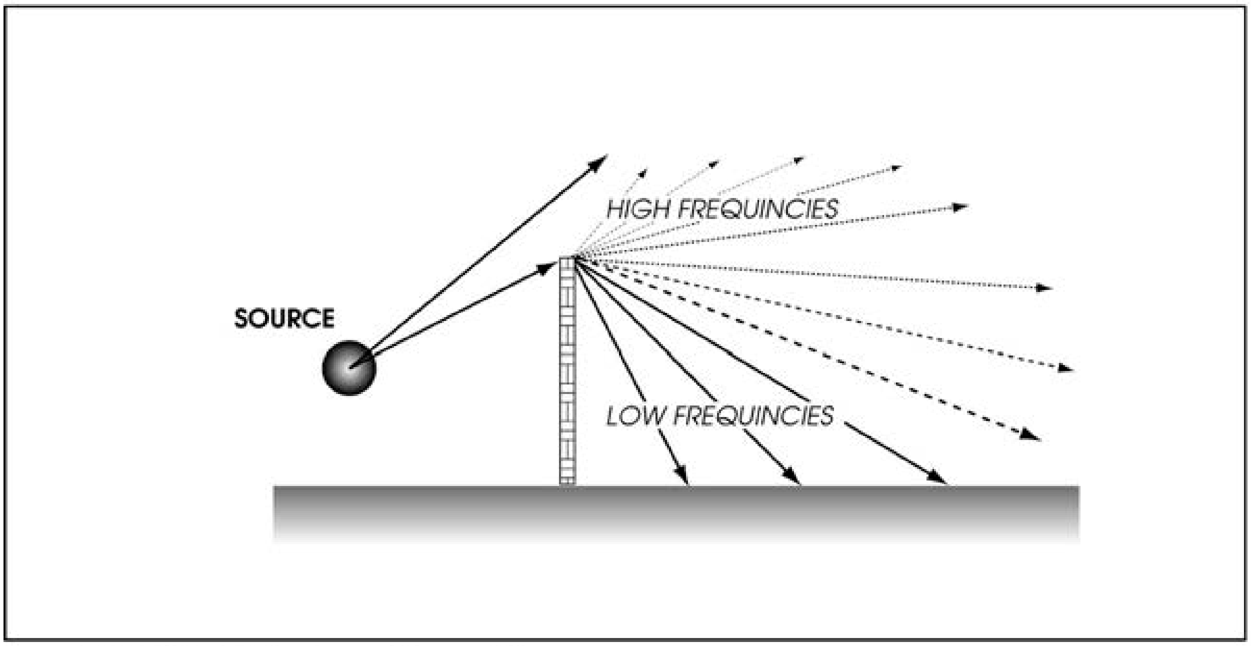

Figure 2-13. Diffraction of Sound Waves

The angle of diffraction is also related to the path length difference (δ) between the direct noise and diffracted noise. Figure 2-14 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 $\delta = a + b - c$. If the horizontal distances from the source to receiver and the source to barrier, as well as the differences in elevation between the source, top of barrier, and receiver, are known, *a*, *b*, and *c* can readily be calculated. Assuming that the source in Figure 2-14 is a point source, *a*, *b*, and *c* are calculated as follows:

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

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

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

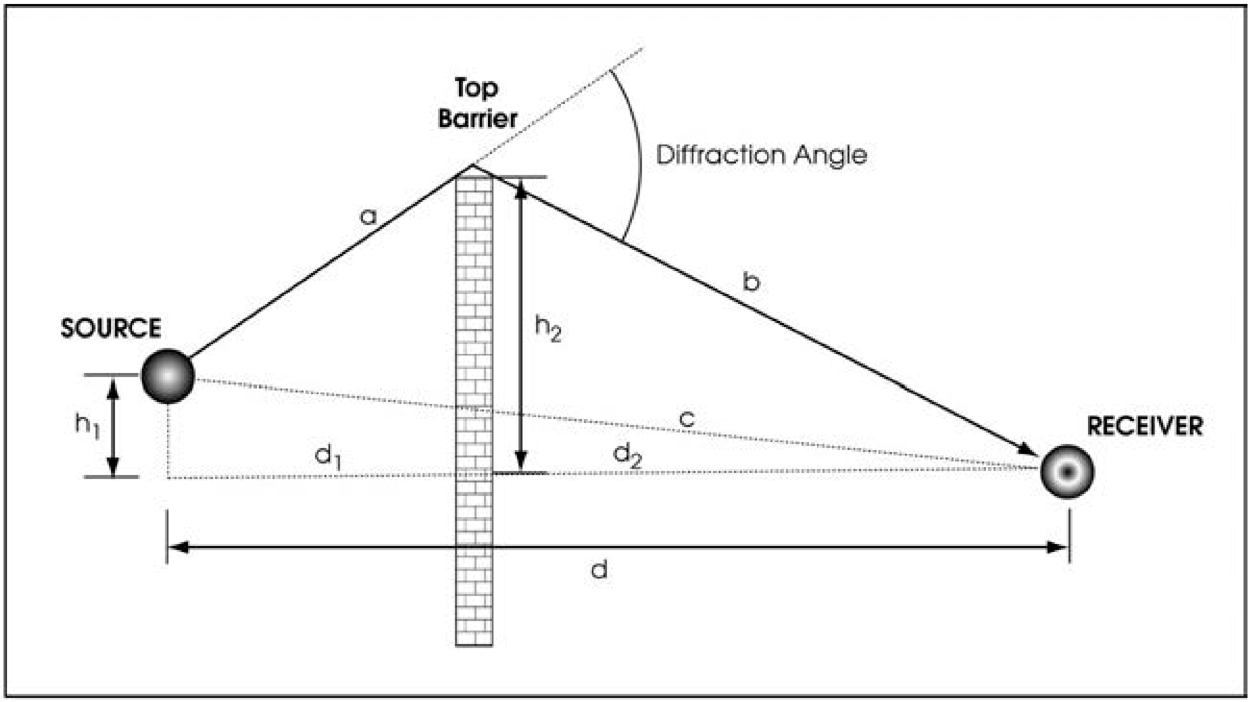

Figure 2-14. Path Length Difference between Direct and Diffracted Noise Paths

Highway noise prediction models use δ in barrier attenuation calculations. Section 5.5 covers the subject in greater detail. However, it is appropriate to include the most basic relationship between δ and barrier attenuation through the Fresnel number (N_0). If the source is a line source (e.g., highway traffic) and the barrier is infinitely long, there is an infinite number 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 follows:

$$N_0 = 2(\delta_0/\lambda) \qquad \textbf{(2-19)}$$

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 perpendicular line to barrier

λ = wavelength of sound radiated by source

According to Equation 2-4, $\lambda = c/f$. Therefore, Equation 2-19 may be rewritten as follows:

$$N_0 = 2(f\delta_0/c) \qquad \textbf{(2-20)}$$

Where:

f =frequency of sound radiated by source

c =speed of sound

Please note that these equations relate δ_0 to N_0. If one increases, so does the other, along with barrier attenuation. Similarly, if frequency increases, so will N_0 and barrier attenuation. Figure 2-15 shows the barrier attenuation Δ_B for an infinitely long barrier as a function of 550 Hz (typical average for traffic).

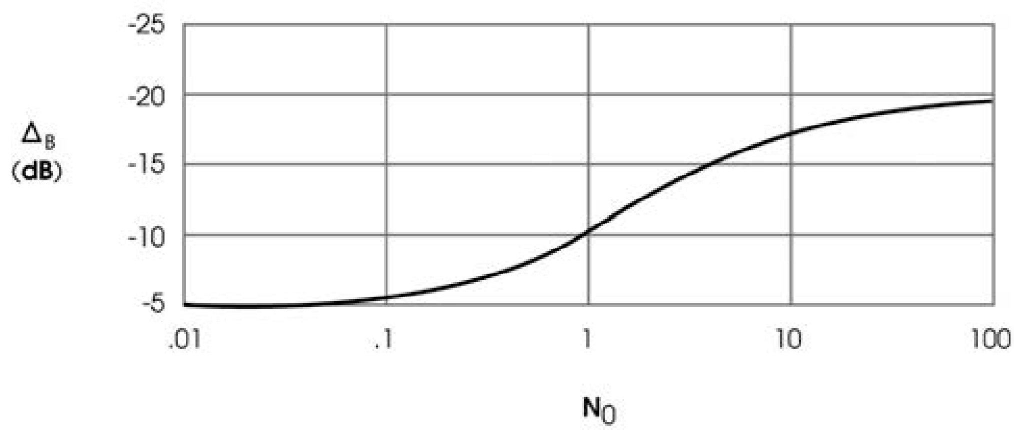

Figure 2-15. Barrier Attenuation (Δ_B) vs. Fresnel Number (N_0) for Infinitely Long Barriers

There are several general rules for noise barriers and their capability of attenuating traffic noise. Figure 2-16 illustrates a special case, in which the top of the barrier is just high enough to graze the direct noise path, or line of sight between the source and receiver. In such an instance, the noise barrier provides 5 dBA of attenuation.

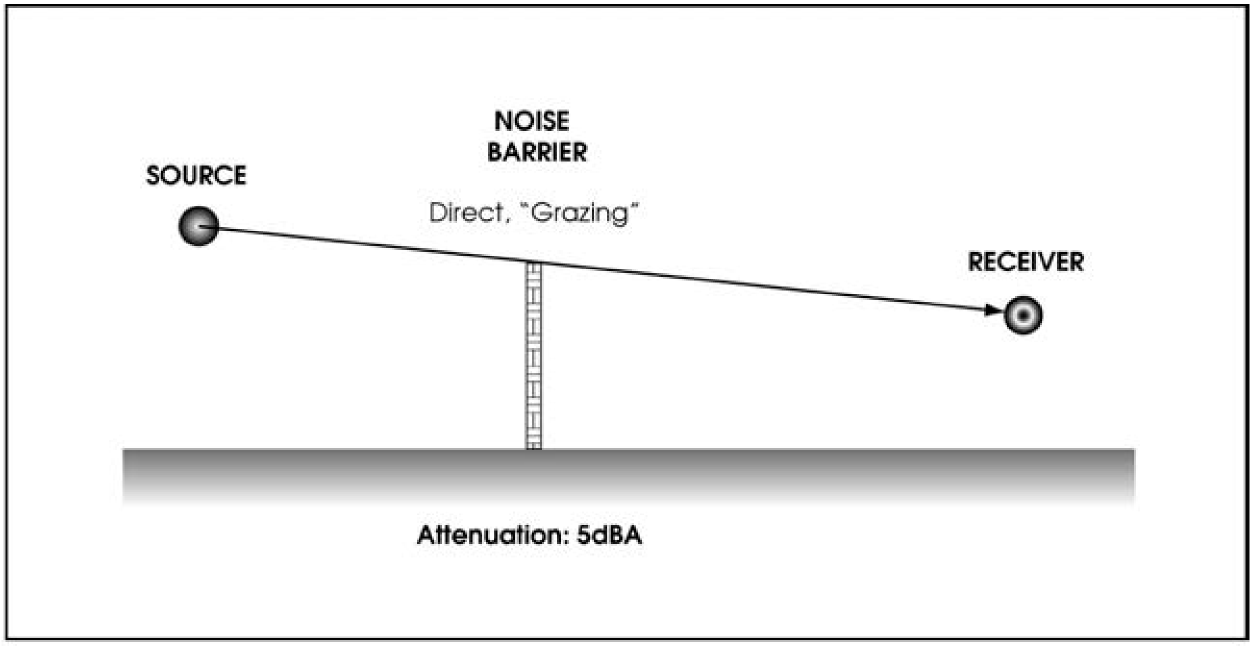

Figure 2-16. Direct Noise Path Grazing Top of Barrier, Resulting in 5 dBA of Attenuation

Another situation, in which the direct noise path is not interrupted but still close to the barrier, will provide some noise attenuation (Figure 2-17). Such negative diffraction (with an associated negative path length difference and Fresnel number) generally occurs when the direct noise path is within 5 feet above the top of the 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 and 5 dBA—5 dBA when the noise path approaches the grazing point, and near 0 dBA when it clears the top of the barrier by approximately 5 feet or more.

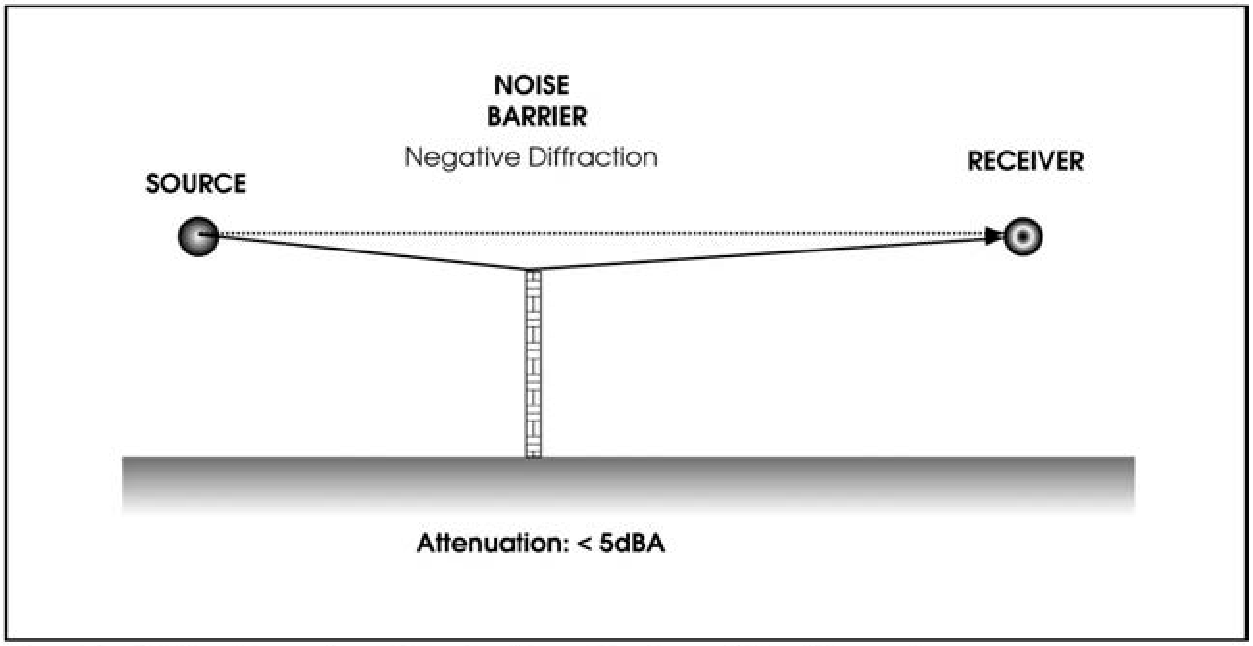

Figure 2-17. Negative Diffraction, Which Provides Some Noise Attenuation

The aforementioned principles of barriers apply loosely to terrain features (e.g., berms, low ridges, other significant manmade features). The principles will be discussed in more detail in Sections 5.5 and 6.

2.2 Effects of Noise and Noise Descriptors

2.2.1 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, or disrupt activities. Human tolerance to noise depends on a variety of acoustical characteristics of the source and environmental characteristics. These factors are briefly discussed below.

- **Noise Level, Variability in Level (Dynamic Range), Duration, Frequency Spectrums, and Time Patterns:** Exposures to very high noise levels can damage hearing. A high level is more objectionable than a low-level noise. For example, 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 the low. This is reflected in the A-scale (Section 2.1.3.5), which deemphasizes the low-frequency sounds. Studies indicate that annoyance or disturbance correlates with the A-scale.

- **Amount of Background Noise Present before Intruding Noise:** People tend to compare an intruding noise with existing background noise. If the new noise is readily identifiable or considerably louder than the background or ambient, it usually becomes objectionable. One example is an aircraft flying over a residential area.
- **Nature of Work or Living Activity Exposed to Noise Source:** Highway traffic noise might not be disturbing to workers in a factory or office, but it 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.

2.2.1.1 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 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, the concept of A-weighting and the reasons for describing noise in terms of dBA were discussed. 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, either in terms of decibels or in terms of acoustical energy. As discussed, there is a mathematical relationship between decibels and relative energy. For example, 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 10 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 2-11, 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.

Table 2-11. Relationship between Noise Level Change, Factor Change in Relative Energy, and Perceived Change

Noise Level Change, (dBA)	Change in Relative Energy ($10^{\pm \Delta dBA/10}$)	Perceived Change	
		Perceived Change in Percentage ($[2^{\pm \Delta dBA/10}-1] * 100\%$)	Descriptive Change in Perception
+40	10,000		16 times as loud
+30	1,000		Eight times as loud
+20	100	+300%	Four times as loud
+15	31.6	+183%	
+10	10	+100%	Two times as loud
+9	7.9	+87%	
+8	6.3	+74%	
+7	5.0	+62%	
+6	4.0	+52%	
+5	3.16	+41%	Readily perceptible increase
+4	2.5	+32%	
+3	2.0	+23%	Barely perceptible increase
0	1	0%	Reference (no change)
-3	0.5	-19%	Barely perceptible reduction
-4	0.4	-24%	
-5	0.316	-29%	Readily perceptible reduction
-6	0.25	-34%	
-7	0.20	-38%	
-8	0.16	-43%	
-9	0.13	-46%	
-10	0.10	-50%	One-half as loud
-15	0.0316	-65%	
-20	0.01	-75%	One-quarter as loud
-30	0.001		One-eighth as loud
-40	0.0001		One-sixteenth as loud

Section 2.1.3.3 mentions that the rms 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 as follows:

$$\text{Factor Change in Perceived Noise Levels} = 2^{\pm\Delta dBA/10} \quad \textbf{(2-21)}$$

According to this equation, 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.

2.2.2 Describing Noise

Noise in our daily environment fluctuates over time. Some fluctuations are minor, and some are substantial. Some occur in regular patterns, and others are random. Some noise levels fluctuate rapidly, and others slowly. Some noise levels vary widely, and others are relatively constant. To describe noise levels, one needs to choose the proper noise descriptor or statistic.

2.2.2.1 Time Patterns

Figure 2-18 is a graphical representation of how noise can have different time patterns depending on the source. Shown are noise levels vs. time patterns of four different sources: a fan (a), pile driver (b), single vehicle passby (c), and highway traffic (d).

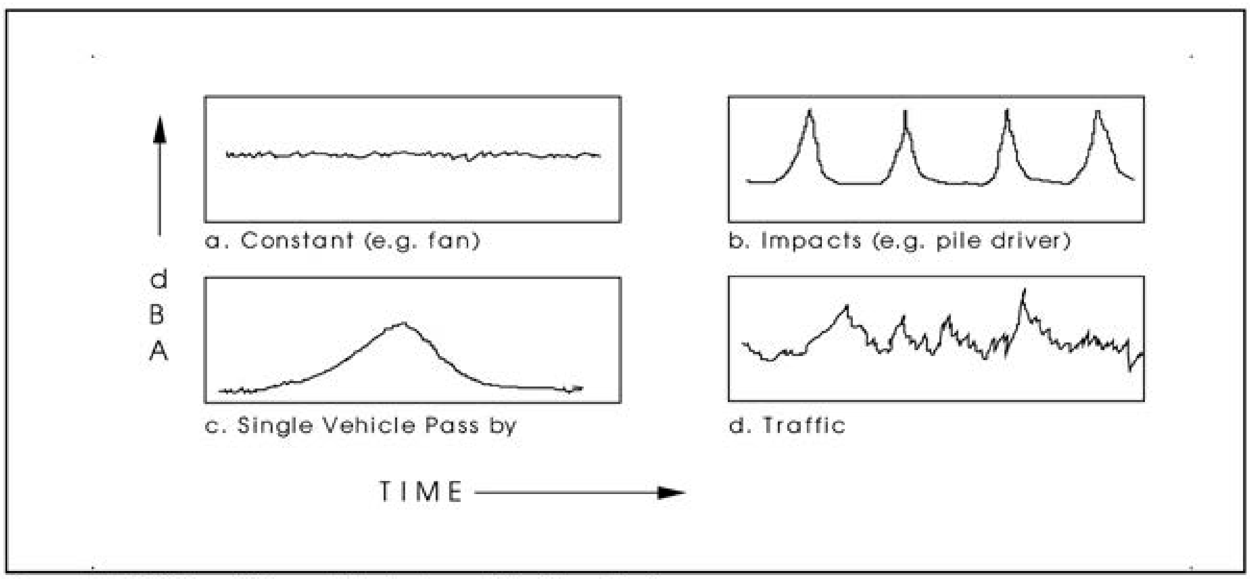

Figure 2-18. Different Noise Level vs. Time Patterns

The simplest noise level time pattern is constant noise, which is essentially a straight, level line. Such a pattern is characteristic of stationary fans, compressors, pumps, and air conditioners. 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 levels would be nearly the same as the average noise level.

Other noise levels vs. time patterns are more complicated. For example, to describe the pile driving noise, noise samples need to include the instantaneous peaks, or maximum noise levels. In our environment, there are a range of noises of many different patterns in addition to the ones shown in Figure 2-18. The levels may be extremely short in duration, such as a single gunshot (transient noise); intermittent, such as the pile driver; or continuous, such as the fan. Traffic noise along major highways tends to lie somewhere between intermittent and continuous. It is characterized by the somewhat random distribution of vehicles, each of which emits a pattern such as shown for a single vehicle passby.

2.2.2.2 Noise Descriptors

To choose the proper noise descriptor, one must know the nature of the noise source and how he or she wishes to describe it. Is the interest in maximum levels; average noise levels; percentage of time above a certain level; or levels that are exceeded 10%, 50% or 90% of the time? How can one compare the noise of a fast-flying jet aircraft—loud but short in duration—with a slower but quieter propeller airplane? The proper descriptor depends on the spatial distribution of noise sources, duration, amount of fluctuation, and time patterns.

Dozens of descriptors and scales have been devised over the years to quantify community noise, aircraft flyovers, traffic noise, industrial noise, speech interference, etc. The descriptors shown in Table 2-12 are those encountered most often in traffic, community, and environmental noise. There are many more descriptors not mentioned here. The word “Level,” abbreviated *L*, is frequently used whenever sound is expressed in decibels relative to the reference pressure. Therefore, all the descriptors shown in Table 2-12 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, see Section 2.2.2.3 for a discussion of descriptor conversions.

Table 2-12. Common Noise Descriptors

Noise Descriptor	Definition
Maximum noise level (L_{max})	The highest instantaneous noise level during a specified time period. This descriptor is sometimes referred to as "peak (noise) level." The use of term "peak level" should be discouraged because it may be interpreted as a non-rms noise signal (see Section 2.1.3.3 for difference between peak and rms).
Statistical descriptor (L_x)	The noise level exceeded *X* % of a specified time period. The value of *X* is commonly 10 (e.g., L_{10}). Other values such as 50 and 90 are used also.
Equivalent noise level (L_{eq}). 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
Day-night noise level (L_{dn}). Used commonly for describing community noise levels.	A 24-hour L_{eq} with a "penalty" of 10 dBA added during the night hours (10 p.m. to 7 a.m.) because this time is normally used for sleep
Community noise equivalent level (CNEL). A common community noise descriptor, also used for airport noise.	Same as L_{dn} with an additional penalty of 4.77 dBA (or 10log3), for the hours 7 p.m. to 10 p.m., which are usually reserved for relaxation, television, reading, and conversation
Sound exposure 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 1 second, expressed in decibels

2.2.2.3 Calculating Noise Descriptors

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

Statistical Descriptor

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 L_{eq}. The most common value of *X* was 10, denoting the level that is exceeded 10% of the time. Therefore, the L_{10} descriptor will be used as an example to represent the L_x family of calculations. The following instantaneous noise samples (Table 2-13) shown as a frequency distribution (dBA vs. number of occurrences) will serve to illustrate the L_{10} calculation.

Fifty samples were taken at 10-second intervals. To determine L_{10}, identify the five highest values (10% of 50) and then count down five values from the top. The "boundary" of the top 10% is 76 dBA. Therefore, L_{10} lies at 76 dBA. L_{50} would be at 66 dBA (25 occurrences from the top).

Table 2-13. Noise Samples for L_{10} Calculation

Noise Level (dBA)	Occurrences (Sampling Interval of 10 Seconds) (Each *X* Is One Occurrence)							Total 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 samples								**50**

Equivalent Noise Level

L_{eq} is an energy average noise level. 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 and the total divided by the number of values. The result is average (relative) energy. The final step is to convert the average energy value back to a decibel level. Equation 2-13 showed the method of adding the energy values. This equation can be expanded to yield L_{eq}:

$$L_{eq} = 10\log_{10}[(10^{SPL_1/10} + 10^{SPL_2/10} + ... 10^{SPL_n/10})/N] \quad \textbf{(2-22)}$$

Where:

SPL_1, SPL_2, SPL_n = first, second, and *n*th noise level

N = number of noise level samples

<u>Example</u>

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

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

Using Equation 2-24:

$L_{eq} = 10\log_{10}[(10^{60/10}+10^{64/10}+10^{66/10}+10^{63/10}+10^{62/10}+10^{65/10})/6] = 10\log_{10}(14235391.3/6) = 63.8$ dBA

Usually, longer time periods are preferred. Using the sampling data in Table 2-13, the following equation can be used to add the dBA levels for each set of equal noise levels:

$$SPL_{Total} = SPL_1 + 10\log_{10}(N) \quad \textbf{(2-23)}$$

Where:

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, the following equation can be used to add the subtotals:

$$SPL_{Total} = 10\log_{10}(10^{SPL_1/10} + 10^{SPL_2/10} + ... 10^{SPL_n/10}) \quad \textbf{(2-24)}$$

Finally, this amount must be energy-averaged to compute L_{eq}. This may be accomplished using the following equation:

$$L_{eq} = 10\log_{10}(10^{SPL_{Total}/10}/N) \quad \textbf{(2-25)}$$

Where:

N = total number of samples (in this case, 50)

The calculation procedures are shown in Table 2-14.

Table 2-14. Noise Samples for L_{eq} Calculation

Noise Level (dBA)	Occurrences (N) (from Table 2-13)	Total Noise Levels [dBA + $10\log_{10}(N)$]
80	0	
79	0	
78	1	78
77	1	77
76	3	80.8
75	2	78
74	2	77
73	2	76
72	0	
71	3	75.8
70	1	70
69	2	72
68	5	75
67	2	70
66	4	72
65	7	73.5
64	5	71
63	3	67.8
62	3	66.8
61	2	64
60	2	63
Total	**50**	**87.5**
$L_{eq} = 10\log_{10}[(10^{8.75})/50] = 70.5$ dBA		

Day-Night Noise Level

L_{dn} is actually a 24-hour L_{eq}, or the energy-averaged result of 24 1-hour L_{eq}s, except that the nighttime hours (10 p.m. to 6 a.m.) are assessed a 10-dBA penalty. This penalty attempts to account for the fact that nighttime noise levels are potentially more disturbing than equal daytime noise levels. Mathematically, L_{dn} is expressed as follows:

$$L_{dn} = 10\log_{10}\left[\left(\frac{1}{24}\right)\sum_{i=1}^{24} 10^{L_{eq}(h)_i + W_i/10}\right] \quad \textbf{(2-26)}$$

Where:

$W_i = 0$ for day hours (7 a.m. to 10 p.m.)

$W_i = 10$ for night hours (10 p.m. to 7 a.m.)

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

To calculate L_{dn} accurately, one must have 24 successive hourly L_{eq} values, representing one typical day. The hourly values between 10 p.m. and 7 a.m. (nine hourly values) must first be weighted by adding 10 dBA. An example is shown in Table 2-15.

The energy average calculated from the nine weighted and 15 unweighted hourly L_{eq} values 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}). Equation 2-22 can be used with the weighted data. The resulting L_{dn} is 65 dBA.

Table 2-15. Noise Samples for L_{dn} Calculations

Begin Hour	$L_{eq}(h)$ (dBA)	Weight (dBA)	Weighted Noise (dBA)
Midnight	54	+10	64
1 a.m.	52	+10	62
2 a.m.	52	+10	62
3 a.m.	50	+10	60
4 a.m.	53	+10	63
5 a.m.	57	+10	67
6 a.m.	62	+10	72
7 a.m.	65	0	65
8 a.m.	63	0	63
9 a.m.	64	0	64
10 a.m.	66	0	66
11 a.m.	66	0	66
Noon	65	0	65
1 p.m.	65	0	65
2 p.m.	63	0	63
3 p.m.	65	0	65
4 p.m.	65	0	65
5 p.m.	63	0	63
6 p.m.	64	0	64
7 p.m.	62	0	62

Begin Hour	$L_{eq}(h)$ (dBA)	Weight (dBA)	Weighted Noise (dBA)
8 p.m.	60	0	60
9 p.m.	58	0	58
10 p.m.	57	+10	67
11 p.m.	55	+10	65

Community Noise Equivalent Level

CNEL is the same as L_{dn} except for an additional weighting of almost 5 dBA for the evening hours between 7 p.m. and 10 p.m. The equation is essentially the same as Equation 2-26, with an additional definition of $W_i = 10\log_{10}(3)$, which is 4.77. Calculations for CNEL are similar to L_{dn}. The result is normally about 0.5 dBA higher than L_{dn} using the same 24-hour data. The equation for the CNEL is as follows:

$$CNEL = 10\log_{10}\left[\left(\frac{1}{24}\right)\sum_{i=1}^{24} 10^{L_{eq}(h)_i + W_i/100}\right] \quad \textbf{(2-27)}$$

Where:

$W_i = 0$ for day hours (7 a.m. to 7 p.m.)

$W_i = 10\log_{10}(3) = 4.77$ for evening hours (7 p.m. to 10 p.m.)

$W_i = 10$ for night hours (10 p.m. to 7 a.m.)

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

The 24-hour data used in the L_{dn} example yields a CNEL of 65.4 dBA, compared with an L_{dn} of 65.0 dBA.

Sound Exposure Level

The sound exposure level (SEL) is useful in comparing the acoustical energy of different events involving different source characteristics. For example, the overflight of a slow propeller-driven plane may not be as loud as a jet aircraft. However, the duration of the noise is longer than the duration of the noise from the jet aircraft overflight. SEL makes a noise comparison of both events possible because it combines the effects of time and level. For example, the L_{eq} of a steady noise level will remain unchanged over time. It will be the same whether calculated for a time period of 1 second or 1,000 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 1 second. Because both values are energy-weighted, they are directly related to each other by time, as shown in the following equations:

$$SEL = L_{eq}(T) + 10\log_{10}(T) \quad \textbf{(2-28)}$$

$$L_{eq}(T) = SEL + 10\log_{10}(1/T) = SEL - 10\log_{10}(T) \quad \textbf{(2-29)}$$

Where:

T = duration of noise level in seconds

Example

L_{eq} of a 65-second aircraft overflight is 70 dBA. What is the SEL?

$SEL = L_{eq}(65) + 10\log_{10}(65) = 70 + 18.1 = 88.1$ dBA

A time period of 1 hour (T = 3,600 seconds) is commonly used for the L_{eq} descriptor when it is applied to criteria in policies and standards. The SEL value accumulated over the 1-hour period can be converted to $L_{eq}(h)$ as follows. $L_{eq}(h) = SEL - 10\log_{10}(3{,}600)$, or 88.1 – 35.6 = 52.5 dBA for the example above. Because a conversion from SEL to $L_{eq}(h)$ always involves subtraction of the constant 35.6 and the following relationships between SEL and $L_{eq}(h)$ always hold true:

$$L_{eq}(h) = SEL - 35.6 \quad \textbf{(2-30)}$$

$$SEL = L_{eq}(h) + 35.6 \quad \textbf{(2-31)}$$

These relationships have many practical applications when one is adding a mixture of SELs and $L_{eq}(h)$s. For example, one wants to calculate the existing worst hour noise level in $L_{eq}(h)$ at a receiver A from the following data:

- Highway noise = 63 dBA, $L_{eq}(h)$
- Two train passbys with SELs of 89 dBA each
- Five aircraft overflights averaging SELs of 93 dBA each

First, all SELs are added:

$$\text{Total SEL} = 10\log_{10}[2(10^{89/10}) + 5(10^{93/10})] = 100.6 \text{ dBA}$$

Next, the SEL is expanded to 1 hour using Equation 2-31:

$$L_{eq}(h) = 100.6 - 35.6 = 65 \text{ dBA}$$

Finally, the $L_{eq}(h)$ of the highway is added:

$$\text{Worst hour noise level at receiver A} = 10\log_{10}(10^{63/10} + 10^{65/10}) = 67.1 \text{ dBA}$$

2.2.3 Conversion between Noise Descriptors

Although Caltrans exclusively uses L_{eq}, there are times that comparisons need to be made with local noise standards, most of which are in terms of L_{dn} or CNEL. If 24-hour traffic and noise data are available, these descriptors can be calculated accurately. However, this information is often not available. The methodologies in this section allow a reasonably accurate conversion of the worst hourly noise level to L_{dn} or CNEL (and vice versa).

Before these conversions are discussed, it should be noted that although these conversions are reasonably accurate, they are only approximate for various reasons. First is the assumption that 24 hourly traffic mixes remain constant and that traffic speeds do not change. Second, the method assumes that the peak hour traffic coincides with the worst-hour L_{eq}, which is often not true. Nevertheless, the methods of conversion discussed may be used if only average daily traffic (ADT) volumes are known and a reasonable estimate can be made of the percentage of peak hour traffic volume of the ADT. Another requirement is a reasonable estimate of the day and night traffic volume split for L_{dn} and day, evening, and night split for CNEL.

The previous section showed that L_{dn} is defined as an energy-averaged 24-hour L_{eq} with a nighttime penalty of 10 dBA assessed to noise levels between 10 p.m. and 7 a.m. If traffic volumes, speeds, and mixes were to remain constant throughout the entire 24 hours and there were no nighttime 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 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 reference condition. First, one must make a correction for peak hour traffic volumes expressed as a percentage of ADT. Second, one must make a correction for the nighttime penalty of 10 dBA. For CNELs, a third correction needs to be made for the evening hour penalty. For this one must know what fractions of the ADT occur during the day and at night. Depending on the accuracy desired and information available, other corrections can be made for different day/night traffic mixes and speeds; these are not discussed in this section.

The first correction for peak hour can be expressed as:

$$10\log_{10}\frac{4.17}{P}$$

Where:
P = peak hour volume as percent of ADT

The second correction for nighttime penalty of 10 dBA is:

$$10\log_{10}(D + 10N)$$

Where:
D = day fraction of ADT
N = night fraction of ADT
D + N = 1

The following equations are used to convert from peak hour L_{eq} to L_{dn}, and vice versa, respectively:

$$L_{dn} = L_{eq}(h)_{pk} + 10\log_{10}\frac{4.17}{P} + 10\log_{10}(D + 10N) \qquad \textbf{(2-32)}$$

$$L_{eq}(h)_{pk} = L_{dn} - 10\log_{10}\frac{4.17}{P} - 10\log_{10}(D + 10N) \qquad \textbf{(2-33)}$$

Where:
$L_{eq}(h)_{pk}$ = peak hour L_{eq}
P = peak hour volume % of ADT
D = daytime fraction of ADT
N = nighttime fraction of ADT
D + N = 1

<u>Example</u>

Peak hour L_{eq} at a receiver near a freeway is 65.0 dBA. Peak hour traffic is 10% of ADT. Daytime traffic volume is 85% of ADT, and nighttime traffic volume is 15% of ADT. Assume that the day and nighttime heavy truck percentages are equal and traffic speeds do not vary significantly. What is the estimated L_{dn} at the receiver?

$$L_{dn} = 65.0 + 10\log_{10}\frac{4.17}{10} + 10\log_{10}(0.85 + 1.50) = 65.0 + (-3.8) + 3.70 = 64.9 \text{ dBA}$$

Please note that in this example, which is a fairly typical case, L_{dn} is approximately equal to $L_{eq}(h)_{pk}$. The general rule is that L_{dn} is within about 2 dBA of $L_{eq}(h)_{pk}$ under normal traffic conditions.

The following equations are used to convert from peak hour L_{eq} to CNEL, and L_{dn} to peak hour L_{eq}, respectively:

$$\text{CNEL} = L_{eq}(h)_{pk} + 10\log_{10}\frac{4.17}{P} + 10\log_{10}(d + 4.77e + 10N) \qquad \textbf{(2-34)}$$

$$L_{eq}(h)_{pk} = \text{CNEL} - 10\log_{10}\frac{4.17}{P} - 10\log_{10}(d + 4.77e + 10N) \qquad \textbf{(2-35)}$$

Where:

The variables *d* and *e* are further divisions of *D* shown in L_{dn} to account for day and evening hours. Please note that $d + e = D$ (shown in Equations 2-34 and 2-34). The factor 4.77 comes from $10\log_{10}(3)$, which is the designated penalty for evening hours in the definition of CNEL. Although an evening hour penalty of 5 dBA is often used to calculate CNEL, the correct value is $10\log_{10}(3)$. The difference between using 4.77 and 5 is usually negligible.

Example

Using the data for the previous L_{dn} example and adding a further division of *D* into $d = 0.80$ and $e = 0.05$, the CNEL result using Equation 2-34 is 65.2 dBA, 0.3 dBA more than L_{dn}.

From Equations 2-34 and 2-35, the following equations can be derived in terms of CNEL and L_{dn}:

$$\text{CNEL} = L_{dn} + [10\log_{10}(d + 4.77e + 10N) - 10\log_{10}(d + e + 10N)] \qquad \textbf{(2-36)}$$

$$L_{dn} = \text{CNEL} - [10\log_{10}(d + 4.77e + 10N) - 10\log_{10}(d + e + 10N)] \qquad \textbf{(2-37)}$$

Example

Using the same example for which L_{dn} was 64.9 dBA, the CNEL in Equation 2-36 yields 65.2 dBA. Please note that CNEL is always larger than L_{dn}.

The values in Table 2-16 can also be used in Equations 2-32 and 2-33. Please notice that the peak hour percentage 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 $L_{eq}(h)_{pk}$ and L_{dn}.

Table 2-16. L_{eq}/L_{dn} Conversion Factors

Peak Hour, %	$10\log_{10}(4.17/P)$	Day	Night	$10\log_{10}(D+10N)$
5	-0.8	0.98	0.02	+0.7
6	-1.6	0.95	0.05	+1.6
7	-2.3	0.93	0.07	+2.1
8	-2.8	0.90	0.10	+2.8
9	-3.3	0.88	0.12	+3.2
10	-3.8	0.85	0.15	+3.7
11	-4.2	0.83	0.17	+4.0
12	-4.6	0.80	0.20	+4.5
13	-4.9	0.78	0.22	+4.7
14	-5.3	0.75	0.25	+5.1
15	-5.6	0.73	0.27	+5.4
17	-6.1	0.70	0.30	+5.7
20	-6.8	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 2-19 illustrates the difference between $L_{eq}(h)_{pk}$ and L_{dn}. For example, if *P* is 10% and *D*/*N* = 0.85/0.15, $L_{dn} \approx L_{eq}(h)$.

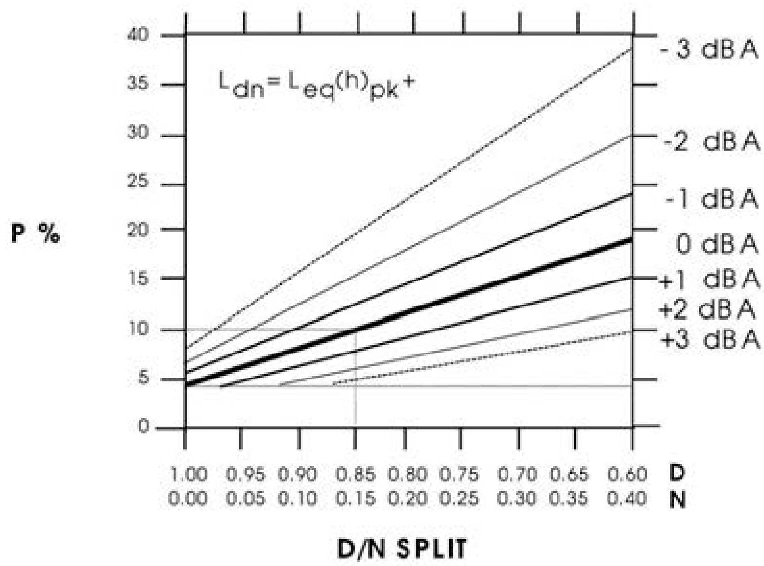

Figure 2-19. Relationship between L_{dn} and $L_{eq}(h)_{pk}$

If CNEL is desired, the L_{dn} to CNEL corrections (Δ) in Table 2-17 may be used. Please note that this table is only calculated for a common day/night volume spilt of 0.85/0.15. Because of the many possible combinations, other tables are not shown. For other *D*/*N* splits, use Equation 2-34 or 2-35 to calculate CNEL. This table is intended to be used when only an L_{dn} is given and CNEL is desired.

Table 2-17. L_{dn}/CNEL Corrections (Δ) (Must Be Added to L_{dn} to Obtain CNEL)

D = 0.85		Δ
D	E	(CNEL = L_{dn} + 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

D = percentage of traffic in hours 7:00 a.m. to 10:00 p.m.
E = percentage of traffic in hours 7:00 p.m. to 10:00 p.m.
d = percentage of traffic in hours 7:00 a.m. to 7:00 p.m.
D = d + E.

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

2.2.4 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 and conversation. Less obvious are the stress effects of noise. A brief discussion of each of the topics follows.

2.2.4.1 Hearing Damage

A person exposed to high noise levels can suffer hearing damage, either gradual or traumatic. These are described as follows.

- **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 considered permanent hearing damage. The primary cause of permanent hearing damage is daily exposure to industrial noise. Transportation noise levels experienced by communities and the general public are normally not high enough to produce hearing damage.
- **Traumatic:** Short, sudden exposure to an extremely high noise level, such as a gunshot or explosion at very close range, can cause a traumatic hearing loss, which 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, shielding the receiver with a barrier, or having the receiver wear proper ear protection. Occupational exposure to noise is controlled at the Federal Level by OSHA and at the state level by the state level by the California Division of Safety and Health. The maximum allowable noise exposure over an 8 hours period is a level of 90 dBA. For each halving of the exposure time, the maximum noise level is allowed to increase 5 dBA. Therefore, 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.

2.2.4.2 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, such as the inability to hear warning signals or verbal warnings in noisy industrial situations or situations involving workers next to a noisy freeway. Figure 2-20 gives an estimate of the speech communication that is possible at various noise levels and distances.

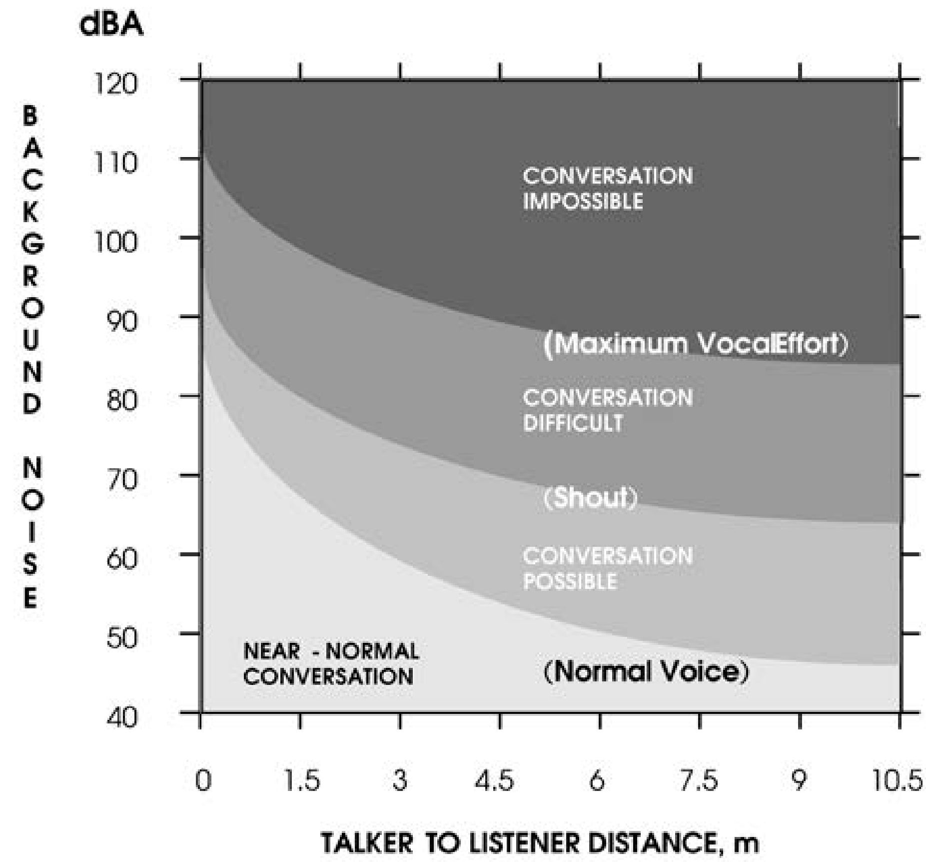

Figure 2-20. Interference of Conversation from Background Noise

For example, if the talker-to-listener distance is 6 meters, 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 or her voice or decrease the distance to the listener to 3 meters.

2.2.4.3 Stress-Related Diseases

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

Section 3
Measurements and 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 is discussed only at a general level. For additional detail, manufacturers' manuals should be consulted.

The noise analyst should be aware of both the importance and limitations of noise measurements. As with all field work, quality noise measurements are relatively expensive, requiring time, personnel, and equipment. Therefore, the noise analyst should carefully plan the location, time, duration, and number of repetitions of noise measurements before actually taking the measurements. Efforts should be made during the measurements to document location, traffic levels, weather, and other pertinent factors discussed in this section.

The contents of this section represent Caltrans measurement procedures and are consistent with methods described in FHWA's *Measurement of Highway-Related Noise* (1996).

3.1 Purposes of Noise Measurements

There are five major purposes for measuring transportation noise:

- determine existing ambient and background noise levels,
- calibrate noise prediction models,
- monitor construction noise levels for compliance with standard specifications, special provisions, and local ordinances,
- evaluate the effectiveness of abatement measures such as noise barriers, and
- perform special studies and research.

Ambient and background noise and model calibration measurements are routinely performed by the Caltrans districts. Construction noise monitoring is also conducted frequently by the districts. Some districts conduct before-and-after noise abatement measurements. Special studies and noise research measurements, however, are only done rarely by the districts and are often contracted 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 measurements, what they include, and how the results are used.

3.1.1 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 and 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 natural and mechanical sources and human activity considered usually to be present should be included in the measurements.
- To investigate citizens' traffic or construction noise complaints. Noise measurements are usually reported via memorandum to the interested party, with recommendations for further actions or reasons that further actions are not justified.

Background noise is considered to be the total 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 acoustically representative locations away from the highway where highway noise does not contribute to the total noise level. Background noise levels are routinely measured to determine the feasibility of noise abatement and to ensure that noise reduction goals can be achieved. Noise abatement cannot reduce noise levels below background levels. Section 6.1.6 discusses the importance of background noise levels.

Depending on the situation, noise sources measured may typically include highway traffic, community activity, surface street traffic, trains, and sometimes airplanes (when project is near an airport).

3.1.2 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 5.3.3 and 5.4). Model calibration can only be performed on projects involving reconstruction of existing highways.

3.1.3 Construction Noise Levels

Construction noise measurements are frequently conducted by districts to check the contractor's compliance with the standard specifications, special provisions, and local ordinances.

3.1.1 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 check on the design and construction procedures of the abatement. Although these measurements are occasionally performed by some districts, they are not part of a routine program.

3.1.2 Special Studies and Research

These measurements are usually done by Caltrans headquarters staff and consultants. They may involve district assistance and generally involve noise research projects. Setups are usually complex and include substantial equipment and personnel positioned at many locations for simultaneous noise measurement. The studies generally require more sophisticated equipment and setups than routine noise studies.

3.2 Measurement Locations

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

Many tools are available in the search for quality noise measurement sites. Preliminary design maps, 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.

3.2.1 General Site Recommendations

Some general site requirements common to all outside noise measurement sites are listed below (more detailed considerations are discussed in Section 3.2.2).

- Sites must be clear of major obstructions between the source and receiver unless these are representative of the area of interest. Small reflecting surfaces should be more than 10 feet from the microphone positions. Large reflecting surfaces should be avoided unless they are the subject of study.
- Sites must be free of noise contamination by sources other than sources of interest. Avoid sites located near such sources as barking dogs, lawnmowers, pool pumps, and air conditioners unless it is the express intent of the analyst to measure these sources.
- Sites must be acoustically representative of areas and conditions of interest. They must either be located at or represent locations of human use.
- Sites must not be exposed to prevailing meteorological conditions that are beyond the constraints discussed in this section. For example, in areas with prevailing high wind speeds, sites in open fields should be avoided.

3.2.2 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 in which a noise measurement site is used for a specialized purpose, all noise measurement sites may be considered receivers. However, not all receivers are noise measurement sites. Additional information on receivers and noise measurement sites can be found in Section 5.3.

For 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. In such cases, the existing noise levels must be modeled. This can only be accomplished along an existing facility, where traffic can be counted.

In general, 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.

Factors that should be considered when selecting noise measurement sites are described in Sections 3.2.2.1 to 3.2.2.3.

3.2.2.1 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 6.1.5) and to document pre-project noise levels at distant receivers. Past controversies concerning unsubstantiated increases in noise levels at distant receivers attributed to noise barriers could readily have been resolved if sufficient background noise receivers had been selected (see Section 8.2) after the project has been built.

Classroom noise measurements (Street and Highways Code Section 216) or receivers lacking outside human use require both inside and 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 affected by infiltrating noise from the sources of interest. These points are typically desks, chairs, or beds near windows. Several sensitive points may need to be tested, and the results averaged. No measurements should be made within 3 to 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, measurements should be taken with windows open and closed. Devices such as fans, ventilation, clocks, appliances, and telephones should be turned off. People should 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 Section 5.4 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., L_{max} of 86 dBA at 15 m [50 feet]) and other requirements.

Before-and-after measurements for evaluations of noise barriers (refer to Section 8.12) and other abatement options, as well as measurements for special studies or research, are non-routine and require a detailed experimental design. Coordination with Caltrans Headquarters staff is advisable.

3.2.2.2 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 divided into subregions in which acoustical equivalence can generally be maintained. Subregion boundaries 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 subregions may be defined by each purpose. The areas of regions or subregions vary. For example, noise abatement for a school may cover only the school itself, while a noise study for a large freeway project may range from a large region to many subregions.

The number of measurement sites selected within each region or subregion under study depends on the area's size, number of receivers, and remaining variations in acoustical parameters. If subregions are carefully selected, the number of measurement sites can be minimized. The minimum number of sites recommended for each region or subregion is two.

Figure 3-1 shows an example of receiver and noise measurement site selections for an at-grade freeway widening and noise barrier project. Alternate noise measurement sites to be used if the selected receivers are not accessible or otherwise not suitable for noise measurement locations are shown also. Only sites near the freeway are shown. Background noise measurement sites would typically be off the map, farther from the freeway. Actual site selection would depend on field reviews and more information not shown on the map.

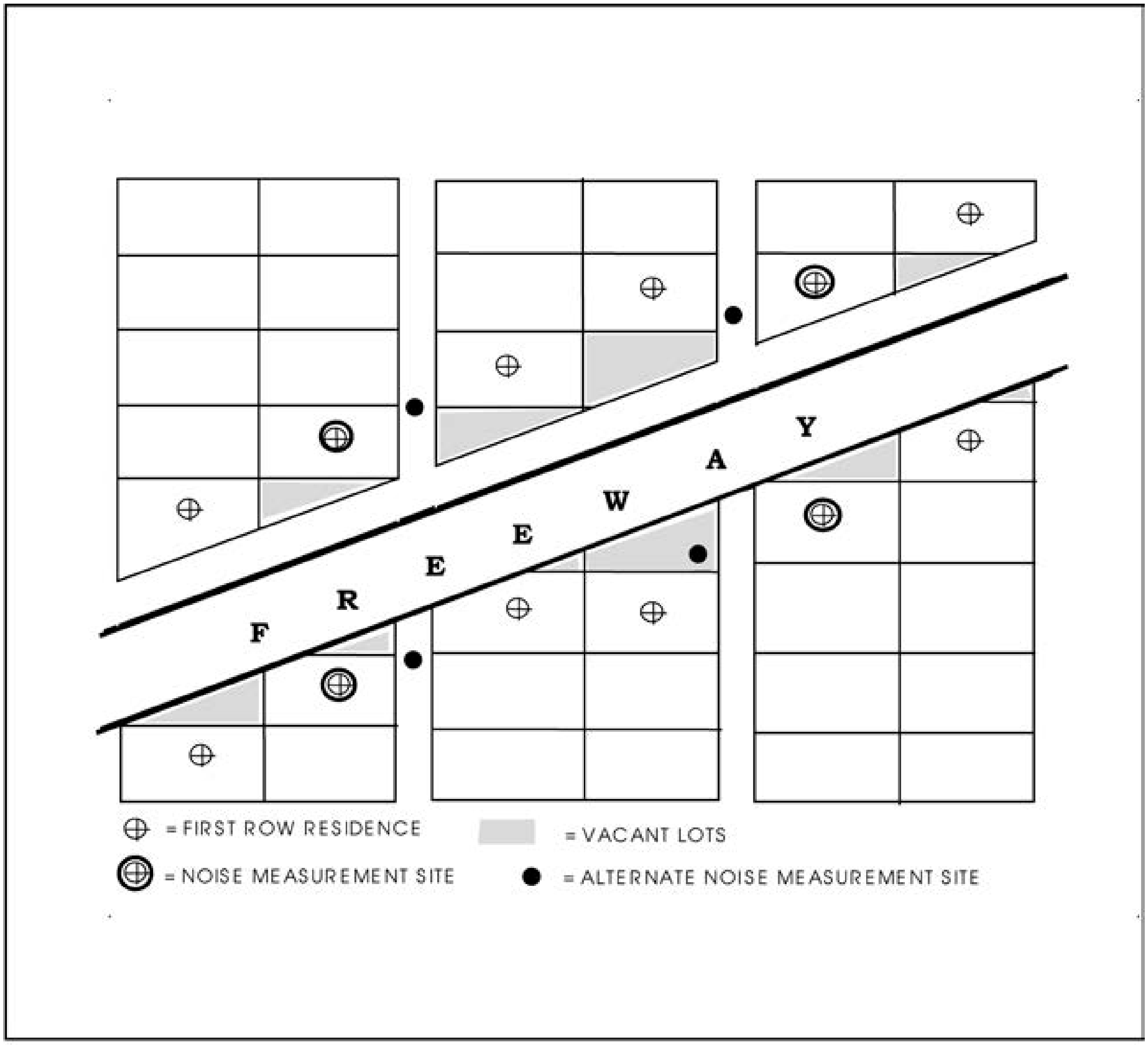

Figure 3-1. Typical Measurement Site Locations

3.2.2.3 Site Selection by Geometry

In addition to being an important consideration in determining acoustical equivalence, topography (site geometry) plays an important role in determining locations of worst exposure to highway noise. 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 they are farther from the source. This concept is shown in Figure 3-2. Another common situation involves a receiver close to the source, shielded by the top of a highway embankment, and an unshielded receiver farther from the source. The attenuation provided by the embankment is often more than the distance effect, resulting in higher noise levels at the farther receiver.

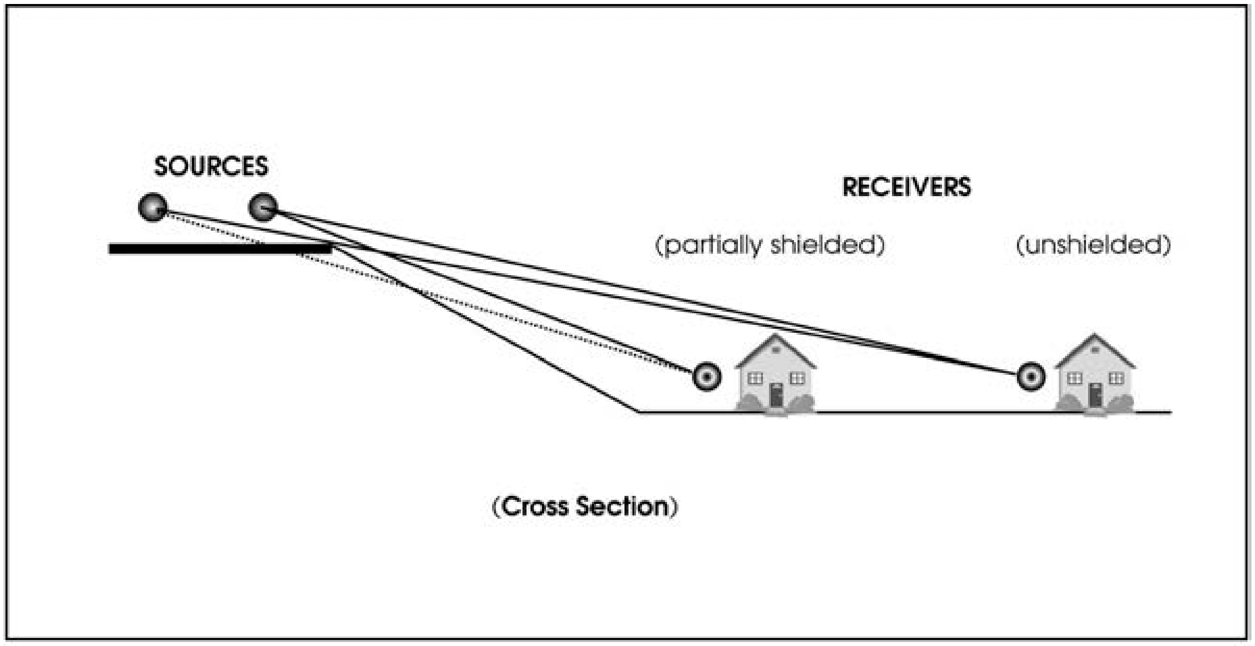

Figure 3-2. Typical Noise Measurement Site Locations

Figure 3-3 illustrates another example of the effects of site geometry on the selection of highest noise exposure. The unshielded Receiver 1 shows a higher noise level than Receiver 2 even though the latter is closer to the freeway. Other examples can be generated in which the nature of terrain and natural or artificial 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 interest usually focuses on the noisiest locations.

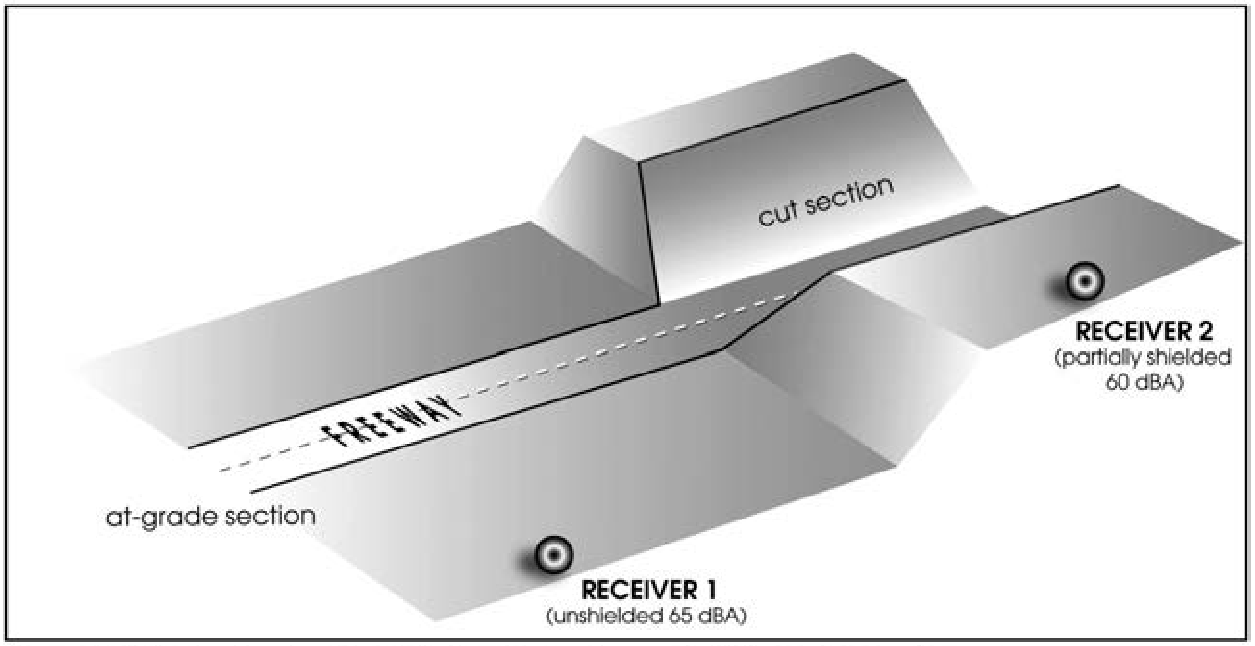

Figure 3-3. Receiver Partially Shielded by Top of Cut vs. Unshielded Receiver

3.3 Measuring Times, Duration, and Number of Repetitions

3.3.1 Measuring Times

23 Code of Federal Regulations (CFR) 772 requires that traffic characteristics that 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 noise, the measurements must reflect the highest existing hourly noise level that occurs regularly. In some cases, weekly or seasonal variations need to be considered. In recreational areas, weekend traffic may be higher than on weekdays and may be heavily influenced by season, depending on the type of recreation. 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. To avoid contaminated measurements, it is often necessary to vacate classrooms for the duration of the measurements or to take measurements during vacation breaks.

Noise measurements for model calibration do not need to be made during the worst noise hour, but it is desirable to have about the same estimated traffic mix (e.g., heavy truck percentages of the total volume) and speeds as during the noisiest hour. Accurate traffic counts and meteorological observations (see Section 3.6) must be made during these measurements.

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

Noise monitoring for investigating citizen complaints may need to be done at a time to which the parties mutually agree. 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 abatement performance should be done during the noisiest hour. Noise barriers are designed for noisiest hour traffic characteristics, which probably include highest truck percentages, and to minimize contamination by background noise. Traffic should be counted during these measurements. If before-and-after traffic conditions differ, measurements should be normalized or adjusted to the same conditions of traffic (see Section 3.3.1.2).

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

3.3.1.1 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 rush hour 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 valuable in determining the noisiest hour for a particular facility.

3.3.1.2 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. During each measurement, take noise measurements and count traffic simultaneously. Although lane-by-lane traffic counts yield the most accurate results, it is usually sufficient to count traffic by direction (e.g., east- and westbound). Separate vehicles into 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 driving a test vehicle through the project area at the prevailing traffic speed.
2. Expand vehicle counts for the measurement period to hourly values (e.g., if the measurement period was 15 minutes, multiply the vehicles counted in each group by 4). Section 3.3.2 discusses duration of measurement as a function of hourly vehicle volumes.
3. Enter the hourly traffic volumes and speeds from steps 1 and 2 into the FHWA traffic noise model. Also include the proper roadway and receiver geometry and site parameters. Run the model.
4. Enter the traffic volumes and speeds associated with the noisiest hour and the same roadway and receiver geometry and site parameters as used in step 3. Run the model.
5. Subtract results of step 3 from step 4. The 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.

Example

Measured noise level in step 1, L_{eq} = 66 dBA

Calculated for step 1 conditions (step 3) = 67 dBA

Calculated for noisiest hour (step 4) = 69 dBA

Difference (step 5) = 2 dBA

Measured noise level adjusted to noisiest hour (step 6) = 66 + 2 = 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 contamination. If hourly noise relationships are in agreement between the two monitors, there is reasonable assurance that neither was contaminated. There is, however, no assurance that regional contamination such as frequent aircraft flyovers did not take place. As such, measurements with remote noise monitoring equipment must be approached with extreme caution and only with at least some familiarity of nearby noise sources.

3.3.2 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 higher the fluctuations, the longer the measurement must be. Vehicle spacing and differences in vehicle types are responsible for fluctuating noise levels. These fluctuations decline 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 durations in Table 3-1 are recommended for highway traffic noise measurements as a function of number of vehicles per hour (vph) per lane.

Table 3-1. Suggested Measurement Durations

Traffic Volume	Vehicles per Hour per Lane	Duration (Minutes)
High	>1,000	10
Medium	500–1,000	15–20
Low	<500	20–30

Most sound level meters automatically integrate and digitally display cumulative L_{eq}. Near the beginning of each measurement period, the displays fluctuate considerably. However, after more data are collected, they tend to stabilize. The time necessary to stabilize depends on the amount of noise fluctuation. A measurement may be terminated when the range of the fluctuation in displayed L_{eq} is less than 0.5 dBA. However, measurements can be lengthened if necessary.

3.3.3 Number of Measurement Repetitions

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

- change in traffic volumes, speeds, and/or mixes;
- contamination from other noise sources, such as barking dogs, aircraft, and nearby construction;
- change in weather (e.g., wind speed, wind direction, temperature, and humidity);
- changes in site conditions;
- instrument, operator, or calibration error; and
- malfunctioning instruments.

Because of these potential variables and errors that may occur during a measurement, it is strongly recommended that a time-averaged measurement (e.g., 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, however. Whenever three or more noise measurements are made in the same general area, simultaneously or in relatively rapid succession, one measurement at each site may be sufficient if the sites are acoustically equivalent (see Section 3.2.2.2). However, to determine whether a measurement at a particular site is acceptable, the measurement should be compared to 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). However, the operator is not precluded from taking more than one measurement per setup and calibration. In fact, if time permits, multiple measurements during each setup are encouraged to improve accuracy. The two setups may be made consecutively, at different times, or on different days.

If done consecutively, the setup should be broken. Power must be turned off and on, and instruments must be recalibrated. 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 also recommended that equipment be disassembled and reassembled to avoid undetected errors through bad connections in the cables or microphone.

Repeat measurements should be compared with the originals under the same conditions of traffic, meteorology, and site. Noise contamination, instrument malfunction, operator error, or any other anomalies in the measurements can then readily be detected. To ensure that conditions are the same for all measurements, traffic counts and some basic meteorological measurements should be made during the noise measurements (see Sections 3.3.4 and 3.6). If the repeat measurements do not agree with the originals, additional 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 dBA. Repetitive measurements for each setup should then be within about 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 SLMs approved for transportation noise measurements (American National Institute of Standards [ANSI] S1.4 1983, Types 1 and 2). Some examples illustrating these criteria are listed below and were purposely selected to show the extreme allowable limits. Usually, better agreement between setups and within setups can be expected. Examples 1 to 3 assume that all meteorological conditions, traffic conditions, and site conditions are the same throughout all measurements.

Example 1

Measurement 1

Setup 1: 74.5 dBA, L_{eq}

Setup 2: 76.5 dBA, L_{eq}

Mean: 75.5 dBA, L_{eq}

Conclusion: Measurements are acceptable because they agree by 2 dBA.

Example 2

Measurement 1

Setup 1: 69 dBA, L_{eq}

Setup 2: 71 dBA, L_{eq}

Measurement 2

Setup 1: 67 dBA, L_{eq}

Setup 2: 69 dBA, L_{eq}

Mean

Setup 1: 68 dBA, L_{eq}

Setup 2: 70 dBA, L_{eq}

Overall: 69 dBA, L_{eq}

Conclusion: Measurements are acceptable because they agree by 2 dBA and measurements within each setup are within about 1 dBA of the setups' mean.

Example 3

Measurement 1

Setup 1: 61.6 dBA, L_{eq}

Setup 2: 58.6 dBA, L_{eq}

Measurement 2

Setup 1: 59.6 dBA, L_{eq}

Setup 2: –

Mean

Setup 1: 60.6 dBA, L_{eq}

Setup 2: 58.6 dBA, L_{eq}

Overall Mean: 59.9 dBA, L_{eq} (round to 60)

Conclusion: Measurements are acceptable.

Examples 1 to 3 indicate that as long as the agreement criteria between the two setups and within each setup are met, all measurements can be averaged together. Examples 4 and 5 illustrate the process if the setups do not agree by 2 dBA.

Example 4

Measurement 1

Setup 1: 65.3 dBA, L_{eq}

Setup 2: 68.0 dBA, L_{eq}

Conclusion: Measurements are not acceptable; difference of more than 2 dBA).

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, although if the decision is to take another measurement during Setup 2, and the agreement criteria still cannot be met, it is recommended to break Setup 2 and perform additional measurements with Setup 3. If agreement is reached between Setups 2 and 3, Setup 1 should be eliminated, as illustrated in Example 5:

Example 5

Measurement 1

Setup 1: 65.3 dBA, L_{eq}

Setup 2: 68.0 dBA, L_{eq}

Setup 3: 69.0 dBA, L_{eq}

Measurement 2

Setup 1: –

Setup 2: 68.5 dBA, L_{eq}

Setup 3: –

Mean

Setups 2 and 3: 68.5 dBA, L_{eq}

Conclusion: Setup 2 and 3 measurements are acceptable.

If Setup 3 measurement would have agreed with both Setups 1 and 2 (e.g., 67.0 instead of 69.0), another decision would have to be made, such as:

- use Setups 1 and 3,
- use Setups 2 and 3, or
- use the average of all three setups (all measurements).

The safest approach would be to use the average of all measurements unless there would be a good reason to eliminate one setup.

These examples illustrate some extreme cases; 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. The analyst may need to rely more on individual judgment and experience in more complicated situations.

In some cases, more accuracy is required than the criteria allow. These cases apply mostly 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, a 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 about 1 dBA. Table 3-2 shows the maximum allowable standard deviations (S_{max}) as a function of the number of samples (measurements). Although the table is calculated for up to 10 measurements, the criterion can be met by five or fewer measurements in most cases. A scientific calculator with statistical functions is essential when making calculations in the field.

Table 3-2. Maximum Allowable Standard Deviations for a 95% Confidence Interval for Mean Measurement of about 1 dBA

Number of Measurements	Maximum Allowable Standard Deviations
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 1

Setup 1: 67.8 dBA, L_{eq}

Setup 2: 68.7 dBA, L_{eq}

Measurement 2

Setup 1: 66.9 dBA, L_{eq}

Setup 2: 67.9 dBA, L_{eq}

Measurement 3

Setup 1: –

Setup 2: 67.8 dBA, L_{eq}

Standard Deviation (Maximum)

Setups 1 and 2: 0.73 (0.63)

Setups 1 to 3: 0.64 (0.81)

Mean

Setups 1 to 3: 67.8 dBA, L_{eq} (round to 68)

Conclusion: Use Setups 1 to 3 (five measurements).

The preceding examples assume 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, performance, manufacturers' manuals, and accuracy standards (discussed later in Section 3.7) will give a good estimate of instrument error.

The next section covers a method of normalizing noise measurements made under different traffic conditions. Meteorological limits for comparisons of noise measurements will be discussed in Section 3.6.

3.3.4 Normalizing Measurements for Differences in Traffic Mixes and Volumes

Before applying the criteria discussed in Section 3.3.3, 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 optional use in the field.

This 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 3.3.3.

The obvious advantage of using this method is that it may eliminate the need to return to the same site at a later date if repetition criteria are not met. However, as with most simplified methods, there are certain limitations to the use of this procedure. The method should not be used in the following cases.

- 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.
- Truck speeds are significantly different (more than 5 mph) from auto speeds.
- Speeds cannot be determined within 5 mph.
- The ratio of distances from the receiver to the centerline of the far (directional) lane group and the receiver to the centerline of the near

(directional) lane group is more than 2:1. For most eight-lane urban freeways, this means that the receiver should not be closer than 45 feet from the edge of the traveled way.

- The directional split of traffic is different by more than 20% for each vehicle group between measurements. For example, if the directional split between heavy trucks during the first measurement is 60/40 and 80/20 or 40/60 during the next measurement, the method would be valid. However, a second split of 85/15 or 35/65 means that 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 (Calveno) Reference Energy Mean Emission Levels (REMELs) (see Section 5.5.1), 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 five autos passing at the same speed. These relationships are speed-dependent and the same for the maximum noise level (L_{max}) and time-averaged noise levels (L_{eq}).

The relationships do not consider source heights and may not be used if the path from the source to the measurement site is intercepted by a barrier or natural terrain feature. Table 3-3 shows V_E for speeds from 56 to 105 km/h (35 to 65 mph) in 5-mph increments, based on the Calveno REMELS. Table 3-4 shows the same table based on the new FHWA TNM REMELs for baseline conditions. Table 3-4 should be used on any new project now that TNM has been officially implemented (see Section 5.5.2).

Table 3-3. Equivalent Vehicles Based on California Vehicle Noise Reference Energy Mean Emission Levels

	Equivalent Vehicles		
Speed (km/h [mph])	1 Heavy Truck	1 Medium Truck	1 Auto
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: Based on Calveno REMELs and vehicle definitions in the FHWA Highway Traffic Noise Prediction Model (also see Section 5.5.1).

Table 3-4. Equivalent Vehicles Based on Federal Highway Administration Traffic Noise Model Reference Energy Mean Emission Levels

	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

Note: Based on FHWA TNM REMELs and vehicle definitions in FHWA 1996a and FHWA 1996b (also see Sections 4.4 and 5.5.2).

The following is an example of calculating V_E using Table 3-3:

Given

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

Solution

76 heavy trucks = 76 x 10.4 = 790 V_E

34 medium trucks = 34 x 4.1 = 139 V_E

789 autos = 789 x 1 = 789 V_E

Total = 1,718 V_E

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

1. $L_{eq}(1)$ is the first noise measurement, which is used as the reference measurement. Convert the traffic count for $L_{eq}(1)$ to V_E, which is designated $V_E(1)$.
2. $L_{eq}(2)$ is the second noise measurement, which is to be normalized. Convert the traffic count for $L_{eq}(2)$ to $V_E = V_E(2)$.
3. *c* is the correction to be applied to $L_{eq}(2)$ for normalization to the traffic of $L_{eq}(1)$. The equation to compute *c* is $10\log_{10}[V_E(1)/V_E(2)]$. Note that *c* may be negative or positive.
4. $L_{eq}(2N)$ is the normalized $L_{eq}(2)$. The equation to compute $L_{eq}(2N)$ is $L_{eq}(2) + c$.
5. $L_{eq}(2N)$ may be directly compared to $L_{eq}(1)$ in the field to determine whether the agreement criteria discussed in Section 3.3.3 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-minute measurements for different traffic conditions meet the agreement criteria in Section 3.3.3 (for convenience the measurements have been numbered consecutively regardless of setup):

Given

		15-Minute L_{eq}					
Measurement	Setup	dBA	Heavy Trucks	Medium Trucks	Autos	Speed (mph)	Equivalent Vehicles (V_E)
1	1	74.4	100	50	1,275	55	2,810
2	1	75.5	150	100	850	55	3,280
3	2	74.0	60	30	1,700	55	2,621

Correction Calculations (Using Table 3-4)

Correction c for $L_{eq}(2) = 10\log_{10}\left(\frac{V_E(1)}{V_E(2)}\right) = 10\log_{10}\left(\frac{2{,}520}{2{,}820}\right) = -0.5$

$L_{eq}(2N) = L_{eq}(2) + c = 75.5 - 0.5 = 75.0$ dBA

Correction c for $L_{eq}(3) = 10\log_{10}\left(\frac{2{,}520}{2{,}447}\right) = 0.2$

$L_{eq}(3N) = 74.0 + 0.2 = 74.1$ dBA

Normalized Data Using Table 3-4

Measurement	Setup	Normalized L_{eq} (dBA)
1	1	74.4
2	1	75.0
3	2	74.1

Further examination indicates that the agreement criteria of Section 3.3.3 are met, and no further measurements are necessary. Please note that the normalized data are only used to determine agreement between measurements. The actual measurements and traffic counts may be used in later calculations as follows:

Average Energy of Measurements

74.5 dBA (report as 75 dBA)

Average 15-Minute Traffic Counts

$$\text{Mean Heavy Trucks} = \left(\frac{100 + 150 + 60}{3}\right) = 103.3$$

$$\text{Mean Medium Trucks} = \left(\frac{50 + 100 + 30}{3}\right) = 60.0$$

$$\text{Mean Autos} = \left(\frac{1275 + 850 + 1700}{3}\right) = 1{,}275.0$$

Expand Average 15-Minute Traffic Counts to 1 Hour

Mean Heavy Trucks = 103.3 x 4 = 413

Mean Medium Trucks = 60.0 x 4 = 240

Mean Autos = 1,275.0 x 4 = 5,100

The expanded average traffic counts may be used in the prediction model to calculate the noise level. The result may be compared to the energy-averaged measurement. Section 5.4 explains how this comparison may be used for "calibrating" the prediction model.

Although Tables 3-3 and 3-4 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 3-3 instead of Table 3-4 would yield only slight differences (0.2 dBA) in normalized measurements 2 and 3 and the same energy-averaged noise level, as shown by the following results. These normalized data also meet the agreement criteria.

Normalized Data Using Table 3-3

Measurement	Setup	Normalized L_{eq} (dBA)
1	1	74.4
2	1	74.8
3	2	74.3

3.3.5 Classroom Noise Measurements

These measurements meet the requirements of the Streets and Highways Code Section 216 and are referenced in the Protocol. Under these provisions:

> [t]he noise level produced by traffic on, or by construction of, a state freeway shall be measured in the classrooms, libraries, multipurpose

> rooms, and spaces used for pupil personnel services of a public or private elementary or secondary school if the rooms or spaces are being used for the purpose for which they were constructed and they were constructed under any of the following circumstances: …

Section 216 lists all of these circumstances and should be consulted to determine applicability of these measurements. For convenience, the rooms mentioned above will be referred to as "classrooms" in this section.

Please note that the requirements for Section 216 are not to be confused with those under 23 CFR 772 Noise Abatement Category E for interior noise levels. Consult Section 216 for appropriate application.

Determining a project's traffic noise impacts on classroom interiors under Section 216 requires taking noise measurements inside the classroom. Please note that Section 216 requires that all measurements "be made at appropriate times during regular school hours and shall not include noise from other sources that exceed the maximum permitted by law." The noise of vehicles that exceed the maximum allowable level in the California Vehicle Code (L_{max} of 90 dBA at 50 feet for vehicles traveling more than 45 mph) should be excluded. Because this is difficult, however, the requirement is ignored. It is customary to take outside and inside noise levels to determine building insertion loss. This information is useful when noise abatement is necessary.

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 Figures 3-4a and 3-4b.

Figure 3-4a 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 avoid significant shielding by the corner of the building. This can be accomplished by maintaining at least a 70º angle between a perpendicular line to the freeway and a line to the corner of the building. Mic. 2 should be placed in the center of the classroom.

Figure 3-4b shows an alternate setup to be used if the former setup 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 distances 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- by 10-m classroom, the error would be 0.5 dBA or less. Between 20 and 60 m, a distance reduction of

1 dBA would have to be applied to Mic. 1 to normalize Mic. 1 to Mic. 2. If the distance from Mic. 1 to the freeway is less than 20 m, a larger adjustment will be necessary. The prediction model may be used to calculate the adjustments.

If the classrooms are not air-conditioned and rely on open windows or doors for ventilation, simultaneous measurements should be made with doors and windows open and closed. The noise insertion loss provided by the building under these conditions is useful for predicting inside classroom noise levels and for 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 and doors open but will meet the criterion with them closed, noise abatement considered may include adding air conditioning.

If the project is on a new alignment or construction noise will be the dominant noise source, 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 3-5).

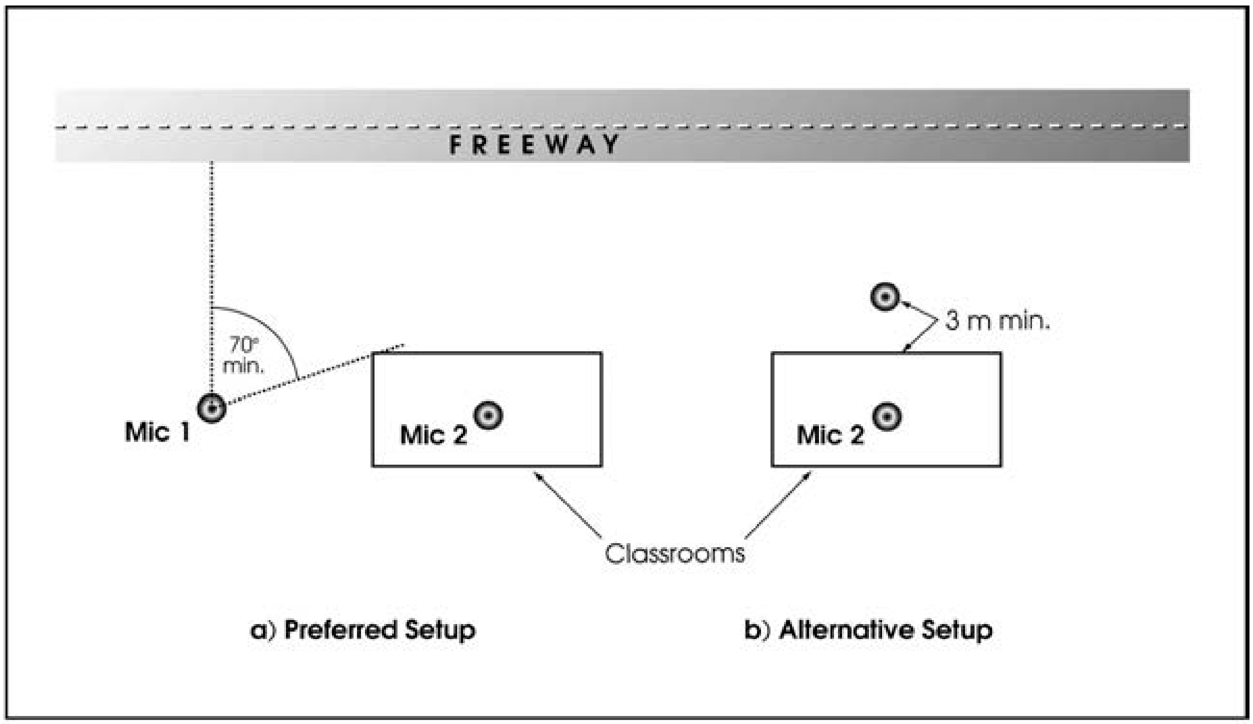

Figure 3-4. Classroom Noise Measurements (Reconstruction of Existing Freeway)

Acceptable choices of an artificial source 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 to 500 Hz, and decrease at 6 dB per octave from 500 to 4,000 Hz. Amplification should be sufficient to produce A-weighted sound levels at least 10 dBA more than background noise levels at exterior and interior locations. A commercial-quality loudspeaker should be used with directional characteristics such that a 2,000-Hz signal measured at 45º from perpendicular to the face of the speaker is no more than 6 dB less than the level measured at the same distance on the perpendicular axis. The sound level output must be kept constant for inside and outside measurements.

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 3-5 for the indoor noise measurements.

Placing the speaker and microphone so that there is a direct line of sight between them through an open door or window should be avoided. If possible, additional measurements at 15º, 30º, and 60º should be taken and the results averaged. If only one angle is used, it should be 45º.

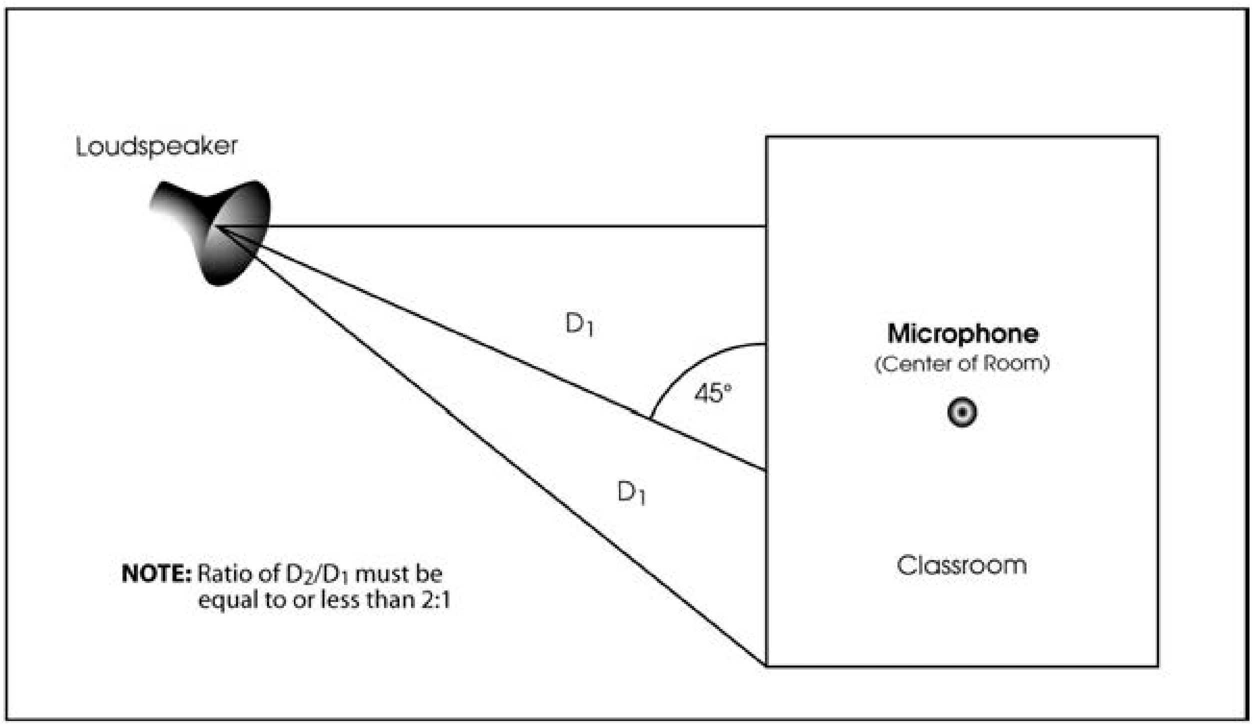

Figure 3-5. Classroom Noise Measurements (Project on New Alignment with Artificial Sound Source)

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

Section 8.4 discusses noise measurements for interior abatement in residential units. Interior noise abatement (home insulation) is rarely employed and subject to extraordinary abatement guidelines issued by Caltrans in a separate document. It is only approved by FHWA on a case-by-case basis. Home insulation has no relationship with the requirements of Section 216.

3.4 Instrumentation

The instruments used for measuring or recording noise include a range of manufacturers, models, types, accessories, degrees of accuracy, prices, and levels of sophistication. It is not the intent of this section to discuss all details of noise instruments or to endorse certain manufacturers. Informative catalogs are available from all major manufacturers to help in deciding what equipment to purchase, and sales representatives are usually very helpful in demonstrating the equipment. Once purchased, user manuals will be useful, ready references for specific operating procedures. It is strongly recommended that Caltrans Headquarters staff be consulted before purchasing noise instrumentation.

This section will cover general features common to most instruments. The categories discussed are sound level meters, recording devices, frequency analyzers, acoustical calibrators, and meteorological and other non-noise-related equipment.

3.4.1 Sound Level Meters

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:

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

The expected total allowable error for a Type 1 SLM in the field is about 1.5 dB; for a Type 2 SLM in the field, the allowable error is about 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 SLM 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, and digital displays. 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. For example, "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 special purpose (if any).

All SLMs 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 an SLM not marked with the type shall not be used. Type 3 was discontinued with adoption of ANSI S1.4-1983.

Although SLMs are available in many levels of sophistication, they all have the following general components:

- **Microphone System (Microphone and Preamplifier):** The microphone converts air pressure fluctuations into an electrical signal that is 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. 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 0.5-inch-diameter microphone is used most commonly. The air condenser microphone (most common) consists of a membrane and 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 SLMs 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.

- **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 3.6). The wind screen should always be used, even in absence of wind, because it helps to protect the microphone against dust or mishaps.

- **Root Mean Square Detector:** Converts peak-to-peak signals to a root mean square (RMS) signal. This measure is derived by squaring the signal at each instant, obtaining the average (mean) of the squared values, and taking the square root of this average.
- **Amplifier:** Amplifies the electrical signal.
- **Frequency Weighting Filters (A to C):** These filters are required by ANSI S1.4-1983 and ANSI S1.4-1985. The A-weighting is used internationally for environmental noise measurements (including transportation noise).
- **Slow 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. The fast setting, however, gives a better resolution of instantaneous sound levels.
- **Range Setting:** Allows setting of the correct range of sound levels to be measured.
- **Analog or Digital Display:** Displays instantaneous noise levels or integrated averages. Digital displays often have multi-function switches that allow the user to view various noise descriptors such as L_{eq} and L_{max}.
- **Battery Check Switch:** Allows user to check battery voltage.
- **Output:** For various recording devices.
- **Power On/Off Switch**

Many SLMs also have pause switches to interrupt data sampling, preset time switches that allow sampling over a predesignated time period, reset switches for starting a new sampling period, and other features. More sophisticated SLMs can be mated to external filter sets to allow 1- or 1/3-octave frequency analysis in the field.

3.4.2 Recording Devices

Three main types of recording devices can be connected to most SLM outputs: graphic level recorders (GLRs), audio recorders, and microprocessors.

3.4.2.1 Graphic Level Recorder

The graphic level recorder (GLR) records sound levels graphically in terms of instantaneous decibels vs. time. GLRs 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. An independent party can analyze the trace and derive various noise descriptors from it.
- The traces can be used as a backup for noise levels obtained from a visual display, which guards against errors.

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

3.4.2.2 Audio Recorder

Audio recording of sound levels for lab analysis at a later time are especially suited for special studies and research. Recordings give the noise analyst a great amount of freedom to perform different types of analysis, using any noise descriptor desired, and various frequency analyses. Analog audio tape recorders have been used for many years for audio recording. Today digital audio recording devices that utilize digital audio tape (DAT) or digital solid state memory are more commonly used. Recorders need to be high-quality professional recorders, with flat frequency response and high signal-to-noise ratios.

3.4.2.3 Microprocessors

Microprocessors can analyze the signals from one or more SLMs simultaneously. The signals are converted into various noise descriptors designated by the noise analyst and digitally logged. Depending on the available software, frequency analysis can be performed also. The microprocessor is invaluable in research because 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.

3.4.3 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. These analyzers can be software-based on a computer or stand-alone hardware devices.

3.4.3.1 Real-Time Analyzers

The output of an SLM or audio 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 an audio recorder is used to feed 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.

3.4.3.2 Fast Fourier Transform 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. However, this is not a tool for routine environmental noise measurements.

3.4.4 Acoustical Calibrators

Acoustical calibrators are used to calibrate the SLM/recorder system in the field. They are manufactured to fit specific SLMs 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 1,000 Hz. The SLM/recorder system then can be adjusted to this level.

3.4.5 Meteorological and Other Non-Noise-Related Equipment

Basic meteorological instruments are necessary to perform measurements for Section 3.6. It is recommended that, at a minimum, certain meteorological equipment be used simultaneously with noise measurements, including a hand-held anemometer, thermometer, and relative humidity meter.

The hand-held anemometer must measure wind speed to the nearest mile per hour or knot up to at least 15 mph, and direction to the nearest 22.5 degrees (16-point compass). Hand-held anemometers may be adapted to fit on a tripod for easier use. The anemometer must be oriented to true north with an accurate pocket compass and adjusted for magnetic declination.

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, as well as 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.

3.5 Noise Measurement Procedures

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

3.5.1 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, and billboards. 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, it should be placed on a tripod or other stand (test tube clamps are useful for this purpose).

When meteorological equipment is set up, thermometers should be in the shade, and the anemometer should have good exposure to representative winds.

3.5.2 Field Calibration

Acoustical calibrators are described under Section 3.4.4. Some calibrators provide a choice of several frequency settings. If the calibrator offers these choices, 1,000 Hz should be used for calibration. The SLM/recorder system can then be adjusted to this level. The procedures in manufacturers' user manuals should be followed.

The SLM/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 (C_R) indicated on the calibrator, the SLM/recorder system does not need to be adjusted. If the SLM reading deviates by 0.5 dB or more, or if measurements are part of a special study in which extreme accuracy is required, the SLM/recorder system should be adjusted within 0.1 dB of the reference level.

If the final calibration (C_F) of the acoustic instrumentation differs from the initial calibration (C_I) by 1 dB or more, all data measured with the system between the calibrations should be discarded and repeated. The instrumentation and connections should be checked thoroughly 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 calibrations should be adjusted as follows:

$$\text{Data Adjustment} = C_R – [(C_I + C_F\}/2)].$$

Example

C_R = 94.2 dB

C_I = 94.4 dB

C_F = 94.6 dB

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

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

The field calibration procedure is described below.

1. Adequate warm-up of instruments should be allowed before calibration (at least 1 minute or as specified in the manufacturer's manual). The analyst should check that all proper connections have been made and that batteries are fresh or adequately charged.
2. The calibrator should be placed carefully over the microphone and properly seated. Touching the calibrator during calibration should be avoided.
3. A proper screwdriver should be used 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. The SLM should be calibrated first, then the GLR.
4. The manufacturer's user manual should be consulted for other particular instructions.

3.5.3 Measurements

Following calibration of equipment, a wind screen should be placed over the microphone. The frequency weighting should be set on "A." The proper response setting should be set at "fast" or "slow." "Fast" should be used whenever possible.

On more sophisticated SLMs, the sampling time, sampling interval, and proper noise descriptor (L_{eq}, sometimes L_{max}) should be preset. The proper range of noise levels should also be set. A short preliminary measurement should be taken in cases of uncertainty.

During the noise measurements, any noise contamination, such as barking dogs, local traffic, lawnmowers, and aircraft, should be noted. If the SLM is equipped with a "pause" or "standby" switch or button, the measurement should be temporarily interrupted until the contamination ceases. The contaminated section of the GLR trace should be marked with pre-assigned codes, such as "D" for barking dog or "AC" for aircraft.

Talking during measurements should be avoided. Curious bystanders will often ask the operator about the monitoring. A possible way to avoid talking near the microphone is to stand 25 to 50 feet from it, which is far enough not to contaminate the measurement but close enough to watch the setup.

If highway noise measurements are taken, traffic should be counted simultaneously with the noise measurements. At a minimum, directional traffic should be counted separately. Traffic counts by lane are best but often not practical because they are too labor-intensive. Traffic should be divided into heavy trucks, medium trucks, and autos as defined by FHWA. Definitions of these are covered in Section 5. Average speeds for each vehicle group and direction should be estimated using a radar gun (if available) or test runs with a vehicle in the flow of traffic during the noise measurements.

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

After the last measurement of the setup, the equipment should be recalibrated before power is turned off. Also, if the power is interrupted during or between measurements, the instruments need to be recalibrated before additional measurements are taken. The procedure for calibration and necessary data adjustment was discussed in Section 3.5.2.

3.5.4 Documentation

Measurement data should be carefully recorded. If the data are read from a display and hand-copied on a form, the readings should be checked and confirmed by another if possible. 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. Specifically, the following items should be documented:

- **Noise Measurement Sites:** A sketch should be made showing the microphone location in relation to natural or artificial landmarks. Distances should be shown to the nearest foot to such features as building corners, trees, street signs, curbs, and fences. Enough detail should be included on the sketch to enable anyone to reoccupy, at a later date, the three-dimensional (including height above ground) position of the microphone within 1 foot horizontally and 0.5 foot vertically. Accurate three-dimensional relationships between source and site should be shown. Cross sections should be obtained from accurate maps or field surveys. Sites should be located on maps showing all receivers used in the noise analysis. The district, county, route number, and kilometer post of the site should be included.

- **Noise Measurements:** All instruments used for the noise measurements should be recorded, including manufacturer, model number, and serial number. Also important are the calibrator make, model, serial number, reference level, frequency, and last calibration date. Names of instrument operators and persons recording the data should be shown. Pre- and post-calibration data should be shown. Site number, date, time, length of measurement, noise descriptor, pertinent settings on the SLM/recorder system, and noise data should be recorded. Remarks, notes of contamination, or anything that might have a possible effect on the measurement results should be included.
- **Meteorological Conditions:** Prevailing wind direction and speed during the noise measurements, temperature, relative humidity, and sky conditions should be noted. Approximate height, and location of measurements should be indicated. Date, time, site number, and name of observer should be shown also.
- **Traffic Counts:** The number of vehicles broken down by classification should be shown. It is important to indicate the location of traffic counts, number of lanes or lane groups counted, direction, length of time, time, district, county, route, post mile, names of personnel, and counts and speeds.

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

3.6 Meteorological Constraints on Noise Measurements

Meteorological conditions can affect noise measurements in several ways. At an ambient noise level of 40 to 45 dBA, wind speeds of more than 5 m/s (11 mph) may begin to contaminate noise measurements with a rumbling noise because of 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 affect critical components of sound level meters. For example, during conditions of high humidity, water condensation can form on the vibrating microphone membrane, causing a “popping” sound that can contaminate noise measurements.

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

Refraction caused by wind shear or temperature gradients near the ground surface will also alter noise levels. The effects of refraction are discussed in Section 2.1.4.3. When noise levels are compared to determine the effects 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.

3.6.1 Meteorological Criteria

Noise measurements should not be made when one or more of the following meteorological conditions exists.

- Wind speeds are more than 5 m/s (11 mph) for routine highway noise measurements.
- Manufacturers' recommendations for acceptable temperature and humidity ranges for instrument operation are exceeded. Typically, these ranges are from –10 to 50°C (14 to 122°F) for temperature and 5 to 90% for relative humidity. Heavy fog conditions usually exceed 90% relative humidity.
- There are rain, snow, or wet pavement conditions. All reported highway noise levels are assumed valid for dry pavements only.

3.6.2 Equivalent Meteorological Conditions

Wind effects on noise levels are caused by refraction (bending) of the noise rays because of wind shear near the ground. Noise rays are bent upward upwind and downward downwind from the source, resulting in a noise decrease upwind and increase downwind from a source.

Recent studies by the Caltrans Division of New Technology, Materials, and Research and others have shown that this wind effect can affect noise measurements significantly even at relatively close distances to noise sources. Section 3.3.3 indicates that 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 - 1998 "Methods for Determination of Insertion Loss of Outdoor Noise Barriers" recommends that meteorological equivalence be based on wind, temperature, and cloud cover. The following criteria are recommended 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 ANSI may be used to define meteorological equivalency for the purposes of comparing noise levels for agreement with Section 3.3.3 or any time before and after noise measurements are performed on noise barriers.

3.6.2.1 Equivalent Wind Conditions

Wind conditions are equivalent for noise measurements if

- the wind class (Table 3-5) 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 the source to receiver. To keep the measurement accuracy due to atmospheric wind conditions to within about 1 dB, this limit should be 1 m/s (2.2 mph) for distances less than 230 feet. If it is desired to keep this accuracy within about 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 the highway to receiver (microphone position) is positive, while the same component blowing from the receiver to highway is negative.

Table 3-5. 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 and –1 m/s, –1 and –2 m/s, or –2.5 and –3.5 m/s, but not when their respective components are 0.5 and 1.5 m/s, because of the change in wind class. For the purposes of comparison with the results from the FHWA Traffic Noise Model, which has no provisions for wind inputs and therefore predicts noise levels for calm (no wind) conditions, the perpendicular wind component needs to be between –1 and +1 m/s (–2.2 and +2.2 mph).

Please 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:

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

3.6.2.2 Equivalent Temperature and Cloud Cover

Measurements to be compared (e.g., before or after noise barrier measurements or repeat measurements) should be made for the same class of cloud cover, as determined from Table 3-6, and with the average air temperatures within 14°C (25°F) of each other.

Table 3-6. Cloud Cover Classes

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

3.6.2.3 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. For example, comparisons of measurements made under extremely dry conditions (e.g., less than 25%) with those made during humid conditions (e.g., more than 75%) should be avoided.

3.7 Quality Assurance

All SLMs should be calibrated by and at the interval recommended by the manufacturer, 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. Consult with Caltrans Headquarters staff for service contracts in effect for instrument calibrations.

Instrument manuals and calibration and repair records should be kept on file in the office of the responsible party (e.g. District office, headquarters environmental unit). Historical data on the instrument performance may be useful in determining the reliability and accuracy of the equipment.

Section 4
Traffic Noise Impact Screening Procedure

This screening procedure was developed as an aid in determining whether a potential for a traffic noise impact will exist with a proposed Type I highway project as defined in the Protocol. If the project passes the screening procedure, a detailed noise analysis is normally not be necessary. Even if the screening procedure may indicate otherwise, however, prudent engineering judgment should still be exercised to determine whether a detailed noise analysis is warranted. For instance, a detailed analysis per Sections 5 and 6, if applicable, is still recommended if the project is controversial or sensitive, or if the net results of the effects of topography and shielding are complex or ambiguous. If the project fails the screening procedure, a detailed noise analysis must be performed. A noise analysis screening procedure checklist, shown in Section 4.5, is included for the reader's convenience.

4.1 Screening Procedure Steps

The steps of the screening procedure are listed below. Definitions of italicized words and terms are contained in Section 4.2.

1. If existing, planned, designed, and programmed adjacent land uses are not residential and do not have sensitive land uses (i.e., areas of *frequent human use* that would benefit from a lowered noise level), no further analysis will be necessary. These findings should be documented. If there are no *potentially impacted receivers* in the vicinity, this screening procedure will be considered passed. If there are *potentially impacted receivers* in the vicinity, the conditions in the following steps should be satisfied. Failure of one condition constitutes failure of this screening procedure, and the detailed analyses described in Sections 5 and 6 should be performed.
2. The proposed project must be along an alignment or realignment of an existing facility. If the project involves new alignments, the screening procedure is failed and a detailed analysis is required.
3. For *critical receivers,* after-project *shielding* conditions should be equal to or better than pre-project conditions. If after-project *shielding*

conditions are worse than pre-project conditions the screening procedure is failed and a detailed analysis is required.

4. Existing worst-hour noise levels should be measured at the *critical receivers* per Section 3. If the existing worst hourly noise is less than 5 dBA below the appropriate NAC (e.g. L_{eq}[h] more than 62 dBA for Land Use Category B), this screening procedure should be stopped; a detailed noise analysis should be performed according to the procedures covered in Sections 5 and 6, if applicable. If the existing noise levels at the most *critical receivers* are 5 dBA or more below the NAC, step 5 should be followed.

5. The following equation in terms of existing and future hourly *equivalent vehicles* (V_E) and *equivalent lane distances* (D_E) should yield a value of less than 3.0 dBA:

$$10\log_{10}\left[\frac{V_{E(FUTURE)}}{V_{E(EXISTING)}}\right]+15\log_{10}\left[\frac{D_{E(EXISTING)}}{D_{E(FUTURE)}}\right]< 3.0 \text{ dBA}$$

   Where:

   $V_{E(FUTURE)} = V_E$ per hour after the project.

   $V_{E(EXISTING)} = V_E$ per hour before the project.

   $D_{E(EXISTING)} = D_E$ before the project.

   $D_{E(FUTURE)} = D_E$ after the project.

   See Sections 4.3 and 4.4 for guidance in determining D_E and V_E. Because of the approximation of the coefficient 15 in the preceding equation, the ratio $D_{E(EXISTING)}/D_{E(FUTURE)}$ should not exceed 4. If it does, a detailed technical noise analysis is recommended.

6. If the preceding value is less than 3.0 dBA, the project passes the screening procedure and a detailed impact analysis is not required.

7. If the preceding value is equal to or more than 3.0 dBA, the project does not pass the screening procedure and a detailed impact analysis is required.

4.2 Definitions for Screening Procedure

The following are definitions of italicized terms used in the screening procedure steps described previously:

Critical Receiver: A potentially impacted receiver where the worst noise impacts would occur. Critical receivers are potentially impacted receivers where the after-project noise level or noise increase is expected to be the highest.

Equivalent Lane: An imaginary single lane that acoustically represents a multi-lane highway. An equivalent lane contains the total traffic volumes present on the highway. See Section 4.3.

Equivalent Lane Distance: Distance from the receiver to an equivalent lane. See Section 4.3.

Equivalent Vehicle: A basic noise source unit that expresses the noise level emitted by heavy and medium trucks in terms of the equivalent noise level emitted by a certain number of autos. This number is speed-dependent. For example, at 88.5 km/h, 1 heavy truck produces the same noise level as 13 autos; at 56 km/h, the noise level is that of 31 autos. V_E is synonymous with auto, but it should be used when a vehicle mix normalized to autos is implied. Definitions of heavy trucks, medium trucks, and autos are the same as those used in the FHWA Traffic Noise.. See Section 4.4.

Frequent Human Use: Any activity that results in human exposure to traffic noise for at least 1 continuous hour on a regular basis.

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

Potentially Impacted Receiver: A receiver that may be impacted by the predicted traffic noise level. Determining whether a receiver has a reasonable chance of being exposed to traffic noise impact can be determined by the steps described in Section 4.1. In many cases, however, the determination will be obvious without going through the steps.

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

- the straight-line noise path from the noise source (vehicles on a highway) to receiver is partially or completely interrupted, or
- the noise path is less than 1.5 m above the highest point of the intervening terrain or major obstacle (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, as shown in Figure 4-1).

A judgment of whether shielding is the same or better after the project or before it 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 behind the hill would obviously cause an improvement. A less obvious example would be where the existing noise path grazes gently rolling terrain, but the after-project noise path will be 1 m above the high points in the terrain because of raising the highway profile. The latter case would degrade the shielding and invalidate the screening procedures.

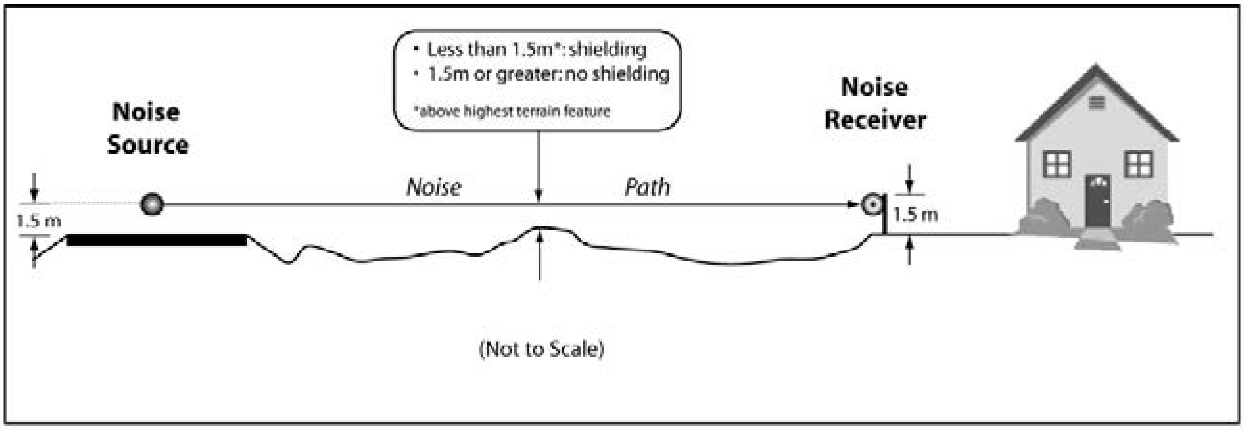

Figure 4-1. Shielding Criterion

4.3 Method of Calculating Equivalent Lane Distance

TNM allows traffic to be segregated by lane, with the centerline of each lane associated with a different source-to-receiver distance. Normally, traffic data are not available by lane, but by direction (e.g., eastbound [E/B] and westbound [W/B]). The normal procedure is to use the centerline of the lanes in each direction to approximate an acoustical representation of two source locations (e.g., centerline E/B and centerline W/B). However, it is more accurate to use D_E, as determined by the formula shown in Figure 4-2.

This screening procedure recommends a further simplification by grouping all lanes, in 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 approximately balanced directional traffic flows and normal medians, although this method may still be used if traffic flows will have roughly the same (unbalanced) directional flow ratio with or without the project and if changes in source-to-receiver distances are not excessive.

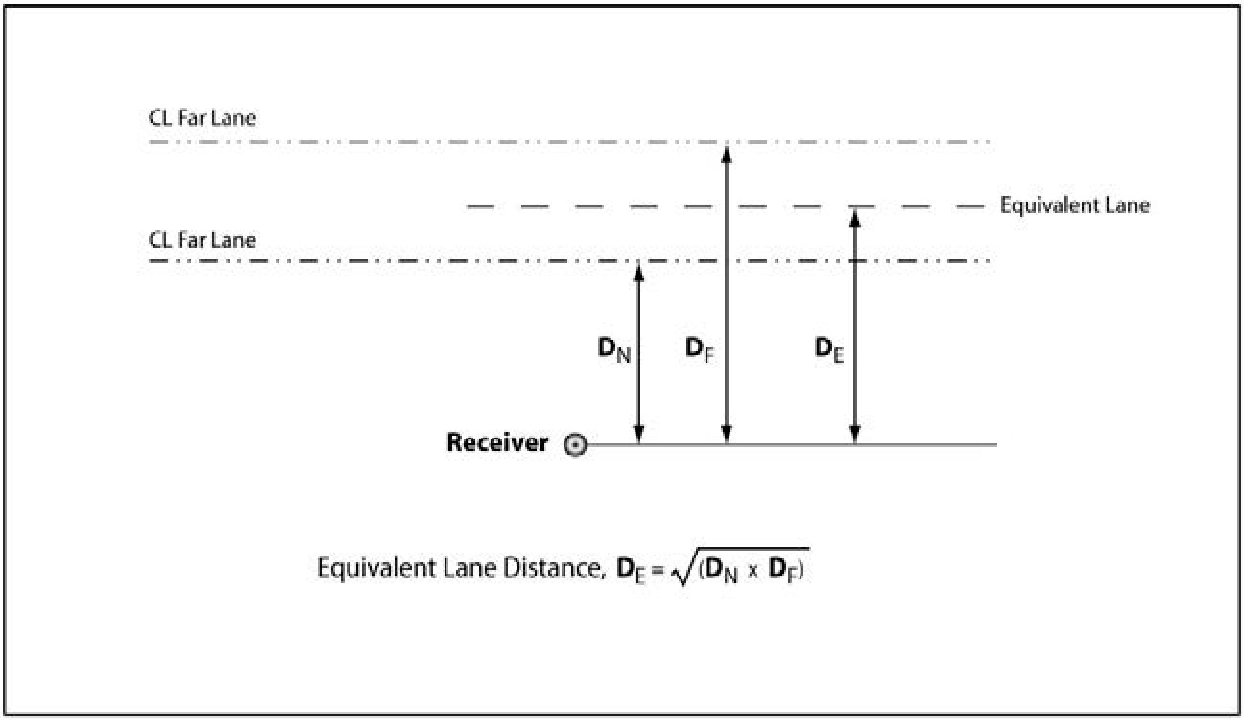

Figure 4-2. Equivalent Lane Distance

The following is an example of a D_E calculation:

Given

Eight-lane freeway with a 6.6-m median.

Distance from receiver to centerline of near lane (D_N) = 35 m.

Distance from receiver to centerline of far lane (D_F) = 66.8 m.

Solution

$D_E = (D_N \text{ x } D_E)^{0.5} = (35 \text{ x } 66.8)^{0.5} = 48.4$ m.

Notes

When using one equivalent lane distance for an entire freeway, the total 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.

4.4 Method of Calculating Number of Equivalent Vehicles

The following method is used to calculate V_E. The method essentially normalizes heavy trucks, medium trucks, and autos to one vehicle group on the basis of their acoustical energy. The auto is used as a reference (1 auto = 1 V_E). Table 4-1 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 4-1. Number of Equivalent Vehicles as a Function of Vehicle Type and Speed Based on TNM Reference Energy Mean Emission Levels

		Equivalent Vehicles		
Speed (km/h [mph])		1 Heavy Truck	1 Medium Truck	1 Auto
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

The following is an example of a V_E calculation using Table 4-1:

Given

Hourly vehicle volume = 5,000 autos, 175 medium trucks, and 325 heavy trucks.

Traffic speed = 88.5 km/h (55 mph).

Solution

5,000 autos = 5,000 x 1 = 5,000 V_E

175 medium trucks = 175 x 4.1 = 718 V_E

325 heavy trucks = 325 x 10.4 = 3,380 V_E

Total = 9,098 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 vehicle type by a factor that normalizes the speed to 55 mph for all vehicles (Table 4-2).

Table 4-2. Speed Corrections for Equivalent Vehicles Based on TNM Reference Energy Mean Emission Levels

Speed (km/h [mph])		Noise Level of 1 Auto at 15 m (50 feet), $L_{eq}(h)$, dBA	Energy Ratio[a]
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

[a] 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 Menge et al. 1998 and Fleming et al. 1995.

The following is an example of how speed corrections are used:

Given

Hourly vehicle volume = 3,000 autos at 105 km/h (65 mph), 150 medium trucks at 97 km/h (60 mph), and 325 heavy trucks at 80 km/h (50 mph).

Solution

3,000 autos = 3,000 x 1 x 1.70 = 5,100 V_E

150 medium trucks = 150 x 3.7 x 1.32 = 733 V_E

325 heavy trucks = 325 x 11.5 x 0.74 = 2,766 V_E

Total = 8,599 V_E

4.5 Noise Analysis Screening Procedure Checklist

The checklist format shown on the next page may be used for convenience by the user of the screening procedure. See Section 4 for the complete screening procedure.

NOISE ANALYSIS SCREENING PROCEDURE CHECKLIST

Dist.__________ Co.__________ Rte.________ P.KM.____________________ E.A.____________________

1. Are there residential areas, sensitive land uses, and potentially impacted receivers adjacent to the project?

   Yes___ *(Continue.)* No___ *(Stop. Passed screening procedure. Check step 6.)*

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

   Yes___ *(Continue.)* No___ *(Stop. Did not pass screening procedure. Check step 7.)*

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 7.)*

4. Measure existing worst hourly noise levels at critical receivers. Results:

   Receiver: ______ (L_{eq}[h]) ______ dBA; Receiver: ______ (L_{eq}[h]) ______ dBA.

   Are above noise levels more than 5 dBA below the NAC?

   Yes___ *(Continue.)* No___ *(Stop. Did not pass screening procedure. Check step 7.)*

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

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

   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 Section 4.3 to determine D_E and Section 4.4 to determine V_E.

   Yes___ *(Passed the screening procedure. Check step 6.)*

   No___ *(Did not pass screening procedure. Check step 7.)*

   Note: The ratio $D_{E(EXISTING)}/D_{E(FUTURE)}$ should not exceed 4:1 (*See Note in Section 4.1*). The ratio for this project is ___:1.

THE PROPOSED PROJECT: *(Check one.)*

6. ____ **PASSED** screening procedure; no further analysis is necessary.

7. ____ **DID NOT PASS** the screening procedure; proceed per Section 5.

Prepared by: ____ Date: ____________________________

Section 5

Detailed Analysis for Traffic Noise Impacts

If the project fails the screening procedure or conditions discussed in Section 4 warrant a more extensive analysis, 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.

5.1 Gathering Information

The first step in a technical noise analysis is to determine the level of detail necessary for the study, which depends on the size and nature of the project. Generally, as the size of the project, the complexity of terrain, and the population density increase, 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 alternatives and their spatial relationships to potentially noise-sensitive areas. A "no build" alternative should be included. Early in the project, final design details usually are not available, and additional analyses may need 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 alternatives is also required for the analysis.

5.2 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 the Protocol). Existing activities, developed lands, and undeveloped lands for which development is planned, designed, and programmed that may be affected by noise from the highway should be identified. Land development is considered to be planned, designed, and programmed on the date that a noise-sensitive land use (subdivision, residences, schools, churches, hospitals, libraries, etc.) has received all final discretionary approvals from the local agency with jurisdiction, generally the date that the building permit or vesting tentative map is issued. This information is essential to determine which noise abatement criteria (NAC) apply for determining traffic noise impacts (see the Protocol). For convenience, the NAC are shown in Table 5-1.

Table 5-1. Activity Categories and Noise Abatement Criteria

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 Activity Categories A and B above.
D	–	Undeveloped lands.
E	52; Interior	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals, and auditoriums.

5.3 Determining Existing Noise Levels

Existing noise levels may be determined at discrete locations in the project area by actual noise measurement (see Section 3) or using the traffic noise prediction model (see Sections 5.5.1 and 5.5.2). The latter is usually the case. This section discusses how to select these locations, the methods used to determine existing noise levels, and how to “calibrate” the noise prediction model with measurements where appropriate.

5.3.1 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. It is far less expensive to model (calculate) noise levels for receivers than to take noise measurements in the field. If the project involves the reconstruction of an existing facility, existing noise levels are measured at representative receivers and compared with modeled results for the conditions observed during the measurement. The difference between modeled and measured results may then be applied to the results for modeled future conditions. This process, called model calibration, is fully described in Section 5.4.

5.3.1.1 Receivers

Within the identified land use activity categories adjacent to the project, there are typically numerous noise receivers that need to be analyzed for future noise impacts or benefits from noise abatement under consideration. It is not reasonable or possible to examine these factors at all receivers. Therefore, receivers should be carefully selected for the noise analysis on the basis of their acoustical representativeness. Some general recommendations for selecting receivers are listed below.

- Although noise impacts must be evaluated at all developed land uses, receivers locations should focus on areas of frequent human use (defined in the Protocol glossary).
- Select receivers generally in locations that are receiving or are expected to receive the highest noise levels over the period covered by the analysis. Because in most cases impacts will be at receivers closest to the highway, most receivers should be in the first row of residences relative to the project alternative. Some common exceptions include:
    - projects where realignment would move the noise sources toward receivers other than those adjacent to the existing alignment;
    - projects involving geometry where the first row of homes is partially shielded and second-row homes actually may receive higher noise levels (e.g., roadways on high embankments);
    - areas near the ends of proposed barriers where second- or third-row receptor sites may be needed to better define the barrier limits; and
    - projects that involve widening where additional right-of-way requirements may clear the first row of residences and turn the second row into the first.

- A noise measurement site should coincide with a receiver whenever possible. However, this often may 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 that is acoustically representative of the receiver should be selected in a more accessible location.
- Other noise-sensitive locations, such as libraries, churches, hospitals, and schools, should be included.
- Receivers that are acoustically equivalent of the area of concern should be chosen. 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 generally can 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.
- A minimum of two receivers should be selected 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 complexity of the highway profile and 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 few receivers to adequately define the noise impacts. However, 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 is likely to need more receivers.
- Receivers are 1.5 meters above the ground elevation, unless dictated by unusual circumstances, special studies, or other requirements. Exceptions would include placing a receiver 1.5 meters above a wooden deck of a house situated on a steep slope, instead of 1.5 meters above the ground. Similar situations might be encountered where residential living areas are are built above top of garages, where second-story levels would be more logical receiver locations.
- Noise should be evaluated at second-story elevations or at higher elevations in the case of multistory buildings when there are exterior areas of frequent human use at the higher elevations that could benefit from noise reduction. Examples include large patios or decks that are the primary outdoor use area in an apartment complex. Clearly, it will not be feasible or reasonable to construct a wall that protects a receiver location several stories above a freeway. There may, however, be

situations where an upper story of a building is at the same elevation as the highway (i.e., the highway is on a fill section). In this case, it may be both feasible and reasonable to build a wall to reduce noise at the upper stories.

- To determine the number of benefited receivers (defined in the Protocol glossary), it is usually necessary to include receivers in the first, second, and third rows of residences (or beyond in some cases) in the noise analysis.
- Critical-design receivers, as defined in the Protocol glossary, are used primarily in the determination of noise abatement reasonableness. These receivers are normally selected at locations that are affected and for which the absolute noise levels, build vs. existing noise levels, and the achievable noise reduction from considered abatement are at a maximum. However, selection of a single receiver that by virtue of a unique location or situation will receive considerably higher values for these factors than surrounding receivers, and is therefore not acoustically representative, should be avoided.

5.3.1.2 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 and the cost and availability of resources. Preliminary design maps, cross sections, aerial photographs, and field survey data are all helpful sources of information for selecting noise measurement sites, but the sites should be selected only after a thorough field review of the project area. Some recommended site characteristics common to all outside noise measurement sites are listed below.

- Sites should be clear of major obstructions. Reflecting surfaces such as walls of residences should be more than 3 meters from the microphone positions.
- Sites should be free of noise contamination by sources other than those of interest. Sites located near barking dogs, lawn mowers, pool pumps, air conditioners, etc. should be avoided unless it is the express intent to measure noise from these sources.
- 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 these general requirements, the selection of noise measurement sites is governed by the same general guidelines as those for selection of receivers in Section 5.3.1.1. Of particular importance is the concept of acoustical equivalence for representativeness of the area of concern. More detailed considerations are discussed in Section 3.2.

5.3.2 Measuring Existing Noise Levels

When possible, existing noise levels should be determined by field measurements. As with all field work, quality noise measurements are relatively expensive, requiring time, personnel and equipment. The noise analyst should carefully plan the locations, times, duration, and number of repetitions of the measurements before taking the measurements. Meteorological and other environmental conditions can significantly affect noise measurements. Particular attention should be given to the meteorological and environmental constraints described in the Section 3.6.

In the noise analysis for a project, the noise measurements are used to determine existing ambient and background noise levels, and to calibrate the noise prediction model when appropriate. The analyst should refer to Section 3, which contains details of noise measurements.

5.3.3 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 models described in Section 5.5. 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 ensures that existing noise levels at the measured and modeled receivers are based on the same data.

5.4 Calibrating the Prediction Model

The main purpose of modeling is to predict future noise levels. The computer models and procedures used to predict future noise levels are discussed in Section 5.5. However, as mentioned in Section 5.3, models also can be used for modeling existing noise levels where measurements are not possible or undesirable because of lack of access or local environmental conditions. In both cases, the models should be calibrated with measurements wherever possible. This section, which discusses the model calibration procedures that rely on measurements and modeling, should be used with Section 5.5. However, for convenience, all information needed except for running the models is contained in this section.

Traffic noise prediction models cannot account for all the variables present in the real world. They use relatively simple algorithms to approximate physical processes that are complex in nature. Whenever possible, the models should be calibrated with measurements. This section discusses how this is accomplished. Section 5.4.1 deals with model calibrations that are performed routinely by Caltrans. The procedures for these are straightforward but rely on sound judgment and place a heavy burden on quality noise measurements. Section 5.4.2 discusses additional calibrations that may be performed by more experienced personnel and are intended to reduce unexplained errors in the model.

5.4.1 Routine Model Calibration

5.4.1.1 Introduction

The purpose of model calibration is to fine-tune the prediction model to actual site conditions that are not adequately accounted for by the model. In general, model calibrations are recommended if the site conditions, highway alignment, and profile in the design year relative to existing conditions are not expected to change significantly.

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—calibration constant, K-constant, or *K*—is defined as measured noise level *M* minus calculated noise level *C*, or $K = M - C$. Please note that *K* is positive when *M* is greater than *C*, and *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.

5.4.1.2 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, and barking dogs, which are impossible to model. Also, the site and source characteristics change substantially after the project, making model calibration meaningless, even if it were possible.

Highway reconstruction projects that 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.

5.4.1.3 Pertinent Site Conditions

To determine whether the model can be calibrated successfully, the site conditions that 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, which include:
  - traffic mix, speeds, and volumes;
  - noise dropoff rates, terrain conditions, ground types, and distances;
  - opaque barriers (noise transmission through barrier material may be ignored [i.e. high transmission loss]);
  - roadway and barrier segment adjustments;
  - receptor locations; and
  - grade corrections.
- **Group 2:** Site conditions that cannot be accounted for by the model and therefore are ignored, although they affect the local noise environment. These include:

- pavement types and conditions (the model has no provisions to deal with these conditions);
- typical (or non-typical) vehicle noise populations (Calveno levels are statewide averages, and 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], and such materials include wood fences with shrinkage gaps (noise leaks) and areas of heavy brush or trees);
- reflections off nearby buildings and structures; and
- meteorological conditions.

For the purposes of model calibration of future noise levels, Group 1 site conditions are allowed to change somewhat. The degree becomes a judgment call and is discussed further in Section 5.4.5. Group 2 site conditions, however, are not allowed to change. These conditions affect noise levels to an unknown extent but are ignored by the model. As long as they remain constant during the entire analysis period, they may be corrected for with *K*. If they change at some point in the future, however, *K* also must change by an unknown amount, and model calibration becomes invalid.

Some cautions and pitfalls are associated with site conditions of Groups 1 and 2 that will be discussed in Section 5.4.1.5. First, however, the calibration procedures will be explained.

5.4.1.4 Procedures

The actual mechanics of model calibration are fairly straightforward:

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 the noisiest time. This may be estimated. Typically, this condition occurs during daytime whenever traffic is free-flowing.
3. Calculate the noise levels with the prediction model after having input the traffic counts (expanded to 1 hour), site geometry, and any other pertinent existing features.

4. Compare measured and calculated noise levels. The difference, *K*, is determined as described previously:

$$K = \text{Measured} - \text{Calculated, or } K = M - C \quad \textbf{(5-1)}$$

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

$$P = C + K \quad \textbf{(5-2)}$$

Some simple examples to illustrate the mechanics of the above calibration procedures with some typical values are provided below. Example A is a straightforward noise prediction problem. Example B includes a barrier design problem. To distinguish between the various *C*'s and *P*'s in the two examples, a sequential number was added.

Example A

Existing Noise Levels (L_{eq}[h], dBA)	Future Noise Levels (L_{eq}[h], dBA)
73 (C_1)	75 (C_2)
70 (M)	? (P_1)

$K = M - C_1 = 70 - 73 = -3$ dBA

$P_1 = C_2 + K = 75 + (-3) = 72$ dBA

The predicted future noise level is 72 dBA. In essence, although the model calculated the future noise level to be 75 dBA, it is expected that the actual future noise level will be 72 dBA, possibly because of the inability of the model to account for existing obstacles or other site features that attenuate noise.

Suppose it is necessary to construct a noise barrier that will attenuate the noise level to 65 dBA. The problem must be reversed; an alternate form of Equation 5-2 would be used. In Example A, the predicted (or expected actual) noise level was sought. In Example B, however, the predicted noise level is known. Therefore, the calculated with-barrier noise level should be:

Example B

Without Barrier (L_{eq}[h], dBA)	With Barrier (L_{eq}[h], dBA)
72 (from Example A)	65 (P_2)
75 (from Example A)	? (C_3)

$C_3 = P_2 - K = 65 - (-3) = 68$ dBA

To reduce the noise level to 65 dBA with the barrier, the calculated noise level should be 68 dBA. TNM allows input of *K*, eliminating the need for manual conversion of calculated to predicted values.

5.4.1.5 Cautions and Pitfalls

Section 5.4.1.3 indicated that Group 1 conditions are allowed to vary somewhat. However, the meaning of “somewhat” is somewhat vague. Experience has shown that significant changes in traffic volumes, speeds, and mix, as well as shielding by barriers more than 6 feet and segment adjustments within the range normally encountered, can be accounted for adequately by the model. The main problem areas in Group 1 site conditions pertaining to model calibrations are differences in source-to-receiver distances and low barriers.

First, distances should be considered. Accuracy associated with models used prior to adoption of TNM appeared to decrease as distance from the highway increased. TNM, however, has superior propagation algorithms and is more capable of dealing with noise path heights above terrain and groundcover types. However, no model can satisfy entirely all conditions encountered in the real world. Therefore, *K* tends to be at least somewhat distance-dependent. This has two major implications for the calibration process:

- Source-to-receiver distances, their relative heights, and the groundcover between them should not change significantly during the analysis period. Slight changes in distances (e.g., from widening projects) or even slight changes in profile or receiver height are permissible. Also, the differences between ground effects before and after construction of a noise barrier appear to be adequate in the models (more so in TNM than previous models).
- Receivers need to be selected for several representative distances to include the effects of propagation inaccuracies in *K*. Each receiver may have a different *K*. The user must decide on their radius of influence and whether to group some *K*’s together (if they are close enough). This is clearly a matter of judgment based on experience.

The second Group 1 problem area concerns low barriers. Although it is Caltrans’ policy to build barriers that are at least 6 feet high, it is possible that the before-barrier condition includes a low rise in terrain, or a hinge point. Because of noise centroid (vehicle source height) assumptions in the older models, low barrier calculations are usually less accurate with older models relative to TNM. Model calibrations should be avoided at these sites if the future condition includes a noise barrier. TNM is much more capable of dealing with these conditions, which may reduce the need for calibration under these conditions.

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. Because the prediction model does not take weather into consideration, noise measurements have to be taken under calm wind conditions. Section 3.6 discussed the criteria for calm winds. Any attempt to calibrate the model for a prevailing wind condition is only valid for that condition. Noise standards, however, are not linked to weather.

Finally, noise contamination from other sources not considered by the model cannot be corrected by model calibration, as illustrated in the following hypothetical case. In this case, at a calibration site, the existing measured noise level is 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 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, which happens to agree with the actual freeway contribution. There is no reason to believe that the background noise will change in the future. Therefore, the model is incorrectly calibrated. The calculated future noise level is 70 dBA. However, the predicted future level must be determined. This problem is outlined below.

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 (calculated)
K = M – C = 68 - 65 = +3	Freeway: ? dBA (predicted)

Predicted Freeway

P = C + K = 70 + 3 = 73 dBA

(Compared with 71 dBA actual)

In this situation, the calibration process caused an overprediction of 2 dBA, although the background remained the same during the analysis period. Therefore, background noise high enough to contaminate the noise measurements cannot be considered a Group 1 or 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 likely will be contaminated.

5.4.1.6 Tolerances

Because of the inherent uncertainties in the measurements and calibration procedures, model calibration should 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 to 4 dBA may routinely be calibrated unless the validity of the measurements is in serious doubt. Differences of 5 dBA or more should be approached with caution: The analyst should retake measurements, look for obvious causes for the differences (e.g., weather, pavement conditions, obstructions, reflections), check traffic and other model input parameters (and remember to expand traffic counted during the noise measurement to 1 hour), and confirm that the traffic speeds are accurate. If differences of 5 dBA or more still exist after confirming the measurements and input parameters, the decision about whether to calibrate the model should be made after determining whether any of the responsible Group 2 site conditions will change during the project life.

5.4.1.7 Common Dilemmas

The following hypothetical cases present some common dilemmas the noise analyst may need to resolve when selecting model calibration sites. In one case, a receiver was selected in a backyard abutting a freeway right-of-way. The only obstacle between the receiver and the freeway is a 6-foot-high wood tract line fence running parallel to the freeway. The fence boards are standard 1- by 6-inch boards with shrinkage gaps between them. The question is whether this receiver should 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 about the next 20 years and no noise barrier is planned, this probably would be a good representative location to measure existing noise levels and predict model-calibrated future noise levels for all the backyards bordering the right-of-way.

In another case, 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 the fence remains (i.e., the effects of a Group 2 site condition change). In this 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. There are also no assurances of the longevity of wooden backyard fences. In the preceding 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 that dead-ends at the freeway right-of-way. Similar situations may exist in areas of heavy shrubs or dense woods.

Opaque shielding, such as by a block wall of at least 6 feet in height, can be handled adequately by the model and does not represent a problem in calibration.

5.4.2 Additional Non-Routine Model Calibrations

5.4.2.1 Introduction

Section 5.4.1.1 defines routine model calibration 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. Noise measurements can be made only for current conditions. The underlying assumptions in model calibration are that:

- future site conditions will not change or will change minimally, and
- future changes in site conditions can be accounted for in the model.

These necessary assumptions normally preclude the routine calibration of models for highway reconstruction projects where site conditions will be significantly altered or in cases where a highway is proposed on an entirely new alignment.

Over the years, Caltrans and its contractors have gathered sufficient data through measurements to establish a categorical relationship between traffic noise and pavement surface types. Additionally, procedures have been developed to adjust the model for vehicle noise emissions that are different from the REMELs used in the model and to normalize noise measurements for various wind conditions through measurements at a representative site. The information can be used to further calibrate noise prediction models and to refine noise measurements to increase model calibration accuracy. The result of such a refinement is a reduction of *K* and an accompanying reduction in unexplained errors in the model results.

Unlike the procedures for routine calibrations, the additional calibration procedures presented in Sections 5.4.2.1 to 5.4.2.3 allow optional adjustments to be made for the following three Group 2 site conditions, which are discussed in Section 5.4.1.3:

- Section 5.4.2.1—adjustments for non-typical vehicles,
- Section 5.4.2.2—adjustments for non-average pavement surface type, and
- Section 5.4.2.3—normalizing measurements to zero-wind conditions.

The first two adjustments are made to the model. The third, a wind correction, is made to the measured noise levels. The three adjustments can be made in conjunction with each other. The effect of each or all three should be a reduction of *K*. The additional calibration procedures are also discussed in the Caltrans technical advisory *Additional Calibration of Traffic Noise Prediction Models* (2003).

5.4.2.2 Adjustments for Non-Typical Vehicle Populations

These procedures should be performed only when the traffic moves at highway speeds between 55 and 65 mph. The procedures may be used with Section 5.4.2.2 if future pavement surface type (e.g., PCC, DGAC, OGAC) will be different from the existing pavement surface type. If the pavement surface type does not change, this procedure may be used directly.

When highway noise is measured at a site, it is normally assumed that the traffic on the highway is typical of that measured for the REMELs used in the noise prediction models. REMELs used in models prior to TNM were measured at various sites throughout California. The data for the TNM REMELs (Section 5.5.2.1) were gathered at various sites throughout the nation. At highway speeds, the differences between the two are no more than 1 dBA for each vehicle group. Both sets of REMELs were derived from a variety of geographic areas and represent average values. Although the individual differences in each vehicle group are quite large, the average values are representative of the REMELs at most sites.

Some sites, however, may be exposed to traffic noise from a non-typical vehicle fleet. Examples might be an agricultural area, where a disproportionate number of the trucks are farm trucks; a mining area or quarry, where specialized trucks are used; or recreational areas frequented by a large number of recreational vehicles. The non-typical vehicle group may be only for existing conditions, not future conditions, or it may be for both conditions. In the latter case, the existing non-typical vehicle group must be the same as the future group. At these sites, the REMELs used in prediction models are not representative of the actual vehicle noise emission levels. With measurements of the actual vehicle population, however, the models can be adjusted by the procedures outlined in this section. These procedures are divided in three stages: measurement, adjustment calculation, and application to the model. The vehicle groups most frequently suspected of being non-typical are heavy trucks. However, the procedures described in this section may be applied to any suspect vehicle group.

Measurements

Generally, individual vehicle passby measurements (L_{max}, dBA) at 50 feet must be performed at sites that conform to the requirements set forth in the Calveno report (Hendriks 1987). These sites must be located along the highway of interest. A short summary of the site requirements is provided below (for complete details, the Calveno report should be consulted).

- The site must be an open area, such as a field, without obstacles or reflecting surfaces within 100 feet of the vehicle path or microphone locations.
- The site must be free of electromagnetic interference (i.e., no overhead powerlines or electrical substations nearby).
- The base of the microphone stand shall be no more than 2 feet above or below the plane of roadway pavement.
- The roadway side slope shall not vary more than 2 feet in elevation. The ground between the highway and microphone may be hard or soft (soft is preferred).
- No contamination from other noise sources is allowed.

- The microphone must be placed at a height of 5 feet above the ground at 50 feet from the centerline of the roadway on which the vehicles of interest travel.
- All vehicle speeds must be constant and must be between 55 and 65 mph. Speeds may be measured by radar gun or by timing the passby vehicle through a known marked distance.

The individual passby noise measurements must be not be contaminated by noise from other vehicles. For a single heavy truck, which on average is about 10 dB louder than automobiles, it is relatively easy to measure an L_{max} that is at least 10 dB more than the ambient noise from other vehicles when measured during a break in traffic. For a single automobile, this would be much more difficult. However, most model calibrations that involve non-typical vehicle groups probably target heavy trucks. Experiences with Calveno measurements indicated that if there were a short break in traffic and no other heavy trucks within at least 400 feet, the L_{max} of the truck would not be contaminated. The Calveno report should be consulted regarding recommended minimum vehicle separation distances and procedures to ensure that the measurements are not contaminated.

Examination of Calveno data shows an average population standard deviation of 2.5 dBA for heavy and medium trucks at 50 feet within each 3-mph speed window between 53 and 64 mph. For automobiles, the average standard deviation was 2.7 dBA under the same conditions. For such standard deviations, a minimum of 25 vehicles for each medium and heavy truck group and 30 vehicles for each automobile group within a 3-mph speed window must be measured for the average REMELs to be accurate within 1 dBA with a 0.05 significance level (95% confidence level). Normally, highway noise measurements involve a much larger number for each vehicle group. Therefore, the REMELs usually can be relied on with great confidence in the model calibration process.

To allow for extending a 3-mph speed window to 10 mph, which results in a higher standard deviation, the minimum number of measurements for the target vehicle group is extended to 50 for the sample mean to be accurate within 1 dB of the population mean.

Adjustment Calculation

The TNM Baseline REMEL can be calculated from Equation 5-4 and Table 5-2:

$$L(S_i) = 10\log_{10}[(S_i)^{A/10} * 10^{B/10}) + 10^{C/10}] \qquad \textbf{(5-4)}$$

Where:

$L(S_i)$ = REMEL for vehicle type *i* at average measured speeds *S* (mph)

S_i = average measured speed (mph)

A, B, and C = constants for vehicle types shown in Table 5-2

Table 5-2. TNM REMEL Constants for Equation 5-3

Vehicle Type	A	B	C
Autos	41.740807	1.148546	50.128316
Medium Trucks	33.918713	20.591046	68.002978
Heavy Trucks	35.879850	21.019665	74.298135

The above-calculated REMEL then should be compared with the measured energy-averaged L_{max}. No adjustment will be necessary if the difference is 1 dB or less. If the difference is 2 dB or more, the model may be adjusted according to the procedure explained in the following section.

Applying Adjustment to the Model

The REMEL equations shown in the previous section are incorporated into TNM. Accordingly, they are not easily accessible. However, because REMELs are energy-averaged noise levels, they can be easily related to the source strength (in this case, the vehicle volumes input into the model). By adjusting the volume of the measured vehicle group, the model can be manipulated into yielding the same result as if the difference between the measured and model REMELs had been entered. The following procedure can be used to arrive at an adjusted volume.

ΔdBA represents the difference between measured and model REMELs. Please note that when the sign is properly accounted for, ΔdBA becomes the adjustment to the model REMEL. This adjustment can be related to the vehicle volume input to the model. If the measured REMEL is higher than the model REMEL, this difference can be taken into account by increasing the vehicle volume. If the measured REMEL turns out to be less than the model REMEL, the vehicle volume needs to be decreased. The following equation shows the relationship between ΔdBA and the volume change:

$$(\pm)\Delta dBA = 10\log(V_A/V) \qquad \textbf{(5-5)}$$

Where:

ΔdBA = measured REMEL – model REMEL

V_A = adjusted volume

V = actual volume

$V_A/V = N$ = ratio of adjusted volume to actual volume, or multiplier used to adjust the actual volume.

Therefore:

$(\pm)\Delta dBA = 10\log(N)$

To solve for *N*:

$$N = 10^{(\pm)\Delta dBA/10} \quad \textbf{(5-6)}$$

Please note that if ΔdBA is negative, *N* will be a fraction between 0 and 1. To adjust the model, the volume should be multiplied by *N* and input into the model. An example of the calibration process is provided below.

Example of Calibrating for Non-Typical Vehicle Population

A noise analysis for a proposed highway widening from two lanes to four lanes includes a location labeled Receiver A. The existing noise measurement at Receiver A was 75 L_{eq}(h), dBA. The traffic volumes corresponding with the measurement, expanded to 1 hour, were 2,500 autos, 90 medium trucks, and 210 heavy trucks. The average observed speed was 60 mph.

Based on these data, the result calculated by the model result is 71 L_{eq}(h), dBA. The heavy truck population is suspected to be non-typical of the population represented in the model. To verify this suspicion, a site was selected along the highway to take 50 L_{max} measurements of heavy trucks in accordance with the procedures described in the previous section. The energy average of the individual passby measurements was 86.2 dBA. The average observed speed for the passbys was 58 mph.

Equation 5-4 and Table 5-2 should be used to calculate the TNM REMEL for 58 mph. In this case, the heavy truck REMEL is calculated as:

$10\log[(58^{3.5879850} * 10^{2.1019665}) + 10^{7.4298135}] = 84.7$ dBA

The difference between the measured and Calveno REMELs is:

$$\Delta dBA = 86.2 - 84.7 = +1.5 \text{ dBA.}$$

Therefore, the suspicion that the heavy truck population was non-typical, is justified. To adjust the model for this difference, Equation 5-6 should be used, as follows:

$$N = 10^{(\pm)\Delta dBA/10} = 10^{+1.5/10} = 1.41$$

The heavy truck volume counted during the existing measurement at Receiver A (210) is then adjusted by multiplying by 1.41, resulting in an adjusted heavy truck volume of 296. The new calculated (modeled) noise level based on the adjusted heavy truck volume is 72 L_{eq}(h), dBA. The new *K* is the difference between the measured and modeled levels: 75 (measured) – 72 (modeled) = +3 dBA.

This *K*, in conjunction with the multiplier *N* = 1.41 for heavy trucks, now can be used for predicting existing worst traffic noise and future traffic noise conditions. If the future conditions would include the same heavy truck population as the existing conditions, both *N* and *K* should be used. If the future population will be judged typical, only *K* should be applied to the future noise predictions.

5.4.2.3 Adjustments for Non-Average Pavement Surface Type

Over the years, Caltrans' and other studies have shown distinct differences in noise levels from traffic on DGAC, OGAC, and PCC pavements. Examination of the original Calveno data indicated that of the 11 sites where traffic moved predominantly at highway speeds, five were PCC and six were DGAC. Therefore, the REMELs for speeds between 55 and 65 mph were obtained from vehicles traveling on PCC and DGAC in a ratio of about 45/55. Consequently, the "average" pavement surface type on which Calveno REMELs are based lies about halfway between PCC and DGAC. The same representation exists in the REMELs used in the TNM.

Adjustments for Pavement Surface Type

Using DGAC as a reference, data from studies suggest that the PCC pavement surface type, as used in California (longitudinal tining or grooving), is at least 2 dBA louder at highway speeds than DGAC for all vehicle groups and that OGAC is at least 3 dBA quieter than DGAC. These values are conservative because they tend to understate the differences. In a landmark study along I-80, OGAC was about 5 dBA quieter than original DGAC and has maintained this level of attenuation for 5 years. Although more studies are recommended, Caltrans

Headquarters Division of Environmental Analysis is confident, based on completed and ongoing studies, that the preliminary figures of +2 dBA for PCC and -3 dBA for OGAC are conservatively valid with reference to DGAC. These values may be used in absence of other site-specific evidence. If such evidence is available and properly documented, other values based on the evidence may be used. An example of this may be an existing highway paved with DGAC and subsequently repaved with OGAC. If the difference between the original and subsequent pavement surface types has been measured and sufficiently documented, this value may be used for calibration for noise studies for a proposed reconstruction project along the existing alignment, at least for existing conditions. If the reconstruction specifically calls for the same type of OGAC, the measured calibration value may be used for postconstruction conditions.

Applying Adjustments

Using the above relationships with a conservative assumption that the "average pavement" in TNM is DGAC instead of the mix of DGAC and PCC, TNM can be adjusted further for PCC and OGAC. These adjustments should be made only for highway speeds of 55 mph or more. The following scenarios outline how the adjustments may be made to the model.

1. **Noise Predictions for Construction on a New Alignment:**

   The following adjustments should be made to the future predicted noise levels at each receiver.

   a. If the proposed pavement surface type is DGAC or is unknown, there is no adjustment.

   b. If the proposed pavement surface type is PCC, add 2 dBA.

   c. If the proposed pavement surface type is OGAC, subtract 3 dBA.

2. **Reconstruction on an Existing Alignment:**

   a. For comparison with measurements at model calibration sites, the model results for each receiver should be adjusted as follows:

      1) If the existing pavement surface type is PCC, add 2 dBA.

      2) If the existing pavement surface type is DGAC, there is no adjustment.

      3) If the existing pavement surface type is OGAC, subtract 3 dBA.

      4) Measured data, if available, should be used to develop adjustment factors in cases 1 or 3. Then:

$$K = M - C_{adj}$$

Where:

K = calibration constant

M = measured noise level

C_{adj} = adjusted calculated noise or pavement surface type–adjusted model result

b. *K* derived from the process described above should be applied for predicted future noise level. The following future pavement surface type adjustments should be added to the calibrated noise results:

1) If the future pavement surface type is PCC, add 2 dBA.

2) If the future pavement surface type is DGAC, there is no adjustment.

3) If the future pavement surface type is OGAC, subtract 3 dBA.

Examples of Calibrating for Pavement Surface Type

The following examples show the calibration process for a new alignment and reconstruction on an existing alignment.

Example 1—New Alignment

Given

Model calculated = 68 dBA at receiver

Pavement surface type = OGAC (adjustment = -3 dBA)

Step 1

Pavement surface type–adjusted predicted = 68 – 3 = 65 dBA at receiver

Example 2—Reconstruction on Existing Alignment

Given

M = 68 dB at receiver

C = 69 dBA at receiver

Existing pavement surface type = PCC (adjustment = +2 dBA)

Future calculated by model = 70 dBA (without K) at receiver

Future pavement surface type = OGAC (adjustment = -3 dBA)

Step 1—Adjust Model Result for Existing Pavement Surface Type

C_{adj} = 69 + 2 = 71 dBA at receiver

Step 2—Calculate Calibration Constant

$K = M - C_{adj}$ = 68 – 71 = -3 dBA

Step 3—Apply K to Future Calculated by Model

70 – 3 = 67 dBA at receiver

Step 4—Apply Pavement Surface Type Adjustment for OGAC

67 – 3 = 64 dBA at receiver

Check on Process

If *K* = 0 and the model-calculated noise levels for existing and future remain the same, but pavement surface types change, the difference between measured existing and future predicted noise should be the same as the combined pavement surface type adjustments. In the preceding example, the difference from PCC and OGAC should be +2 – (-3) = 5 dBA. To check this, Example 2 can be rewritten so that *K* = 0 and the model calculated noise levels do not change:

Example 2 (Revised)—Reconstruction on Existing Alignment

Given

M = 68 dB at receiver

C = 66 dBA at receiver

Existing pavement surface type = PCC (adjustment = +2 dBA)

Future calculated by model = 66 dBA (without K) at receiver

Future pavement surface type = OGAC (adjustment = -3 dBA)

Step 1—Adjust Model Result for Existing Pavement Surface Type

C_{adj} = 66 + 2 = 68 dBA at receiver

Step 2—Calculate Calibration Constant

K = M – C_{adj} = 68 – 68 = 0 dBA

Step 3—Apply K to Future Calculated by Model

66 – 0 = 66 dBA at receiver

Step 4—Apply Pavement Surface Type Adjustment for OGAC

66 – 3 = 63 dBA at receiver

The difference between existing and predicted (adjusted for pavement surface type) is 68 – 63 = 5 dBA, which is the correct amount, even though the model results stayed the same.

5.4.2.4 Normalizing Measurements to Zero-Wind Conditions

Prediction models calculate noise levels without considering atmospheric conditions, such as wind speed/direction and temperature profiles. Federal and state noise policies and standards also do not consider atmospherics and are assumed to be for zero wind and neutral temperature gradients.

Noise measurements, on the other hand, are normally made under varying atmospheric conditions. The same traffic volumes, truck mixes, and speeds yield varying noise levels at receivers near a highway, depending on these atmospheric conditions. Therefore, it is highly desirable to normalize noise measurements to the neutral conditions before the model is compared and adjusted to the measurements.

The findings from a 1991 Caltrans SR 99 study (Caltrans 1991) indicated that for a given site the change in noise levels from atmospheric conditions can be explained in significant part by crosswind components (CWCs). Without a noise barrier, an average of half of the fluctuations in noise levels normalized for traffic can be explained by variations in CWCs within 250 feet of a freeway. With a noise barrier present, about two-thirds of the fluctuations can be explained by variations in CWCs. Apparently, barriers enhance wind effects on noise with the effect being greater at higher elevations above the ground. The SR 99 study (Caltrans 1991) findings have been used to develop a procedure for normalizing noise measurements taken under various conditions of wind speeds and directions to a zero-wind, or calm, condition. This procedure should be planned and executed under supervision of personnel experienced in taking noise and meteorological measurements. It can be used only for projects involving reconstruction of an existing highway.

Existing Analysis Procedures

In a typical Caltrans noise analysis for highway reconstruction projects, several receivers are selected throughout the project area for traffic noise impact analysis. Receivers are defined as any location of interest in the project area. They are further described in the Protocol and Section 5.3.1. Several noise measurement sites representing the receivers are also selected. The number of noise measurement sites depends on the size of the project, complexity of terrain, and amount of controversy associated with the project. These sites may or may not coincide with receivers, but they must be acoustically representative of the receivers. Refer to Section 3.2.2.2 for guidance on acoustical representation. At sites, the noise and basic meteorological conditions (i.e., wind speed and direction, relative humidity, and temperature) are measured. The purpose of the measurements at these sites is to document existing noise conditions and collect information that can be used to calibrate the model per procedures described in this section.

Need for Normalization Sites

Measurements taken at the routine noise measurement locations ideally should be taken under neutral atmospheric conditions (i.e., zero wind and isothermal temperature profiles). For logistical reasons, it may not be possible to take measurements only during ideal conditions. The procedure described in this section is designed for a more detailed study at one or more noise measurement sites (normalization sites) involving at least two microphones and repeat visits under varying wind conditions. The number of normalization sites depends on the highway alignment and number of acoustically different areas in the project area.

The meteorological and noise data collected at the normalization sites are then used to normalize the noise data at the represented routine noise measurement sites. The concept is that an accurate "wind vector" with both speed and direction must be determined. In effect, the noise measurements taken under each specific wind condition are adjusted to a zero-wind condition based on the data collected at the normalization sites.

Normalization Site Selection and Requirements

The normalization procedure should not be attempted in complex topographies or where local features cause significant variations in wind speeds and directions in the area of interest. Additional selection requirements for a normalization site are listed below:

- The site must be acoustically representative of the noise measurement sites.
- A site with generally flat terrain and minimal obstructions is preferred.
- The anemometers should be placed in open areas, away from obstructions, and in the vicinity of the noise instrumentation. A basic understanding of how the wind flows around obstacles and interacts with the ground surface is essential.
- At least one normalization site should be assigned to each side of the highway.
- One set of normalization sites should be assigned for each tangent section if the alignment changes more than 22.5º in direction.
- If an existing barrier is present in the study area, a normalization site should be selected behind the barrier. The reference microphone then should be placed 5 feet above the top of barrier.

Figure 5-1 shows a hypothetical normalization site selection map using three microphones.