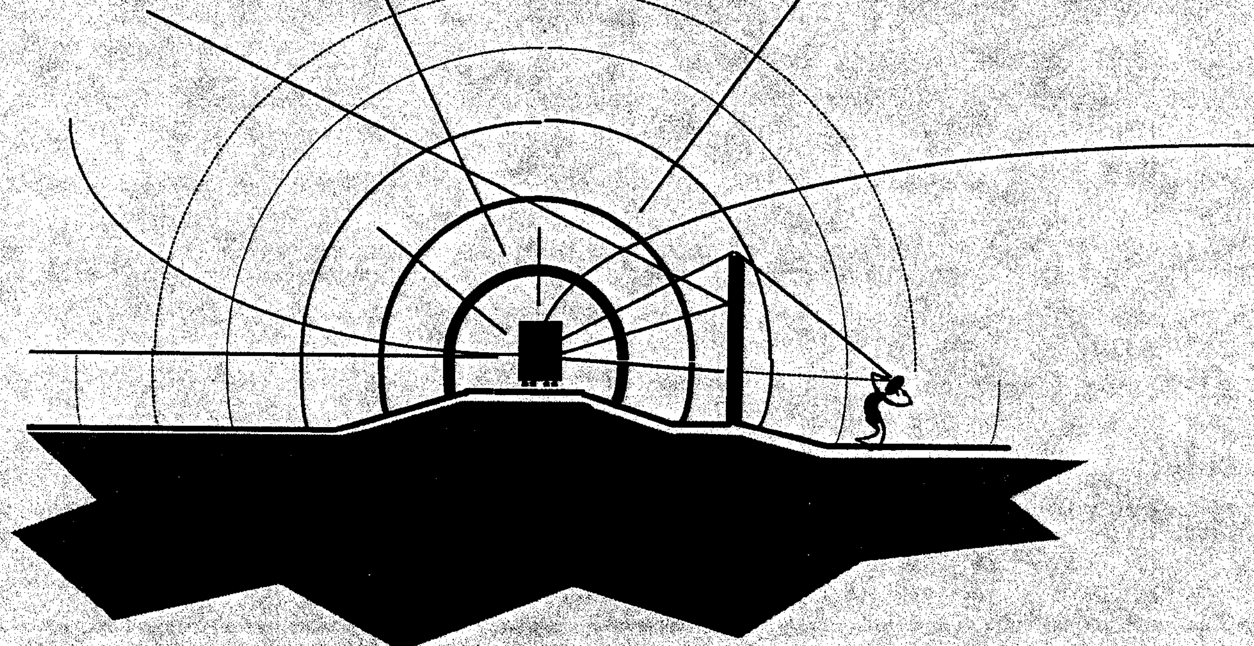
Technical Noise Supplement

TeNS

A Technical Supplement To The Traffic Noise Analysis Protocol



October 1998

California Department of Transportation
Environmental Program
Environmental Engineering-
Noise, Air Quality, and Hazardous Waste Management Office

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

I also owe a great debt of gratitude to:

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To all mentioned above, I sincerely appreciate your help.

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N-1000 INTRODUCTION AND OVERVIEW

N-1100 INTRODUCTION

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

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

N-1200 OVERVIEW

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

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

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

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

N-2000 BASICS OF HIGHWAY NOISE

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

N-2100 PHYSICS OF SOUND

N-2110 Sound, Noise, Acoustics

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

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

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

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

N-2120 Speed of Sound

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

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

Where:

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

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

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

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

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

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

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

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

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

Where:

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

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

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

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

N-2130 Sound Characteristics

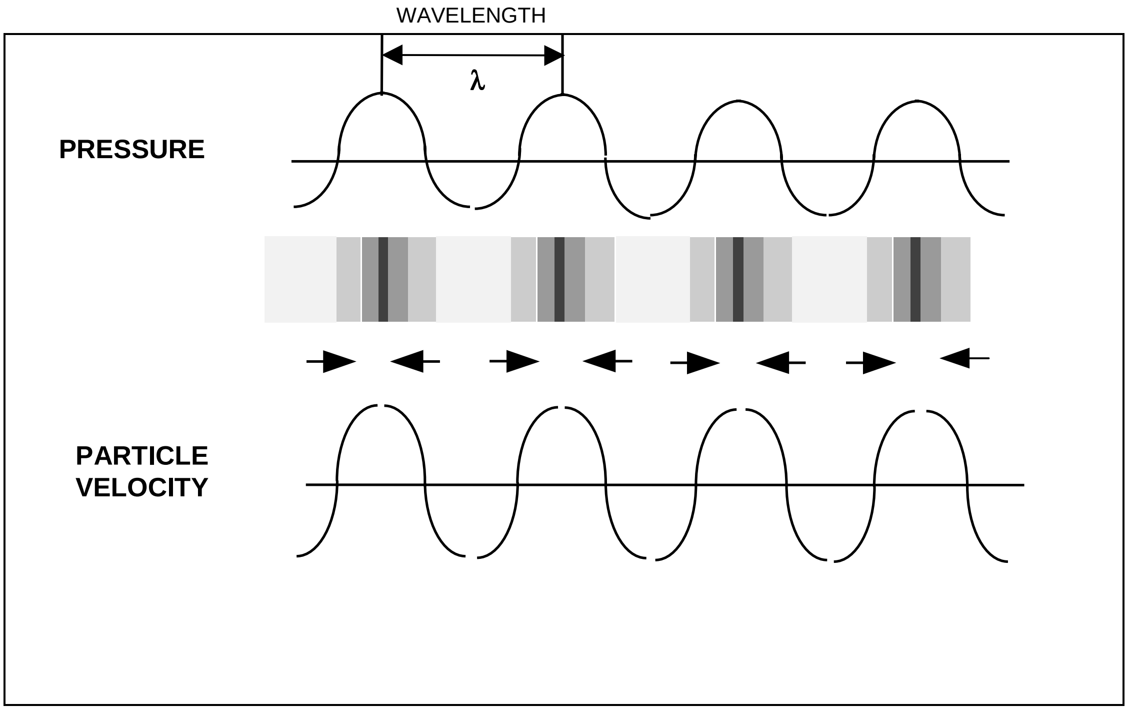
In its most basic form, a continuous sound can be described by its *frequency* or *wavelength* (pitch) and its *amplitude* (loudness).

N-2131 Frequency, Wavelength, Hertz

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

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

Figure N-2131.1. Sound Pressure

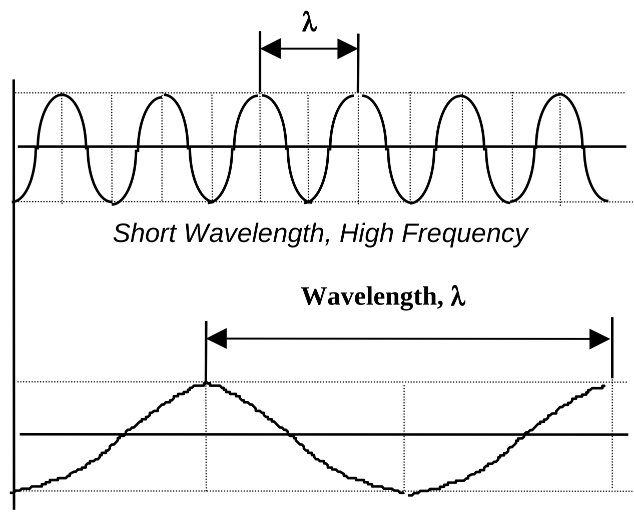


Frequency is expressed in *cycles per second*, or *Hertz* (*Hz*). One Hertz equals one cycle per second. High frequencies are sometimes more conveniently expressed in units of *Kilo Hertz* (*KHz*) or thousands of Hertz. The extreme range of frequencies that can be heard by the healthiest human ears spans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

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

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

Figure N-2131.2 - Frequency and Wavelength



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

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

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

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

Where:

λ = Wavelength (m or ft)

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

f = Frequency (Hertz)

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

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

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

Table N-2131.1 Wavelength of Various Frequencies

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

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

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

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

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

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

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

Where:

P_1 is sound pressure

P_0 is a reference pressure, standardized as 20 μPa

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

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

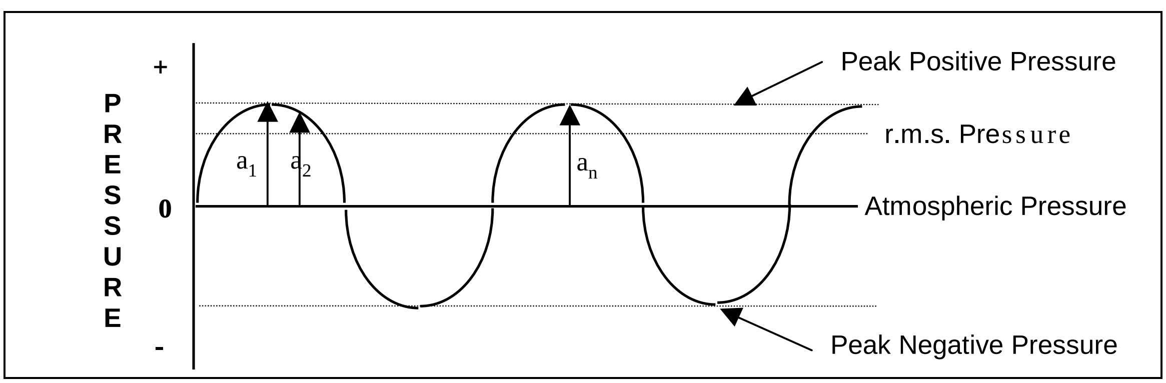
Note that 0 dB is not the absence of any sound pressure. Instead, it is an extreme value that only those with the most sensitive ears can detect. Thus, it is possible to refer to sounds as less than 0 dB (negative dB), for sound pressures that are weaker than the threshold of human hearing. For the majority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

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

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

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

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



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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Note: P_0 = 20 μPa = Reference Pressure

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

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

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

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

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

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

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

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

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

Equation N-2135.1 may also be rewritten as:

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

This form is useful for subtracting equal SPL's.

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

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

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

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

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

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

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

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

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

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

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

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

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

Table N-2135.1 Decibel Addition

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

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

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

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

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

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

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

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

N-2136 A-Weighting, Noise Levels

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

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

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

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

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

Figure N-2136.1 A-Weighting Network

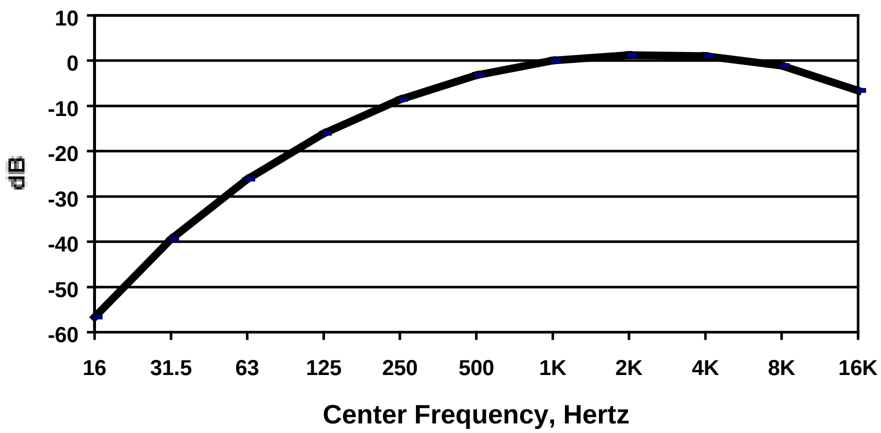


Table N-2136.1 "A"-Weighting Adjustments for 1/3 Octave Center Frequencies

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

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

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

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

Table N-2136.2 - Typical Noise Levels

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

N-2137 Octave and Third Octave Bands, Frequency Spectra

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

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

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

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

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

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

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

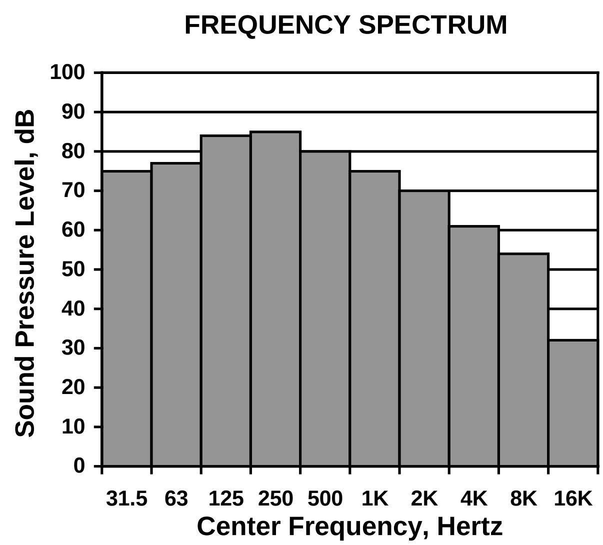
Table N-2137.1 Standardized Band No's, Center Frequencies, 1/3 Octave and Octave Bands, and Octave Band Ranges

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

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

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

Figure N-2137.1 - Typical Octave Band Frequency Spectrum



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

Table N-2137.2 Tabular Form of Octave Band Spectrum

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

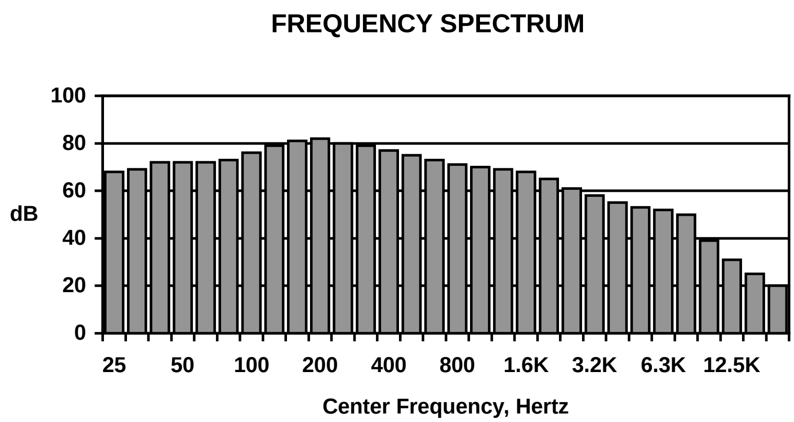
Total Sound Pressure Level = 89 dB

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

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

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

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



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

Table N-2137.2 Tabular Form of Octave Band Spectrum

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

Total Sound Pressure Level = 89 dB

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

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

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

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

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

N-2138 White Noise, Pink Noise

White noise is noise with a special frequency spectrum that has the same amplitude (level) 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 third-octave band spectrum of white noise would be a straight line. This is, however, not true. Beginning with the lowest audible octave, each subsequent octave spans twice as many frequencies than the previous ones, and therefore contains twice the energy. This corresponds with a 3 dB step increase for each octave band, and 1 dB for each third octave band.

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

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

N-2140 Sound Propagation

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

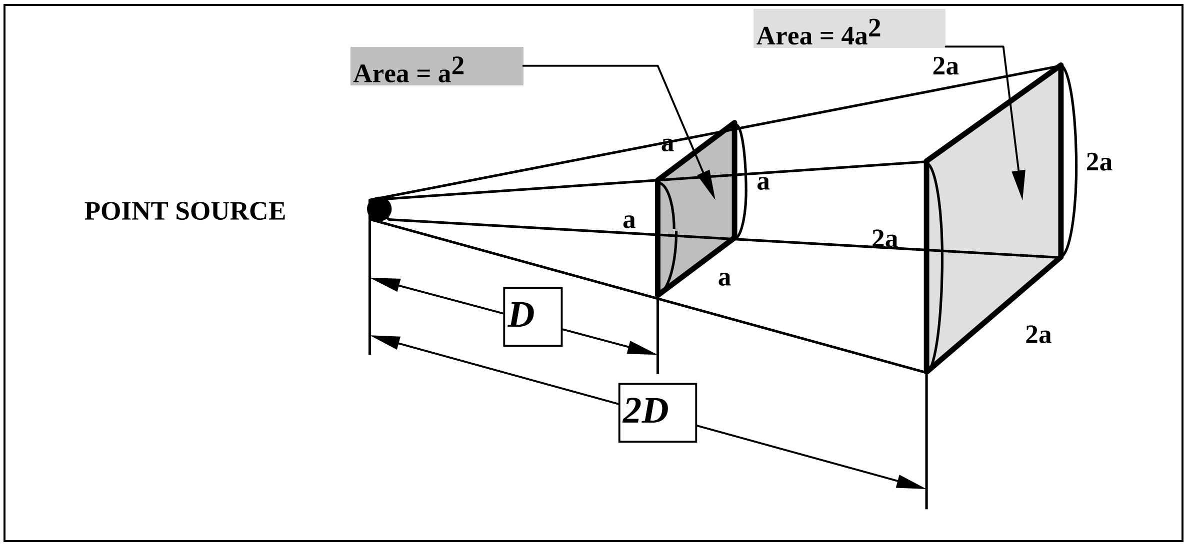
- Geometric Spreading from Point and Line Sources
- Ground Absorption
- Atmospheric Effects and Refraction
- Shielding by Natural and Manmade Features, Noise Barriers, Diffraction, and Reflection

N-2141 Geometric Spreading from Point and Line Sources

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

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

Figure N-2141.1 Point Source Propagation (Spherical Spreading)



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

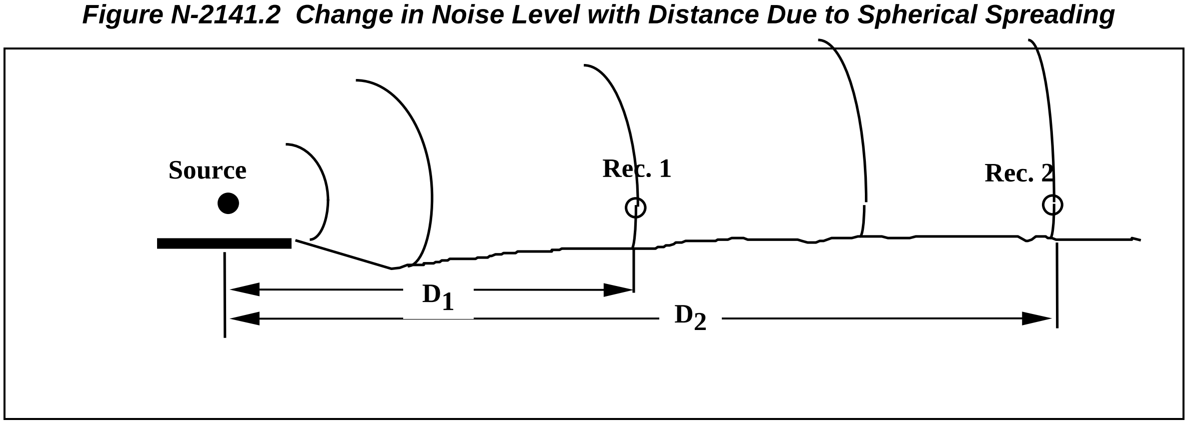
$$\mathbf{dBA_2 = dBA_1 + 10\ Log_{10}\ [(D_1/D_2)]^2 =}$$

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

Where:

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

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



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

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

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

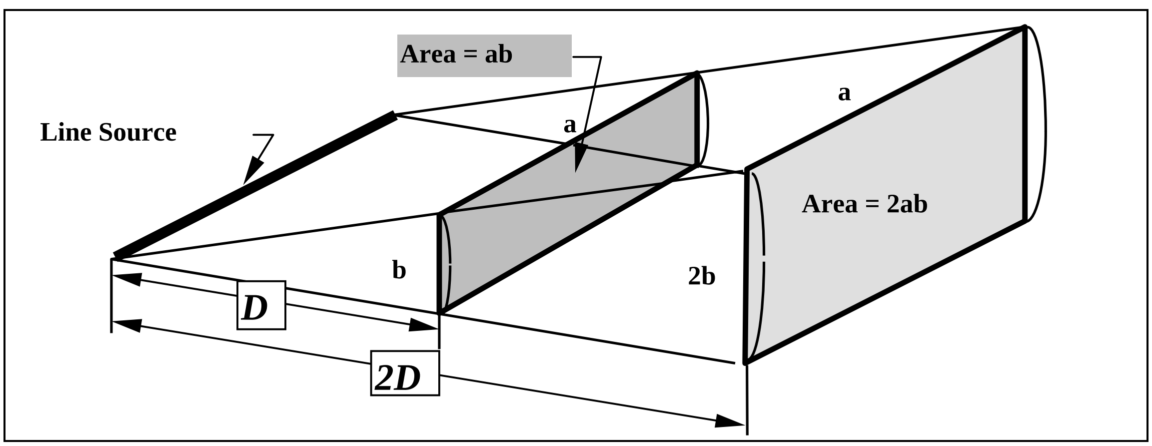
Where:

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

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

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

Figure N-2141.3 Line Source Propagation (Cylindrical Spreading)



N-2142 Ground Absorption

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

N-2143 Atmospheric Effects and Refraction

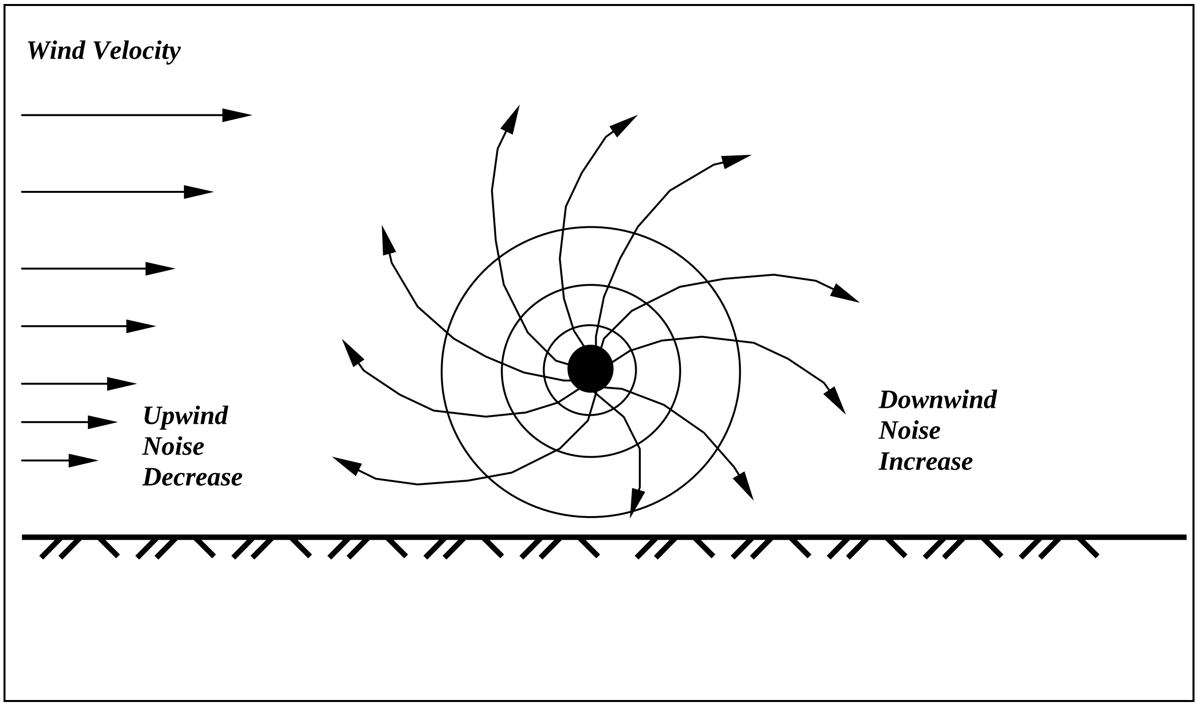
Research by Caltrans and others has shown that atmospheric conditions can have a profound effect on noise levels within 60 m (200 ft) from a highway. Wind has shown to be the single most important meteorological factor within approximately 150 m (500 ft), while vertical air temperature gradients are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

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

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

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

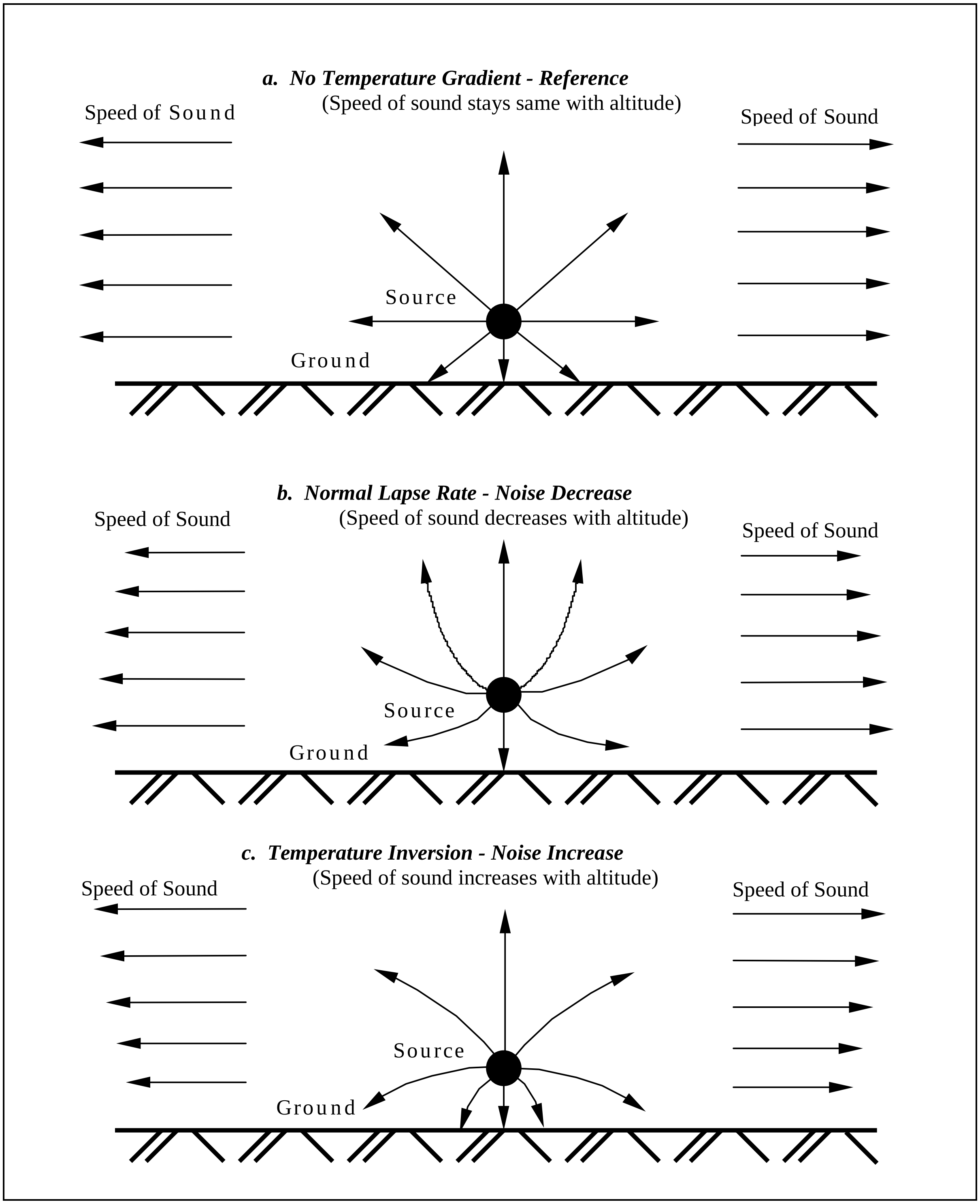
Figure N-2143.1 - Wind Effects on Noise Levels



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

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

Figure N-2143.2 - Effects of Temperature Gradients on Noise



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

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

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

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

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

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

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

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

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

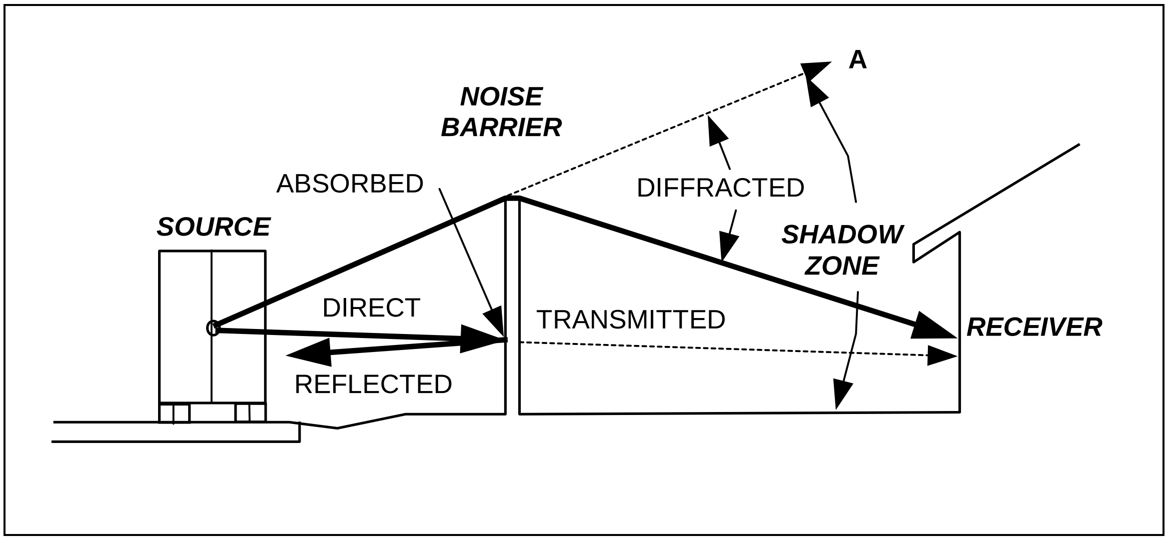
Referring to Figure N-2144.1, when a noise barrier is inserted between a noise source and receiver, the *direct* noise path along the line of sight between the two is interrupted. Some of the acoustical energy will be *transmitted* through the barrier material and continue to the source, albeit at a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

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

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

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

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



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

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

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

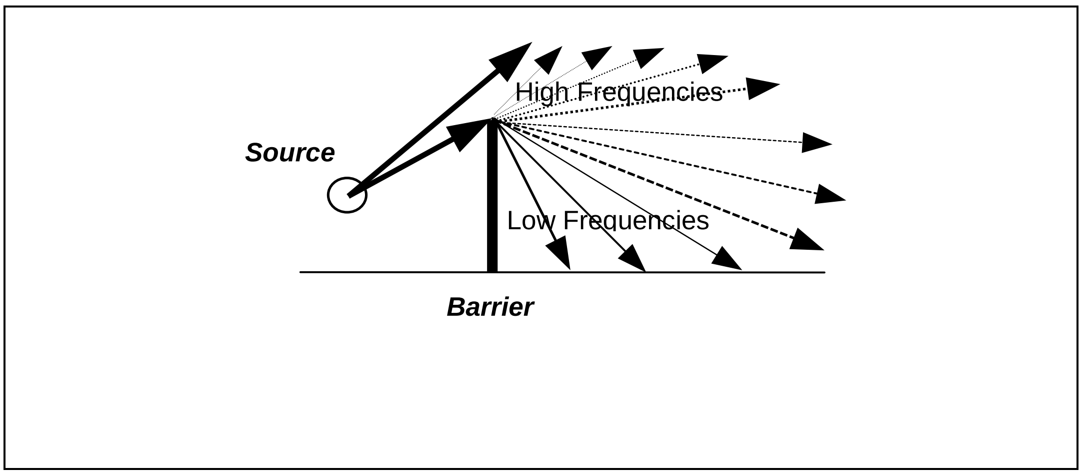
Referring back to Figure N-2144.1, we have discussed the ***direct***, ***transmitted***, ***absorbed***, and ***reflected*** noise paths. These represent all the variations of the direct noise path due to the insertion of the barrier. Of those, only the transmitted noise reaches the receiver behind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

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

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

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

Figure N-2144.2 - Diffraction of Sound Waves



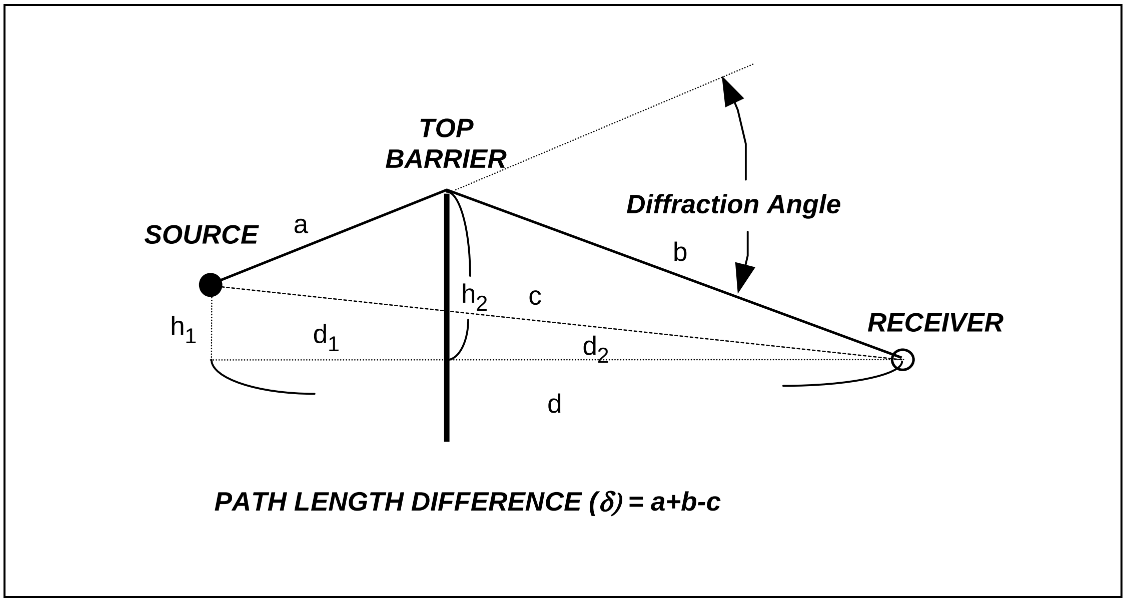
The angle of diffraction is also related to the path length difference (δ) between the direct noise and the diffracted noise. Figure N-2144.3 illustrates the concept of path length difference. A closer examination of this illustration reveals that as the diffraction angle becomes greater, so does δ.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

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

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

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

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



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

Mathematically, N_0 is defined as:

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

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

δ_0 = δ measured along the perpendicular line to the barrier

λ = wavelength of the sound radiated by the source.

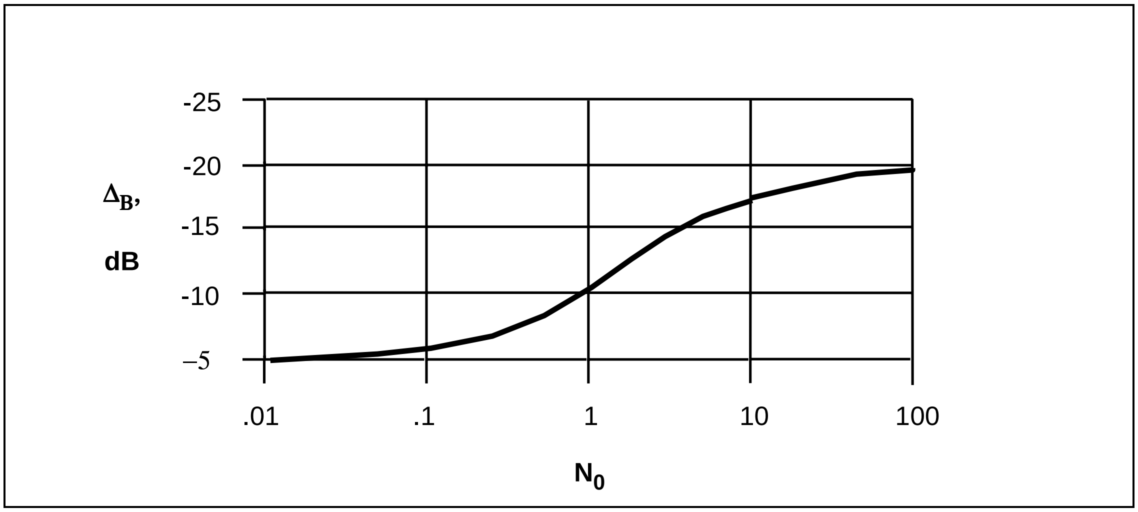
According to eq. N-2131.1, $\lambda = c/f$, and we may rewrite eq. N-2144.2:

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

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

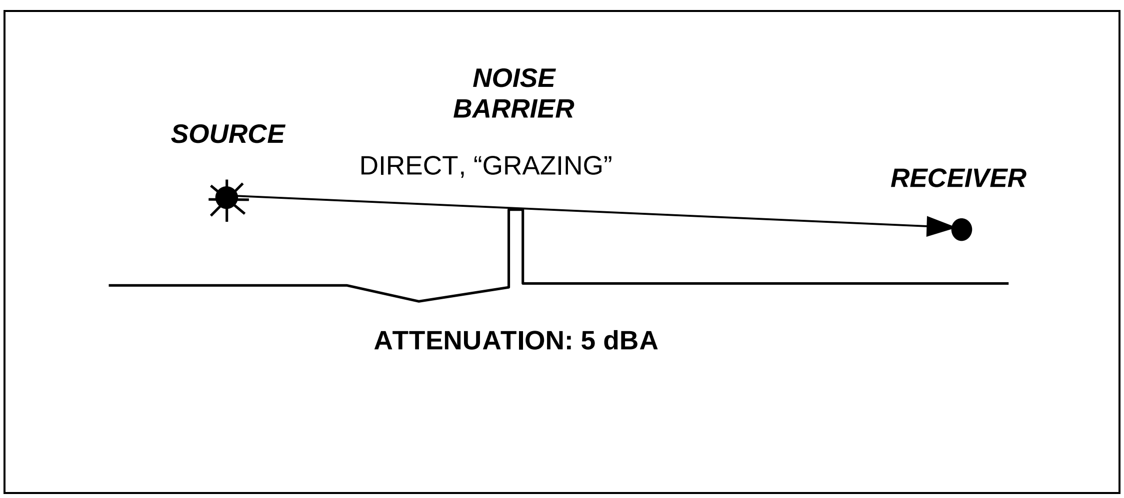
Note that the above equations relate δ_0 to N_0. If one increases, so does the other, and barrier attenuation increases as well. Similarly, if the frequency increases, so will N_0, and barrier attenuation. Figure N-2144.4 shows the barrier attenuation Δ_B for an infinitely long barrier, as a function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

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



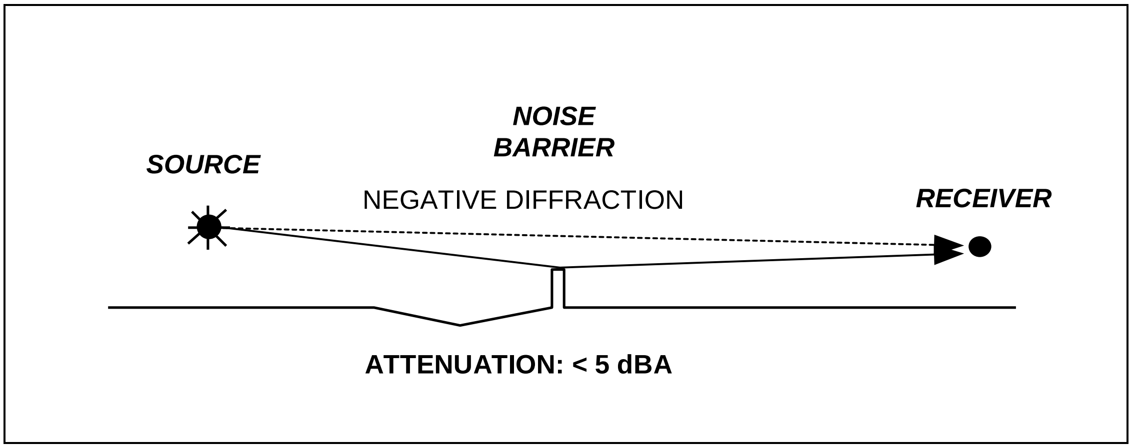
There are several "rules of thumb" for noise barriers and their capability of attenuating traffic noise. Figure N-2144.5 illustrates a special case where the top of the barrier is just high enough to "graze" the direct noise path, or line of sight between source and receiver. In such an instance the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

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



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

Figure N-2144.6 - “Negative Diffraction” Provides Some Noise Attenuation



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

N-2200 EFFECTS OF NOISE; NOISE DESCRIPTORS

N-2210 Human Reaction to Sound

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

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

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

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

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

N-2211 Human Response to Changes in Noise Levels

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

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

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

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

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

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

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

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

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

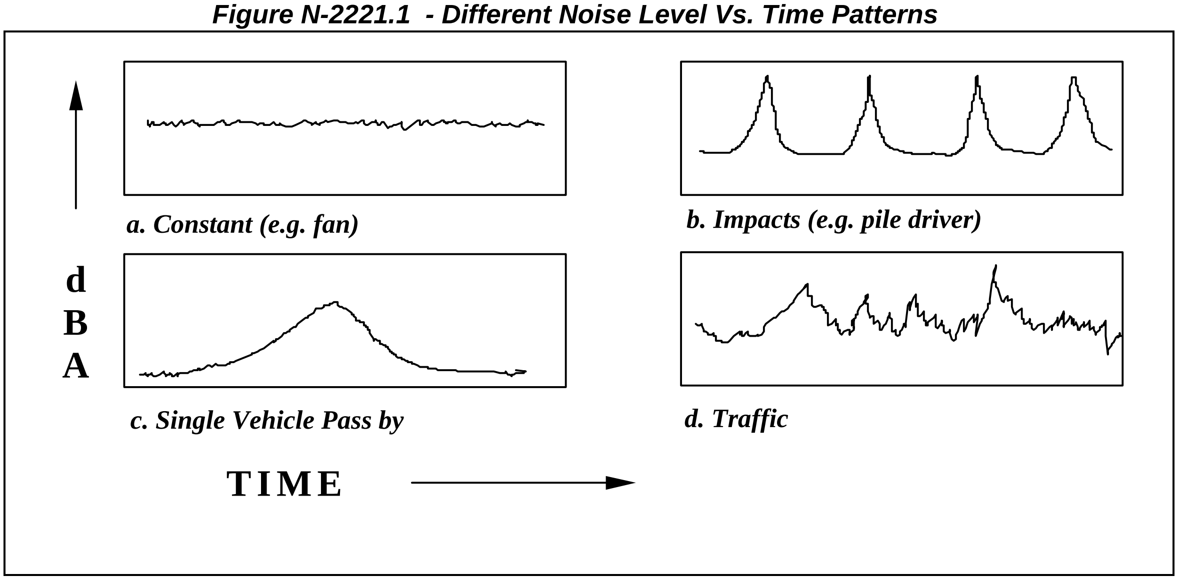
N-2220 Describing Noise

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

N-2221 Time Patterns

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

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



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

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

N-2222 Noise Descriptors

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

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

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

Table N- 2222.1. Common Noise Descriptors.

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

N-2223 Calculating Noise Descriptors

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

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

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

Table N-2223.1 Noise Samples for L10 Calculation

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

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

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

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

N = number of noise level samples

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Table N-2223.2 - Noise Samples for Leq Calculation

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

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

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

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

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

W_i = 10 for night hours (2200 - 0700)

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

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

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

Table N-2223.3 Noise Samples for Ldn Calculations

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

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

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

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

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

W_i = 10 for night hours (2200 - 0700)

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

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

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

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

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

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

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

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

N-2230 Conversion Between Noise Descriptors

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

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

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

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

The first correction for peak hour can be expressed as:

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

where :

P = Peak Hour volume % of ADT

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

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

where :

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

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

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

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

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

Where:

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

P = Peak Hour volume % of ADT

D = Day-time fraction of ADT

N = Night-time fraction of ADT

Note: (D + N) must equal 1

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

Solution:

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

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

$$= 64.9 \text{ dBA}$$

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

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

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

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

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

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

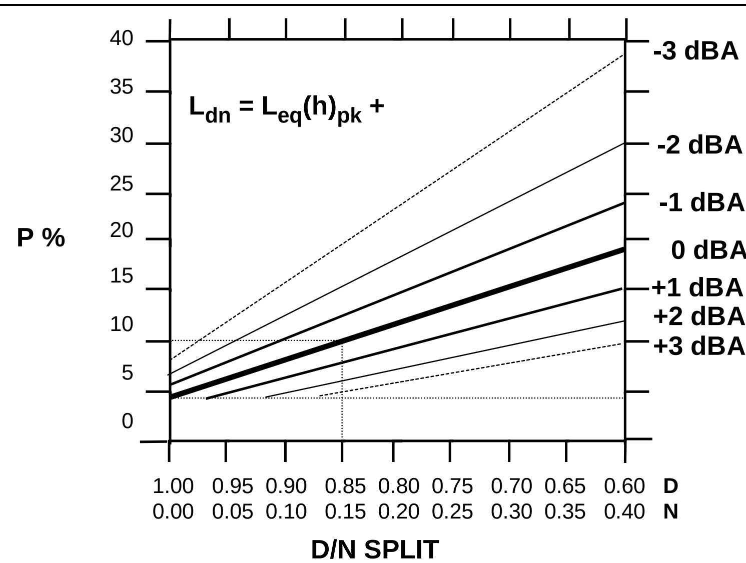


Figure N-2231.1 - Relationship Between L_{dn} and $L_{eq}(h)_{pk}$

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

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

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

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

N-2240 Negative Effects on Humans

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

N-2241 Hearing Damage.

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

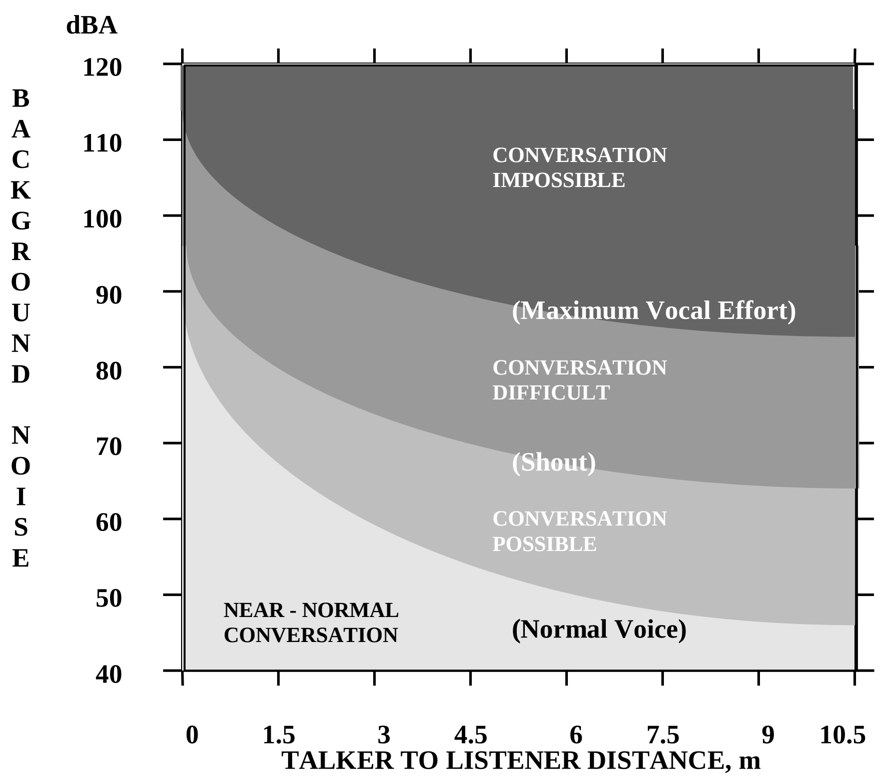
1. *Gradual.* Sustained exposure to moderately high noise levels over a period of time can cause **gradual hearing loss**. It starts out as a temporary hearing loss, such as immediately after a loud rock concert. The hearing usually restores itself within a few hours after exposure, although not quite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

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

N-2242 Interference with Activities.

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

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



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

N-2243 Stress Related Diseases

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

N-3000 MEASUREMENTS & INSTRUMENTATION

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

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

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

N-3100 PURPOSES OF NOISE MEASUREMENTS

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

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

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

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

N-3110 Ambient and Background Noise Levels

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

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

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

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

N-3120 Model Calibration

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

N-3130 Construction Noise Levels

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

N-3140 Performance of Abatement Measures

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

N-3150 Special Studies and Research

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

N-3200 MEASUREMENT LOCATIONS

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

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

N-3210 General Site Recommendations

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

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

More detailed considerations will be discussed in the next section.

N-3220 Measurement Site Selection

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

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

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

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

N-3221 Site Selection By Purpose of Measurement

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

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

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

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

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

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

N-3222 Site Selection By Acoustical Equivalence

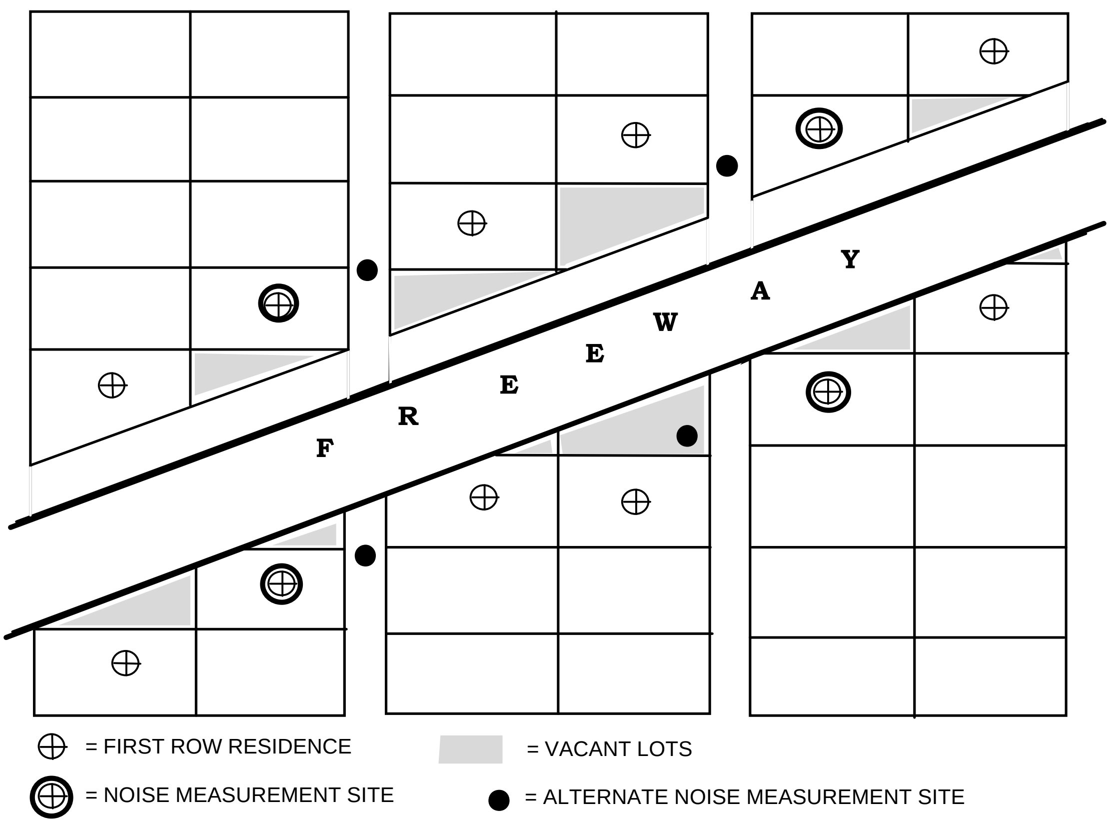
Noise measurement sites should be representative of the areas of interest. Representativeness in this case means *acoustical equivalence*. The concept of acoustical equivalence incorporates equivalences in noise sources, distances from these sources, topography, and other pertinent parameters.

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

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

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

Figure N-3222.1 - Typical Measurement Sites



N-3223 Site Selection By Geometry

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

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

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

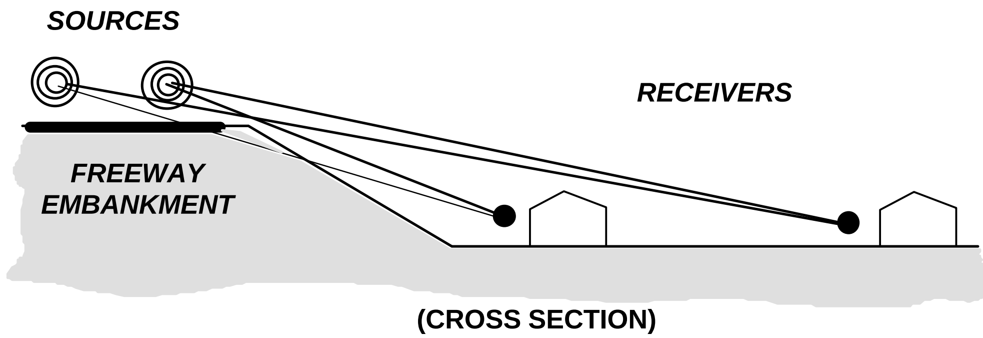
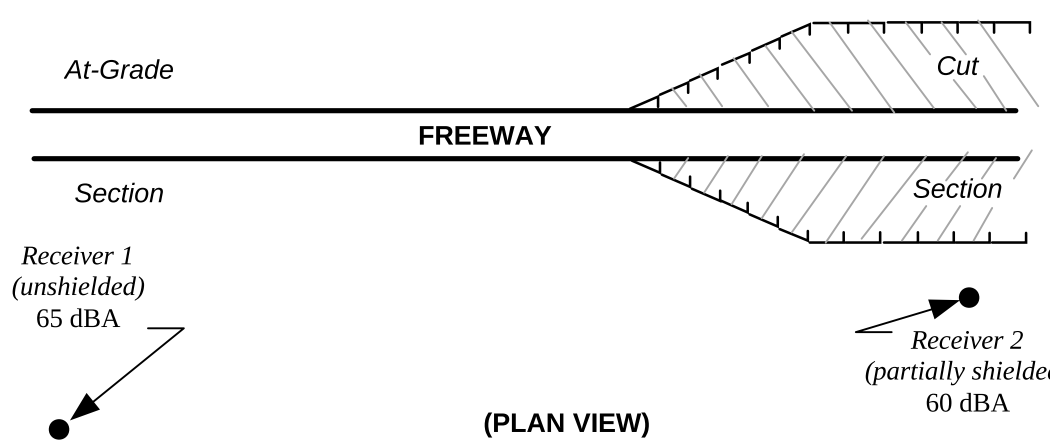


Figure N-3223.2 - illustrates the effects of site geometry on selection of highest noise exposure. The unshielded Receiver 1 shows a higher noise level than Receiver 2, although the latter is closer to the freeway.

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

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



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

N-3310 Measuring Times

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

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

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

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

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

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

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

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

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

N-3311 Noisiest Hour For Highway Traffic

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

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

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

N-3312 Adjusting Other-Than-Noisiest Hour

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

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

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

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

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

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

N-3320 Measurement Duration

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

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

Table N-3320.1 - Suggested Measurement Durations

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

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

N-3330 Number of Measurement Repetitions

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

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

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

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

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

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

Repeat measurements should be compared with the original(s) 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 insure that conditions are the same for all measurements, traffic counts and some basic meteorological measurements should be made during the noise measurements (see sections N-3340 and N-3600).

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

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

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

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

Example 1 data:

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

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

Use the mean of 2 measurements = 75.5 dBA

Example 2 data:

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

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

Use mean of all measurements = 69 dBA

Example 3 data:

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

(Example 3 measurements are acceptable)

Use mean of all measurements = 60 dBA

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

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

Example 4 data:

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

(Example 4 measurements are NOT acceptable:)

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

Example 5 data:

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

(Setup 2 & 3 measurements are acceptable.)

Mean of setup 2 and 3 = 68.5 dBA

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

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

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

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

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

Example:

Measurement No.	L_{eq}(dBA) Setup 1	Setup 2
1	67.8	68.7
2	66.9	67.9
3	-	67.8

S = 0.73 S_{MAX} = 0.63 (for 4 meas.)

(Need more data)

S = 0.64 S_{MAX} = 0.81 (for 5 meas.)

(Accept the 5 measurements)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

	NUMBER OF EQUIVALENT VEHICLES		
Speed, km/h (Mph)	1 Heavy Truck =	1 Medium Truck =	1 Automobile =
56 (35)	30.9	9.4	1
64 (40)	24.1	7.8	1
72 (45)	19.0	6.7	1
80 (50)	15.3	5.8	1
88.5 (55)	12.8	5.1	1
97 (60)	10.9	4.7	1
105 (65)	9.5	4.3	1

*Based on California Vehicle Noise Reference Energy Mean Emission Levels and vehicle definitions in FHWA-RD-77-108 (Also see sections N-4400 and N-5510)

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

	NUMBER OF EQUIVALENT VEHICLES		
Speed, km/h (mph)	1 Heavy Truck =	1 Medium Truck	1 Automobile =
56 (35)	19.1	7.1	1
64 (40)	15.1	5.8	1
72 (45)	12.9	5.0	1
80 (50)	11.5	4.5	1
88.5 (55)	10.4	4.1	1
97 (60)	9.6	3.7	1
105 (65)	8.9	3.5	1
113 (70)	8.3	3.2	1

**Based on FHWA Traffic Noise Model (TNM) Reference Energy Mean Emission Levels and vehicle definitions in FHWA-PD-96-008, DOT-VNTSC-FHWA-96-2 (Also see sections N-4400 and N-5520)

Example of calculating equivalent vehicles using Table N-3340.1:

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

Assignment: Convert traffic counts to Equivalent Vehicles.

Solution: (using Table N-3340.1)

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

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

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

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

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

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

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

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

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

Normalized Data, L_{eq}, dBA:

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

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

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

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

Average the 15-minute traffic counts:

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

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

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

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

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

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

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

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

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

Normalized Data, L_{eq}, dBA:

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

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

N-3350 Classroom Noise Measurements

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

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

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

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

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

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

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

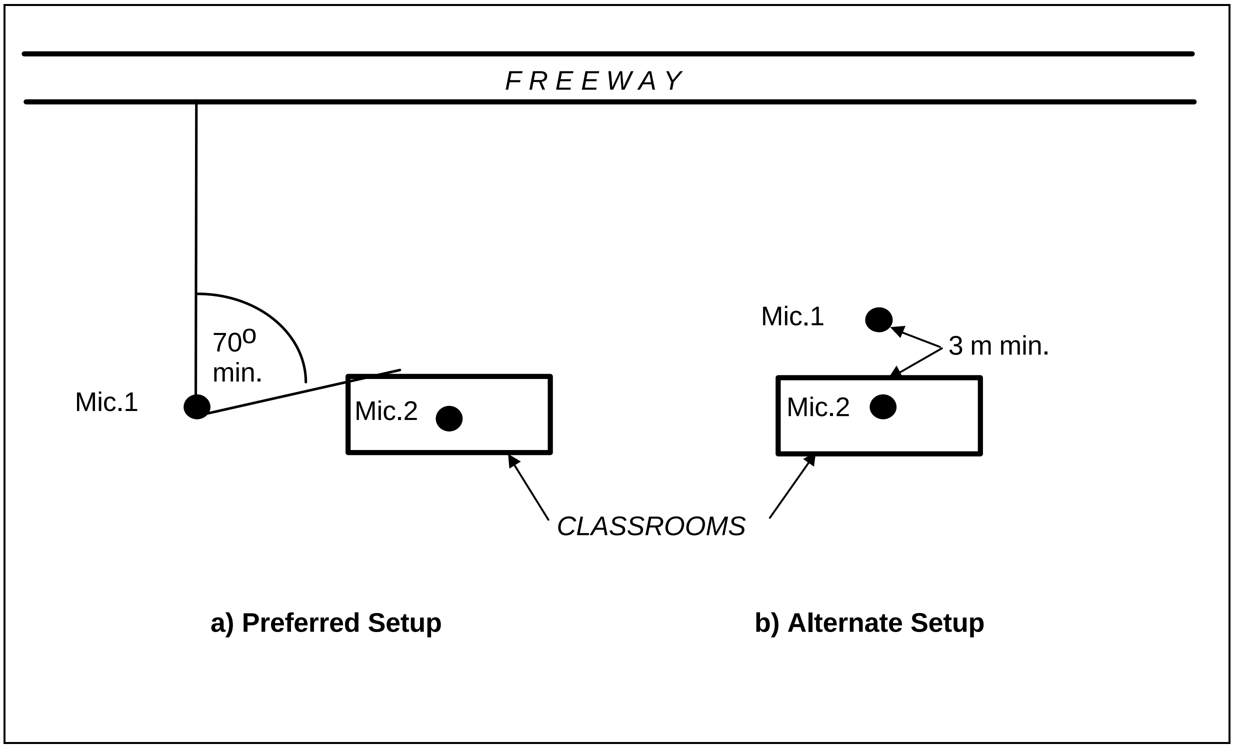
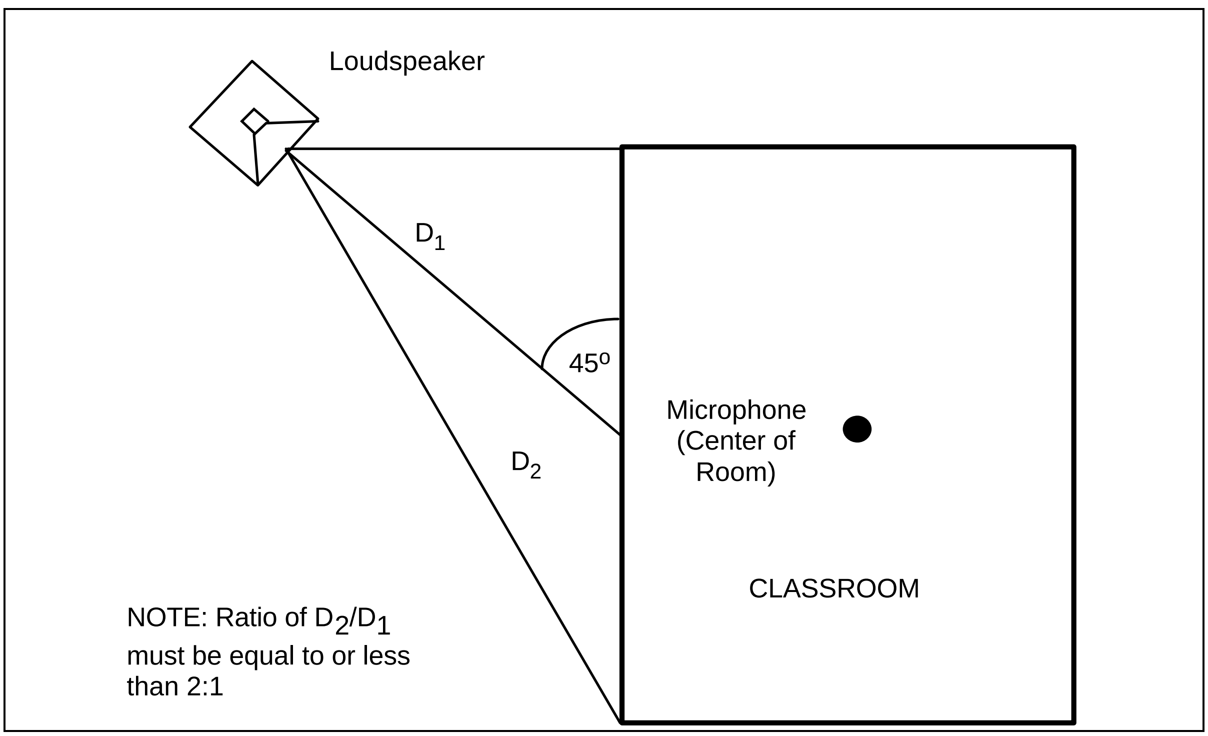


Figure N-3350.2 - Classroom Noise Measurements (Project on New Alignment, Using Artificial Sound Source)



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

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

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

N-3400 INSTRUMENTATION

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

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

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

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

N-3410 Sound Level Meters (SLM)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

10. *Output* for various recording devices.

11. *Power On/Off Switch*

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

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

N-3420 Recording Devices

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

N-3421 Graphic Level Recorder (GLR)

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

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

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

N-3422 Audio Tape Recorders

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

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

N-3423 Microprocessors

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

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

N-3430 Frequency Analyzers

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

N-3431 Real Time Analyzers

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

N-3432 Fast Fourier Transform (FFT) Analyzers

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

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

N-3440 Acoustical Calibrators

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

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

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

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

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

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

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

N-3500 NOISE MEASUREMENT PROCEDURES

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

N-3510 Instrumentation Setup

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

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

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

N-3520 Field Calibration

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

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

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

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

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

An example for routine measurements follows:

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

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

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

The field calibration procedure follows:

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

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

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

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

N-3530 Measurements

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

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

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

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

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

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

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

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

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

N-3540 Documentation

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

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

The following items should be documented:

1. *Noise measurement sites.* A sketch showing microphone location in relationship to natural or artificial land marks. Show distances to the nearest foot to building corners, trees, street signs, curbs, fences, etc. Include enough detail on the sketch to enable anyone to reoccupy, at a later date, the three dimensional (including height above ground) position of the microphone within one foot horizontally and 0.5 foot vertically. Show accurate three dimensional relationships between source and site. Cross sections should be obtained, either from accurate maps or field surveys. Sites should also be located on maps showing all receivers used in the noise analysis. Also include District, County, Route No. And Kilometer Post of site.
2. *Noise Measurements.* Record all instruments used for the noise measurements, manufacturers, model numbers, serial numbers. Also important are the calibrator make, model, serial number, reference level, frequency, and last calibration date. Show names of instrument operators and persons recording the data. Show before and after calibration data. Record site number, date, time, length of measurement, noise descriptor, pertinent settings on SLM/Recorder system, and noise data. Include remarks, notes of contamination, or anything that might have a possible effect on the measurement results.
3. *Meteorological Conditions.* Include prevailing wind direction and speed during the noise measurements, as well as temperature, relative humidity, and sky conditions. Indicate approximate height, and location of measurements. Show date, time, site no., name of observer.
4. *Traffic Counts.* Show the number of vehicles broken down by classification. It is important to indicate the location of the traffic counts, no. of lanes or lane groups counted, direction, length of time, time, District, County, Route, Post Mile, names of personnel, along with the counts and speeds.

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

N-3600 METEOROLOGICAL CONSTRAINTS ON NOISE MEASUREMENTS

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

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

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

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

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

N-3610 Meteorological Criteria

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

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

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

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

N-3620 Equivalent Meteorological Conditions

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

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

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

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

Table N-3600.1 - Classes of Wind Conditions

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

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

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

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

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

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

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

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

Table N-3600.2 - Cloud Cover Classes

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

N-3700 QUALITY ASSURANCE

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

N-4000 TRAFFIC NOISE IMPACT SCREENING PROCEDURE

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

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

N-4100 SCREENING PROCEDURE STEPS

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

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

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

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

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

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

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

7) If the above value is less than 3.0 dBA the project passes the screening procedure.

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

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

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

N-4200 DEFINITIONS FOR SCREENING PROCEDURE

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

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

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

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

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

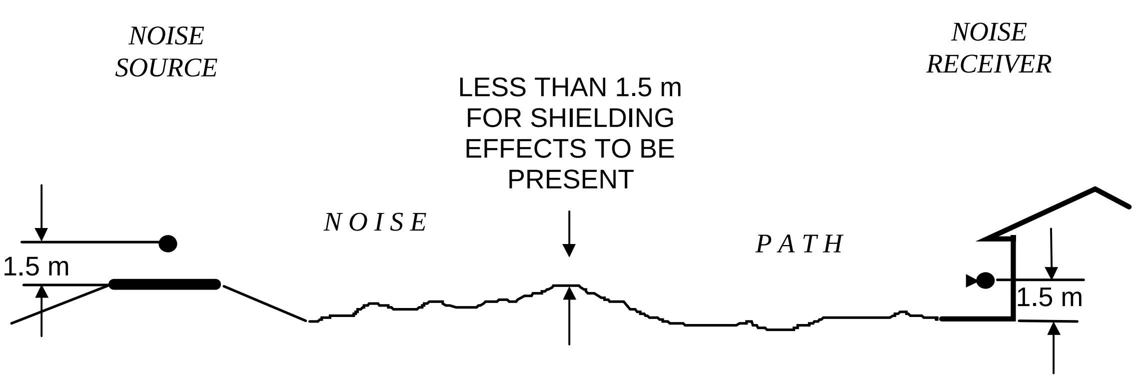
Noise Sources - The existing or future traffic along the before or after project alignment.

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

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

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

Figure N-4200-1 Shielding Criterion



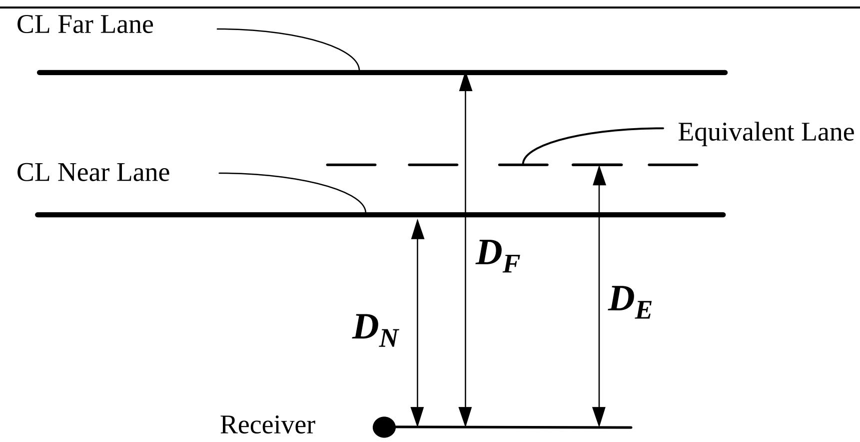
(Not To Scale)

N-4300 METHOD OF CALCULATING EQUIVALENT LANE DISTANCE

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

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

Figure N-4300.1 - Equivalent Lane Distance.



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

Equivalent Lane Distance, D_E

Example of Equivalent Lane Distance Calculation:

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

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

Notes:

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

N-4400 METHOD OF CALCULATING NUMBER OF EQUIVALENT VEHICLES

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

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

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

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

Note:

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

Example of Equivalent Vehicle calculation using Table N-4400.1:

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

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

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

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

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

Notes:

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

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

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

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

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

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

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

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

Note:

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

Example of Equivalent Vehicle calculation using Table N-4400.3:

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

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

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

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

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

Notes:

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

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

Example of using speed corrections:

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

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

N-4500 NOISE ANALYSIS SCREENING PROCEDURE CHECKLIST

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

NOISE ANALYSIS SCREENING PROCEDURE CHECKLIST

Dist______Co______Rte_______P.KM.___________________E.A ______________________

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

    Yes___*(continue)*

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

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

    Yes___*(continue)*

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

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

    Yes___*(continue)*

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

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

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

    Yes___*(continue)*

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

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

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

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

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

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

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

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

THE PROPOSED PROJECT: *(Check one)*

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

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

Prepared By:__________________________________ Date:__________________

N-5000 DETAILED ANALYSIS - TRAFFIC NOISE IMPACTS

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

N-5100 GATHERING INFORMATION

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

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

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

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

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

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

N-5300 DETERMINING EXISTING NOISE LEVELS

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

N-5310 Selecting Noise Receivers and Noise Measurement Sites

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

N-5311 Receivers

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

Following are some general recommendations for selecting receivers:

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

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

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

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

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

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

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

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

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

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

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

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

N-5312 Noise Measurement Sites

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

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

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

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

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

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

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

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

N-5320 Measuring Existing Noise Levels

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

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

N-5330 Modeling Existing Noise Levels

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

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

N-5400 CALIBRATING THE PREDICTION MODEL

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

N-5410 Definitions

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

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

N-5420 Limitations

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

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

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

N-5430 Pertinent Site Conditions

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

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

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

- Receptor locations.
- Grade Corrections.

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

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

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

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

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

N-5440 Procedures

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

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

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

   K = Measured - Calculated

   or for short:

   K = M - C **(eq. N-5450.1)**

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

   P = C + K **(eq. N-5450.2)**

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

Example A.

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

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

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

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

Example B.

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

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

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

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

N-5450 Cautions And Pitfalls of Model Calibration

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

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

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

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

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

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

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

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

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

Following is an outline of the problem:

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

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

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

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

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

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

N-5460 Tolerances

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

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

N-5470 Common Dilemmas

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

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

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

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

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

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

N-5500 PREDICTING FUTURE NOISE LEVELS

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

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

N-5510 FHWA-RD-77-108 METHODOLOGY

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

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

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

OR

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

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

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

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

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

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

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

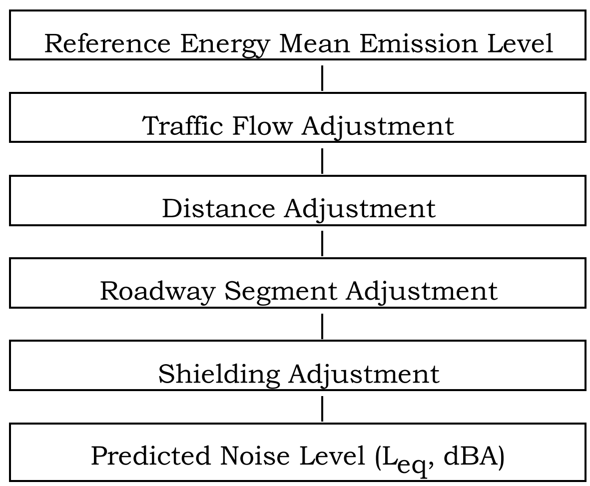
For the same conditions under which LEQV2 can be used, SOUND32 yields approximately the same results. Some negligible differences of generally less than 0.5 dBA could result, due to rounding.

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

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

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

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

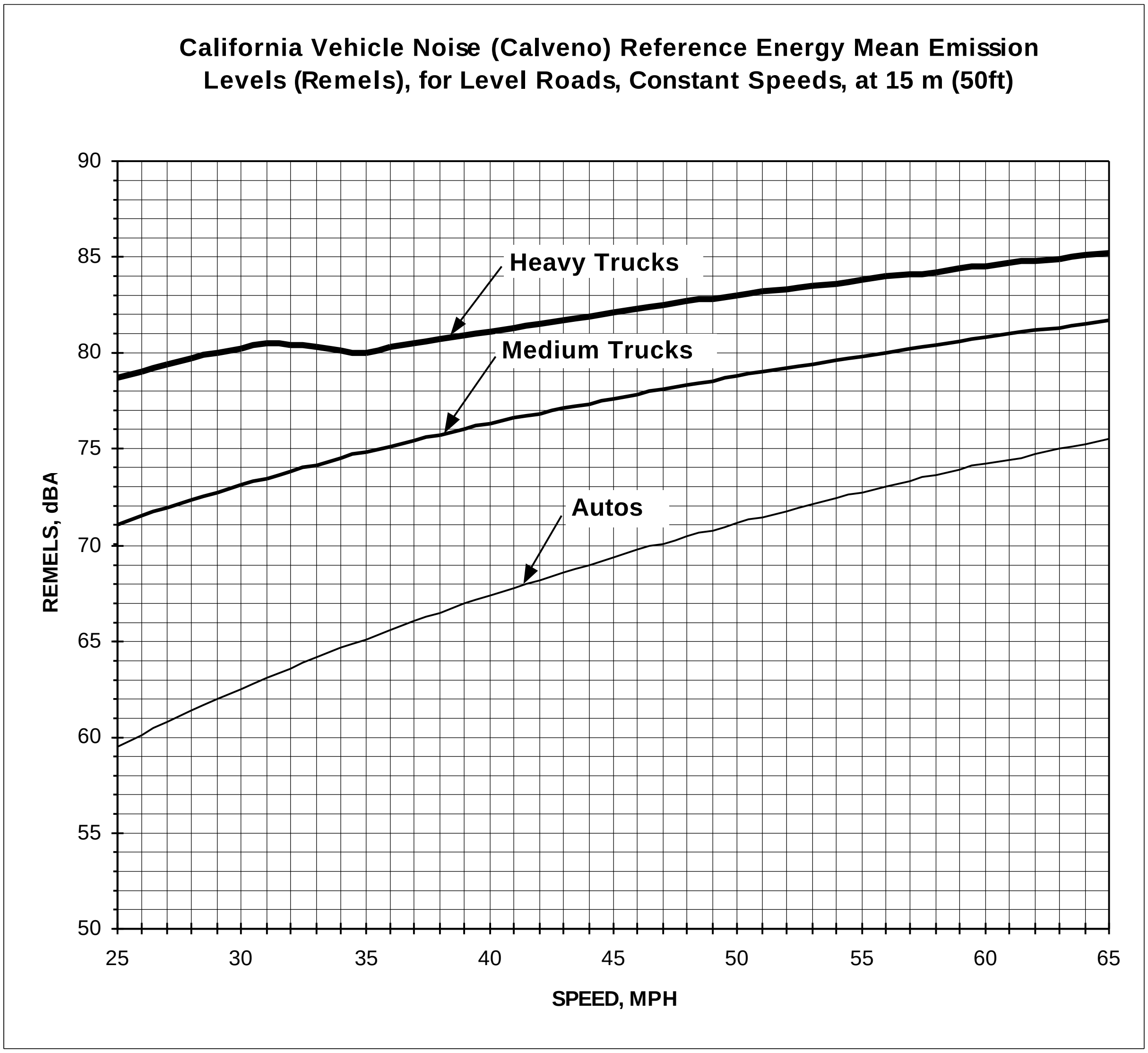


N-5511 Reference Energy Mean Emission Levels (REMELS)

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

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

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



Heavy Trucks:

25-31 mph (40-50 km/h): **$51.9+19.2Log_{10}$(Speed, mph) or $47.9+19.2Log_{10}$(Speed, km/h)**

35-65 mph: (56-105 km/h): **$50.4+19.2Log_{10}$(Speed, mph) or $46.4+19.2Log_{10}$(Speed, km/h)**

31-35 mph: (50-56 km/h): **Straight line**

Medium Trucks:: **$35.3+25.6Log_{10}$(Speed, mph) or $30.0+25.6Log_{10}$(Speed, km/h)**

Autos: **$5.2+38.8Log_{10}$(Speed, mph) or $-2.8+38.8Log_{10}$(Speed, km/h)**

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

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

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

N-5512 Traffic Flow Adjustment

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

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

Where :

- N_i is the number of vehicles in the ith class
- D_0 is 15 metres
- T is the time (normally 1-hour)
- S_i is the speed in kph

The equation can be simplified to:

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

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

N-5513 Distance Adjustment

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

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

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

D_0 is the reference distance of 15 metres

α is the excess attenuation due to ground effects

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

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

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

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

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

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

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

N-5513.1 Lane-by- Lane

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

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

N-5513.2 Equivalent Lane Distances

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

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

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

Where:

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

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

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

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

Where:

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

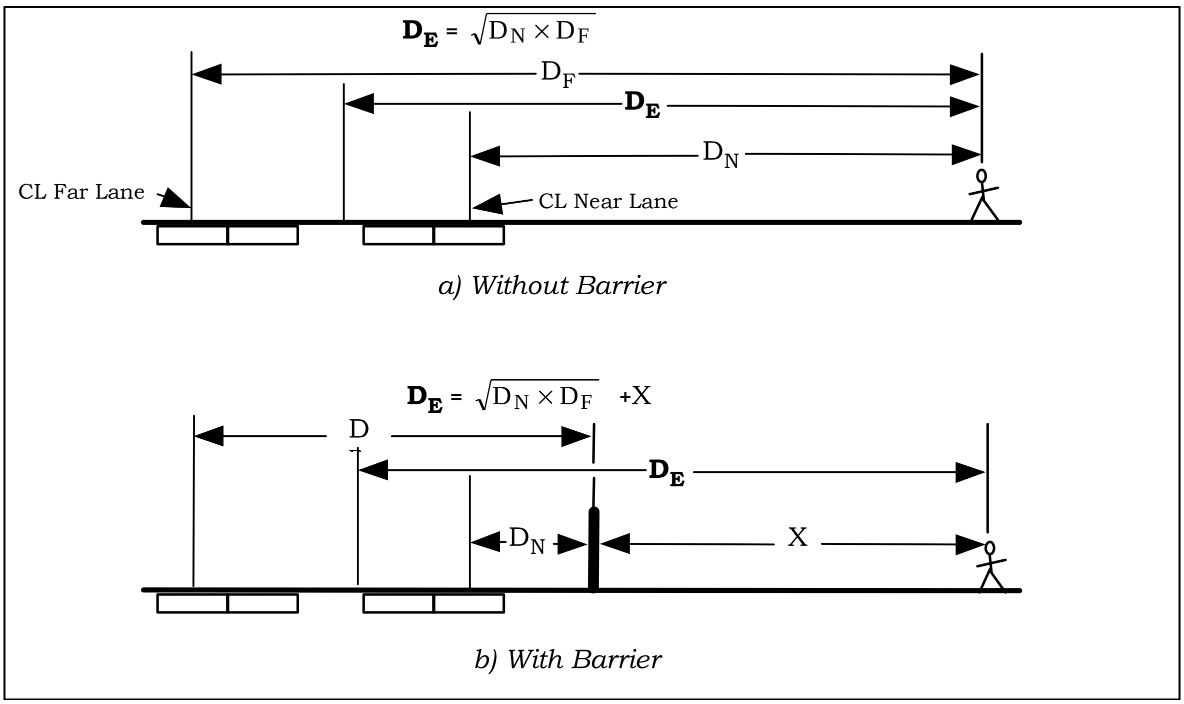
These distances are shown in of Figure N-5513.1(b)

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

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

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

Figure N-5513.1 - Equivalent Lane Distances, D_E



N-5513.3 Centerlines of Directional Traffic

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

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

N-5514 Finite Roadway Adjustment

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

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

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

Where:

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

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

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

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

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

N-5515 Shielding Adjustments

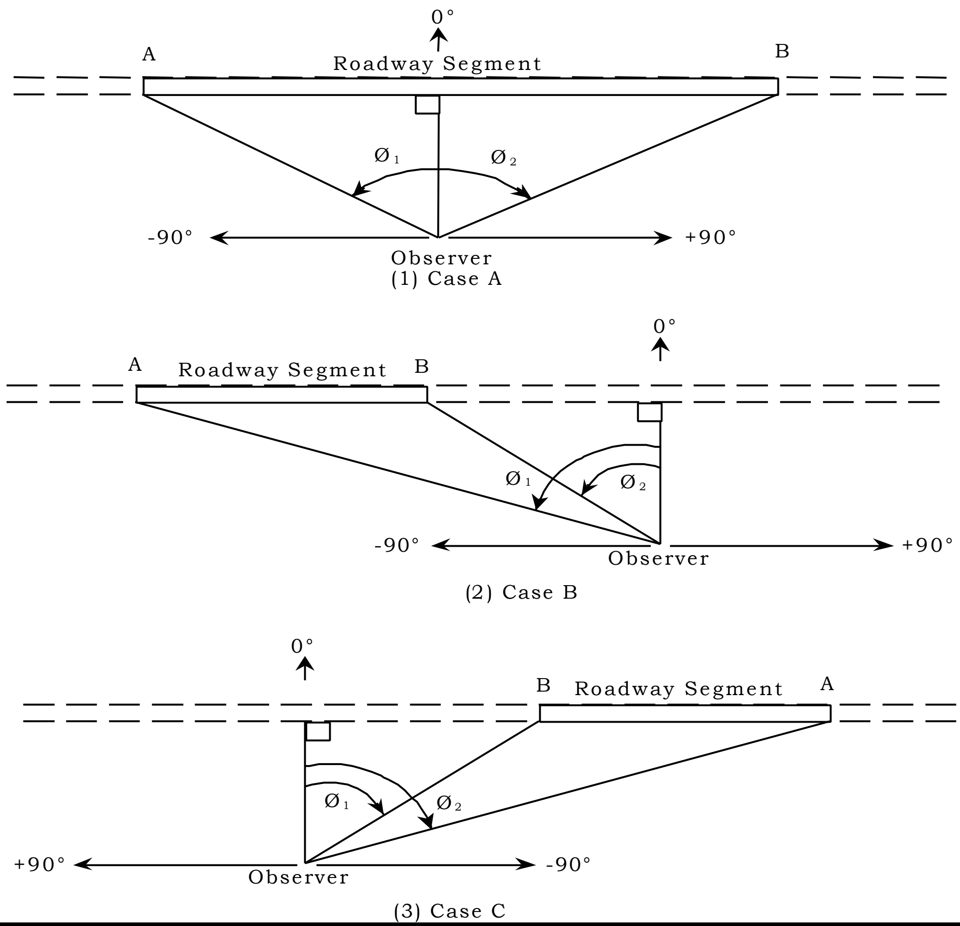
Shielding is one of the most effective ways of reducing traffic noise. Shielding occurs when the observer's view of the highway is obstructed or partially obstructed by natural or man-made features interfering with the propagation of the sound waves. Figure N-5515.1 illustrates the general rules of thumb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

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

Figure N-5514.1 - Identification of Angles

Based on this procedure, only three cases are possible:

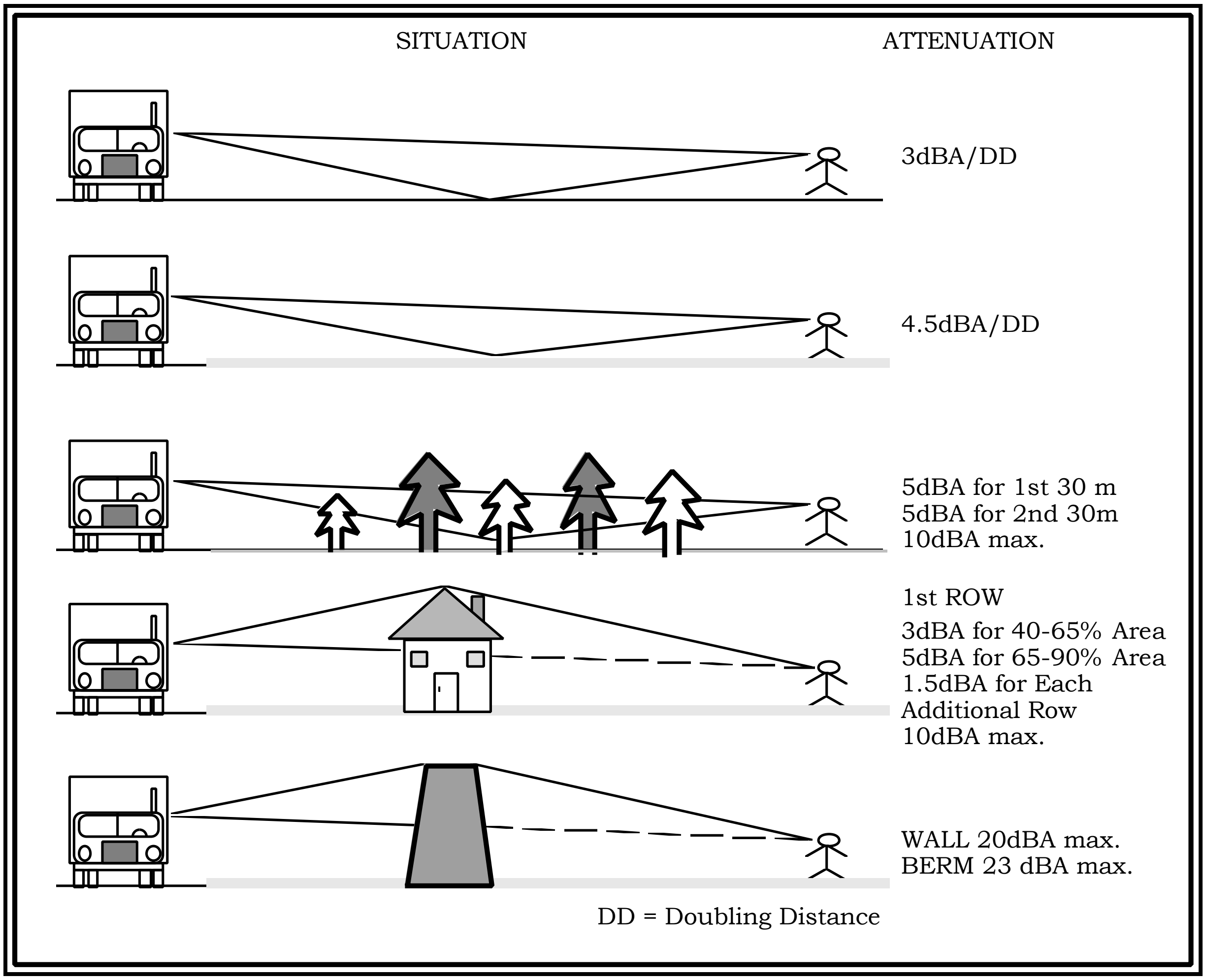
Case A – $Ø_1$ is negative, $Ø_2$ is positive.
Case B – $Ø_1$ is negative, $Ø_2$ is negative.
Case C – $Ø_1$ is positive, $Ø_2$ is positive.



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

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

Figure N-5515.1 - Shielding Adjustments

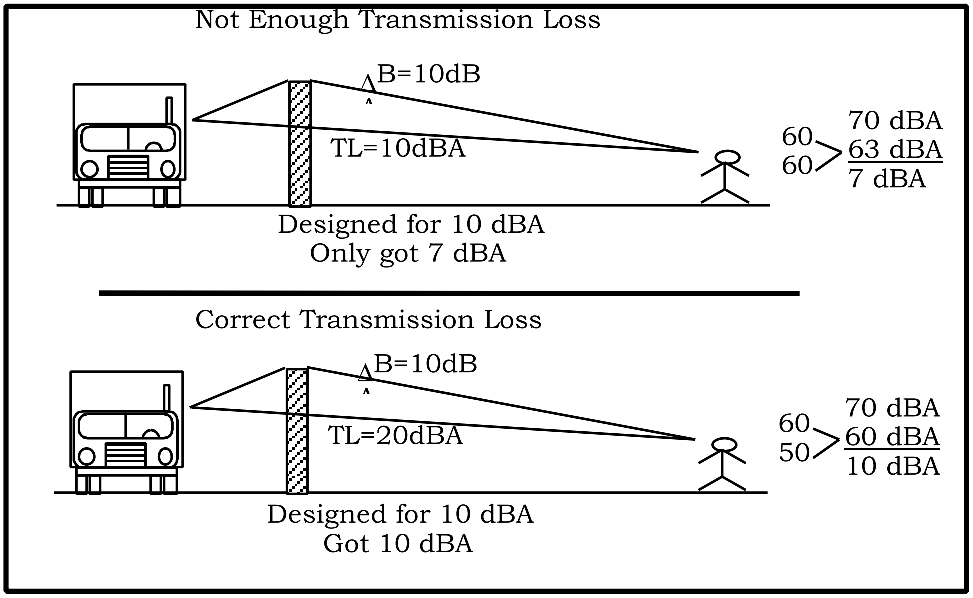


N-5515.1 Noise Barriers

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

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

Figure N-5515.2 - Barrier Transmission Loss



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

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

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

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

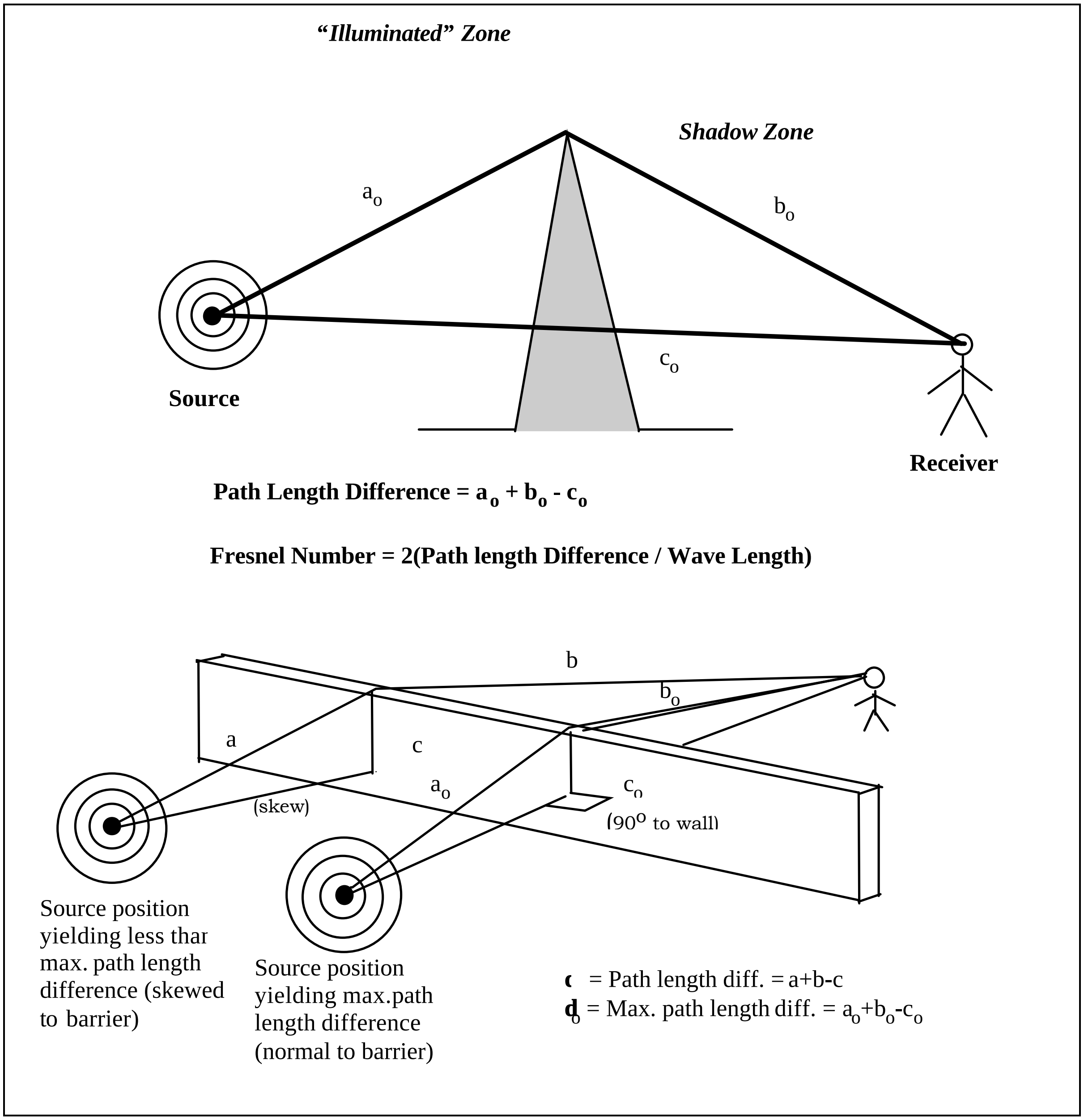
$$N_o = \frac{f\,\delta_o}{550} \qquad \textbf{(eq. N-5515.2)}$$

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

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

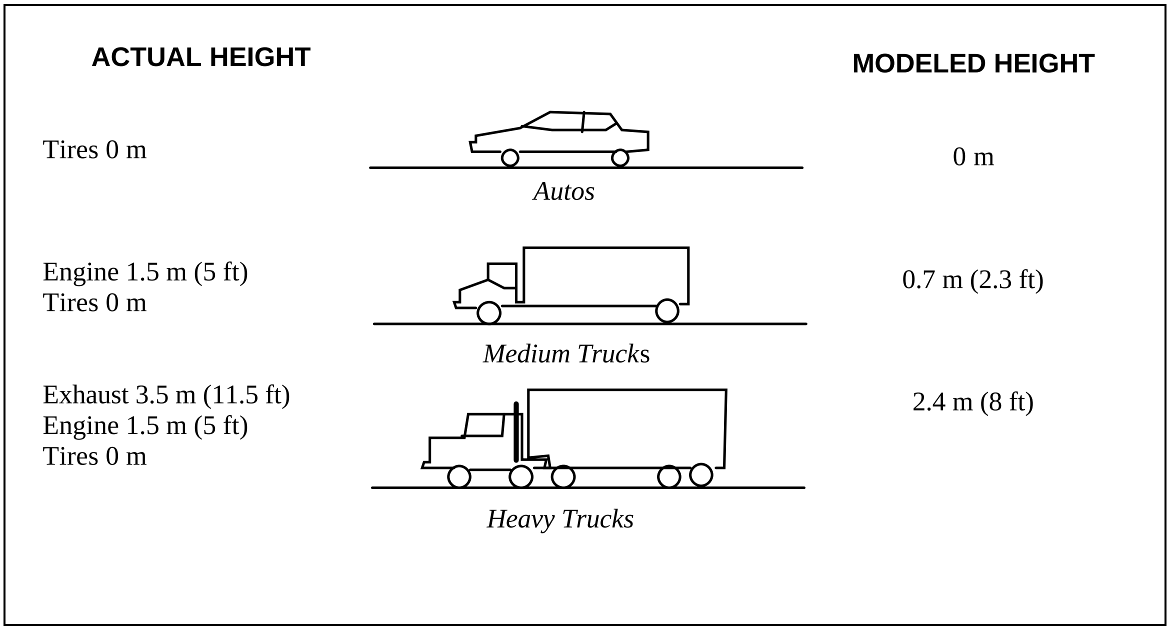
where the distances a_o, b_o and c_o are the distances normal to the barrier, as shown in Figure N-5515.3.

Figure N-5515.3 - Path Length Difference and Fresnel Number



For barrier calculation purposes, the vehicle noise sources are also simplified to those shown in Figure N-5515.4. These heights attempt to take into account and centralize the locations of the many individual sources of noise radiated from the vehicle types.

Figure N-5515.4 - Vehicle Source Heights Above Pavement



For barriers of finite length, the attenuation provided by a barrier depends on how much of the roadway is shielded from the observer. As with the finite roadway adjustment for soft sites, the finite barrier attenuation, Δ_{B_i}, calculations involves the solution of an integral:

$$\Delta_{B_i} = 10\log_{10} \frac{1}{f_R - f_L} \int_{f_L}^{f_R} (x)\,df \text{, where:} \qquad \textbf{(eq. N-5515.4)}$$

$$X = 1 \text{ for Ni} \leq -0.1916 - 0.0635 \qquad \textbf{(eq. N-5515.5)}$$

$$X = \frac{10^{-0.3\varepsilon} \tan^2 \sqrt{2\pi}|N_0|_i \cos\phi}{\sqrt{10} \cdot 2\pi|N_0|\cos\phi} \text{ for } (-0.916\text{-}0.0635\varepsilon) \leq N_i \leq 0 \qquad \textbf{(eq. N-5515.6)}$$

$$x = \frac{10^{-0.3\varepsilon} \tanh^2 \sqrt{2\pi(N_0)_i \cos\phi}}{\sqrt{10} \cdot 2\pi(N_0)_i \cos\phi} \text{ for } 0 \leq N_i \leq 5.03$$

Note: $\tanh(x) = (e^x - e^{-x})/(e^x + e^{-x})$

(eq. N-5515.7)

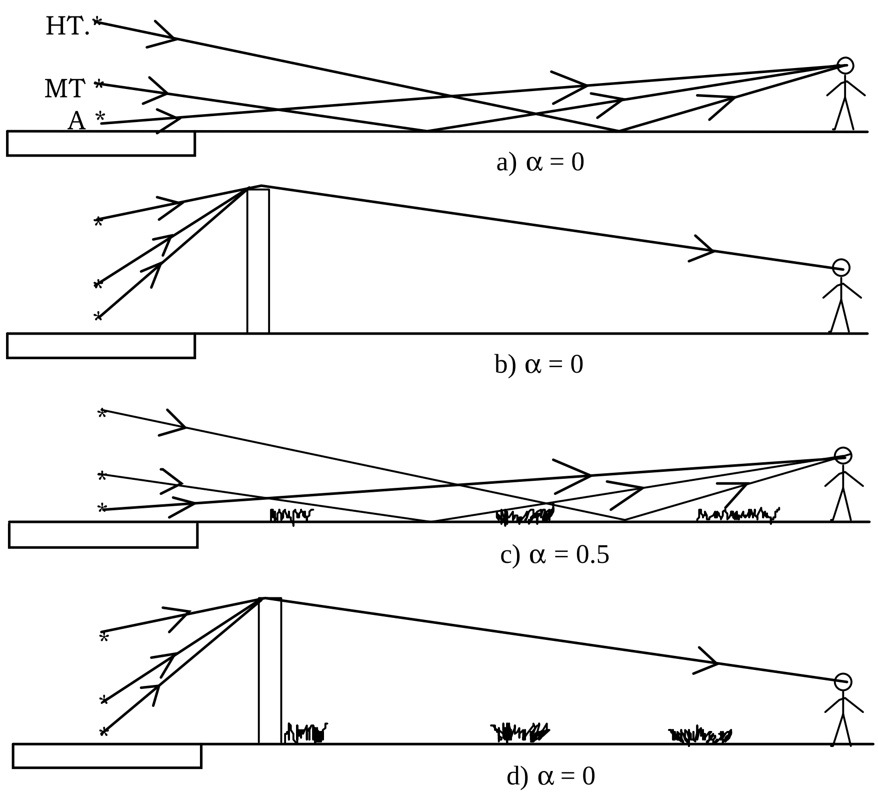
$$x = \frac{10^{-0.3\varepsilon}}{10^0} \text{ for Ni} \geq 5.03 \qquad \textbf{(eq. N-5515.8)}$$

Note the ε (epsilon) term in the equations: $\varepsilon = 0$ for a wall, and $\varepsilon = 3$ for a berm. The FHWA model assumes that earth berms perform about 3 dB better than free standing walls due to the top of barrier shape. ε accounts for this difference.

N-5515.2 Ground Effects

Consider the situation where the ground between the roadway and the observer is reflective (the drop-off rate is 3, or α = 0). This situation is illustrated in Figure N-5515.5(a). As was indicated in Table N-5513.1, under these circumstances the drop-off rate is 3 dBA/DD [from 3(a)]. When a barrier is constructed between the roadway and the observer, the top of the barrier appears to be the noise source to the observer and again, the drop-off rate should be 3 dBA/DD (Figure N-5515.5(b)).

Figure N-5515.5 - Ground Effects



Effects of Noise Barrier on α = 0 (a and b) and α = 0.5 (c and d).

However, when the ground between the roadway and the observer is soft (4.5 dBA/DD, α = 0.5) the ground effects can provide an additional 1.5 dBA/DD when both the source and the receiver are close to the ground (Figure N-5515.5(c)). In this case, when a barrier is constructed between the observer and the roadway, the top of the barrier again appears to be the noise source to the observer and the appropriate drop-off rate is 3 dBA/DD (Figure 5515.5(d)). Thus, the 1.5 dBA/DD excess attenuation from the ground effects has been lost. Constructing a barrier effectively raises the source height and the ground effect is lost. Consequently, if the barrier attenuation was 9 dBA, an observer at 200 ft would get a field insertion loss of only 6 dBA (9 dBA barrier attenuation minus the 3 dBA lost excess ground effects).

N-5520 FHWA-TRAFFIC NOISE MODEL® (FHWA-PD-96-009 & -010; DOT-VNTSC-FHWA-98-1 & -2) OVERVIEW

The FHWA Traffic Noise Model® (TNM) was released on March 30, 1998. TNM will replace the FHWA-RD-77-108 methodology and the computer versions LEQV2 and SOUND32. The phase in period will be two years from the above date. The model is described in the "FHWA Traffic Noise Model® - Technical Manual ", Report Number: FHWA-PD-96-010; DOT-VNTSC-FHWA-98-2. The instructions for using the TNM version 1.0 software are contained in "FHWA Traffic Noise Model® - User's Guide", Report Number: FHWA-PD-96-009; DOT-VNTSC-FHWA-98-1.

FHWA TNM is a registered Copyright. The Copyright encompasses the User's Guide, Technical Manual, and software source and executable codes. FHWA TNM is also a registered Trademark. The Trademark encompasses the copyrighted User's Guide, Technical Manual, and software source and executable codes. It provides the FHWA with the exclusive right to use the names "Federal Highway Administration Traffic Noise Model" and "FHWA TNM". A TNM package, including the model software, the User's Guide, the Technical Manual and a TNM tutorial CD-ROM has been distributed to each Caltrans District, and Caltrans may make sufficient copies for internal use. All other users must purchase the TNM package through:

The McTrans Center at the University of Florida, Telephone (904) 392-3225,
Fax: (904) 392-3224, World Wide Web: http://www-mctrans.ce.ufl.edu

Following sections provide a brief overview of TNM. For detailed information the above referenced TNM Technical Manual and User's Guide should be consulted.

Limited TNM test runs results have generally agreed within two decibels with Sound 32 results.

N-5521 TNM Reference Energy Mean Emission Levels (REMELs)

TNM computes highway traffic noise at nearby receivers and aids in the design of noise barriers. The noise sources include an entirely new data base of 1994-1995 noise reference energy mean emission levels (REMELs) that is detailed in "Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model (FHWA TNM®), Version 1.0", Report Number: FHWA-PD-008; DOT-VNTSC-FHWA-96-2. The database includes speed-dependent emission levels for constant speeds on level roadways from idle to 80 mph (129 km/h), for the following vehicle types:

- Automobiles: same definition as in FHWA-RD-77-108
- Medium Trucks: same definition as in FHWA-RD-77-108
- Heavy Trucks: same definition as in FHWA-RD-77-108
- Buses: all vehicles designed more than nine passengers; and
- Motorcycles: all vehicles with two or three tires and an open-air driver/passenger compartment

In addition, the database includes data for:

- vehicles on grades
- three different pavements (dense-graded asphaltic concrete, open-graded asphaltic concrete, and Portland cement concrete)
- accelerating vehicles
- acoustic energy apportioned to two sub-source heights above the pavement: 0 m and 1.5 m (5 ft) for all vehicles, except for heavy trucks where the sub-source heights are 0 m and 3.66 m (12 ft)
- data stored in 1/3 octave bands

Figure N-5520.1 compares the new TNM Baseline REMELs with the Calveno REMELs. The latter were used in SOUND32 and LEQV2 programs (see Section N-5510) and must not be used with TNM. The TNM Baseline REMEL curves in Figure N-5520.1 were plotted from the TNM Baseline equations:

Speed 0 km/h (IDLE): $L_{(s_i)} = 10 \log_{10} (10^{C/10}) =$ **(eq.N-5520.1)**

$L_{(s_i)} = C$ **(eq.N-5520.1a)**

Speed > 0 km/h: $L_{(s_i)} = 10 \log_{10} [(0.6214\ s_i)^{A/10}\ 10^{B/10} + 10^{C/10}]$ **(eq.N-5520.2)**

Where: $L_{(s_i)}$ = REMEL for vehicle type i, at speed s (km/h)

s_i = Speed of vehicle type i in km/h

A, B, C are constants for each vehicle type, shown below (Table N-5521.1)

Note: For speeds in mph omit 0.6214 in above eq. 2.

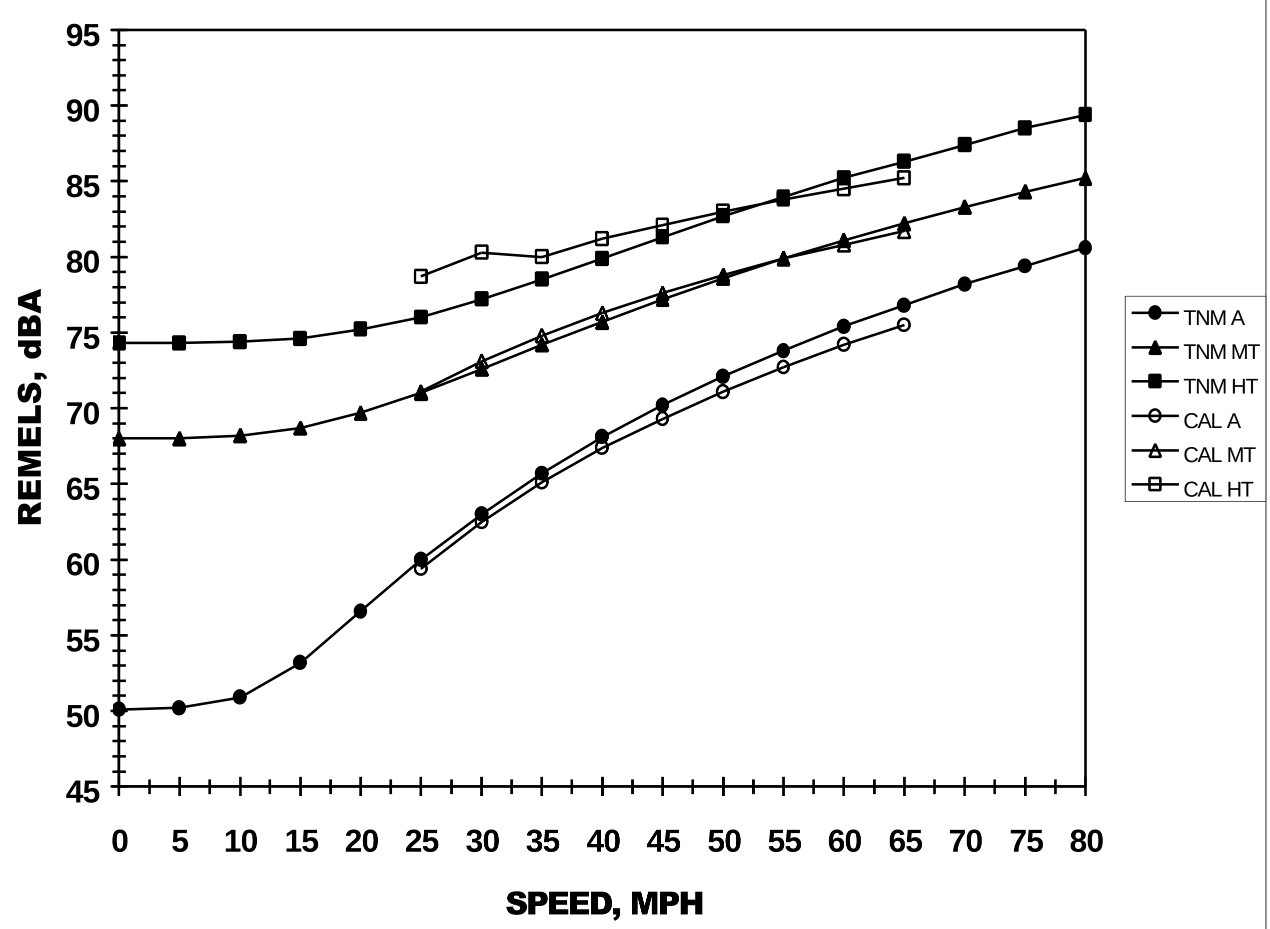
Table N-5521.1

Vehicle Type	Constants A	Constants B	Constants C
Autos (A)	41.740807	1.148546	50.128316
Medium Trucks (MT) (2-axles, dual wheels)	33.918713	20.591046	68.002978
Heavy Trucks (HT) (3-axles)	35.879850	21.019665	74.298135

***Baseline REMELs =** *Reference Energy Mean Emission Levels for the following conditions:*

- **Average Pavement -** *Average for all pavements in the study, including Concrete (PCC), Dense-graded Asphalt (DGAC), and Open-graded Asphalt (OGAC)*
- **Level Roadways** - *Grades of 1.5 % or less*
- **Constant-Flow Traffic**
- **A-weighted, Total Noise Level at 15 m (50 feet)**

Figure N-5520.1 - Comparison Of A-Weighted Baseline FHWA TNM Vs Calveno REMELs



The exact TNM REMEL and Calveno REMEL values at 55 mph (88.5 km/h) are shown in Table N-5521.2:

Table N-5521.2 – Comparison of A-Weighted TNM and Calveno REMELs at 55 mph (88.5 km/h)

	Auto	**Medium Truck**	**Heavy Truck**
Calveno REMEL	72.8 dBA	79.9 dBA	83.8 dBA
TNM REMEL	73.8 dBA	79.9 dBA	84.0 dBA

N-5522 Noise Level Computations

TNM calculations of noise levels include:

- Three noise descriptors: Leq(h), Ldn, and CNEL (see Section N-2222).
- Capability of inserting traffic control devices. Such devices include traffic signals, stop signs, tollbooths, and on-ramp start points. TNM calculates vehicle speeds and emission levels, and noise levels accordingly.

- Computations performed in 1/3 octave bands for greater accuracy (not visible to users).
- Noise contours if specified.

Roadways and roadway segments define noise source locations (x-y-z-coordinates). Hourly traffic volumes determine the noise characteristics of the source.

N-5523 Propagation, Shielding, and Ground Effects

TNM incorporates state-of-the art sound propagation and shielding (e.g. noise barriers) algorithms, which are based on recent research of sound propagation over different ground types, atmospheric absorption, and shielding effects of noise barriers (including earth berms), ground, buildings and trees. However, TNM does not include the effects of atmospheric refraction, such as varying wind speed and direction or temperature gradients. TNM propagation algorithms assume neutral atmospheric conditions (zero wind speed, isothermal atmosphere).

The propagation algorithms can use the following user input information:

- Terrain lines (x-y-z coordinates) define ground location. Height above the ground is important in noise propagation.
- Ground zones (x-y-z coordinates) define perimeters of selected ground types. The latter may be selected from either a ground types menu (e.g., lawn, field grass, pavement, etc.), specified default, or user input flow resistivity (if known).
- Berms may be defined with user-selectable heights, top widths, and side slopes; they are computed as if they are terrain lines.
- Rows of buildings (x-y-z coordinates) with percentage of area shielded relative to the roadway(s) may be input to calculate additional attenuation.
- Tree zones (x-y-z coordinates) may be included for additional attenuation calculations if appropriate.

The propagation algorithms also include double diffraction. The net effect from the most effective pair of barriers, berms, or ground points that intercept the source-receiver line of sight is computed.

N-5524 Parallel Barrier Analysis

TNM includes a multiple reflection module that computes a degradation of the performance of one reflective barrier in the presence of another reflective barrier on the opposite side of the roadway. Unlike other TNM acoustics, which are computed in three dimensions, the multiple reflection module computes the results from a two dimensional cross-section. The results of this module are used to modify the TNM noise levels.

N-5600 COMPARING RESULTS WITH APPROPRIATE CRITERIA

After the predicted noise levels (including model calibration, if appropriate) have been determined they should be compared with the appropriate impact criteria in the Traffic

Noise Analysis Protocol, Section 2.4. Examination of traffic noise impacts includes comparing for each project alternative the following:

a) Predicted noise levels with existing noise levels (Section 2.4.1)
b) Predicted noise levels with the appropriate Noise Abatement Criterion (Section 2.4.2)
c) Predicted noise level of classroom interior with 52 dBA L_{eq}(h) (Section 2.5)

N-5700 EVALUATING NOISE ABATEMENT OPTIONS

If traffic noise impacts have been identified, noise abatement must be considered as discussed in the Traffic Noise Analysis Protocol, Sections 2.7 (Noise Abatement Feasibility) and 2.8 (Noise Abatement Reasonableness). Noise abatement measures may include, but are not necessarily limited to the measures listed in Traffic Noise Analysis Protocol Section 5.3. These potential measures are based on avoiding impacts, interrupting the noise paths, or protecting selected receivers. If the project alternative locations are flexible, alignments and profiles can be selected to avoid sensitive receivers or lessen the noise impacts. Most often highway alignments and profiles are selected on the basis of other overriding factors. The construction of noise barriers is then usually the most common noise abatement option available.

The consideration of noise abatement described in the Traffic Noise Analysis Protocol Sections 2.7 and 2.8 requires at a minimum a preliminary design of the abatement. The following Section N-6000 gives guidance on the design considerations of noise barriers.

N-6000 DETAILED ANALYSIS - NOISE BARRIERS DESIGN CONSIDERATIONS

The primary function of highway noise barriers is to shield receivers from excessive noise generated by highway traffic. While there are other ways to attenuate transportation-related noise, noise barriers are the most reasonable noise attenuation option available to Caltrans.

Many factors need to be considered in the proper design of noise barriers. First of all, barriers must be acoustically adequate. They must reduce the noise as described by policies or standards. Acoustical design considerations include barrier material, barrier locations, dimensions, shapes, and background noise levels. Acoustical considerations, however, are not the only factors leading to proper design of noise barriers.

A second set of design considerations, collectively labeled as non-acoustical design considerations, are equally important. As is often the case, the solution of one problem (in this case noise), may cause other problems such as unsafe conditions, visual blight and lack of maintenance access due to improper barrier design. With proper attention to structural integrity, safety, aesthetics, and other non-acoustical factors, these potential negative effects of noise barriers can be reduced, avoided, or even reversed.

Caltrans Highway Design Manual, Chapter 1100, "Highway Traffic Noise Abatement" should be consulted for specific noise barrier design criteria. As these may change in the future, the discussion in this section of this manual will focus on general applications and consequences of the design criteria, rather than on the criteria themselves.

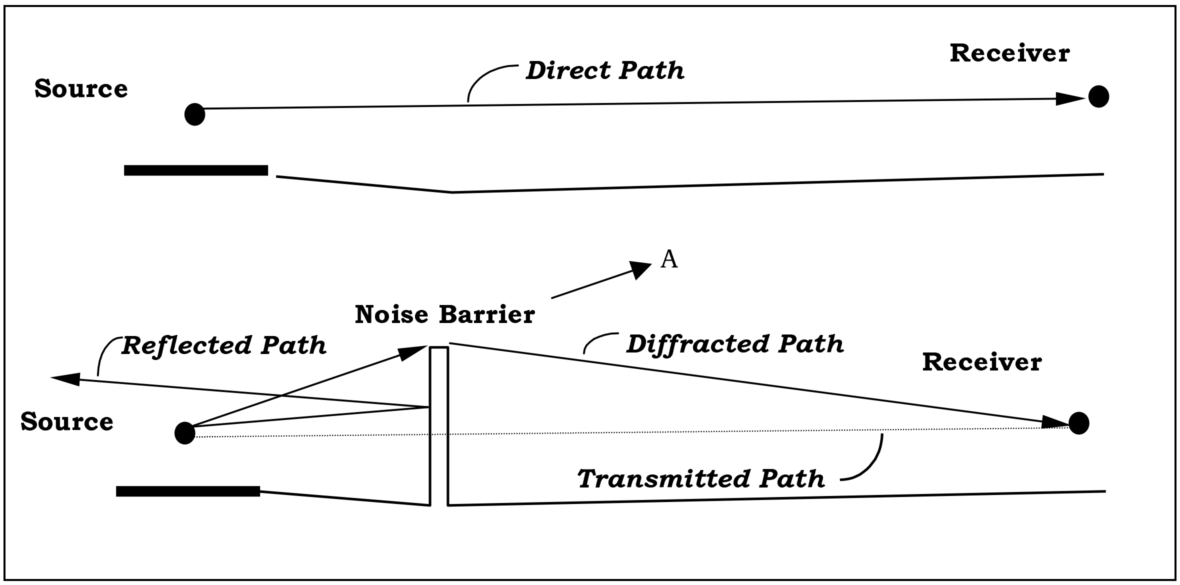
N-6100 ACOUSTICAL DESIGN CONSIDERATIONS

The FHWA models described in Section N-4000 are used for determining proper heights and lengths of noise barriers. The models assume that the noise barriers do not transmit any sound through the barrier. Only the noise diffracted by the barrier, as well as any unshielded segments are considered. The material of the barrier must therefore be sufficiently dense or thick to insure that the sound transmission through the barrier will not contribute to the total noise level calculated by the model at the receiver.

The material, location, dimensions, and shape of a noise barrier all affect its acoustical performance. In order to gain a better understanding of the interaction of these acoustical factors, it is essential to review the concepts of shielding of noise barriers in sections N-2144 and N-5515.1, as well as to introduce some new concepts.

Figure N-6100.1 is a simplified sketch showing what happens to vehicle noise when a noise barrier (sound wall) is placed between the source (vehicle) and receiver. The original straight line path from the source to the receiver is now interrupted by the barrier. Depending on the barrier material and surface treatment, a portion of the original noise energy is reflected or scattered back towards the source. Another portion is absorbed by the material of the barrier, while still another portion is transmitted through the barrier. Notice that the reflected (scattered) and absorbed noise paths never reach the receiver.

Figure N-6100.1 Alteration of Noise Paths by a Noise Barrier

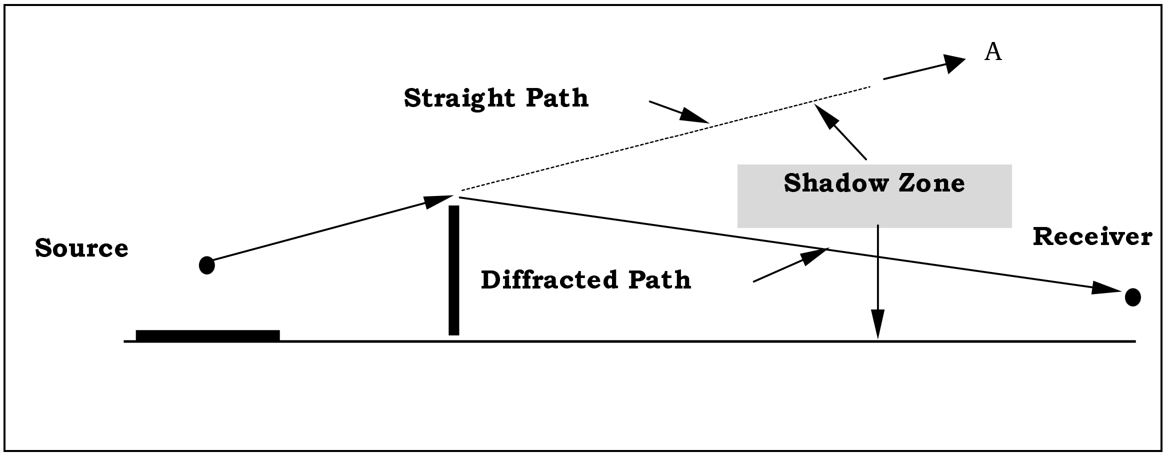


The transmitted noise, however, continues on to the receiver with a "loss" of acoustical energy (acoustical energy redirected and some converted into heat). The common logarithm of energy ratios of the noise in front of the barrier and behind the barrier, expressed in decibels, is called the transmission loss (TL). The TL of a barrier depends on the barrier material (mainly its weight), and the frequency spectrum of the noise source.

The transmitted noise is not the only noise from the source reaching the receiver. The straight line noise path from the source to the top of the barrier, originally destined in the direction of A without the barrier, now is diffracted downward towards the receiver (Figure N-6100.2). This process also results in a "loss" of acoustical energy.

The receiver is thus exposed to the transmitted and diffracted noise. Whereas the transmitted noise only depends on barrier material properties, the diffracted noise depends on the location, shape, and dimensions of the barrier. These factors will be discussed in the following sections.

Figure N-6100.2 Barrier Diffraction



N-6110 Barrier Material, Transmission Loss

For acoustical purposes, any material may be used for a barrier between a noise source and a noise receiver as long as it has a transmission loss (TL) of at least 10 dBA greater than the desired noise reduction. This insures that the only noise path to be considered in the acoustical design of a noise barrier is the diffracted noise path.

For example, if a noise barrier is designed to reduce the noise level at a receiver by 8 dBA, the TL of the barrier must be at least 18 dBA. The transmitted noise may then be ignored, because the diffracted noise is at least 10 dBA greater.

As a rule of thumb, any material weighing 4 lbs/sq ft or more has a transmission loss of at least 20 dBA. Such material would be adequate for a noise reduction of at least 10 dBA due to diffraction; this is the average noise reduction of Caltrans noise barriers. Note that a weight of 4 lbs/sq.ft can be attained by lighter and thicker, or heavier and thinner materials. The greater the density of the material, the thinner the material may be. TL also depends on the stiffness of the barrier material and frequency of the source.

Barrier theory used in the FHWA Model states that the maximum noise reduction that can be achieved is 20 dBA for thin screens (walls) and 23 dBA for berms. A material that has a TL of 33 dBA or greater would therefore always be adequate for a noise barrier in any situation.

Table N-6110.1 gives approximate TL values for some common materials, tested for typical A-weighted traffic frequency spectra. They may be used as a rough guide in acoustical design of noise barriers. For accurate values, consult material test reports by accredited laboratories. These usually accompany literature provided by the manufacturer of the materials.

Table N-6110.1 - Approximate Transmission Loss Values For Common Materials

Material	Thickness	Weight lbs/Sq. ft	Transmission Loss (dBA)
Concrete Block, 8"x8"x16" light weight	8"	31	34
Dense Concrete	4"	50	40
Light Concrete	6"	50	39
Light Concrete	4"	33	36
Steel, 18 ga	0.050"	2.00	25
Steel, 20 ga	0.0375"	1.50	22
Steel, 22 ga	0.0312"	1.25	20
Steel, 24 ga	0.025"	1.00	18
Aluminum, Sheet	1/16"	0.9	23
Aluminum, Sheet	1/8"	1.8	25
Aluminum, Sheet	1/4"	3.5	27
Wood, Fir	1/2"	1.7	18
Wood, Fir	1"	3.3	21
Wood, Fir	2"	6.7	24
Plywood	1/2"	1.7	20
Plywood	1"	3.3	23
Glass, Safety	1/8"	1.6	22
Plexiglass	1/4"	1.5	22

Table N-6110.1 assumes no openings or gaps in the barrier material. Some materials, such as wood, however, are prone to develop openings or gaps due to shrinkage, warping, splitting, or weathering. These openings decrease the TL values. The TL of a barrier material with openings can be calculated if the ratio of area of openings to total barrier area and the TL of the material is known. The following formula can be used to calculate the transmission loss with the openings (TLo):

$$TLo = TL - 10Log_{10}(Ao \times 10^{TL/10} + Ac)$$

where:

TLo= transmission loss of material with openings.

TL = transmission loss of material without openings.

Ao = area of openings as a fraction of the total area of the barrier.

Ac = area of closed portion as a fraction of the total area of the barrier = 1 - Ao

The above method of calculation assumes that the openings or gaps are equally distributed over the surface of a barrier.

For example, a barrier made of 2" thick fir planks has openings that make up about 5% of the total area, and are more or less equally distributed. What is the transmission loss of the material with these gaps?

From Table N-6110.1 it is found that the TL for 2" fir is 24 dBA. The Ao is 5%, or 0.05; Ac is 1-0.05 = 0.95.

$$TLo = 24 - 10Log_{10}(0.05 \times 10^{2.4} + 0.95) = 12.7, \text{ or about } 13 \text{ dBA}$$

The reduced TL could have an effect on the barrier's performance. For example, assume that the before barrier noise level was 75 dBA and the intention was to reduce noise levels by 10 dBA (i.e., the diffracted noise was to be 65 dBA and the transmitted noise 75 - 24 = 51 dBA). The total noise level would have been 65 dBA + 51 dBA = 65 dBA. With the gaps, however, the transmitted noise is now 75 - 13 = 62 dBA, and the total noise level is 65 dBA + 62 dBA = 66.8 dBA. The effectiveness of the barrier is reduced by almost 2 dBA. Instead of a designed noise reduction of 10 dBA, an actual noise reduction of only 8 dBA will be realized in this case.

Properly treated materials will reduce or eliminate noise leakage. For example, lumber should be treated with preservatives that provide proper penetration and do not interfere with any protective coatings (such as paint) to be applied later. The wood should also have a low moisture content, requiring kiln drying after waterborne preservatives have been used. Wood planks should have tongue and grooves deep enough to allow for shrinkage without gaps to maintain a high TL. Such tongue and grooving is usually non-standard.

There are several other ratings used to express the ability of materials in specific construction configurations to resist sound transmission. Two of these are worth mentioning. They are the Sound Transmission Class (STC), and the Exterior Wall Noise Rating (EWNR). Both are most often used in conjunction with indoor acoustics.

STC is universally accepted by architects and engineers. The STC rating uses a standard contour against which the TL values in one-third octave bands are compared in the frequency range between 125 Hz and 4000 Hz. The standard contour is moved up or down relative to the test curve until the sum of the differences between them is 32 dB or less, and the maximum difference at each 1/3 octave center frequency is no greater than 8 dB. The STC is then the TL value of the standard contour at the 500 Hz center frequency.

The disadvantage of the STC rating scheme is that it is designed to rate noise reductions in frequencies of normal office and speech noises, and not for the lower frequencies of highway traffic noise. The STC, however, can still be used as a rough guide, but it should be pointed out that for frequencies of average traffic conditions, the STC is 5 to 10 dBA greater than the TL. For example, material with an STC rating of 35 has a TL of about 25 - 30 dBA for traffic noise.

The EWNR rating scheme is different from the STC, in that it uses a standard contour developed from transportation noise frequencies. It therefore agrees closely with the A-weighted TL for traffic noise.

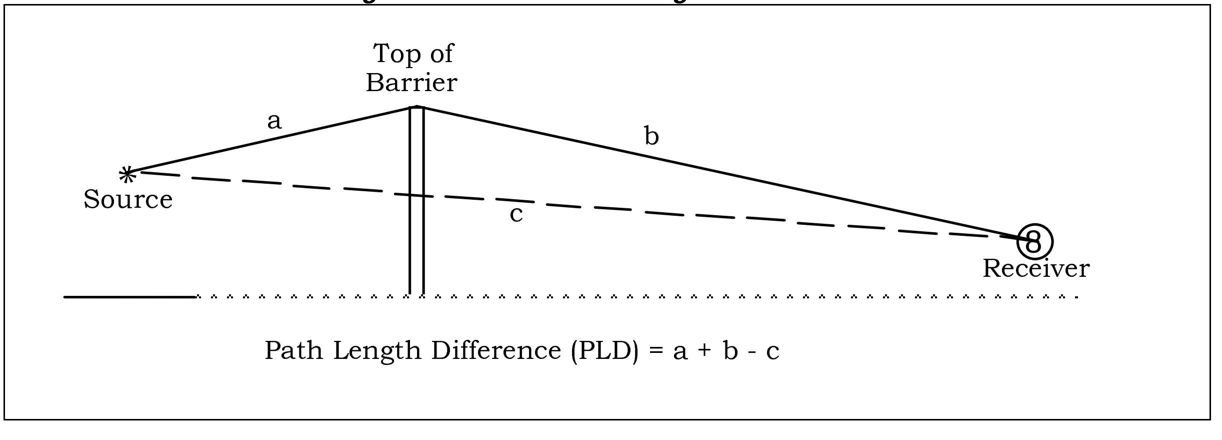
The Federal Highway Administration report, *Insulation of Buildings Against Highway Noise*, FHWA-TS-77-202 provides further useful information for calculating outdoor to indoor traffic noise reductions.

N-6120 Barrier Location

The previous section indicated that by selecting materials with sufficient TL, noise transmitted through a barrier may be ignored since its contribution to the total noise level is negligible (less than 0.5 dBA).

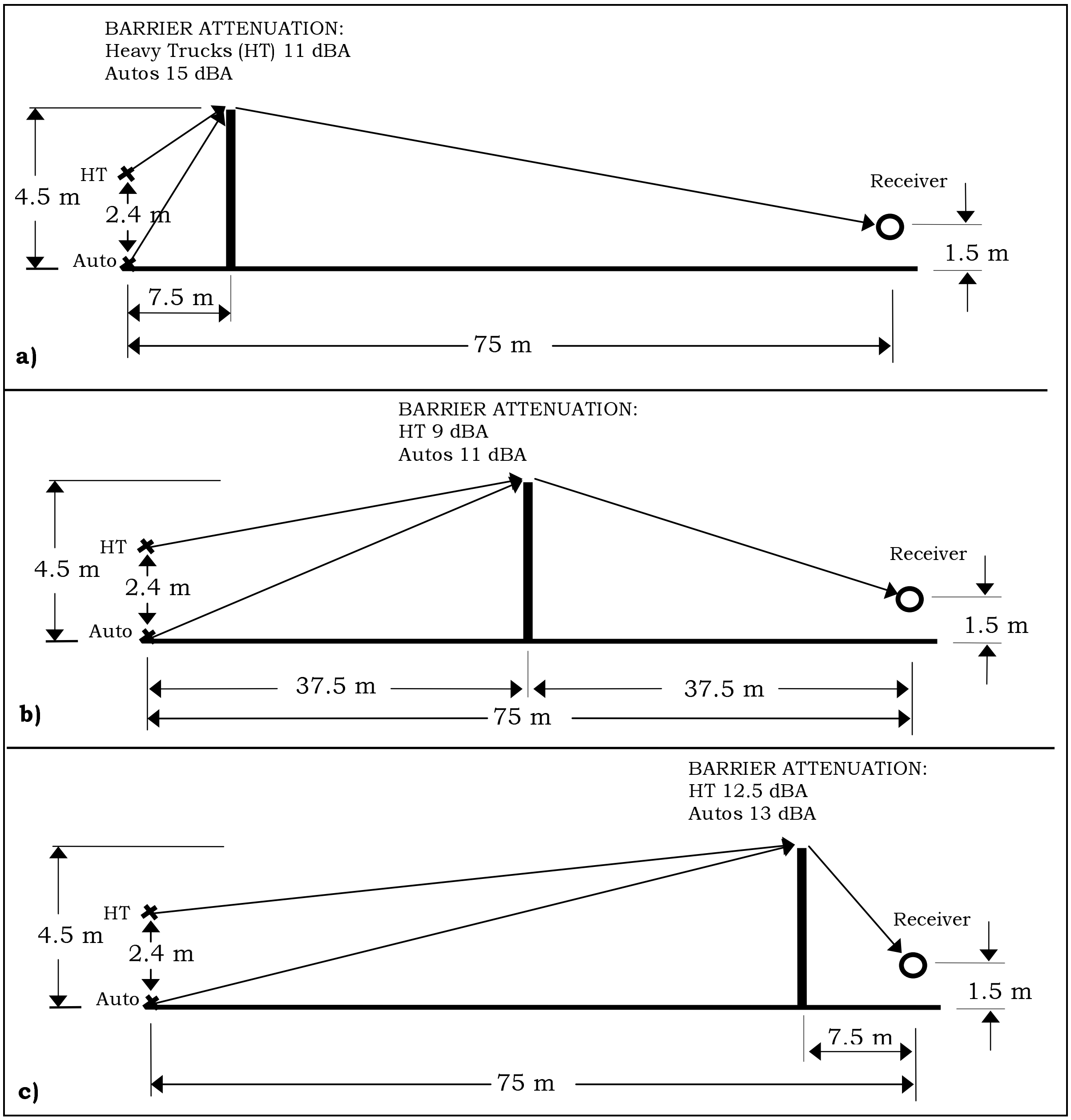
The only remaining noise of concern then, is the diffracted noise. Sections N-2144 and N-5515.1 discussed the basics of diffraction and barrier attenuation. The principal factor determining barrier attenuation is the Fresnel Number, which is related to the path length difference (PLD) between the original, straight line path between source and receiver, and the diffracted path, described by source-top of barrier-receiver. The greater this difference, the greater the barrier attenuation (up to a limit of 20 dB for walls, and 23 dB for berms). Figure N-6120.1 shows the PLD concept.

Figure N-6120.1 - Path Length Difference



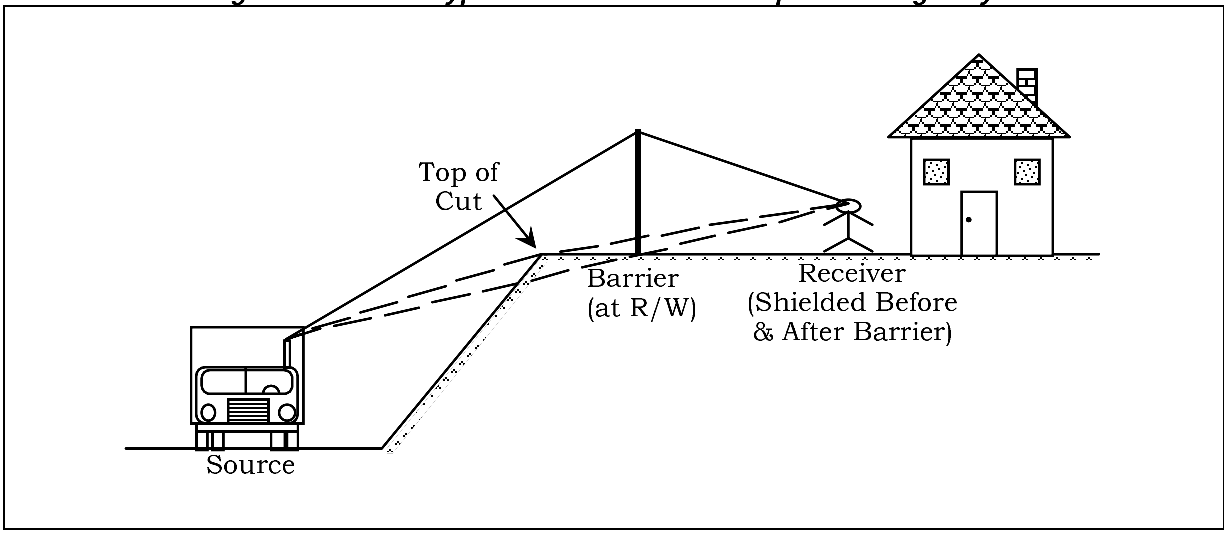
In level, at-grade roadway-receiver cross sections, a noise barrier of a given height provides greater barrier attenuation when it is placed either close to the source, or close to the receiver. The least effective location would be about halfway in between the source and receiver. Figure N-6120.2a), b), and c) shows these situations for two source heights (autos and heavy trucks). Location b) gives the lowest barrier attenuations for a given barrier height.

Figure N-6120.2 - Barrier Attenuation as a Function of Location (at-grade highway). Barrier attenuation is least when barrier is located half way between source and receiver (b). Best locations are near the source (a), or receiver (c).



In depressed highway sections, the barrier is obviously most effective near the receiver on top of the cut (Figure N-6120.3). Note that the without barrier path is generally not a straight path between source and receiver. The top of cut is already a fairly effective noise barrier. The PLD in this case is the difference between the paths described by source-top of barrier- receiver, and source-top of cut-receiver. The barrier attenuation is then calculated from the difference in barrier attenuation provided by the top of cut and the top of the noise barrier.

Figure N-6120.3 - Typical Barrier Location Depressed Highways



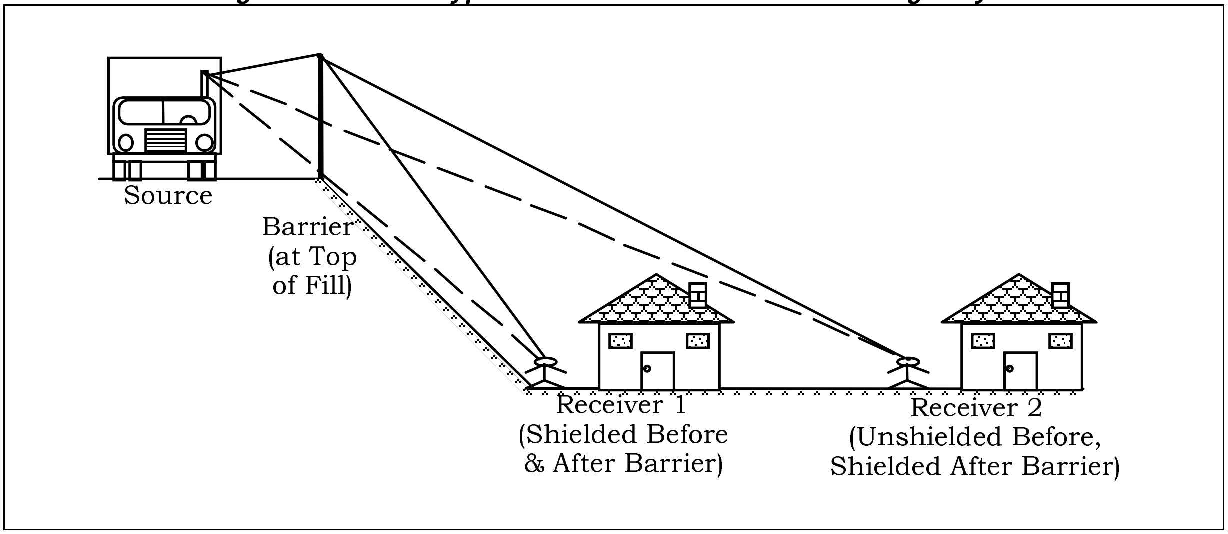
Since the attenuation per incremental increase in barrier height diminishes with the effective height of a barrier (see Sec. N-6130), this difference may be small; noise barriers in depressed highway sections are generally not very effective in reducing noise. This is mostly because the cut section by itself may already be an effective barrier (earth berm).

The most effective location of noise barriers along highways on fills is on top of the embankment, as shown in Figure N-6120.4. Any attempt to place the barrier closer to the receivers will result in a higher barrier for the same or less attenuation. The same holds true for elevated highways on structures. The most effective barrier location from an acoustical standpoint is on top of the structure.

The foregoing discussions point out that the most acoustically effective location for a noise barrier depends on the source to receiver geometry. In most cases, the choices are fairly obvious. To recap the simplest situations:

1. Highway at-grade: barrier location near the edge of shoulder, or at the right-of-way (R/W).
2. Highway in depressed section: barrier at the R/W.
3. Elevated highway on embankment or structure: barrier near edge of shoulder.

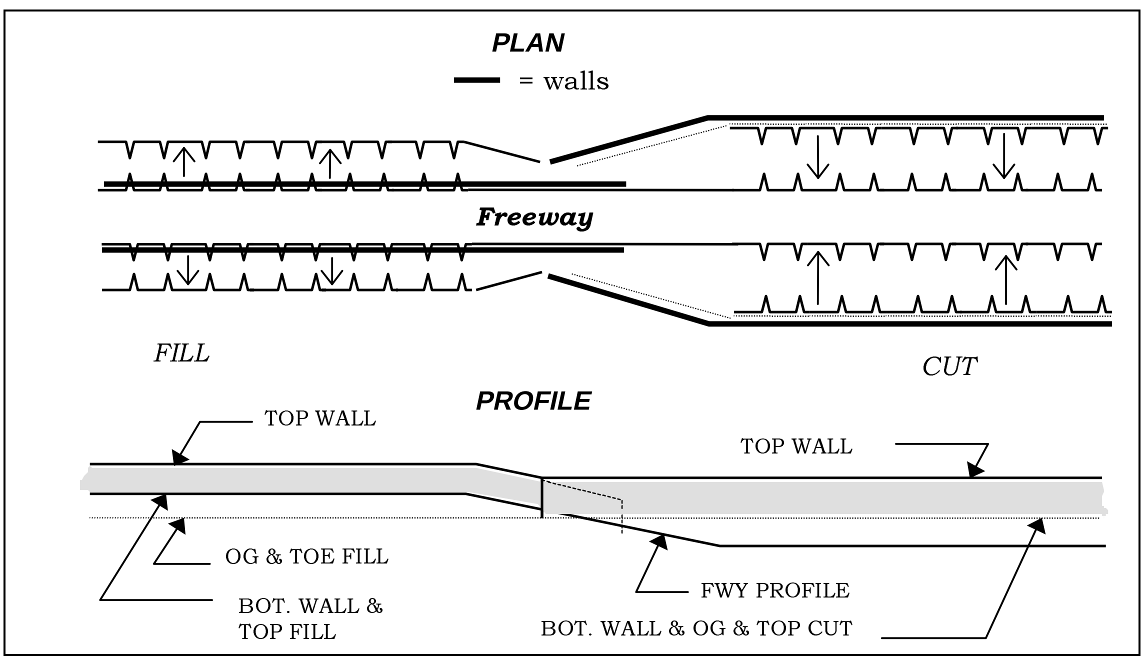
Figure N-6120.4 - Typical Barrier Location - Elevated Highways



In some cases, however, the choices are not so simple. In more complex highway/receiver geometries, the best locations from an acoustical standpoint may not be obvious. They may have to be determined by using the FHWA Highway Traffic Noise Prediction Model, for several barrier location alternatives.

Transitions between cuts and fills, ramps, and interchanges are some examples of cases needing careful consideration. Figures N-6120.5 through N-6120.7 show typical noise barrier locations in some of these transitional areas. Barrier overlaps are often necessary in these cases, as shown in Figures N-6120.5, and N-6120.6.

Figure N-6120.5 Barriers for Cut and Fill Transitions



One of the more common reasons for barrier overlaps are to provide maintenance access to those areas within the R/W that are on the receiver side of noise barriers (Figure N-6120.5). This will be discussed in greater detail in the maintenance consideration portion of this section.

Figure N-6120.6 - Barriers for Highway on Fill With Off-Ramp

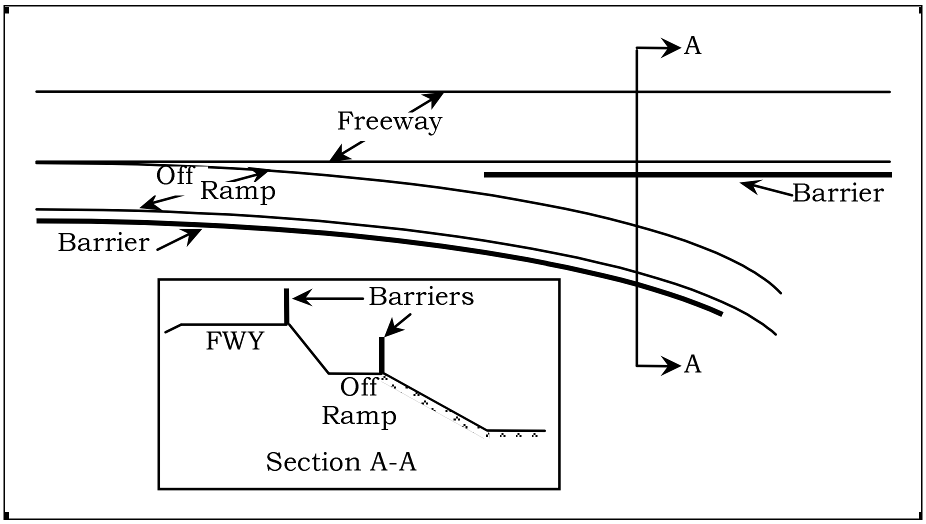
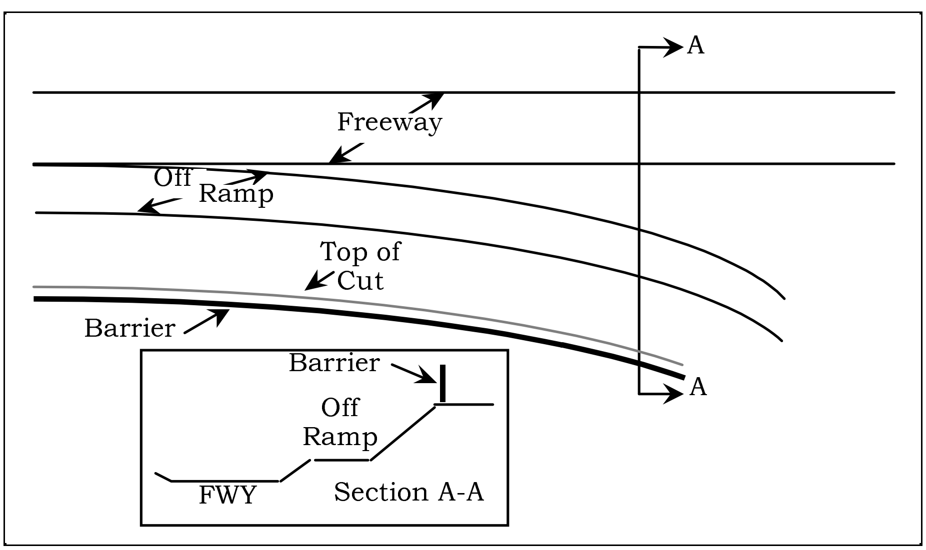


Figure 6120.7   Barriers for Highway in Cut with Off-Ramp



Restrictions on lateral clearances, sight distances and other safety considerations may also dictate final noise barrier locations. The Caltrans Highway <u>Design Manual</u> should always be consulted before finalizing alternate noise barrier alignments.

N-6130 Barrier Dimensions (Height and Length)

Noise barrier dimensions depend largely on freeway geometry, topography of the surrounding terrain, the location of the noise barrier, and the size of the area to be shielded by the barrier. According to sections N-2144 and N-5515, barrier attenuation depends on the path length difference between the direct (before barrier) and diffracted (after barrier) noise paths. Figure N-6120.1 reviewed the concept. Regardless of its orientation, the triangle formed by the source, top of noise barrier and the receiver, will always yield the same barrier attenuation. Since the location of the bottom of the barrier is not part of the triangle, the highway geometry and terrain topography determine how high the barrier should be for a given barrier attenuation. Figure N-6130.1 shows this concept.

Similarly, the length of the barrier is governed by the extent of the area to be shielded and also the site geometry/topography as shown in Figure N-6130.2.

Figure N-6130.1 - Actual Noise Barrier Height Depends on Site Geometry and Terrain Topography (same barrier attenuation for a), b), c), and d)).

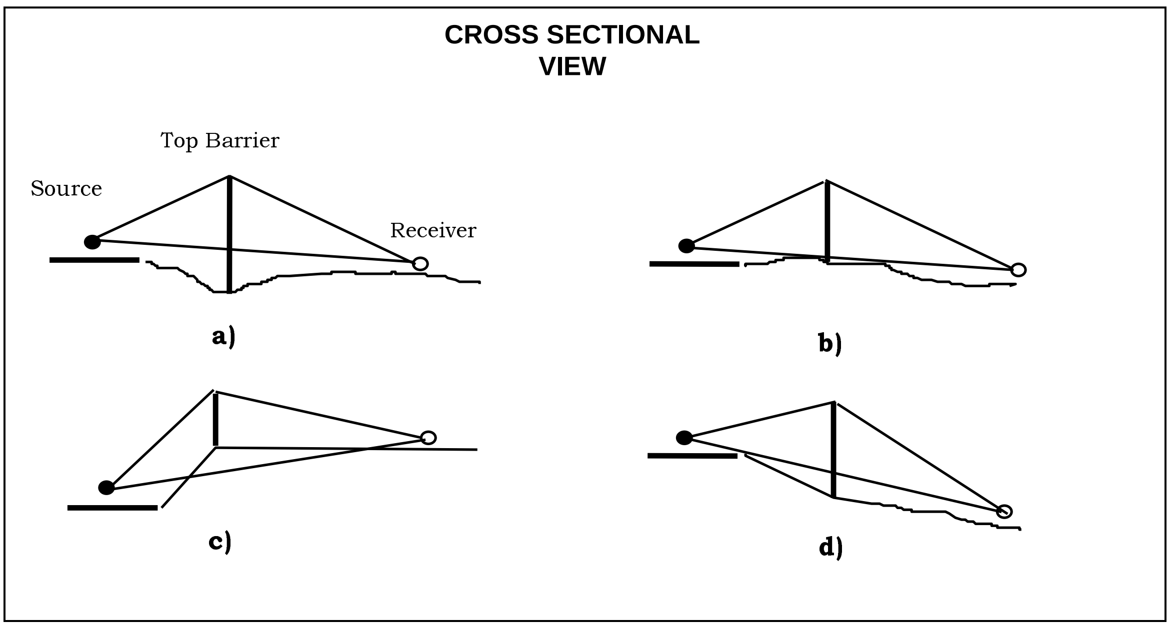
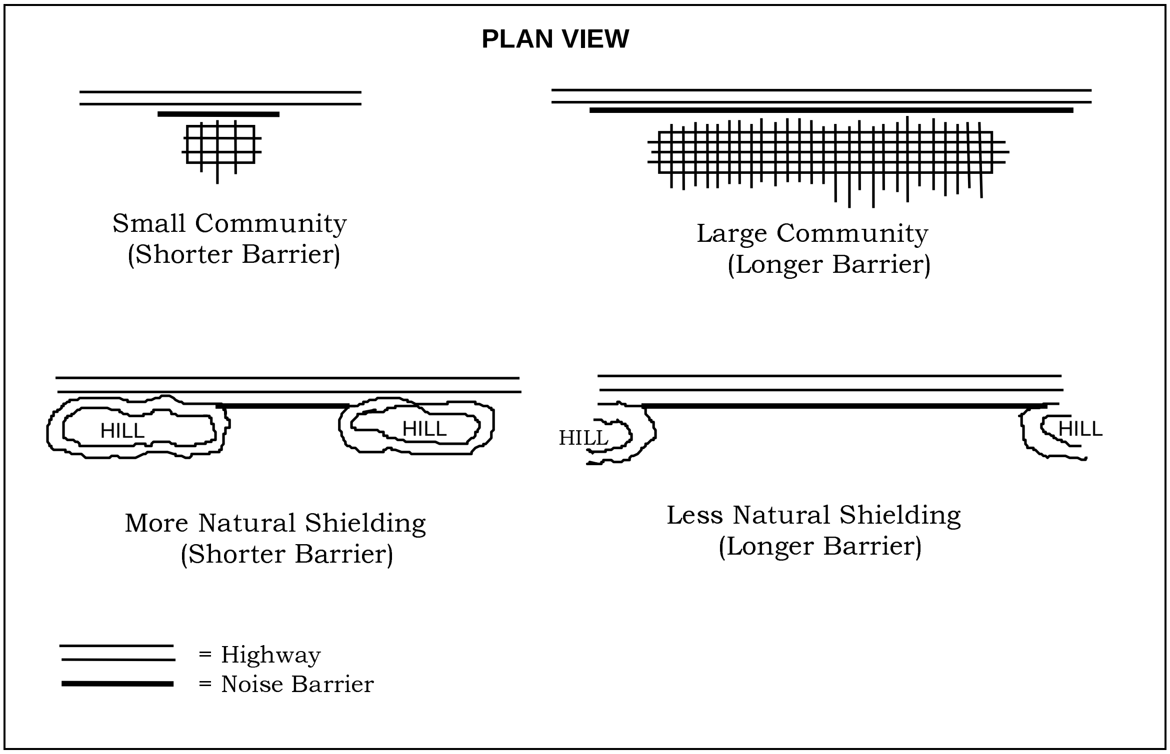


Figure N-6130.2 - Noise Barrier Length Depends on Size of the Area to be Shielded and Site Geometry/Topography

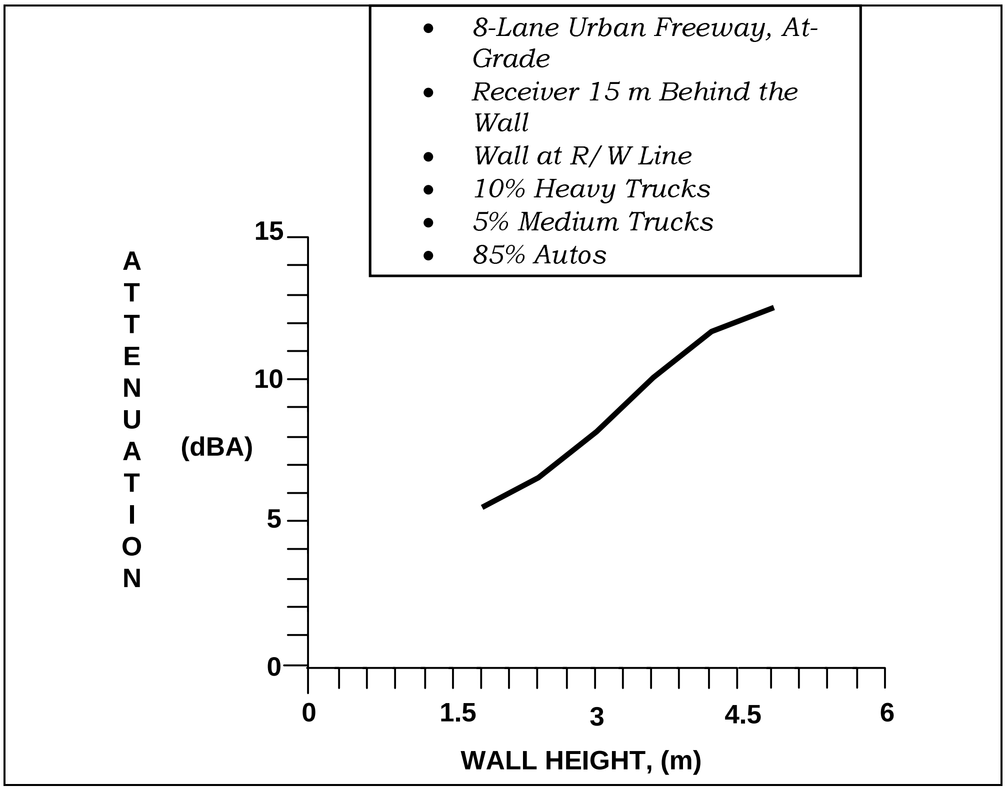


N-6131 Noise Barrier Height

Barrier height generally has the greatest direct influence on the the effectiveness of a noise barrier. Figure N-6120.1 reviewed the PLD concept. An increase in height of a noise barrier will result in a greater PLD and therefore a greater noise attenuation. This increase in height is not linear, however.

Figure N-6131.1 shows the barrier attenuation as a function of wall height at a 1.5 m (5 ft) high receiver, 15 m (50 ft) behind a sound wall located along the R/W of a typical urban at-grade 8-lane freeway. The traffic consists of 10% heavy trucks, 5% medium trucks, and 85% autos. Attenuations are plotted for wall heights from 2 to 5m (6 to 16 ft), representing minimum and maximum heights allowed by Chapter 1100 of the Caltrans Highway Design Manual. Also shown is the height at which the line-of-sight between a 3.5 m (11.5 ft) truck stack and a 1.5 m (5-ft) high receiver is intercepted by the wall. For this particular highway/barrier/receiver geometry this height is 2.75 m (9 ft).

Figure N-6131.1 Sound Wall Attenuation Vs. Height - At-Grade Freeway



Note that in this case, the change in attenuation per incremental change in wall height is highest between wall heights of 2.7 and 3.4 m (9 - 11 ft), at 0.9 dBA per 0.3 m (1 ft). Above and below this range the values are lower. Once the optimum height has been reached, any further increases in noise barrier height result in diminishing returns in effectiveness. However, higher barriers are often necessary to meet design goals.

Noise barriers along depressed freeways are less effective than those along at-grade freeways. In deep cuts, the receiver often is already effectively shielded by tops of cuts. In some cases this shielding may not reduce noise levels enough to satisfy noise abatement criteria, and an additional barrier behind the top of cut may be necessary to achieve further noise reductions.

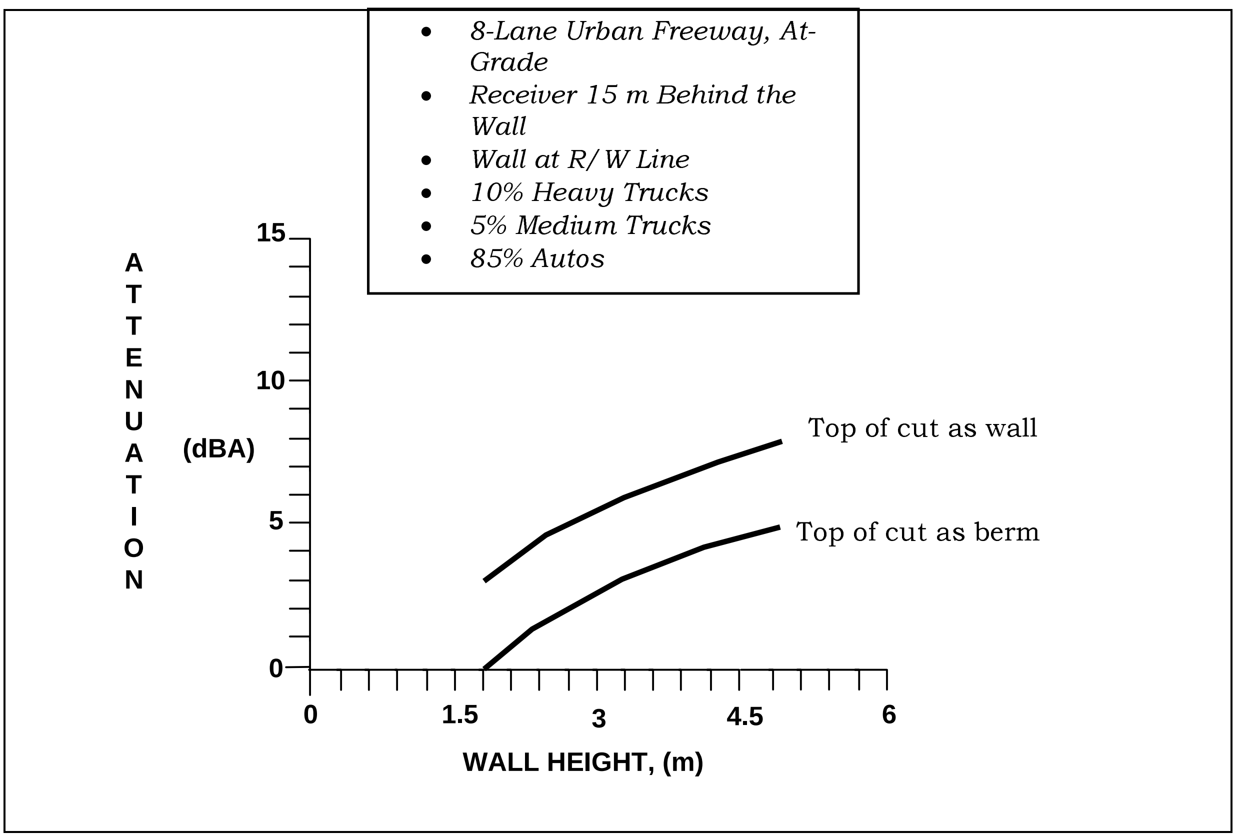
When designing such a barrier, the designer should recognize that the without barrier or *before* condition includes the shielding of the existing top of cut. Because of the before-mentioned diminishing returns effect, a barrier of a given height along a depressed freeway will generally be less effective than a barrier of the same height at-grade. The diminishing return effect, however, is not the only thing to take into consideration.

It has been mentioned that a berm is more effective than a wall. Computer noise prediction models generally give berms 3 dBA more attenuation than a wall of the same height. A wall built at or near the top of cut essentially eliminates the 3 dBA extra attenuation afforded by the original top of cut, thereby further reducing the effectiveness of the wall.

Figure N-6131.2 shows the barrier attenuation vs. height plots for a receiver 15 m (50 ft) behind a barrier located on the R/W of a typical urban 8-lane freeway, in a 7.5 m (25 ft) deep depressed section. The traffic mix is the same as that for Figure N-6131.1, described above. Two attenuation curves are shown.

The upper curve represents attenuation differences between a wall (after construction condition), and the top of cut (before construction condition), in which the latter is treated as an existing wall. Such a condition would exist if a sound wall were built on top of an existing retaining wall: i.e., the top of cut would be the top of retaining wall.

Figure N-6131.2 - Sound Wall Attenuation vs Height, 7.5m (25 ft) Depressed Freeway



Both the before and after conditions would then involve a wall. Likewise, if the before and after conditions consist of berms (built at or near a top of cut), the upper curve would also be a correct representation.

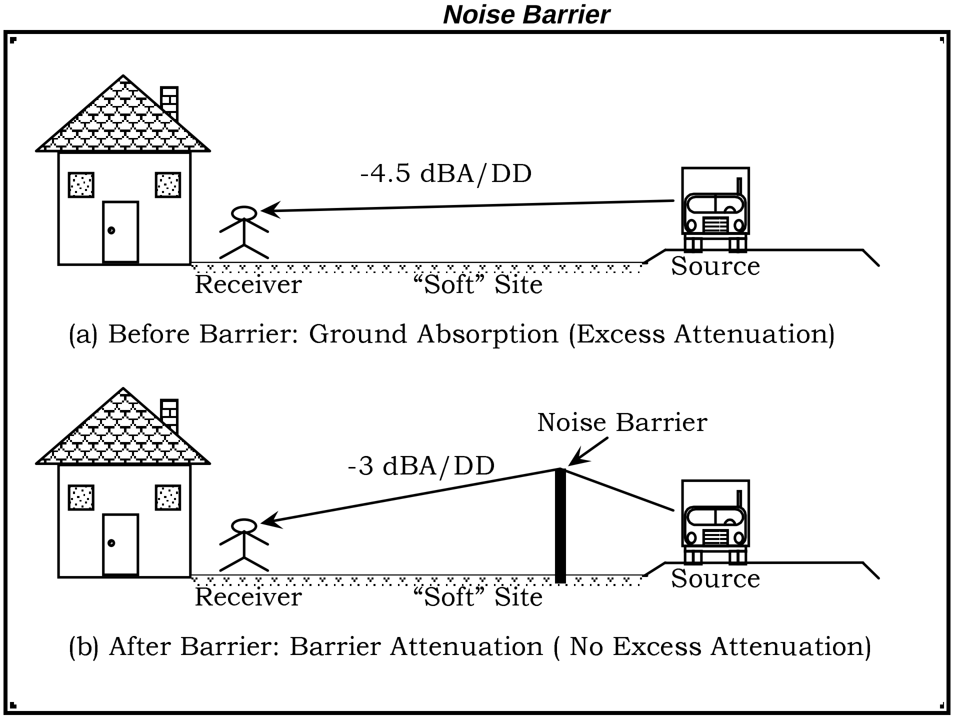
The lower curve consists of attenuation differences between a sound wall and the existing top of cut, with the latter treated as a berm. The additional 3 dBA attenuation provided by the before condition is eliminated by the wall, making it less effective.

A similar phenomenon may also be encountered when freeways are built on embankments. Receivers located near the toe of the fill may be fully or partially shielded from the traffic by the top of the fill or hinge point. For these receivers a wall built on top of the embankment may be less effective than for receivers located farther from the freeway.

The above discussions illustrate the importance of noise source, barrier, and receiver relationships in designing effective noise barriers. These geometries not only affect the barrier attenuation, but also noise propagation in many cases.

Sections N-2140 and N-5513 discussed hard site and soft site characteristics. The excess noise attenuation provided by a soft site is caused by the noise path's proximity to a noise absorbing ground surface. If a noise barrier is constructed between a source and a receiver, the diffracted noise path is lifted higher off the ground. This causes less noise absorption by the ground, and a lesser rate of noise attenuation with distance. Figure N-6131.3 illustrates this concept.

Figure N-6131.3 - Loss of "Soft" Site Characteristics Due to Constructing a Noise Barrier



In (a), the before barrier situation shows a noise attenuation rate of 4.5 dBA per doubling of distance (/DD), in (b), the after barrier attenuation is 3 dBA/DD. The lesser attenuation rate reduces the barrier's effectiveness.

The potential of a barrier to be less effective than indicated by barrier attenuation alone, gave rise to the term *insertion loss*. The insertion loss of a barrier is the net noise reduction provided by a barrier at a receiver. It includes barrier attenuation and before and after barrier differences in noise propagation characteristics: i.e., it is the actual noise reduction caused by inserting a noise barrier between source and receiver. A measured insertion loss is usually referred to as *field insertion loss*.

Finally, another very important height consideration in the acoustical design of noise barriers is a Caltrans requirement to break the line of sight (L.O.S.) between a 3.5 m (11.5 ft) high truck exhaust stack and a 1.5 m (5 ft) high receiver in the first tier of houses. This requirement, detailed in Chapter 1100 of the Highway Design Manual, was intended to lessen the visual and noise intrusiveness of truck exhaust stacks at the first line receiver(s). Barrier heights determined by the noise prediction model often satisfy the acoustical requirements without shielding high truck exhaust stacks. Even though such barriers may reduce noise levels sufficiently in terms of noise abatement criteria, they will still generate complaints from the public The L.O.S. break criterion frequently governs the height of a noise barrier.

The 3.5 m (11.5 ft) height used for truck stacks was determined to be the average height of truck stacks in a 1979 District 7 study, including 1000 heavy trucks measured at a truck inspection station along I-5. This means that the L.O.S. break will shield first line receivers from the exhaust stacks of about half of the the trucks on the highways.

The 3.5 m (11.5 ft) dimension is in no way related to the 2.44 m (8 ft) high noise centroid used for heavy trucks in the traffic noise prediction model, and should therefore not be used for noise predictions. The noise centroids indicated in FHWA-RD-77-108 are the resultant location of the noise sources coming from a truck, not just the noise from the exhaust outlet.

Determining the L.O.S. break is a separate process from predicting noise. Generally, it is desirable to calculate and plot the L.O.S. break profile along the barrier alignment before the acoustical design of the noise barrier. A Caltrans computer program named *LOS* is available for this purpose. If more than one barrier alignment is under consideration, the L.O.S. break must be calculated for each alignment alternative.

The L.O.S. break height depends on the three dimensional location of the 3.5 m (11.5 ft) truck stack, the three dimensional location of the receiver, and the three dimensional location of bottom of the barrier (interface between barrier and ground).

To calculate the L.O.S. break height for a certain source, barrier, and receiver combination the designer needs to determine the critical truck stack lane. This is the lane in which the

3.5 m (11.5 ft) truck stack creates the highest L.O.S. break. Figure N-6131.4 shows a quick method of determining which lane is critical. If the receiver is located above a base line drawn through far and near lane truck stacks, the far lane is critical. If the receiver is located below this line, the near lane is critical, and when the receiver is on the line, either lane is critical. Note that the line need not be horizontal or level.

Chapter 1100 of the Highway Design Manual does not give guidance on whether the entire barrier or just a portion of the barrier should break the L.O.S. for a certain receiver. On one extreme, a series of L.O.S. intercepts can be calculated from one receiver, covering the entire barrier; on the other extreme only one intercept can be calculated using a perpendicular line from the receiver to the barrier or highway. In absence of official policy, it is recommended that a distance of 2D left and right along the centerline of the critical lane, measured from a perpendicular line from the receiver to the lane, be used; where D is the distance from receiver to the lane. Also, it is recommended that the above be further constrained by a maximum distance from receiver to truck stack (Dt) of 500 feet. Figure N-6131.5 shows the recommended constraints.

Figure N-6131.4 - Determination of Critical Lane for L.O.S. Height

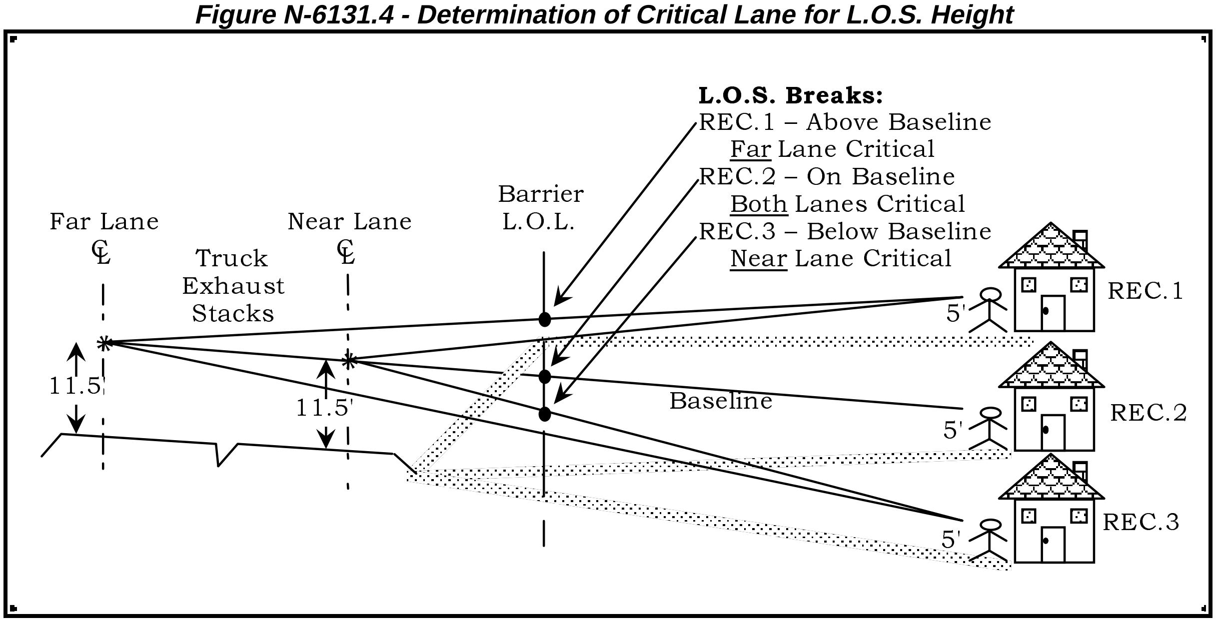
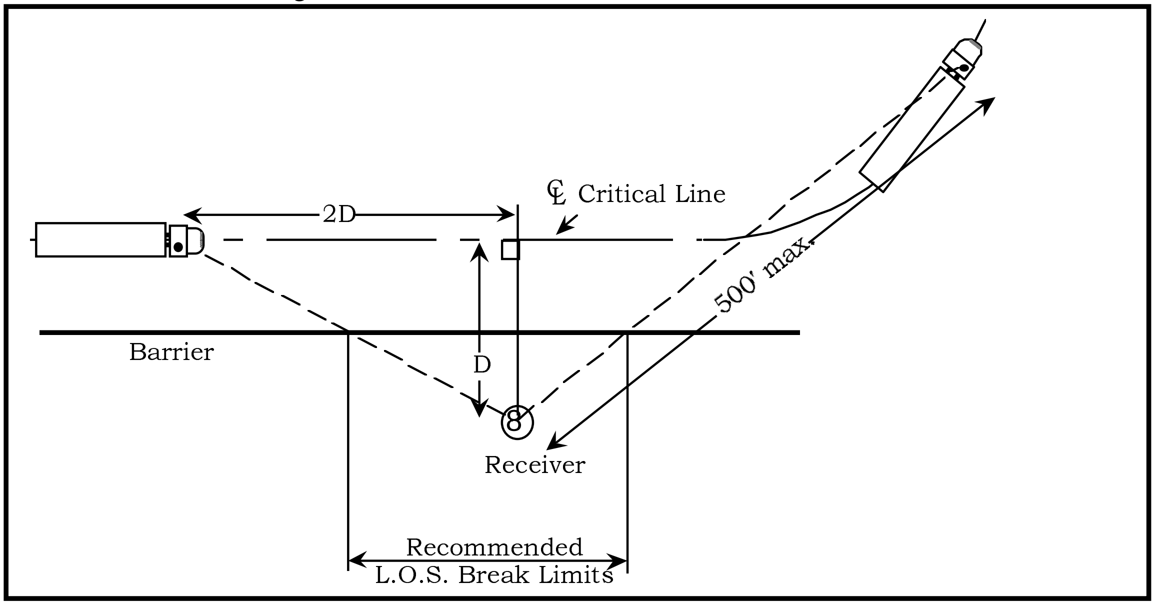


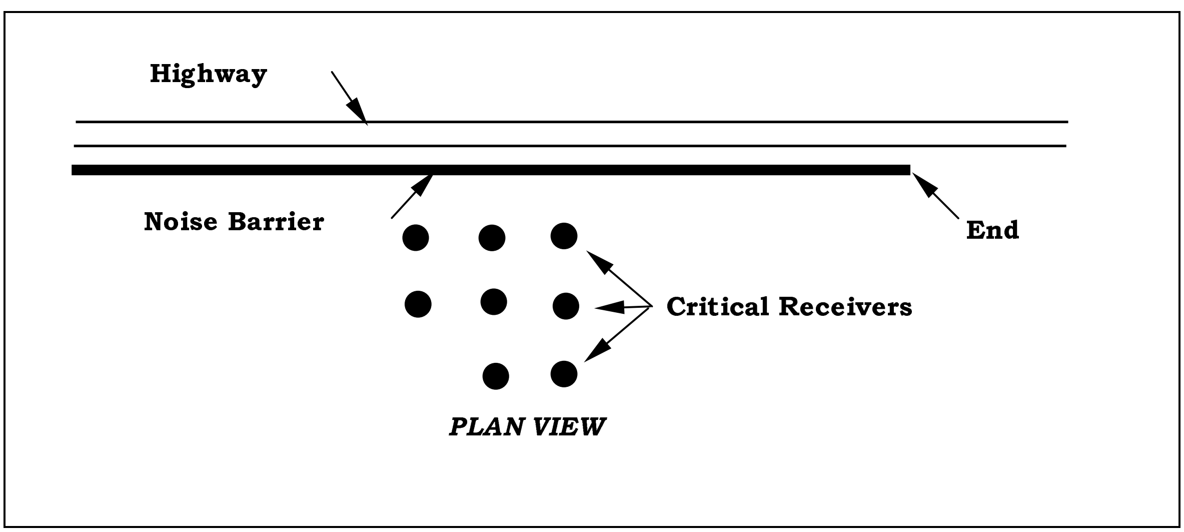
Figure N-6131.5 - Recommended L.O.S. Break Limits



N-6132 Noise Barrier Length

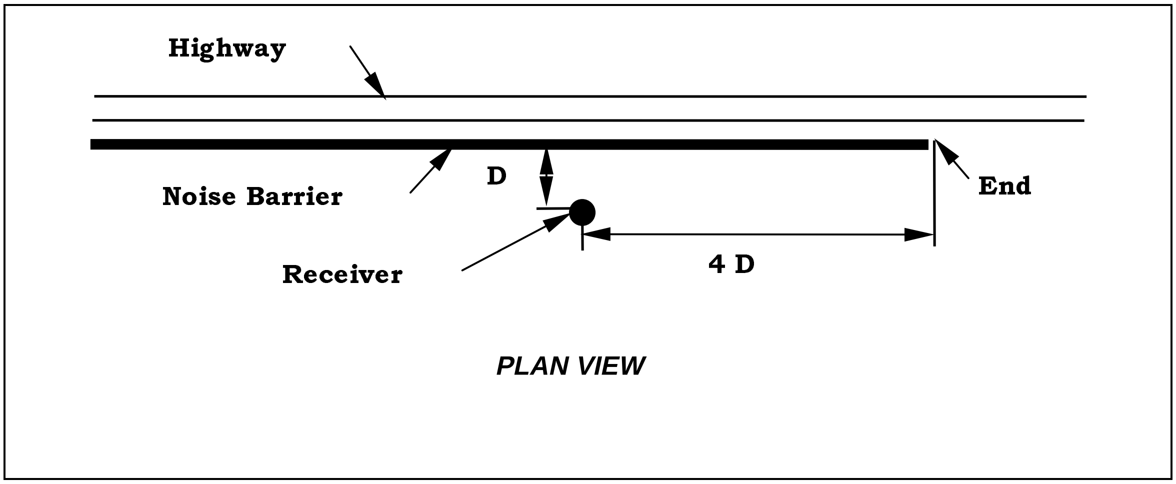
A noise barrier should be sufficiently long to protect the end receivers (See Figure N-6132.1). If the barrier is not long enough the exposed roadway segment will contribute a significant portion of noise energy and sharply reduce the effectiveness of the barrier. For example, if a barrier ends at the receiver, half of the roadway is exposed and the noise reduction by the barrier is 3 dBA or less.

Figure N-6132.1 - Barrier Extended Far Enough to Protect End Receivers



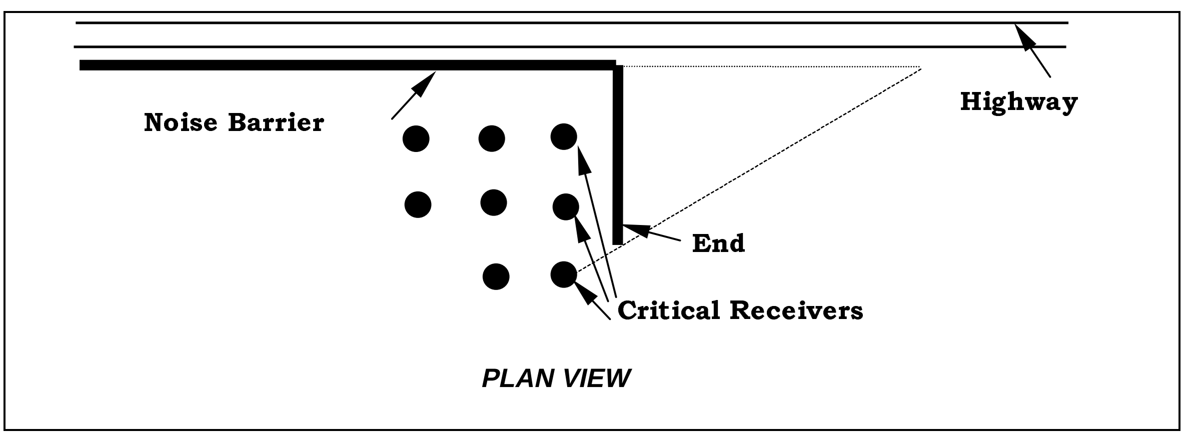
As a rule of thumb, a noise barrier should extend at least 4D beyond the last receiver, where "D" is the perpendicular distance from barrier to receiver (see Figure N-6132.2). The "4D rule", however, should be considered a starting point and the FHWA Model should be used to exactly locate the end of the barrier. Often the critical end receivers are not in the first row of homes, but perhaps several rows farther from the highway as is also shown In Figure N-6132.1. As the barrier to receiver distance increases, the highway noise becomes less, but the barrier segment angle also reduces, which makes a potential noise barrier less effective. The FHWA Model is needed to resolve these opposing factors.

Figure N-6132.2 - The "4D Rule"



Another way of dealing with end receivers is shown in Figure N-6132.3. The barrier is "hooked" around the critical receivers. The obvious advantage of this design is the shorter barrier length compared with the normal barrier extension. The disadvantage is the legal agreements between Caltrans and the private property owners, concerning the construction easements, barrier maintenance and responsibilities.

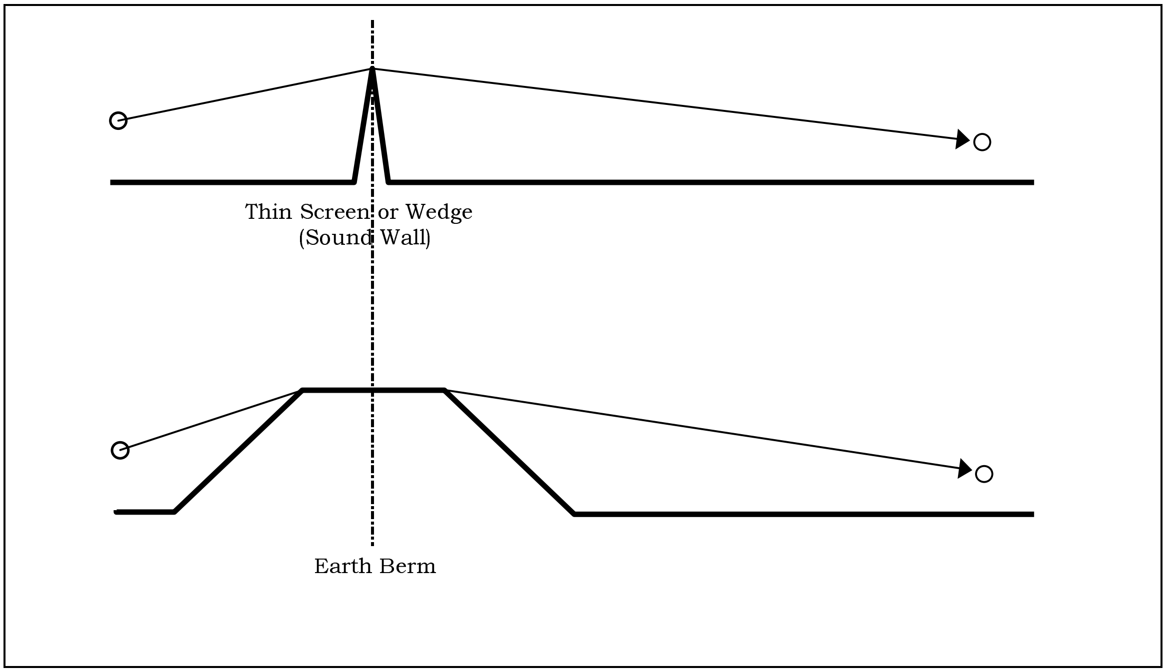
Figure N-6132.3 - Barrier Wrapped Around End Receivers, An Effective Alternative



N-6140 Barrier Shape

Section N-4510 indicated that FHWA Model distinguishes between two noise barrier shapes: the thin screen (wedge) shape, and the earth berm. Figure N-6140 shows representations of the two barrier shapes.

Figure N-6140.1 - Thin Screen Vs. Berm; a Berm Gives More Barrier Attenuation.

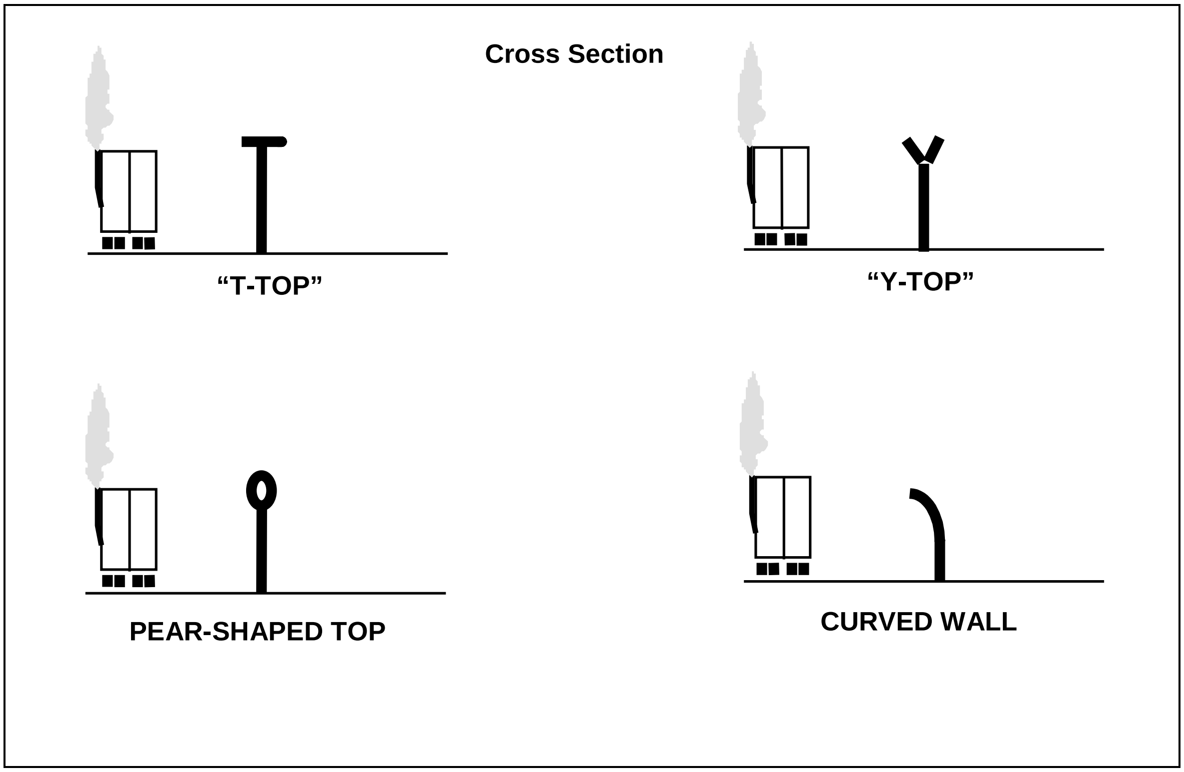


Given the same site cross section, distance between source and receiver, and barrier height, a berm allows a greater barrier attenuation than the thin screen (wedge), such as a sound wall. Although the FHWA assumes 3 dBA more attenuation for the berm than the thin screen, the actual extra attenuation may be somewhere between 1 and 3 dBA.

There are several probable causes for the extra 3 dBA attenuation for a berm. One reason is the shape of the berm. The flat top allows a double diffraction, resulting in a longer path length difference. Another cause may be that the noise path is closer to the ground (berm surface) than that for a thin screen, thus allowing more ground absorption by retaining soft site characteristics.

Other barrier shapes have been researched. These include “T-tops”, “Y-tops, pear shaped tops, curved walls, and others. Given the same total height of wall, these do little to improve barrier attenuation; usually only about 1 or 2 dBA maximum. (Figure N-6140.2 shows some different shapes. The extra cost of constructing these shapes usually does not warrant this small benefit.

Figure N-6140.2 - Various Wall Shapes; Minimal Benefit for the Extra Cost.

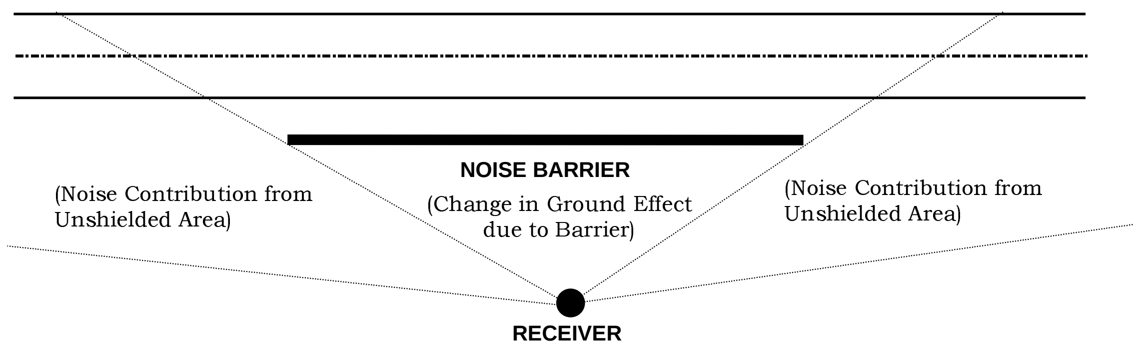


There is also a question of jeopardizing safety with any overhang, especially when the barrier is constructed near the edge of shoulder.

N-6150 Barrier Insertion Loss

In simple terms, barrier insertion loss is the difference in the noise levels before and after a barrier is constructed. It takes into account barrier attenuation, the contributions from unshielded roadway segments, changes in drop-off rates, and interaction with existing barriers (such as reflections, or additional shielding). For example, while the barrier attenuation in Figure N-4530.1 may be 10 dBA, when the change in ground effects and the contribution from the unshielded segments is accounted for the insertion loss is only, say 6 dBA. Section N-6000 "Acoustical Barrier Design Considerations discusses these factors in greater detail.

Figure 6150.1 - Barrier Insertion Loss Vs. Barrier Attenuation



***Barrier Attenuation* =** Noise attenuation due to Barrier (diffraction) only.
***Barrier Insertion Loss* =** Net effect of Barrier Attenuation, change in Ground Effect, and Noise Contribution from unshielded areas; i.e. *Before - After Barrier Noise Level.*

N-6160 Background Noise Levels

One important factor to be considered (and often overlooked) in noise barrier design is the background noise level within a community. A noise barrier cannot reduce noise levels below the noise level generated by local traffic on surface streets within a community. For instance, if the background level (without the highway) is 65 dBA (at the target receivers), and a proposed project will raise this level to 68 dBA at the same receivers, a noise barrier will not be able to lower the noise level down to below 65 dBA. Therefore, the community "background" noise level should always be added into the predicted noise levels and considered in the noise attenuation design process. Only if it is obvious that the background noise from local sources will not influence the noise barrier's insertion loss (i.e. is at least 10 dBA below the predicted noise level with the noise barrier), can the background noise be ignored.

The following two examples illustrates a method of including existing background noise levels. The first example involves a new facility in a residential area. The second involves a project along an existing facility.

Example 1. New Facility

Background noise level:	60 dBA at Receiver(s)
New facility (w/o background)	<u>68 dBA</u> at Receiver(s)
Total predicted:	69 dBA at Receiver(s)

From the above data we decide to design a noise barrier that will reduce the total noise level by 5 dBA. The model predicts noise levels without the background noise level. Yet, the latter should be accounted for in the total noise attenuation. Thus we must calculate what what predicted noise level is needed to reduce the total predicted noise level to 64 dBA.

Background noise level:	60 dBA at Receiver(s)
Predicted noise level:	?? dBA at Receiver(s)
Total desired noise level:	64 dBA at Receiver(s)

Predicted noise level = 64 dBA - 60 dBA = $10\text{Log}_{10}\,(10^{6.4}-10^{6.0})$= 61.8, say 62 dBA.

The calculated insertion loss should then be 69 - 62 = 7 dBA to reduce the total noise level by 5 dBA.

The next example, involving an existing facility, is more complicated, because the background noise levels at the receivers located near the existing highway are contaminated by noise originating from the highway, and therefore not known. Background noise levels can, however, be estimated from measurements taken throughout the community at sites far enough from the highway to not be influenced by it. (see section N-3221). Once this is accomplished, the problem is essentially the same as example 1.

Example 2. Existing Facility

Background noise level:	60 dBA at Receiver(s) (estimated)
Existing noise level:	65 dBA at Receiver(s) (measured)
Existing noise level:	64 dBA at Receiver(s) (calculated, using the model).
With project noise level	68 dBA at Receiver(s) (predicted, without background)

It is obvious that the existing noise level is contaminated by the background noise level, because the difference between the two is less than 10 dBA . Therefore, model calibration is not allowed, and the predicted with project noise level is used without adjustment, as explained in section N-5600 (Model Calibration, “Cautions and Pitfalls”). The problem is then solved as shown in example 1.

N-6200 NON-ACOUSTICAL CONSIDERATIONS

Final selections of materials, locations, heights, lengths, and shapes of noise barriers include non-acoustical considerations such as safety, aesthetics, and maintenance.

N-6210 Safety

Safety considerations include lateral clearances, sight distance requirements, and guard rail or safety shape barrier requirements. These safety considerations are covered in Chapter 1100 of the Highway Design Manual.

The Office of Structure Design has developed standard sheets for noise barriers (sound walls). These have been distributed to the Districts. The standard designs include the following materials:

- Masonry block.
- Precast concrete panel (with post or mounted on safety shaped barrier).
- Wood (post and plank or framed plywood)
- Metal (ribbed steel).
- Composite beam (Styrofoam and wire mesh core with stucco exterior)

Other designs, retrofit treatments such as noise absorptive paneling, and alterations to noise barriers should be approved by the Office of Structure Design.

The standard sheets also include designs for gates providing emergency access to community fire hydrants, emergency access for stranded motorists, rapid access to accidents, etc.

A minimum height requirement of 1.8 m (6 ft) for sound walls in Chapter 1100 of the Highway Design Manual was partially designed to control pedestrian access to the freeway.

N-6220 Aesthetics

The visual impact of noise barriers on adjoining communities, as well as on the motorists is a major consideration in the design of noise barriers. A high noise barrier placed close to single story residences could have a severe visual effect. A high barrier can also create unwanted shadows, impede natural air flows, or block panoramic views. Chapter 1100 of the Highway Design Manual outlines maximum heights for noise barriers located at distances of 4.5 m (15 ft) or less and more than 4.5 m from the traveled way.

In general, visual dominance of high walls near residences is reduced when the sound wall is located at least 2 - 4 times its height from the nearest receiver. The visual impact is further softened with berms and landscaping (see Figure N-6220.1). Landscaped earth berms are acoustically and aesthetically superior to sound walls. However, in many locations they are not suitable because of space limitations.

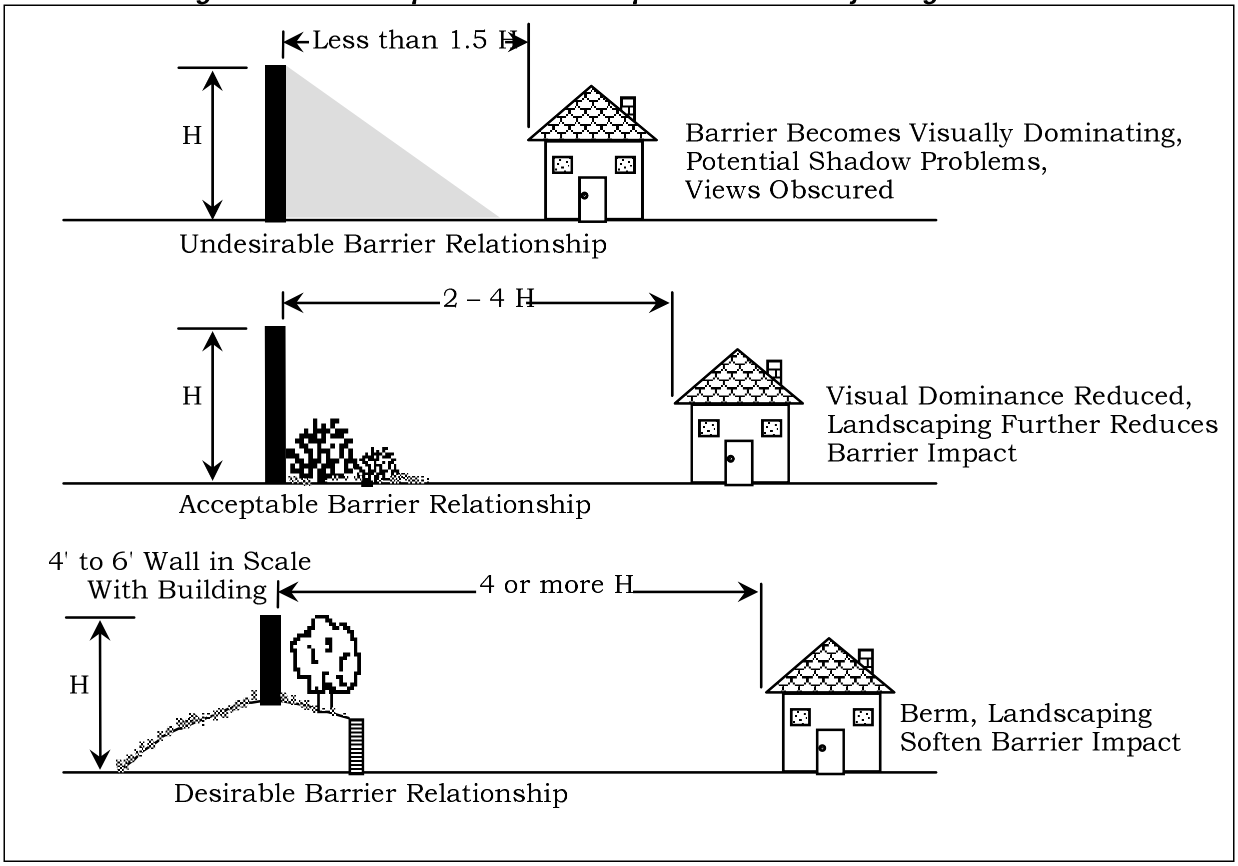
Sound walls should not have abrupt beginnings or endings. Instead they should be tapered or stepped. Only standard aesthetic treatments developed by the Office of Structure Design should be used. If landscaping is to be placed adjacent to the sound wall where it will eventually screen a substantial portion of the wall, only minimal aesthetic treatment is justified.

Walls should as much as possible reflect the character of the surroundings. In cases where the general architecture of a community has a certain character, sound wall material, texture and color should preferably fit this character at the community side of the wall. Ideally, the community should have some input in the aesthetic design of noise barriers.

On the motorist side of the wall the emphasis should be on the overall form of the wall, its color and texture. Small details will not be noticed at normal highway speeds. Instead, the emphasis should be on avoiding a tunnel effect through various forms, and visual treatments. Landscaping can be used effectively to accomplish this.

Further guidance on aesthetics can be found in Chapter 1100 in the Highway Design Manual, and "Instructions for using the Standard Aesthetics Features Sheets". The latter is available from the Aesthetics and Models unit of the Office of Structure Design.

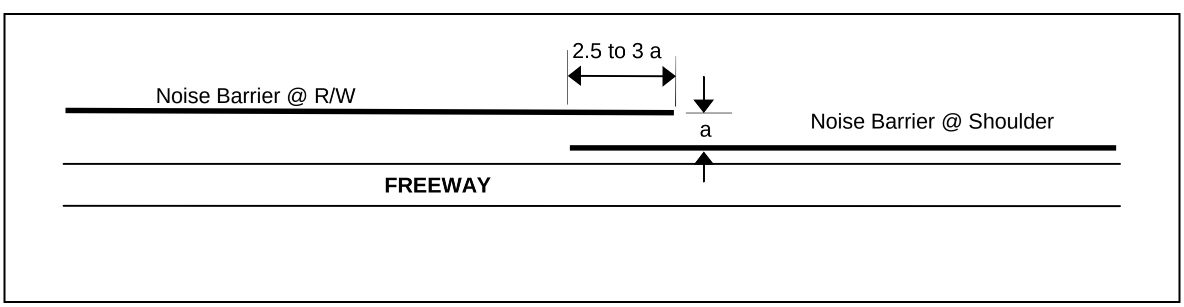
Figure N-6220.1 - Spatial Relationship of Barrier to Adjoining Land Use



N-6230 Maintenance

Access to the back side of noise barriers must be provided if the area is maintained by Caltrans. If access is not available from local streets access gates or openings from the highway must be provided along the noise barrier. Openings created by overlapping barriers must have an overlap distance of at least 2.5 to 3 times the width of the opening (distance between overlapping barriers) (see Figure N-6230.1).

Figure N-6230.1 - Barrier Overlap 2.5 to 3 times the Width of the Access Opening.



The alternate materials selected for noise barriers should be appropriate for the environment in which they are placed. For instance, for walls that are located near the edge of shoulder, the material above the safety-shape concrete barrier should be able to withstand the impact of an occasional vehicle riding up above the top of the safety barrier. Concrete block, cast-in-place concrete, or precast concrete panels are recommended in these locations. In areas of great fire danger, wood barriers should be avoided. See Chapter 1100 of the Highway Design Manual for further information.

N-7000 NOISE STUDY REPORTS

The primary function of a noise study report is to present the methods and results of a traffic noise analysis and the data supporting the conclusions to a target audience that includes both lay persons and technical noise analysts. One way to satisfy both audiences is to provide a summary for lay persons and decision makers, and a technical report for experienced noise analysts, or lay persons desiring more detail than that provided by the summary.

The summary, also called the Executive Summary, should briefly describe existing landuse and noise environment, the project alternatives, future noise environment, traffic noise impacts (if any) and noise abatement/mitgation considered.

The technical report needs to fully support the conclusions that are incorporated into the environmental document and should satisfy technical reviewers who wish to assess the validity of the noise study, including the methods used as well as any assumptions that have been made. Sufficient information should be presented to allow any trained noise analyst to come to the same conclusions.

As is the case with all technical environmental studies, the level of effort to be spend on the noise study report needs to be matched with the size and complexity of the project, and degree of controversy (if any) surrounding it.

N-7100 OUTLINE

Table N-7100-1 shows an outline for a typical noise study report. Not all reports will need this level of effort. On the other hand, some reports may require more information due to special circumstances.

Table N-7100-1 Noise Study Report Outline

I. SUMMARY (OR EXECUTIVE SUMMARY)

- Purpose of noise report
- Brief description of the project
- Brief description of the land use and terrain
- Existing noise levels (ambient and background)
- Future predicted noise levels
- Traffic noise impacts (if any)
- Noise abatement/mitigation considered (range of heights, lengths, insertion losses, and no. of benefited receivers
- Reasonable monetary allowances per benefited receiver for abatement considered
- Areas where abatement/mitigation are not feasible

- Construction noise

Table N-7100-1 Noise Study Report Outline (continued)

II. NOISE IMPACT TECHNICAL REPORT

A. Introduction
1. Purpose of report
2. Background

B. Project Description
1. Detailed description of all project alternatives
2. Maps showing alignment and profiles

C. Fundamentals of Traffic Noise
1. Decibels and frequency
2. Noise source characteristics (vehicles & roadways)
3. Noise propagation
4. Perception at the receiver, A-weighting, noise descriptors
5. Decibel scale

D. Federal & State Policies and Procedures
1. Traffic Noise Analysis Protocol
2. Technical Noise Supplement

E. Study Methods and Procedures
1. Selection of receivers and measurement sites
2. Field measurement procedures: **(Note: field data in appendices)**
   a. instrumentation and setups
   b. noise measurements
   c. traffic counts and speeds
   d. meteorology
   e. data reduction
3. Noise prediction method used:
   a. LEQV2 or SOUND32 based on FHWA RD-77-108 Report and Calveno (FHWA/CA/TL-87/03) Report, or
   b. TNM, based on FHWA-PD-96-009 and – 010 (when mandated)

F. Existing Noise Environment
1. Detailed description of noise sensitive land use
2. Maps showing receivers and noise measurement sites
3. Table showing existing noise levels at receivers:
   a) Field measured results (ambient and background)
   b) Modeled results
4. Discussion on model calibration (if appropriate) for adjusting modeled noise levels (existing or future)

G. Future Noise Environment, Impacts, and Cosidered Abatement/ Mitigation
1. Discuss future traffic data assumptions and site geometry
2. Table showing predicted noise levels, and identification of traffic noise impacts, if any
3. Discussion of noise abatement options

4. Table showing future noise levels and insertion losses (noise reduction) for various noise barrier heights, lengths and locations
5. Table summarizing data necessary for "Reasonableness" determination
6. Discussion of areas where abatement/mitigation is not feasible

Table N-7100-1 Noise Study Report Outline (continued)

H. Construction Noise

I. References

J. Appendices

1. Instrumentation, manufacturer(s),model, type, serial numbers, calibration
2. Measurement site details, instrument setups
3. Measurement procedures, duration, number of repetitions
4. Measured noise data, dates, times
5. Meteorological conditions
6. Traffic counts
7. Data reduction, measurement results
8. Details of computer modeling assumptions, inputs and outputs

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N-7200 SUMMARY (OR EXECUTIVE SUMMARY)

The noise study conclusions should be presented near the front of the Noise Study Report in the form of a summary, also called Executive Summary. The summary of findings and conclusions of the study should be extracted from the technical portion of the noise study report. This requires the technical portion to be written first. The executive summary should target the layperson who is interested in the noise impacts, if any, but does not want to read all of the technical details. Because the author of the Noise Study Report is usually not the same author of the project's environmental document, the executive summary should be written in such a manner, that it can be "cut and pasted" into the environmental document. This will help reduce misinterpretations or loss in translations. The Executive Summary should be short, usually only a few pages. Briefly describe the elements mentioned in the outline (Table N-7100-1). A table listing receivers, existing noise levels, future noise levels without noise barriers, future noise levels with noise barriers (various heights), and insertion loss should be sufficient to summarize the results of the noise study.

N-7300 NOISE IMPACT TECHNICAL REPORT

The noise impact technical portion is the main body of the Noise Study Report. It contains detailed descriptions of why and how the noise study was performed and how the conclusions were reached. Sufficient detail is needed for someone to be able to duplicate the study from the information included in report.

Depending on the size, location and type of project, it may be beneficial to combine the noise report with some of the other technical reports, such as air quality, in order to avoid repetition.

Following are suggested sections of the report with brief descriptions of their contents.

N-7310 Introduction

The introduction should include the purpose of the Noise Study Report, study objectives, and background information such as need for project and need for the study, or any other general information useful to the understanding of the Noise Study Report.

N-7320 Project Description

The project description should include a detailed description of all of the project alternatives. There should be enough information for the reader to understand the project and how it fits into the transportation system of the area. An appropriate location map showing alternative alignments studied and and their spatial relationship with noise sensitive receivers such as residences, schools, hospitals, churches and parks should be included.

N-7330 Fundamentals of Traffic Noise

A short review of the physical principles of traffic noise at the source and its propagation, and subjective human perception will provide a link for lay persons to understand the technical information. The contents of this section may be of standard format or tailored to specific studies.

Briefly describe sound pressure level, the logarithmic nature of decibel units, and frequency (pitch), and the noise characteristics of vehicles. Vehicle noise emissions increase with speed. Increased traffic volumes also increase traffic noise. However it takes a doubling of traffic to increase noise levels by only 3 dB.

Discuss the noise propagation (line source vs point source) over acoustically “hard” and “soft” ground, effects by meteorolgical factors such as wind and temperature gradients, shielding by terrain or noise barriers.

Human perception of noise is also frequency dependent, which leads to a discussion on “A-weighting”, its purpose and its use. Changes in noise levels are perceived as follows: 3 dBA barely perceptible, 5 dBA readily perceptible, and 10dBA perceived as a doubling or halving of noise. Follow this with a discussion on commonly used noise descriptors, such as L_{eq}(h).

Finally, the inclusion of a decibel scale showing a link between everyday activities and associated noise levels will provide the reader with a “yard stick” to evaluate the severity of traffic noise.

The fundamentals of traffic noise discussion need not be restricted to the above items. Other topics may be included as appropriate, some of which may be specifically tailored to the nature of the noise study. The information presented in this TeNS may be beneficial in explaining various phenomena. For instance, where parallel or single noise barrier noise reflections are an issue, it may prove to be beneficial to include selected text of section N-8000, *Special Considerations.*

N-7340 Federal & State Standards and Policies

This section covers the applicable Federal and State standards and policies. Caltrans noise analysis policies are in the Traffic Noise Analysis Protocol and the Highway Design Manual Federal requirements include NEPA and 23CFR772. State requirements and policies are contained in CEQA, California Streets and Highways Code Section 216, and. Terms used in the policies and standards should be mentioned in this section along with the Noise Abatement Criteria (NAC) and their significance, definitions of appropriate noise descriptors, and traffic noise impact criteria.

If the project involves local noise ordinances written in terms of a noise descriptor other than L_{eq}(h) an attempt should be made to equate the noise descriptors rather than duplicating most of the noise report using another descriptor (see Section N-2230 for a discussion of equating worst-hour L_{eq}'s to L_{dn}'s, etc.).

N-7350 Study Methods and Procedures

Study methods and procedures followed should be identified in the Noise Study Report. This section should describe selecting receivers and noise measurement sites, field measurement procedures, and noise prediction methods (Sections N-3000 and N-5000).

The discussion of selecting the receivers and noise measurement sites should focus on why they were selected. Selections are based on expectations of worst noise impacts, geometry of the project, representativeness, acoustical equivalence, and human use (Sections N-3200 and N-5310). The importance of selecting receivers outside the area of project influence must not be overlooked. These receivers are extremely useful for documenting background noise levels and – later, after the project is built - guard against unsubstantiated public claims that noise barriers constructed as part of the project increased noise levels at distant receivers (Section N-8200).

The discussion on field measurement procedures (Section N-3000) should include descriptions of instrumentation, set-ups, noise measurement procedures, traffic counts and speeds, meteorological observations and data reduction methods. Also discuss model calibration procedures (Section N-5400).

Include in the appendices to the noise report the measurement equipment used, calibration information and dates and times of measurements, and measured noise data, traffic counts and speeds, meteorological conditions, site topography, and detailed measurement locations (as a rule of thumb, the microphone locations should be retraceable within one meter horizontally, and 0.3 meter vertically). If measurements were taken at a time different from the worst noise hour, show the adjustment and procedure used (Section N-3312), any receivers modeled and calibrated, and the inputs for these.

Noise level predictions must be based on the methodology in the FHWA Highway Traffic Noise Prediction Model (FHWA-RD-77-108) with California reference energy mean emission (Calveno) levels, or when implemented for use by Caltrans the FHWA Traffic Noise Model (FHWA-PD-96-009 & -010; DOT-VNTSC-FHWA-98-1 & -2),. These, and other documents pertinent to the noise study should be referenced, as appropriate.

N-7360 Existing Noise Environment

Before traffic noise impacts can be evaluated, a detailed knowledge of the existing noise environment is required. A description of the project's surrounding land use (residential, commercial zones, undeveloped land, farm land etc.) should be included in this section. The number and type of receivers involved should be reported so that the reader understands the size and charcteristics of the area under study (e.g. "….approximately 75 first tier single family residences; 5 two-story apartments; 2 grammar schools and 3 parks…" etc. Mention any particularly sensitive land uses. For undeveloped land include future uses if known. Also note the presence of any ather stationary or mobile noise sources, e.g. arterials, airports, etc.

The general topography surrounding the project and any problems in noise measurements or modeling should be pointed out in this section, especially in complicated or unusual situations. A discussion on background noise levels, noise levels unaffected by the existing highway, is also appropriate. The importance of selecting measurement sites to document background noise levels is mentioned in the previous section N-7350.

For each receiver selected for the noise impact analysis, show:

- location or address
- type of development

- the number of units represented by the receiver
- landuse activity category and Noise Abatement Criterion
- existing noise level results (“raw” data should go into appendices)
- whether existing noise level was measured or modeled (predicted); if measured, also indicate if measurement was adjusted to worst hour noise (see Section N-3312); when predicted, indicate if prediction included model calibration (see Section 5400; the details

of the calibration, such as the calibration constant and any explanations of why they were excessiveley large, should be in the appendices).

Table N-7360.1 suggests how the information might be displayed in tabular form. The format shown is only an example. The information may be presented in many other ways, as long as the result is clear, concise and effective.

This section should only show a summary of the results. It is important to mention whether the existing noise levels reflect the worst noise hour, or other time periods. The text should include brief discussions on meteorological conditions during measurements, and meteorological criteria. "Raw" data of noise measurements, traffic counts, speeds, meteorological, site locations and topography should be included in the appendices.

N-7370 Future Noise Environment, Impacts, and Considered Abatement/ Mitigation

This section of the Noise Study Report deals with the future noise environment. A discussion of the assumptions and inputs used for the predicted noise levels is appropriate. Include the source of predicted future traffic volumes (such as: from traffic models, assumed level of service C or D, design hour traffic, etc.), vehicle mix, and speeds. The actual input/output data should be presented in the appendices.

The predicted results for future noise levels, traffic noise impacts, and considered abatement, if any, should be presented in a clear and concise manner. As was shown in Section N-7360, the summary information is most often best displayed in tables. An example of presenting predicted noise levels and impacts is shown in Table N-7370.1. The table shows receivers, receiver type, location, and or address, existing noise levels, predicted noise levels, noise increase or decrease, activity category, NAC, and impact type. Include a project map showing receivers and approximate locations of noise barrier locations considered.

The predicted noise and impact results table covers information for discrete receivers. The information must be expanded to include the entire study area. Table N-7360.1 in the previous section showed how many units were represented by each of the selected receivers. This information can be used to identify areas of traffic noise impacts and the acoustical design of noise barriers, (e.g. length, height, insertion loss). For projects where traffic noise impacts have been identified, show heights and lengths of all feasible noise barriers or other abatement measures, and enough information to determine the reasonable noise abatement allowance per benefitted residence for each noise barrier and height considered. The latter is necessary to determine whether abatement measures are reasonable. Although noise barriers are normally considered for abatement/mitigation, other measures may also be considered (see Protocol, Sec. 5.2), and in some instances a better option.

Table N-7360.1 Existing Noise Levels (Example)

Receiver I.D. No.	Location or Address	Type of Development	Number of Units Represented	Noise Abatement Category and Criterion ( )	Existing Worst Hour Noise Level, Leq(h), dBA	Noise Level Measured* or Modeled**?
1	1234 Elm Street, back yard, center of patio (first row residence)	Residential	15	B (67)	74	Measured
2	4321 Main Street, 5' from façade (first row residence)	Residential	9	B (67)	75	Measured
3	2336 Elm Street, center of backyard (first row residence)	Residential	24	B (67)	73	Modeled
4	3538 Elm Street, center of backyard (first row residence)	Residential	18	B (67)	74	Modeled
5	1212 Church Street, 10' N. of bottom front step	Church	1	B (67)	68	Measured
6	1723 Oak Street, center of front lawn (1/4 mile from the freeway, background noise level)	Residential	24	B (67)	56	Measured
7	1052 Sycamore Drive, middle of cul-de-sac, (1/4 mile from the freeway, background noise level)	Residential	30	B (67)	55	Measured

* **Unless otherwise indicated, all measurements shown reflect worst hour noise levels, i.e. they were either measured during the noisiest hour (Section N-3311) or were adjusted to worst hour traffic characteristics (Section N-3312).**

** **Unless otherwise indicated modeled receivers include a calibration constant (Sections N-3120, N-5330 and N-5400)**

Table N-7370.1 - Predicted Traffic Noise Impacts (Example)

Receiver I.D. No.	Type, Location or Address	Development Either Predates 1978, or Project is a New Highway Construction (Yes or No)	Existing Noise Level, Leq (h), dBA	Predicted Noise Level, Leq (h), dBA	Noise Increase (+) or Decrease (-)	Activity Category and NAC, Leq(h)	Impact Type * (S, A/E, CR or NONE)
1	1234 Elm Street, back yard, center of patio (first row residence)		74	75	+1	B (67)	A/E
2	4321 Main Street, 5' from façade (first row residence)		75	76	+1	B (67)	A/E
3	2336 Elm Street, center of backyard (first row residence)		73	74	+1	B (67)	A/E
4	3538 Elm Street, center of backyard (first row residence)		74	75	+1	B (67)	A/E
5	1212 Church Street, 10' N. of bottom front step		68	69	+1	B (67)	A/E
6	1723 Oak Street, center of front lawn (1/4 mile from the freeway, background noise level)		56	56	0	B (67)	NONE
7	1052 Sycamore Drive, middle of cul-de-sac, (1/4 mile from the freeway, background noise level)		55	55	0	B (67)	NONE

* Impact Type: S = Substantial Increase (12 dBA or more)
A/E = Approach or Exceed NAC
CR = Class Room Noise (Sec 216 of Streets & Hwys Code)

If noise barriers are be considered for the project, include in tabular form the future noise levels and noise insertion losses for various barrier heights, or alternate locations (such as: "…. At the shoulder", or: ….at the R/W". An example is shown in table N7370-2.

Section 2.8 of the Protocol discussed the procedure for determining the preliminary reasonableness of noise abatement. The process requires various inputs (for details, refer to Section 2.8.2.), most of which have been discussed. Table N-7370-3 is an example of how this information may be displayed.

The Protocol, particularly Section 2.9, 3, and 4 discuss further reporting requirements for draft and final environmental documentation.

Point out that barrier heights and locations are preliminary and subject to change (see Protocol Section 2.9.

If appropriate, it should be mentioned that noise barriers under consideration can have their own negative impacts. Barriers may interfere with the passage of air, interrupt scenic views, or create objectionable shadows. They can also create maintenance access problems, make it difficult to maintain landscaping, create drainage or snow removal problems and provide pockets for trash and garbage to accumulate. In certain circumstances they may raise concerns about safety by blocking areas from the view of patrolling police. Noise barriers can also raise concerns about traffic safety by reducing stopping or merging sight distance, or by reducing errant vehicle recovery room.

Include discussions and justifications for any locations where a noise impact has been identified, but where no feasible mitigation measures are available.

Table N 7370-2 - Noise Abatement
Predicted Noise Levels, $L_{eq}(h)$ and Insertion Loss (I.L., Noise Reduction), dBA For Sound Wall 1, at R/W.
(Example)

Receiver I.D.No.	W/o Wall	With Wall H=6' (1.8 m)		With Wall H=8' (2.4 m)		With Wall H=10' (3.0 m)		With Wall H=12' (3.7 m)		With Wall H=14' (4.3 m)		With Wall H=16' (4.9 m)	
		Leq(h)	**I.L.**	**Leq(h)**	**I.L.**	**Leq(h)**	**I.L.**	**Leq(h)**	**I.L.**	**Leq(h)**	**I.L.**	**Leq(h)**	**I.L.**
1	75	70	5	69	6	68*	7	66	9	65	10	64	11
2	76	70	6	69	7	68*	8	67	9	65	11	64	12
3	74	70	4	69	5	68*	6	66	8	65	9	63	11
4	75	70	5	69	6	68*	7	66	9	65	10	64	11
5	69	65	4	64	5	63*	6	61	8	60	9	59	10
6	56	56	N/A**	56	N/A**	56	N/A**	56	N/A**	56	N/A**	56	N/A**
7	55	55	N/A**	55	N/A**	55	N/A**	55	N/A**	55	N/A**	55	N/A**

- *** Breaks Line of Sight between 11.5 ft (3.5 m) truck stack and 5 ft (1.5 m) high receiver in the first row of residences.**
- **** N/A = Not applicable (no barrier considered)**

Table N-7370-3 - Data For Reasonableness Determination (Example)

SOUND WALL I.D.: SW-1						
PREDICTED, W/O SOUND WALL						
Absolute Noise Level, L_{eq}(h), dBA*	75					
Build Vs. No-build, dBA*	+1					
PREDICTED, WITH SOUND WALL	**H=1.8 m**	**H=2.4 m**	**H=3.0 m**	**H=3.7 m**	**H=4.3 m**	**H=4.9 m**
Loss (Noise Reduction), dBA*	5	6	7	9	10	11
No. of Benefited Residences	24	24	24	48	72	96
New Highway, or More Than 50% of Residences Predate 1978? (Yes or No)	NO	NO	NO	NO	YES	YES
Reasonable Allowance Per Benefitted Residence	$21,000	$23,000	$23,000	$25,000	$35,000	$35,000

***At critical receiver(s)**

SOUND WALL I.D.: SW-2						
PREDICTED, W/O SOUND WALL						
Absolute Noise Level, L_{eq}(h), dBA*	74					
Build Vs. No-build, dBA*	+1					
PREDICTED, WITH SOUND WALL	**H=1.8 m**	**H=2.4 m**	**H=3.0 m**	**H=3.7 m**	**H=4.3 m**	**H=4.9 m**
Insertion Loss (Noise Reduction), dBA*	4	5	6	8	9	11
No. of Benefited Residences	0	24	24	48	48	96
New Highway, or More Than 50% of Residences Predate 1978? (Yes or No)	NO	NO	NO	NO	NO	YES
Reasonable Allowance Per Benefitted Residence	Not Feasible	$19,000	$21,000	$21,000	$23,000	$33,000

***At critical receiver(s)**

N-7380 Construction Noise

Construction noise impacts and likely abatement measures thereof (if necessary) should be discussed briefly. Unless the project involves construction activities that are likely to generate unusually high noise levels such as pile driving or pavement breaking, the discussion should be brief and concise. Detailed discussions of typical construction equipment noise levels are probably not necessary unless there are unusually sensitive receptors involved, or if the project is controversial.

N-7390 References

Typical references may include NEPA, CEQA, 23 CFR 772, Traffic Noise Analysis Protocol Highway Design Manual Chapter 1100, FHWA-RD-77-108 or (when TNM is mandated) FHWA-PD-96-009 & -010, DOT-VNTSC-FHWA-98-1 & -2, and other appropriate documents.

N-7400 APPENDICES

Include in the appendices any details that would support the conclusions of the Noise Study Report. Examples are instrumentation used, calibration data, field measurement data, site details and computer modeling input assumptions and results. If the analysis includes model calibrations (Section N-5400) these should be shown in simple table form (see Table 7340.1) Ideally the appendicies should fill in all of the details that are not in the main report such that the analysis could be repeated.

Table N-7340.1 Model Calibration (Example)

Receiver I.D.	Measured Noise Level, Leq(h), dBA	Predicted Noise Level, Leq(h), dBA	Calibration Constant, K (Meas-Pred), dBA
1	68	70	-2
2	66	69	-3
3	70	71	-1
4	69	72	-3

If measurements were taken at a time different from the worst noise hour, show the adjustment and procedure used (Section N-3312), any receivers modeled and calibrated, and the inputs for these.

N-8000 SPECIAL CONSIDERATIONS

This chapter is devoted to special considerations arising from certain site geometries, noise barrier configurations, intervening terrain, distant receivers, interactions with meteorology, and abnormal traffic conditions. Any one or more of these factors can affect noise measurements, analysis, and barrier design, with results that are predicted with more than routine methods.

Continuing research by Caltrans and others have provided some answers to these problems. However, there is a continued need for field research to verify prediction algorithms in new prediction models, alter those in existing ones, and investigate conditions which lead to newly identified problems.

The "special considerations" covered in this chapter include reflected noise and noise barriers, distant receivers, multiple barriers, and dealing with stop-and-go traffic.

N-8100 REFLECTED NOISE AND NOISE BARRIERS

Section N-6100 "Acoustical Design Considerations" briefly discussed the possibility of noise reflections by a single noise barrier causing noise problems at the opposite side of the highway. This is just one of the issues raised in recent years concerning negative effects of noise barriers. As is often the case, the solution of one problem gives rise to the possibility of creating other problems. In the case of noise barriers, reducing noise at receivers on one side of the highway could potentially increase the noise at receivers on the other side. The complex nature of noise barrier reflections, the difficulties in measuring them, and the controversy surrounding the significance of their impacts deserve a detailed discussion.

More noise barriers have been constructed in California than in any other state, in many different configurations of alignment, profile, and height. These barriers are located along one or both sides of highways of different widths, along ramps, connectors and interchanges, in urban, suburban, and sometimes rural regions under varying traffic conditions. The receivers for which they were designed are located in many different types of terrain, topography, and climatic conditions. The combinations and permutations associated with the vast variety of conditions inevitably increase the possibilities of creating controversies over the extent of noise reflections by barriers. Hence, it is only natural that noise reflection issues are on the rise in California, especially since almost all California barriers are made of noise reflective material with hard, relatively smooth surfaces (masonry, concrete). In most cases, the alleged noise increases due to reflections turn out to be so small that most people do not notice them. The people that do perceive increases in noise are usually suddenly made aware of freeway noise by some event that triggers the awareness, such as the construction of the noise barrier. Measured increases due to noise reflections of more than 2 dBA have never been measured by Caltrans, however, claims of 10 and even 20 dBA increases have occasionally been made.

Many of the alleged increases in noise were actually due to changes in meteorology. Atmospheric refraction due to wind shear and temperature gradients can account for 10 to 15 dBA variations when the same sources are measured from distances of 1.5 to 3 km (approximately 1 to 2 miles). In order to measure the effects of noise reflections, before and after barrier noise measurements have to be carefully matched by wind speed, wind direction, temperature gradients, air temperature, humidity, and sky cover. Likewise, if a person perceives a noticeable increase in noise levels due to a reflective noise barrier, he/she must be able to compare it mentally with a before condition that included the same meteorology. Needless to say, this process is very unreliable.

Section 8100 covers various aspects of noise reflection concerns in detail. The following classifications of reflective noise with respect to noise barriers and other structures will be discussed:

1. Single barrier (on one side of a highway)
2. Parallel barriers (on both sides of the highway)
3. Structures and canyon effects

When compared to reflections measured under similar conditions, results of theoretically modeled noise reflections normally show higher values. This over prediction of reflection models has been attributed to the inability of models to accurately account for all the variables, such as interactions with atmospheric effects and the unknown degree to which traffic streams interfere with reflections.

Reflective noise is not peculiar to noise barriers. Retaining walls and other structures reflect noise in the same manner as noise barriers do. The principles discussed in this section can be applied to reflective barriers, reflective retaining walls, or any other smooth, continuous and hard surface.

N-8110 Single Barrier Reflections

N-8111 Simple Terrain

Figure N-8111.1 is the simplest, two-dimensional representation of single barrier reflections. The presence of a reflective barrier on the opposite side of an at-grade highway essentially doubles the acoustic energy at the receiver. In addition to the direct noise "ray" "d", the barrier reflects a noise ray "r" of roughly the same acoustic energy (actually ”r” is longer than “d” and will result in slightly less acoustical energy). Theoretically, only one reflective ray reaches the receiver, because the angle of incidence equals the angle of reflection (both are depicted as ? in Figure N-8111.1). Thus, even if they are equal, “r” and “d” cause a doubling of energy increases the noise level by 3 dB at the receiver.

Figure N-8111.1 - Single Barrier Reflection (Simplest Representation)

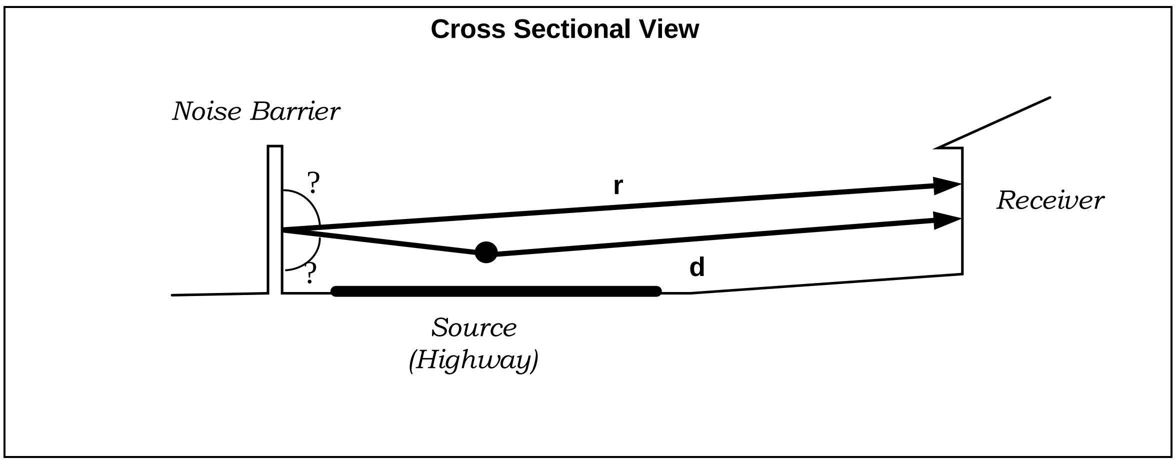


Figure N-8111.2 shows that for an infinite line source and noise barrier the reflections are also an infinite line source. At each point along the highway there is only one reflection ray that reaches the receiver and for which the angle of incidence equals the angle of reflection.

Figure N-8111.2 – Single Barrier Reflections – Infinite Line Source and Noise Barrier

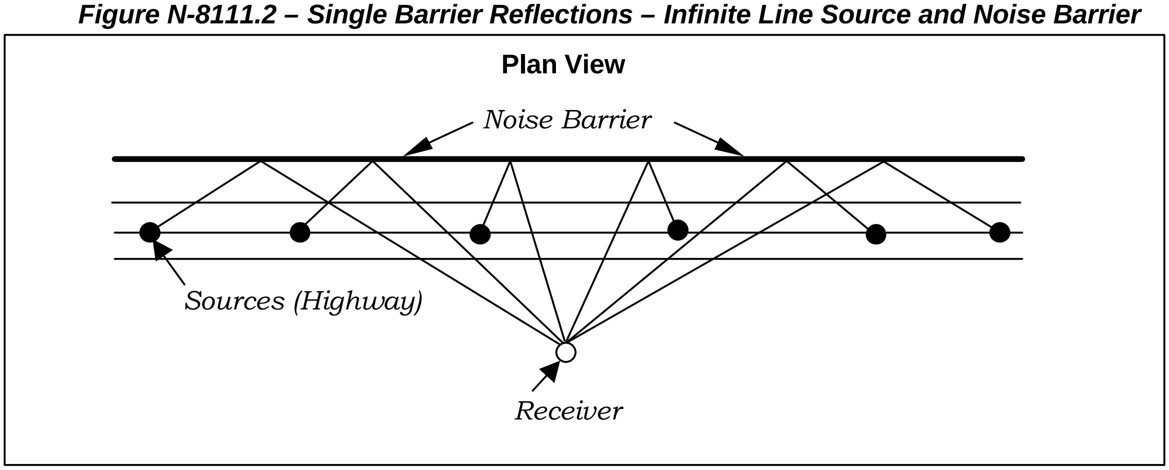
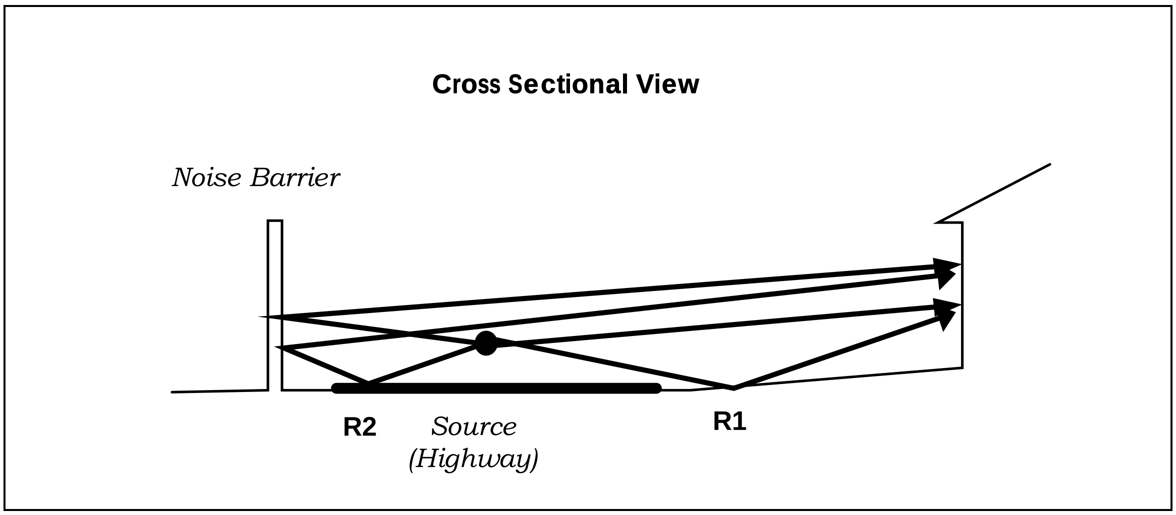


Figure N-8111.3 is a more realistic depiction, which includes pavement reflections. Note, however, that a noise barrier on the opposite side still increases the noise level by 3 dB, although the before and after noise levels are 3 dB higher (due to the pavement reflections) than in Figures N-8111.1 and N-8111.2. In plan view, the pavement reflections would also shown to be a line source.

The reflection point R1, shown on the pavement (Figure N-8111.3) may actually fall off the pavement on absorptive ground, reducing the before barrier noise levels at the receiver. The pavement reflection point R2, however, significant only after building the barrier, will usually be on the pavement. The difference between before and after barrier noise levels could therefore slightly exceed 3 dBA.

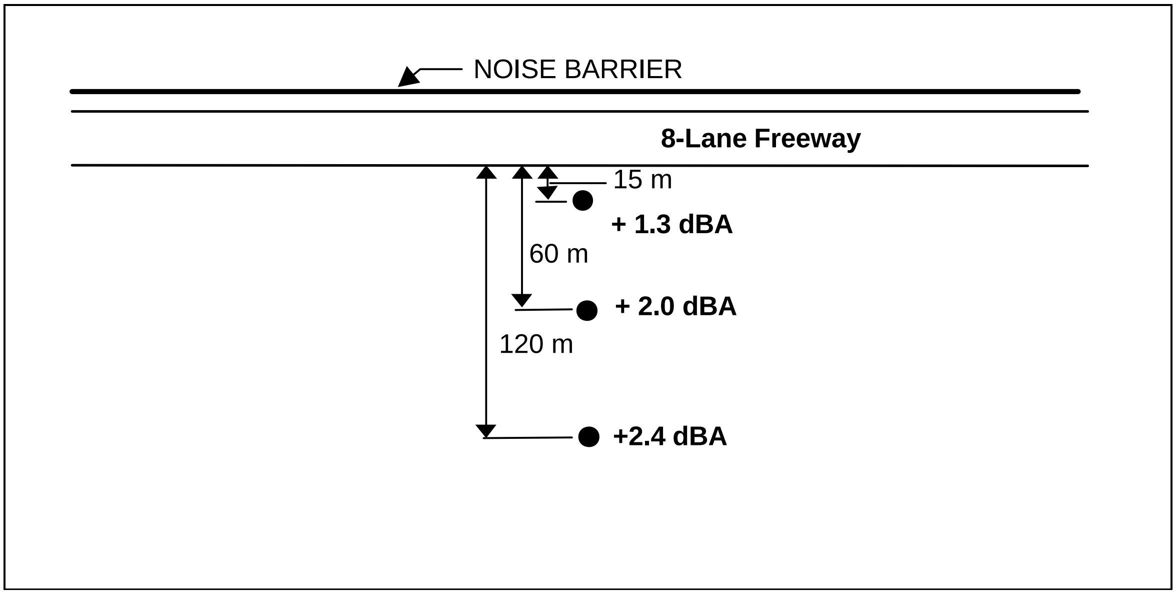
Figure N-8111.3 - Single Barrier Reflection (More Accurate Representation)



The effects of single noise barrier reflections are distance dependent. At distant receivers, the ratios of direct/reflected noise path lengths as well as those for near/far lane distances approach 1. When this is the case, contributions of direct and reflected noise from each lane contributes roughly the same energy (of course there will always remain a slight loss of acoustical energy due to imperfect reflections), with the result that the increase approaches 3 dBA for distant receivers. For receivers close to the highway, however, the distance ratios become less than 1 and the noise at the receiver is dominated by direct noise from the near lanes. The result is less contribution from reflected noise.

Figure N-8111.4 shows the distance dependency of the noise increases due to the barrier reflections, for a typical 8-lane at-grade freeway. At 15 m (50 ft) from the edge of the traveled way (ETW) the increase is only 1.3 dBA; at 60 m (200 ft) the increase is 2.0 dBA, and at 120 m (400 ft) from the ETW the increase is 2.4 dBA. The increases were calculated assuming equal noise source distributions in the near and far (E/B and W/B) lanes, and hard site propagation.

Figure N-8111.4 - Noise Increases due to Single Barrier Reflections.



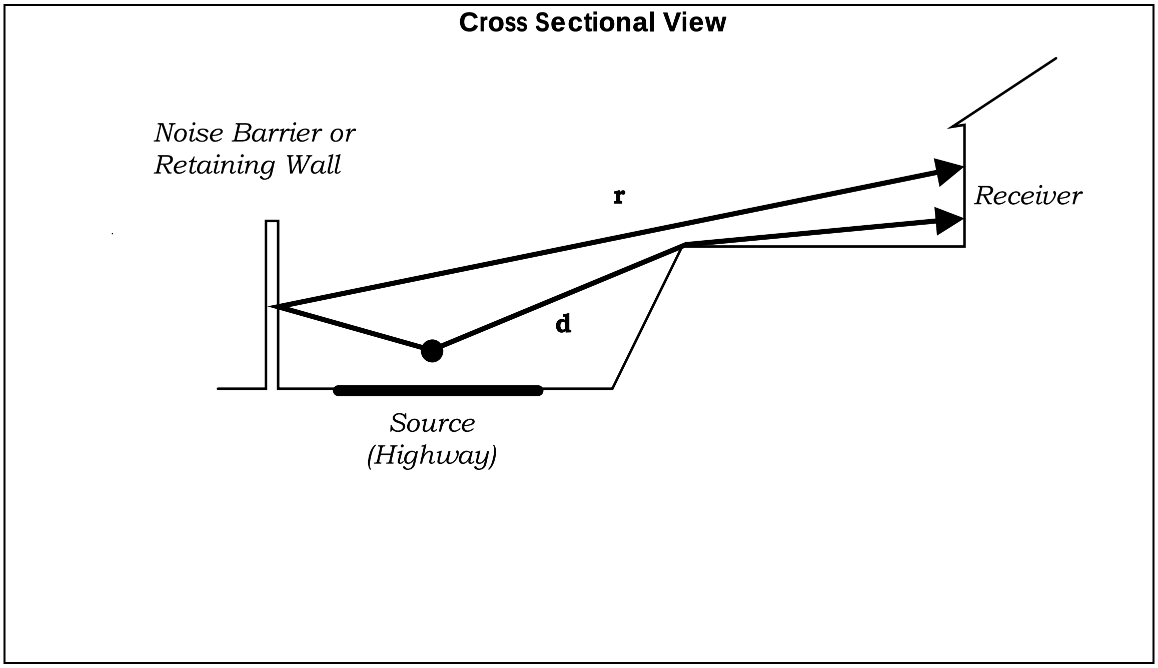
Actually, the "real world" is far more complicated than shown in figures N-8111.1 through N-8111.4. Consider that the noise sources are distributed over the width of the highway; that the paths of the barrier noise reflections are always longer than the direct noise paths; that reflective barriers are not perfect reflectors, and that the traffic stream most likely interfere with the reflections. Because of these factors, reflected noise contributions are less than those of direct noise, and seldom increase noise levels by more than 1 or 2 dB. The human ear cannot perceive such small increases.

N-8112 Complex Terrain

In more complex terrain there are, however, instances when single barrier reflected noise could increase noise levels perceptibly (3 or more dBA) at a receiver. One such case is shown in Figure N-8112.1, which depicts a receiver that is effectively shielded by terrain or top of a depressed highway cut. If a noise barrier or retaining wall were constructed on the opposite side of the highway, unshielded reflected noise ray “r” could contain significantly more acoustical energy than the shielded direct ray “d”, causing a noticeable increase in noise at the receiver. Once again, "real world" situations are far more complex than illustrated. Some of the noise sources may be shielded, while others may not. Similarly, some of the reflected noise paths may be shielded and others not.

In general, if most of the traffic cannot be seen from the receiver while most of the noise barrier is visible, there is a possibility that the barrier noticeably increased noise levels at the receiver.

Figure N-8112.1 - Single Barrier Reflection. Direct Noise Shielded, Reflected Noise Not Shielded.



Reflections off single barriers located at the top of cut (Figure N-8112.2) generally are directed over a 5 foot high receiver on the opposite side and therefore usually not a problem for low receivers. However, higher receivers, such as the second floor of a residence, or receivers located on a higher hill behind the front receivers may still be affected by the reflections, if the direct noise is shielded.

Situations depicted in Figures N-8112.1 and N-8112.2 (high receivers only) usually increase noise levels by a maximum of 3 to 5 dBA, depending on the angle of reflections and the height and length of reflective barrier. Since noise barrier heights are normally restricted to 16 feet by Caltrans policy, the maximum noise increases due to reflections are usually caused by retaining walls, which are not constrained in height.

Single barriers on top of fills (Figure N-8112.3) generally do not present any reflection problems. The reflected noise "ray" is usually well above the receiver.

Figure N-8112.2 - Single Barrier Reflection. Noise Barrier on Top of Opposite Cut.

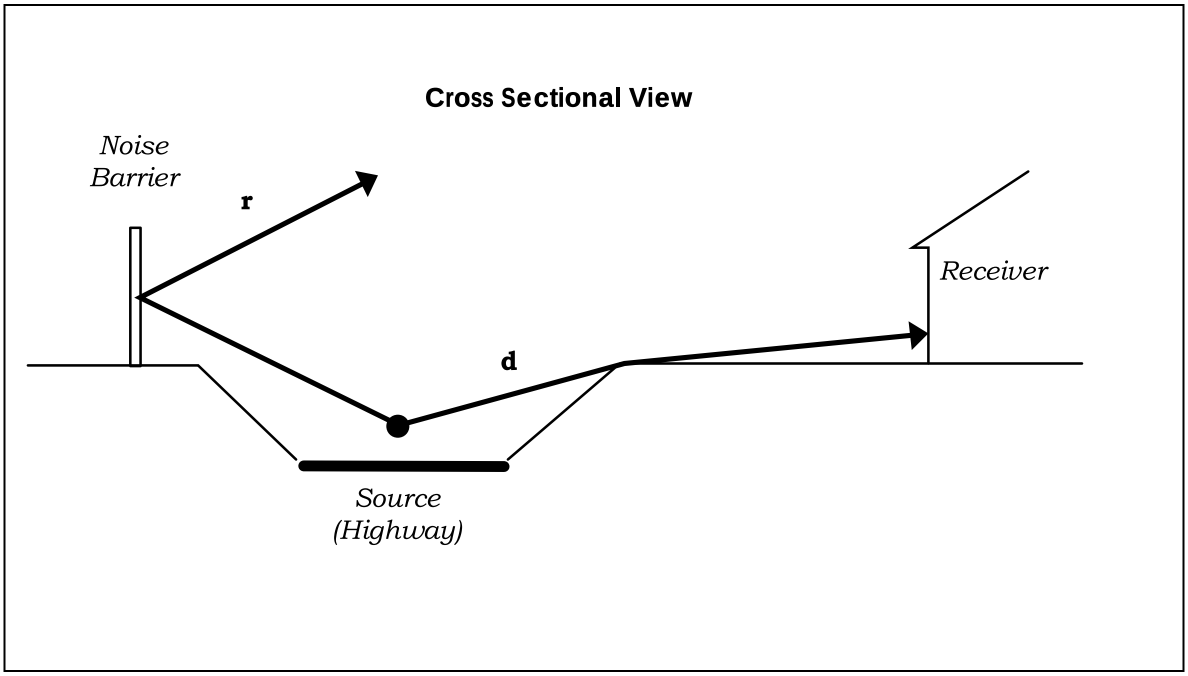
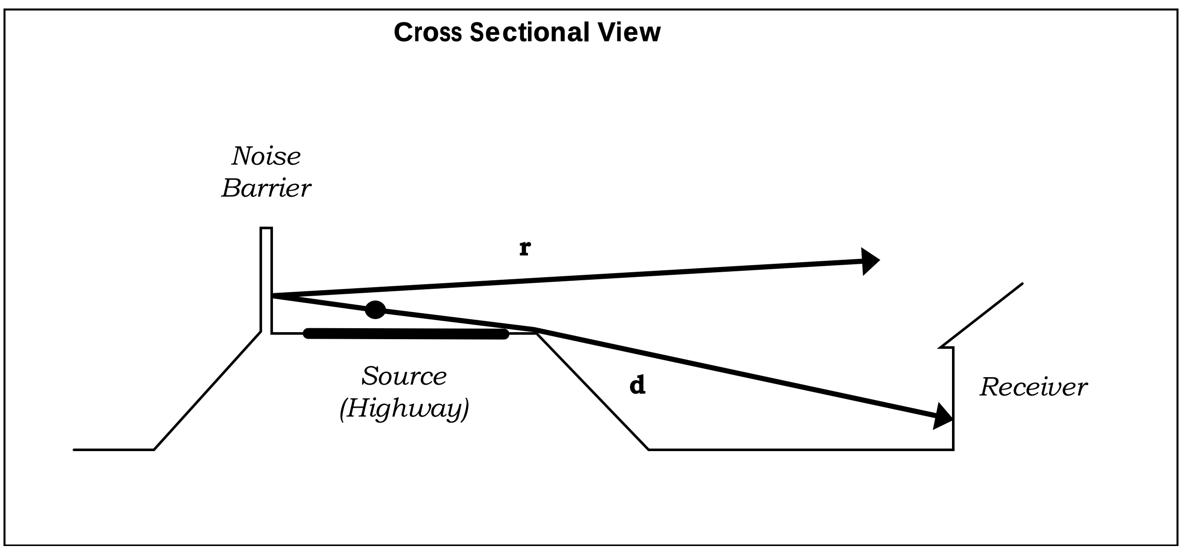


Figure N-8112.3 - Highway and Noise Barrier on Fill.



N-8113 Modeling Single Barrier Reflections

The FHWA Traffic Noise Model (TNM) has at this time no provisions for calculating single barrier reflections. In the future it will have that capability.

Caltrans versions of FHWA Highway Traffic Noise Prediction Model computer programs (LEQV2 and SOUND32), also have no provisions for calculating single barrier noise reflections directly. For simple situations, the effects of reflections can be evaluated in

LEQV2, SOUND32 and TNM using additional elements or coordinates of "image sources". Figures N-8113.1 and N-8113.2 illustrates these in cross section and plan view.

Figure N-8113.1 - Placement of Image Sources (Cross Sectional View)

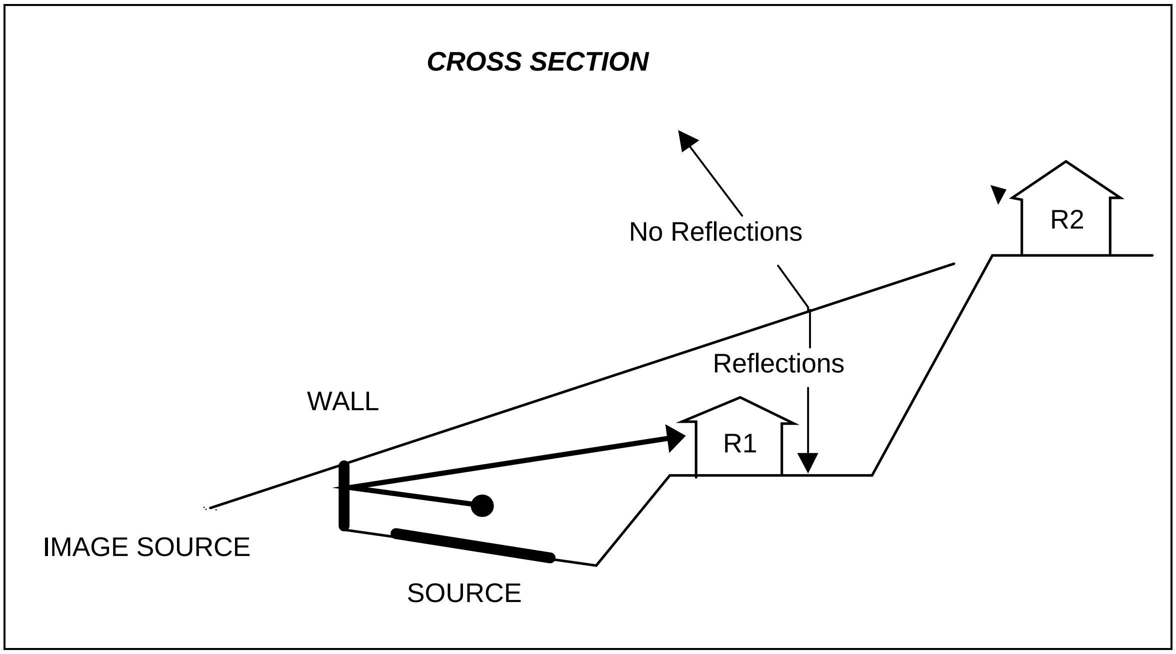
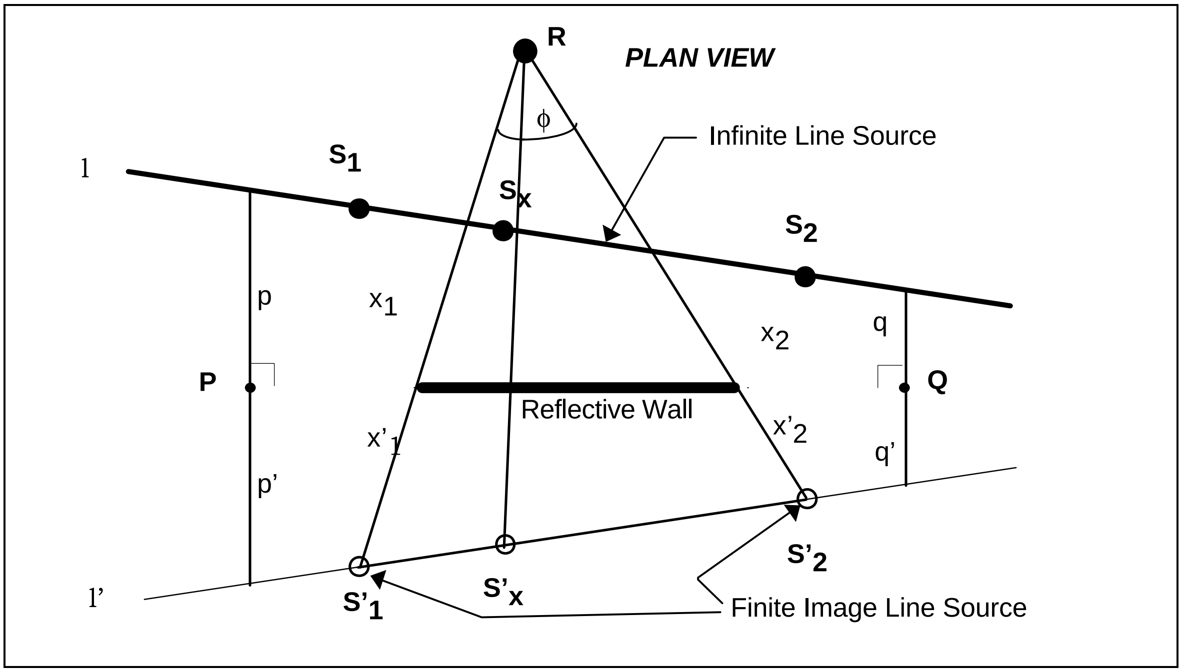


Figure N-8113.1 illustrates the placement of an image source in cross section, by drawing a line perpendicular to the reflective wall (or to its vertical extension) that passes through the real source. The image source is positioned on that line, at the same distance from the wall as the real source, but on the opposite side. The image source is analogous to a mirror image of the real source, with the wall being the "mirror".

It is important to point out that, just as mirror images cannot be seen from all angles, not all image sources necessarily contribute to reflections. A straight line drawn from the image source to the receiver must pass through the wall before the image source can contribute to the noise at the receiver. Note that R1 lies in the "zone of reflections", while R2 does not experience reflective noise. In some cases there are reflections from cars but not from heavy trucks, or vice versa, depending on the site geometry. In other cases only traffic noise from certain lanes will be reflected and others not. Accurate site cross sections will reveal which image sources are relevant.

Figure N-8113.2 shows plotting of image sources in a plan view. A general case is shown, with a finite wall that is not parallel to the roadway. This case was selected to illustrate how image sources are generated in the plan view. Examination of Figure N-8113.2 reveals that a finite wall creates a unique finite image line source for a particular receiver on the opposite side of a highway.

Figure N-8113.2 - Placement of Image Sources (Plan View)



To "construct" the finite image line source, lines perpendicular to the wall (or its extensions) at two different locations (say P and Q) can be drawn. Along these lines, distances "p" and "q" from the wall to the roadway line l, at P and Q respectively, can be drawn on the image side of the wall (p = p' and q = q'). A line l' connecting the two points defined by distances p' and q' establishes the direction of the image line source. Next, the termini of the infinite image line source can be determined by the intersections of line l' with two lines from the receiver R through both end points of the wall. S1' and S2' are now the end points of the finite image line source.

When using LEQV2 program the wall has to be parallel to the roadway. The above process can be used for this special case. The finite image line source will then run parallel to the roadway, and can be defined as an additional element(s), with a segment angle ϕ. A cross sectional drawing is needed to reveal if all image traffic (and image roadways) should be included. If, for instance the heavy trucks do not produce reflections, the heavy truck volume for the image source can be coded as 0.

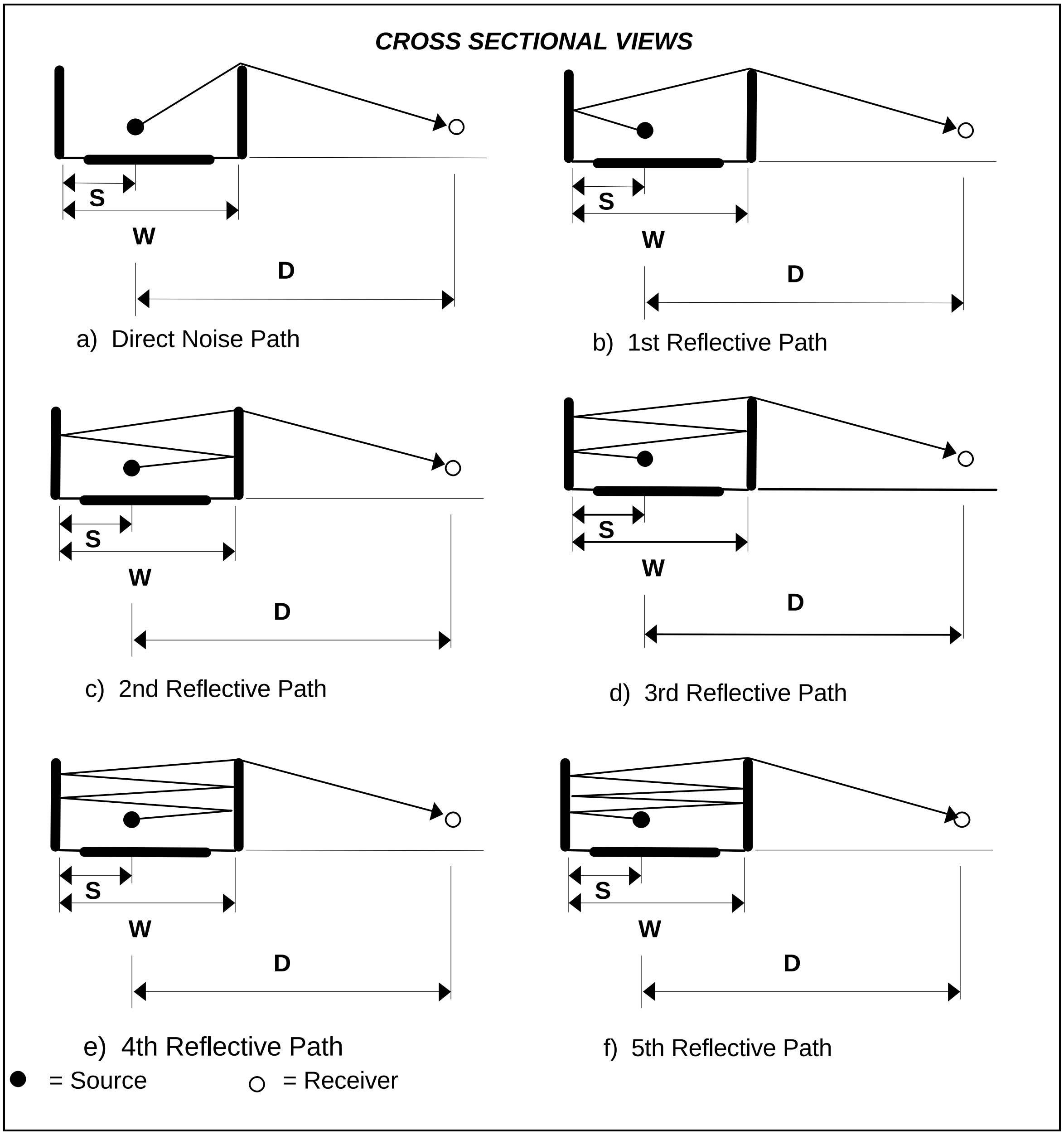
Needless to say, only primary reflections should be considered when employing the above methods. And since each receiver is affected by a different set of reflections, the number of receivers modeled should be kept to a minimum. Even then, modeling of reflective noise can be a very cumbersome process. FHWA Traffic Noise Model (TNM), presently being phased in, does not have, at this time, provisions for reflection calculations other than the parallel barrier analysis mentioned in the next section. However, it is anticipated that in the near future single barrier reflections will be included in routine calculations in TNM, eliminating the need for manipulating the input source data.

N-8120 Parallel Barrier Reflections

Multiple reflections between reflective parallel noise barriers (noise barriers on each side of the highway) can potentially reduce the acoustical performance of each individual barrier. Figure N-8120.1 shows a simple illustration of only five of the many possible reflective paths in addition to the direct path to the top of the barrier. Theoretically, there are an infinite number of possible reflective noise paths. Each reflection essentially becomes a new source, which may add to the noise diffracted by the barrier nearest to the receiver. This in turn may reduce the barrier's effectiveness.

Figure N-8120.1 clearly shows, however, that as the number of reflections for each possible path increases, the path length becomes significantly longer. However, in all instances the barrier to receiver distance is the same. Only that portion of the path length from source to receiver that lies between the barriers changes. For the direct path this distance is **W - S**, where **W** is the separation distance between the two barriers and **S** is the distance between the far barrier to the source. For the first reflective path the distance is approximately (**W + S**), and for the second reflective path approximately **3W - S**. Further examination of Figure N-8120.1 shows that the path length difference between the first reflective path and the direct path is **2S.** The difference between the second and first reflective paths is **2(W - S)**. The pattern repeats itself for subsequent reflections. These increases in path length distances for each subsequent reflection soon make their contribution to the total diffracted noise insignificant, i.e. only the first few reflections are important.

Figure N-8120.1 - Various Reflective Noise Paths for Parallel Noise Barriers



For instance, for the special case where W = 2S (source halfway between the barriers), each subsequent reflective path increases by W. Assuming the distance between the source and receiver D = W (a fairly typical situation) and the NRC is 0.05 (95% of energy reflected at each reflection point), the contribution of each subsequent reflection decreases rapidly due to increasing path length as shown in Table N-8120.1. The table assumes only the effects of increasing distances and a slight absorption by the walls (5% at each reflection point), and does NOT include the effects of the location of the final point of reflection with respect to the source location. This affects the amount of diffraction by the wall on the receiver side, which will be different for each of the reflective paths. Also ignored are pavement reflections, constructive and destructive interference of the sound waves, frequency shifts and the effects of the traffic mix, traffic stream, and lane distribution.

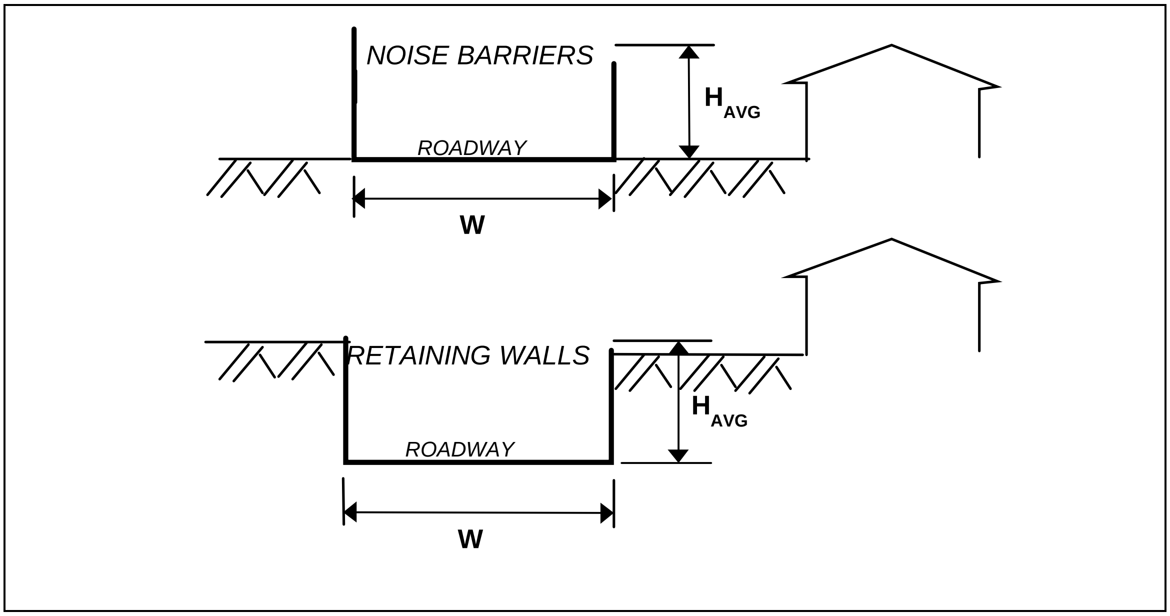
Table N-8120.1 - Contribution of Reflections for the Special Case where W=2S, D=W, and NRC=0.05.

NOISE PATH	DISTANCE, (RE: W) (Source to Receiver)	DISTANCE ADJUSTMENT,(Direct to Reflective Path) 10Log(W/XW) (X=2,3, ,11) dBA (1)	ABSORBED, (NRC=0.05), dBA (2)	CONTRIBUTION, (RE: Direct), dBA (1+2)	CUMULATIVE TOTAL NOISE LEVEL (RE: Direct), dBA (Direct + 1st Refl. + 2nd Refl., etc.)
Direct	W	0 (Ref.)	0	0 (Ref.)	0 (Ref.)
1st Reflective	2W	-3.0	-0.2	-3.2	+1.7
2nd Reflective	3W	-4.8	-0.45	-5.25	+2.5
3rd Reflective	4W	-6.0	-0.7	-6.7	+3.0
4th Reflective	5W	-7.0	-0.9	-7.9	+3.3
5th Reflective	6W	-7.8	-1.1	-8.9	+3.6
6th Reflective	7W	-8.5	-1.3	-9.8	+3.8
7th Reflective	8W	-9.0	-1.6	-10.6	+3.9
8th Reflective	9W	-9.5	-1.8	-11.3	+4.1
9th Reflective	10W	-10.0	-2.0	-12.0	+4.2
10th Reflective	11W	-10.4	-2.2	-12.6	+4.3

Noise contributions from parallel barrier reflections are obviously depended on the source to receiver distance. For a fixed W, the relative distance attenuation for each reflective path decreases as the D increases. The contribution of each reflection also increases as W decreases in relation to D (Figure N-8120.1).

Noise contributions of reflections between parallel barrier degrade the performance (insertion loss) of each noise barrier. How much degradation takes place depends of course on the site geometry and barrier configurations. In addition to the factors shown in Figure N-8120.1 and Table N-8120.1, there is another important relationship between the ratio of the separation between two parallel barriers (W) and their average height (H_{AVG}), and the amount of insertion loss degradation. As a rule, if the W/H_{AVG} ratio is 10:1 or greater, the insertion loss degradation is less than 3 dBA, and not noticeable to the human ear. This has been supported by Caltrans research and research done by others. Because of noise barrier height restrictions of 5 m (16 ft), parallel noise barriers in California have a W/H of 10:1 or greater. Although there have been claims to this effect, there are no known instances where reflective parallel noise barriers in any configuration, anywhere, have ever measurably increased noise levels over those without noise barriers. The W/H_{AVG} guideline applies not only to noise barriers but also to retaining walls or combinations of both. Figure N-8120.2 shows these concepts.

Figure N-8120.2 - W/H$_{AVG}$ Ratio Should be 10:1 or Greater

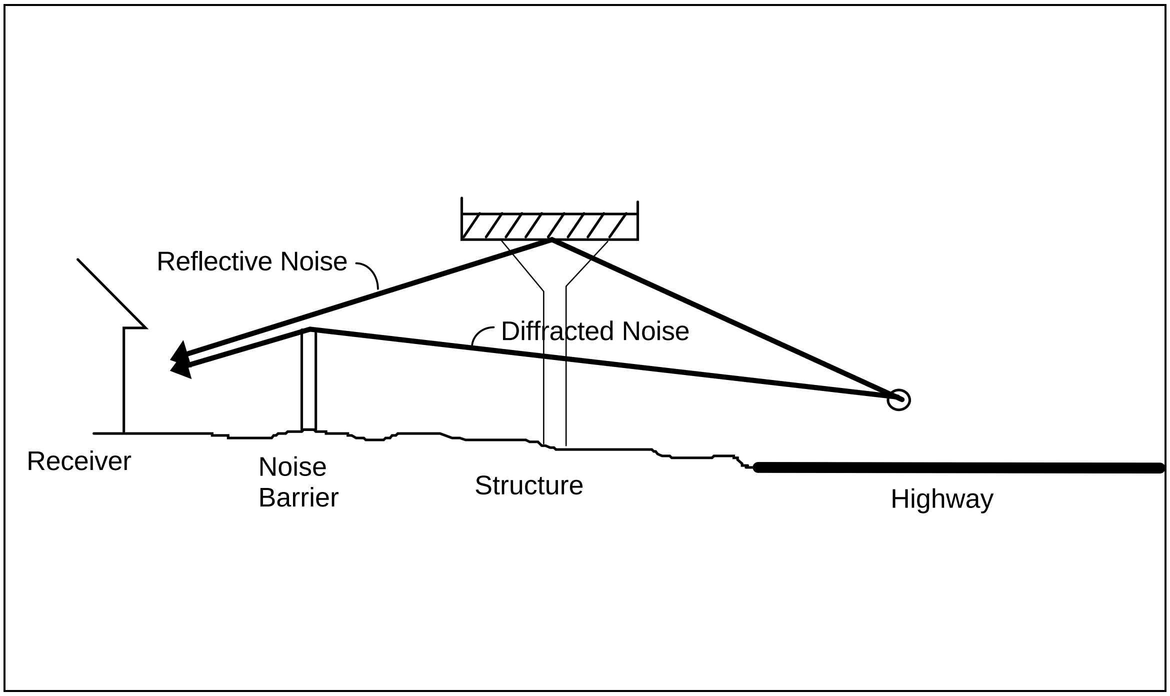


N-8130 REFLECTIONS OFF STRUCTURES AND CANYON EFFECTS

Generally, the same rules that apply to reflections off noise barriers apply to those off *retaining walls*. Since the height limitations to noise barriers do not pertain to retaining walls, there is a greater potential for noise reflections, especially when the retaining walls are along stretches of depressed freeways. However, no noise barriers in this configuration have ever been shown objectively and conclusively to result in higher noise levels than those of a similar, at-grade freeway because of reflective noise.

Complex multi-level highway interchanges can present some challenging problems in noise abatement design. The widespread spatial distributions of traffic noise sources and receivers make it difficult to design noise barriers that interrupt all direct noise paths between the many source-to-receiver combinations. Additionally, reflective surfaces of concrete structural components create many opportunities for noise reflections to circumvent noise barriers. Figure N-8130.1 shows one example of a *potential* problem created by the interaction of structures and noise barriers.

Figure N-8130.1 - Noise Reflection Off Structure (Potential Problem)



The structure in the illustration provides a point (or actually a "line") of reflection off the structure's soffit. This essentially creates a new line source with respect to the receiver shown. Unlike the highway noise sources which are shielded from the receiver by the noise barrier, the reflected noise (new source) is not shielded.

High median barriers (e.g. 5 foot high concrete glare screens) are not considered a problem. Because of the barriers' limited height, reflections are most likely scattered and interrupted by the traffic stream.

The effects of reflections near *tunnel portals* also have a very limited range. A Minnesota study showed that although noise levels are elevated immediately in front of the portal, they drop to ambient levels in about 20-25 m (65-80 ft) from the portal.

Thus far, Caltrans measurements have yet to conclusively uncover problems of interaction with structures and noise barriers. The effects of reflections off structures would be limited due to the small reflecting surface, and therefore affect only a relatively small group of receivers, due to the small reflecting surface.

Studies of highways through canyons typically have shown noise increases of less than 3 dBA from *canyon effects*. Noise increases generated from highways in narrow canyons with steep side slopes theoretically *could* be greater than 3 dBA, depending on ground cover and the steepness and smoothness of side slopes. The canyon walls, to some extent, act as parallel sound walls with respect to multiple reflections. However, unless the slopes are perfectly vertical, build up of reflections will be more limited due to the slope angles.

Highways on hill sides with near vertical rock cuts are somewhat similar to the single barrier situation discussed before. No perceptible noise increases are expected. Due to the angle of the cut slope, reflections are directed skyward, while receivers would most likely be below the highway.

N-8140 MINIMIZING REFLECTIONS

When designing reflective parallel noise barriers it is recommended that a minimum 10:1. W/H_{AVG} is maintained between the two barriers, in order to avoid the possibility of perceivable barrier performance degradations. Earth berm noise barriers are not reflective and are therefore not affected by W/H_{AVG} ratios of less than 10:1.

Sound absorption has been promoted as a solution for noise reflection where actual problems would be identified. As part of an on-going program Caltrans considers a variety of proprietary noise barrier products and systems, some of which have sound absorptive characteristics. For reasons of structural integrity, safety, cost, or other factors, no absorptive material has been approved yet. For more information on barrier materials and new products, the designer should check with HQ Design and Local Programs for availability of approved materials, and the Office of Structures Design to determine which materials have been approved for use on noise barriers. Sound-absorptive materials can either be an inherent property of the barrier, or it can be added on to an existing barrier (retrofit). Either way, the cost of the barrier will likely increase substantially.

The amount of noise absorption of the materials is rated by a noise absorption coefficient **a**. The coefficient is defined as the ratio of the acoustical energy absorbed by the material to the total energy incident upon that material. For any particular material, **a** is frequency-dependent, and its value for each specific frequency ranges from 0 (perfect reflector) to 1 (perfect absorber). In order to rate the overall absorptive characteristics of the material, a measure of the average **a** over the frequency range of interest is useful. For traffic noise frequencies, an appropriate measure is the Noise Reduction Coefficient (NRC), which is the arithmetic average of **a** in four octave bands with center frequencies of 250, 500, 1000, and 2000 Hz, calculated by:

$$\mathbf{NRC = (a_{250} + a_{500} + a_{1000} + a_{2000})/4}$$

If approved absorptive materials are considered, a minimum NRC of 0.85 should be used as a criterion. This value means that 85% of the incident noise energy is absorbed and only 15% reflected. For a single reflection this can only add a maximum of 0.6 dBA to the direct noise level, instead of the theoretical 3 dBA for a perfect reflector (NRC = 0).

N-8200 EFFECTS OF NOISE BARRIERS ON DISTANT RECEIVERS

N-8210 BACKGROUND

With the proliferation of noise barriers in California, some recent public concern has emerged that under certain conditions of topography and meteorology noise barriers increase noise levels at receivers between 1/2 km to 3 km (more than 1/4 mile to 2 miles) from freeways. The concerns are based on subjective perception only. No objective evidence based on noise measurements has ever been advanced that noise barriers increase noise levels at any distance, other than under the limited conditions described in section N-8100.

The concerns raised by various homeowner groups in the San Francisco Bay Area and the Los Angeles Area include all three possible categories of source/ barrier/ receiver configurations:

1. Reflective noise barriers on the sides of highways opposite from that of the receivers (i.e. highways between barriers and receivers)
2. Parallel reflective noise barriers on each side of highways
3. Noise barriers between highways and receivers

The first two issues involve reflective noise of single and parallel barriers, discussed in previous section N-8100. The third issue, however, deals with diffracted noise. All of the issues involve long noise propagation distances, which are difficult to study due to the numerous variables in topography and meteorology. Caltrans experience has been that atmospheric conditions can fluctuate noise levels at those distances by more than 10 dBA, <u>with or without</u> noise barriers.

Refraction is the principle atmospheric process responsible for the fluctuations. A vertical gradient of either temperature or wind velocity produces a corresponding vertical gradient of sound velocity. This causes sound waves to refract (bend) either upwards or downwards. Upward refraction occurs during sound propagation in upwind direction or normal temperature lapse conditions (air temperatures decreasing with height). This tends to send noise skyward, leaving a noise “shadow” near the ground and thereby reducing noise levels. This occurs with or without noise barriers. Downward refraction occurs during sound propagation in downwind direction, or in temperature inversions (temperature increasing with height above the ground). Downward refraction tends to send skyward noise down, concentrating noise near the ground, thereby increasing noise levels, both with and without a barrier. Atmospheric refraction of sound waves was discussed in section N-2143.

N-8220 COMPLETED STUDIES

N-8221 Caltrans Reflective Noise Studies

On the issue of reflective noise, Caltrans has done two very detailed studies, one along 07-LA-405 in the Los Angeles community of Brentwood, and another along 03-Sac-99 in south Sacramento. These studies dealt with the acoustical performance of parallel noise barriers and the possibility of noise reflection problems. The studies are described in the following reports:

1. Hendriks, R., J.Hecker, “Parallel Noise Barrier Report: A Noise Absorptive Demonstration Project - San Diego Freeway, Interstate Route 405 in the City of Los Angeles, Community of Brentwood”, California Department of Transportation, District 7 Environmental Investigations Section (With Assistance of Transportation Laboratory), Los Angeles, CA., July 1989.
2. Hendriks, R., “Field Evaluation of Acoustical Performance of Parallel Noise Barriers Along Route 99 in Sacramento, California”, Report No. FHWA/CA/TL-91/01, California Department of Transportation, Division of New Technology, Materials and Research, Sacramento, CA., January 1991.

The L.A. study (1) was part of a demonstration project to test acoustically absorptive treatment on one of two parallel masonry sound walls. The project was initiated by District 7 (Los Angeles) in response to concerned home owners living in Brentwood at distances of 0.3 - 0.6 km (0.2 to 0.4 miles) away from the freeway. The terrain between the residences and the freeway ranged in height from -6 to +15m (-20 to +50 ft) relative to the freeway and was occupied by single and multi-story residential units. Some homeowners perceived an increase in noise when the opposite sound wall was constructed about seven years after the near sound wall had been completed. Legal action was initiated to have Caltrans remove the wall or have it treated with a noise absorptive material. No noise level increase had been perceived when the first (near) barrier was constructed.

In 1987 the Division of New Technology, Materials and Research (NT,M&R), also known as TransLab - was contacted to perform the before and after treatment noise study. NT,M&R's approach was to take simultaneous noise measurements at 14 different locations, of which 11 were in the vicinity of the freeway sound walls, at distances up to 61 m (200 ft) from the near wall and at heights of up to 7m (23 ft) above the ground, and the remaining 3 near the residences. Concurrent meteorological observations (wind speed, direction, temperature and humidity) and lane-by-lane traffic counts on the Route 405 freeway, on/off ramps, and Sunset Boulevard were also taken. Fifteen "before" and ten "after" measurements were taken at the freeway sites; twenty-seven before and twenty-two after at the 3 distant sites. Each measurement lasted 15 minutes. About thirty District 7 and NT,M&R personnel participated in the study. At Caltrans' request an expert in the discipline of transportation noise, Dr. William Bowlby from Vanderbilt University, also participated in the study by analyzing the data independently. His results and method of analysis were reported the following document:

3. Bowlby, W., "Parallel Noise Barrier Study, 07-LN-405, Prediction and Analysis of Data Before and After Acoustical Treatment", Submitted to California Department of Transportation, District 7, Los Angeles, CA, Contract 07D527, Department of Civil and Environmental Engineering, Vanderbilt University, Nashville, Tennessee, June 2, 1989.

The before and after data were carefully matched by wind speed and direction, and normalized for traffic variations.

Analyses in (1) and (3) showed that the acoustical material reduced the noise by an average of 1 dBA. Human ears cannot perceive a change of 1 dBA. Since the acoustic material was an almost perfect noise absorber of the reflective noise, the after treatment condition, in essence, simulated a no wall condition on the opposite side of the freeway. From the results NT,M&R concluded that there was no reflection problem to begin with.

However, fluctuations in noise levels at 0.3 km (0.2 miles) and greater were as large as 8 dBA with relatively minor changes in wind speed and direction. Even at 61 m (200 ft) behind the barrier minor wind shifts were responsible for noise fluctuations of about 4 dBA. Wind was the single most important factor in changing noise levels at distances beyond 61 m (200 ft) from the barrier, even greater than differences in traffic volumes.

In 1991 NT,M&R completed the Sac-99 study (2), which represented one of the first systematic attempts to quantify the effects of multiple reflections between parallel masonry sound walls for configurations representative of many barrier locations in California. The research consisted of extensive noise, traffic, and meteorological measurements and analyses during three stages: 1) without any sound walls, 2) after construction of the near sound wall, and 3) after completion of the far sound wall. More than one-hundred 15-minute measurements were taken at 11 locations, simultaneously, ranging from 0 to 61 m (200 ft) behind the near barrier and at heights of 1.5 to 7 m (5 to 23 ft) above the ground. The objective was to determine how much the performance of the near barrier would be decreased by the reflections off the far barrier. Once again, the staged data were carefully matched by meteorology. The results indicated that the average reduction in near sound wall performance ranged from 0 to 1.4 dBA, well below the generally recognized 3 dBA human perception threshold of changes in noise levels. As was the case with the L.A. study, the data showed large fluctuations in noise that occurred during all three stages (i.e. with or without noise barriers) as a result of meteorological conditions. Under all measured conditions, however, the barrier provided adequate insertion loss.

The above studies were performed under carefully documented "real world" conditions and showed no evidence of reflection problems. However, the studies did clearly demonstrate the profound effect of meteorological conditions on traffic noise levels. Any before and after comparisons of noise data should therefore be matched as carefully as possible by meteorological conditions to be meaningful. Given the number of variables involved, the level of effort and cost that must go into a noise study involving long distances is substantial.

N-8222 Reflective Noise Studies by Others

The U.S. Department of Transportation, Volpe National Transportation Systems Center completed two parallel barrier studies during the period of October 1986 through April 1994. The studies were funded by the highway agencies of seventeen states, including Caltrans. The findings of the two studies are reported in:

4. Fleming, G.G., E. Rickley, "Performance Evaluation of Experimental Highway Barriers", Report Number DOT-VNTSC-FHWA-94-16, U.S. Department of Transportation, Research and Special Programs Administration, John A. Volpe National Transportation Systems Center, Cambridge, MA 02142, April 1994.

The first study examined the performance of two parallel experimental highway noise barriers constructed on opposite sides of a two-lane asphalt service road at Dulles International Airport near Washington, D.C. The barriers were constructed in such a way that they could be configured to have absorptive and/or reflective roadside facades, or be independently tilted outward, away from the roadway, at angles of 7, 15, and 90 degrees. A

90-degree tilt angle simulated effective removal of the barrrier. The barrier behind which noise measurements were made was 152 m (500 ft) in length; the barrier on the opposite side was 76 m (250 ft) long and centered on the 152 m barrier. For each of 12 individual barrier configurations, noise and meteorological measurements were made at 10 locations behind the 152 m barrier and 10 locations in an adjacent open field site, using the same distances from the noise sources and heights above the ground. The noise sources were four individual test trucks and an artificial fixed point source (speaker system) used to simulate a pass by of each test truck.

The Dulles site was not representative of the typical parallel barrier sites along California highways. Although the 4.3 m height of the barriers was typical, the 26 m (86 ft) separation (width) between the two barriers was much narrower than typical highway widths. This translates into a width/height (w/h) ratio of 6:1 for the Dulles barriers, while almost all parallel barrier sites in the U.S. have at least a 10:1 ratio. The Dulles study concluded that the worst insertion loss degradation reached as high as 6 dBA due to multiple reflections between the parallel reflective barrier facades.

A second site along I-495 in Montgomery County, Maryland, was used to measure parallel barrier degradation under more realistic yet still severe conditions of free-flowing traffic but a w/h ratio of 9:1 (still less than typical). The degradations were measured using 10 microphone locations behind a parallel barrier section and simultaneously at 10 locations behind a single wall adjacent to the parallel barriers. In this configuration the maximum degradation reached 2.8 dBA.

Together with the Caltrans studies (1 and 2) the report (4) concluded that parallel barrier sites with w/h ratios of 10 or more would have a degradation of less than 3 dBA, an imperceptible noise increase over a single barrier.

N-8223 Noise Levels Behind A Single Noise Barrier

The third issue, that of perceived increases in noise levels behind a single noise barrier on the same side of a freeway, relates in part to the above mentioned studies. The noise level fluctuations at distant receivers are far more influenced by varying meteorological conditions than the presence or lack of a noise barrier. Therefore, any study designed to examine with and without barrier conditions will certainly have to include detailed meteorological documentation. Atmospheric equivalency must first be established, before any comparisons of before and after barrier noise data should be made.

There is no question that noise barriers are effective in the vicinity of highways, say within 100 m (330 ft). Caltrans has collected enough data over the years to substantiate this. The following report compared before and after noise measurements at eleven noise barrier sites with those predicted by noise barrier acoustical design procedures:

5. Hendriks, R.W., “Evaluation of Noise Barriers”, Report No. FHWA/CA/TL-81/07, California Department of Transportation, Office of Transportation Laboratory, Sacramento, California, June 1981.

The measurements were part of an overall evaluation of noise barriers’ performances, noise barrier acoustical design procedures, and community acceptance.

Caltrans has also experienced, in the course of many measurements, that beyond 100 m or so, noise levels often approach ambient levels (the noise levels associated with normal day-to-day activities in the community). For obvious reasons, a sound wall cannot attenuate noise below these levels. However, Caltrans has never experienced noise increases (over no-barrier noise levels) at any distance behind noise barriers. Yet, some persist that noise barriers will increase noise levels at distant receivers.

Explanations have sometimes centered on noise waves “going over the wall and coming back to the ground”. This is “diffraction” and is actually responsible for noise attenuation, rather than an increase in noise, when compared with the direct noise received without a noise barrier. (See sections N-2144, N-4510, and N-6100).

Another popular “explanation” for perceived increase in noise due to sound walls is that the sound wall “lifts” the noise over tiers of homes that normally would shield the receiver. Yet, a sound wall will no more elevate the noise source over tiers of homes than the intervening homes will. Sound walls in California are generally restricted in height to 16 feet, an amount approximately equal to the average height of residential development.

There is, however, a loss of “ground effect” behind a noise barrier (see sections N-4520 and N-6131). Without a noise barrier the direct path of the traffic noise to the receiver travels closer to the ground than after a noise barrier is built. Noise waves close to the ground are subject to excess attenuation due to absorption by the ground. Therefore, when a noise barrier is built there is a trade-off between barrier attenuation (a decrease in noise) and a loss of excess attenuation.

The net reduction of noise due to the barrier attenuation and loss of excess attenuation is called “barrier insertion loss”(Section N-6131). Close to a barrier, there is no question that the barrier attenuation benefit far outweighs the loss of excess attenuation. At further distances, however, barrier attenuation diminishes while the cumulative effects of the loss of excess attenuation increase. Our acoustical design procedures for noise barriers take these factors into consideration by applying different noise drop-off rates to with and without noise barrier cases. If we were to keep these drop-off rates constant and apply them to long distances, there would indeed be a distance at which the loss in ground effect would eventually exceed the barrier attenuation.

Extensive amounts of field data gathered during a Caltrans noise propagation research project shows that differences between excess attenuation rates of elevated sources (e.g. truck stacks, noise diffracted over a noise barrier) and those close to the ground (e.g. tire noise) diminish after a hundred meters (few hundred feet) or so. The findings can be applied to noise barriers which in essence “elevate” the source. The cumulative effect of decreasing differences in elevated and near-ground excess attenuation rates with distance appear to cause a “bulge” at about 60 - 90 m (200 - 300 ft) behind the barrier where the effect of the differences is the greatest. At greater distances the differences in elevated and near-ground noise levels appear to become smaller again until they disappear at some distance beyond 120m (400 ft). The research was documented in the following report:

6. Hendriks, R.W., “Traffic Noise Attenuation as a Function of Ground and Vegetation (Final Report)”, Report No. FHWA/CA/TL-95/23, California Department of Transportation, Engineering Service Center, Office of Materials Engineering and Testing Services, Testing and Technology Services Branch, Sacramento, CA, June 1995.

Questions have also been raised at times about whether noise “redirected” by noise barriers “bounces off” temperature inversion layers. Although NT,M&R did not have instrumentation to measure inversion layers in the L.A. study, the probability of the presence of one was very high during the early morning measurements under calm conditions. At any rate, “redirections” on the scale being discussed, involves a maximum of 5m (16 ft) high noise barriers and a distance of 400 m (1/4 mile) or more, are less than one degree and therefore negligible.

In July 1994, Caltrans contracted with a consulting firm to do a detailed before and after noise barrier study along I-680 near Walnut Creek. Caltrans had previously received complaints from residents in nearby Danville who claimed that recently constructed noise barriers increased noise levels more than 0.4 km (1/4 mile) from the freeway. The study was part of an on-going effort by Caltrans to find out if noise barriers do indeed increase noise levels at some distance from a freeway. The study concentrated on receivers from 0.4 to 1 km (1/4 to 2/3 mile) behind a 3.6 m (12 ft) high noise barrier, 1.2 km (3/4 mile) long.

The study included before and after noise barrier noise measurements of traffic noise, traffic volumes and speeds, traffic mix, and meteorological conditions. All before and after noise measurements were carefully matched by meteorology and normalized for different traffic conditions. Although the noise barrier actually decreased noise levels the amounts were insignificant and the conclusion was that the noise barrier did not affect the noise levels at the distant receivers. The results and methodology of the study are described in:

7. "Interstate 680 Livorna - Stonecastle Soundwall Study", Woodward-Clyde Consultants, Oakland, California, and Illingworth and Rodkin, Inc., Fairfax, California, Submitted to California Department of Transportation, Oakland, California, July 1994.

The study also included measurements on the opposite side of the freeway to measure reflections off the noise barrier. As expected, there was a noise level increase of 0-2.4 dBA, with an average of 1.5 dBA. Such a small increase is not noticeable by the human ear.

After years of research, Caltrans has found no objective evidence that noise levels increase perceptibly due to noise barriers. It is widely accepted by acousticians that changes in traffic noise levels need to be 3 dBA before they can be perceived by human ears. Such increases in noise levels due to noise barriers have never been measured.

N-8230 STUDYING THE EFFECTS OF NOISE BARRIERS ON DISTANT RECEIVERS

Allegations of noise barriers increasing noise levels at distant receivers based on perception only are at best unreliable. With possible noise fluctuations of more than 10 dBA due to meteorological factors alone, person(s) making such claims must remember not only the before barrier noise levels, but also have knowledge of the meteorological conditions associated with those noise levels. In order to confirm whether noise barriers indeed do increase noise levels in some instances, a complex before and after barrier field study must be undertaken.

Before and after noise barrier(s) noise measurements do not adequately address the previous issues unless the measurements are carefully matched by before and after conditions of meteorology, traffic, and topography. Such studies are not at this time considered routine. Technical Advisory TAN-97-01-R9301 " General Guidelines for the Effects of Noise Barriers on Distant Receivers", issued in 1997, gives guidelines and criteria to cover these studies. This Technical Advisory can be obtained from the Caltrans Environmental Program, Environmental Engineering – Noise, Air Quality,, and Hazardous Waste Management Office, in Sacramento, CA.

N-8300 STOP AND GO TRAFFIC

Section N-5510 covered the California version of the FHWA traffic noise prediction model per FHWA-RD-77-108. The computer programs SOUND32 and LEQV2 predict the hourly L_{eq} for constant-speed traffic. The model is not equipped to deal with “stop and go” driving conditions typical of ramps, arterials and city streets.

A model suitable for use with STAMINA 2.0 (Federal computerized version of the FHWA Model) has been developed by Dr. William Bowlby of Vanderbilt University under contract to the National Cooperative Highway Research Program (NCHRP). The former Division of New Technology Transportation Materials and Research further revised this model for use with SOUND32 (California version of the STAMINA 2.0). The full report in which the model and its use with STAMINA 2.0 is described is:

8. Bowlby, W., R.L.Wayson, and R.E. Stammer, Jr., “Predicting Stop-and-Go Traffic Noise Levels”, NCHRP Report 311, Transportation Research Board, National Research Council, Washington, D.C., November 1989.

The report, excerpts from the report, and revisions for use with SOUND32 are available from Caltrans Environmental Program, Environmental Engineering – Noise, Air Quality, and Hazardous Waste Management Office, in Sacramento, CA.

When TNM (see Section N-5520) is mandated, the above method will be obsolete. TNM has provisions for dealing with interrupted-flow traffic.

N-9000 GLOSSARY

The terms and definitions in this glossary are either used in this Supplement, or are commonly found in environmental noise literature. To make this glossary more useful to the highway traffic noise analyst, the definitions herein are generally biased towards highway traffic noise and the abatement thereof, instead of general acoustics.

Absorption (of Sound) - The attenuation of sound (noise) caused by conversion of sound energy into other forms of energy (usually heat) within a medium. Absorption is a property of the medium (material). In noise barrier material, absorption can be thought of as the complement of reflection. A perfectly absorptive material does not reflect any sound energy; a non-absorptive (reflective) material reflects almost all of the sound energy. In either case, a small portion of sound energy is transmitted through the barrier and continues in roughly the same direction as the incident noise propagation. (See *Transmission Loss*). In typical highway traffic noise barriers, the sound energy passing through is less than 1% of the incident noise energy.

Absorption Coefficient - A term that approximately equals the ratio of sound energy absorbed by a material to the energy incident upon the material. Absorption coefficients range from 0 (no absorption) to 1 (perfect absorption). In highway noise barriers, material with an absorption coefficient of 0 will reflect back almost all the incident noise energy; material with a coefficient of 1 will not reflect back any sound energy. The absorption coefficient is dependent on material, the sound frequency and angle of incidence.

Absorptive Grounds - Types of ground (such as normal earth and most grounds with vegetation) that are absorptive to sound energy, and that reverse the phase of reflected energy at grazing angles of incidence. (See also *soft sites* and *ground effects*).

Acoustics - The broad field of science that deals with the production, propagation, reception, effects, and control of sound, audible and inaudible to the human ear, and occurring in all media.

Airborne Sound - Sound that reaches the point of interest primarily by propagation through the air.

Ambient Noise (Level) - All-encompassing noise (level) at a given place and time, usually a composite of sounds from all sources near and far, including any specific source(s) of interest.

Amplitude - The strength or magnitude of the pressure of a sound wave.

Anechoic Chamber (Room) - A room whose boundaries have been designed to absorb nearly all of the sound incident on them, thereby affording a test room essentially free from reflected sound, simulating a free field conditions for the limited space defined by the room’s boundaries.

Angle of Diffraction - The angle through which sound energy is diffracted (bent) as it passes over the top of a noise barrier and then proceeds towards the receiver. Receivers deeper into the shadow zone have larger angles of diffraction, and therefore greater barrier attenuation. (See *Diffraction, Shadow Zone.*)

Angle of Incidence - The angle formed by the radial line of sound waves striking a surface at a specific location and the plane of that surface. (See *angle of reflection*).

Angle of Reflection - The angle formed by the radial line of sound waves reflecting off a surface at a specific location and the plane of that surface. (See *angle of incidence*).

Atmospheric Effects - Sound absorption by air molecules and water vapor, sound refraction caused by temperature and near-ground wind gradients, and air turbulence are collectively called atmospheric effects. Although atmospheric effects are mostly responsible for substantial noise fluctuations at distant receivers, they also can have a significant effect at distances within a 100 m (330 feet).

Audible (Frequency) Spectrum - The frequency range normally associated with human hearing, usually considered between 16 - 20,000 Hz. For noise control purposes, the audible spectrum of interest usually lies between 20 - 10,000 Hz.

Audiogram - A graph showing hearing loss as a function of frequency.

Audiometer - An instrument for measuring hearing sensitivity or hearing loss.

Automobile - A vehicle classification for the purpose of noise prediction modeling, defined as all vehicles with two axles and four wheels designed primarily for transportation of nine or fewer passengers (automobiles), or transportation of cargo (light trucks). Generally the gross weight is less than 10,000 lbs (4,500 kg).

Average (Noise) Level - Typically the "energy-averaged" noise level in dB, wherein the contributing levels are first converted to "relative energies" or "energy ratios", and added and divided by the number of contributing levels. The result is then converted back to dB.

A-Weighted Sound Level (abbreviated dBA or dB(A)) - Frequency weighted Sound Pressure Level approximating the frequency response of the human ear. It is defined as the sound level, in decibels, measured with a sound level meter having the metering characteristics and a frequency weighting specified in the American National Standards Institute Specification for Sound Level Meters, ANSI S 1.4 - 1983. The A-weighting de-emphasizes lower frequency sound sounds below 1000 Hz (1kHz) and higher frequency sounds above 4 kHz. It emphasizes sounds between 1kHz and 4 kHz. A-weighting is the most generally used measure for traffic and environmental noise throughout the world.

Background Noise - The total of all noise in a system or situation, independent of the presence of the noise source of interest (i.e without the noise of interest).

Baffle - A shielding structure or series of partitions used to increase the effective external transmission path length between two points in an acoustic system.

Band - (See *Frequency Band*)

Band Center Frequency - The designated (geometric) mean frequency of a band of noise.

Band Pressure Level - The sound pressure level contained within a specified band.

(Noise) Barrier Attenuation - The noise reduction due to barrier diffraction only.

Broadband Noise - Noise with components over a wide range of frequencies.

Calibrator - A device used to calibrate -or properly adjust for valid measurement results- a sound level meter and microphone system. Calibration must be performed before and after sound level measurement sequence.

Community Noise Equivalent Level (CNEL) - A noise level that takes into account all the A-weighted noise energy from a source during 24 hours and weights the evening (7 to 10 p.m.) noise by adding 5 dBA, and night (10 p.m. to 7 a.m.) noise by adding 10 dBA, respectively, during these periods.

Compression (of Sound Wave) - The portion of a sound wave in which the air molecules are slightly compressed with respect to the barometric air pressure (opposite of rarefaction).

Cylindrical Divergence (- Spreading) - Sound waves generated by a line source, such as approximated by a highway, tend to form cylindrical wave fronts that propagate by radiating outward from their original line source in cylindrical pressure waves of ever increasing areas. This process is referred to as cylindrical divergence or spreading. The same sound energy distributed over an ever increasing cylindrical area is reponsible of reducing the sound's energy per unit area (intensity) by one half for each doubling of distance. This corresponds with a noise level decrease of 3 dB per doubling of distance.

Cycles Per Second - (See *Hertz*)

Day-Night Level - (See L_{dn})

Decibel (Abbreviated dB) - A decibel is one-tenth of a Bel. It is a measure on a logarithmic scale which indicates the squared ratio of sound pressure to a reference sound pressure (unit for *sound pressure level*), or the ratio of sound power to a reference sound power (unit for *sound power level*). (See *sound pressure level*, and *sound power level*).

(Noise) Descriptor - A generic term for a noise indicator such as L_{eq}, L_{max}, L_{dn}, etc.

Diffuse Sound Field - A sound field in which the time average of the mean-square sound pressure is everywhere the same and the flow of acoustic energy in all directions is equally probable. For example, a sound source in a reverberation room, where many reflected sound waves are present and the sound level is equal at any location in the room.

Diffraction - The bending of sound pressure waves around an obstacle. The ease with which the pressure waves diffract around an obstacle depends on the ratio of wavelength to the size of the obstacle. Pressure waves with a given wavelength diffract more readily around a small object than a large object. Pressure waves with a longer wavelengths diffract more easily around an object of a given size than pressure waves with a shorter wavelength. Due to the above principles, highway traffic noise barriers provide a more defined noise "shadow" behind the barrier (and more noise attenuation) for higher frequency noise than for lower frequency noise. (See Angle of Diffraction, Shadow Zone)

Doppler Effect - The change in observed frequency of a sound wave caused by a time rate of change in the effective path length between sound source and receiver. If the path length rate of change causes the source and receiver to approach each other, the observed frequency shifts upward. If the source and receiver recede relative to each other, the frequency shifts downward. The frequency shift is called the Doppler Shift, and the unit is Hertz.

Dosimeter - An instrument measuring noise exposure for compliance with OSHA standards.

Dynamic Range - The range in sound levels (in dB) through which a source or receiver can emit or receive sound. For example, the dynamic range of a sound level meter typically ranges from 20 - 140 dB.

Emission Level - A measure of the noise output of a single vehicle. It is the maximum noise level, in dBA, observed during a passby of the vehicle at 15 m (50 ft). (See also Reference Energy Mean Emission Level).

Energy Average (- Mean) - The (noise level) result of energy averaging, or a method of averaging various sound pressure levels on the basis of their squared pressures (energy). This method involves the conversion of decibels to equivalent relative energy or energy ratios, averaging and changing the values back to decibels.

Energy Ratio - (See *Relative Energy)*

Equivalent (Lane) Distance (D_E) - The distance to a specific receiver from an imaginary single lane which acoustically represents a multi-lane highway or a group of lanes, such as directional lanes.

Equivalent Level - (See L_{eq}).

Excess Attenuation - Sound attenuation in addition to that caused by geometric spreading (see *geometric spreading*). Usually meant to be the attenuation due to ground effects and sometimes also the atmospheric effects (see *ground effects, atmospheric effects*).

Existing Noise Levels - The noise, resulting from the natural and mechanical sources and human activity, considered to be usually present in a particular area.

Far (Sound) Field - The region beyond the near field, where the effects of source dimensions are less important and where the noise propagates with a simple relationship between sound level and distance.

Filter - A device for separating components of a signal on the basis of their frequency. It allows components in one or more frequency bands to pass relatively unattenuated, and it attenuates components in other frequency bands.

Flanking Noise - Refers to noise energy that arrives at an observer by some unexpected or unexamined pathway. For example, in the design of noise barriers, the calculations predict the energy that diffracts over the top of the barrier. If significant amounts of noise energy reach the observer by passing around its ends far up and down the roadway, this energy has flanked the barrier along unexpected “flanking paths”.

Free (Sound) Field - A sound field that is free from enclosures or boundaries, and in which there are no reflections and accompanying interference and reverberation effects such as found in auditoriums.

Frequency - The number of oscillations per second (a) of a periodic wave sound, and (b) of a vibrating solid; expressed in units of Hertz (abbreviated Hz), formerly cycles per second (cps). 1 Hz = 1cps = 1 oscillation per second. The value is the reciprocal (1/x) of the period of oscillations in seconds. The symbol for frequency is f.

Frequency Band - An interval of the frequency spectrum defined between an upper and lower cut-off frequency. The band may be described in terms of these two frequencies, or, preferably, by the width of the band and the geometric mean frequency of the upper and lower cut-off frequencies, e.g., an octave band "centered" at 500 Hz.

Frequency Response - The response (or sensitivity) to an oscillating phenomenon (e.g., sound pressure) by an object (e.g., microphone or ear) measured in decibels as a function of frequency. For example, the A-weighting curve (see A-weighted sound level) corresponds closely to the frequency response of human hearing at a certain constant level of sound energy.

Frequency Spectrum - The description of a sound wave's resolution into components, each of different frequency and (usually) different amplitude and phase.

Fresnel Number (N) - A dimensionless value used in predicting the attenuation of a noise barrier located between a noise source and a receiver. In its simplest mathematical form $N=2\delta/\lambda$, where δ is the path length difference between the sound path from source to receiver via the top of the barrier and the straight line between the source and receiver; λ = the wavelength of the sound (units of δ and λ must be the same). Generally, the larger the value of N, the greater the attenuation.

Fundamental Frequency - The frequency with which a periodic function (e.g., a sound wave) reproduces itself, sometimes called the first harmonic (see *harmonic*).

Geometric Divergence (- Spreading) - Refers to the shape of sound pressure wave fronts and the manner in which they propagate. Geometric divergence or spreading is a generic term used for specific types of divergence, such as cylindrical or spherical divergence. (see cylindrical divergence and spherical divergence).

Gradient (Re:Speed of Sound, Temperature, or Wind Velocity) - Variation of speed of sound, temperature, and wind velocity with height above the ground surface. A gradient in speed of sound can be caused by differences in temperature with height above the ground and/or differences in wind velocities with height above the ground. The speed of sound gradient in turn causes (atmospheric) refraction of sound which can create noise "shadows" (decreases) in certain areas and noise concentrations (increases) in others. (See *(atmospheric) refraction*)

Ground Effects - The effects of sound grazing absorptive ground (see *absorptive grounds*).

Hard Site (- Ground) - Term used for reflective characteristics of the ground surface between a noise source and receiver. The term is most often used in traffic noise prediction models, where it is associated with a 3 dB per doubling of distance line source attenuation (i.e. due to geometric spreading only, without excess attenuation).

Harmonic - A sinusoidal (pure tone) component whose frequency is a whole-number multiple of the fundamental frequency of the wave. If a component has a frequency twice that of the fundamental frequency it is called the second harmonic.

Heavy Truck (HT) - A vehicle type for the purpose of noise prediction modeling, defined as all vehicles with three or more axles designed for transportation of cargo. Generally the gross weight is greater than 12,000 kg (26,500 lbs.).

Hertz (Hz) - Unit of frequency, formerly called cycles per second (cps). 1 Hz = 1 cps. (See *frequency*).

Hourly Equivalent Sound Level - See (L_{eq} *(h)*)

Incident Sound - Direct sound striking a surface (see *angle of incidence*).

Infrasound, Infrasonic - Sound(s) with frequencies below the audible sound spectrum (generally lower than 16-20 Hz).

Insertion Loss (IL) - The actual noise level reduction at a specific receiver due to construction of a noise barrier between the noise source (traffic) and the receiver. Generally, it is the net effect of the (noise) barrier attenuation and the loss of ground effects.

Inverse First Power - The lessening (increasing) of sound amplitude due to the process of *cylindrical divergence* (see *cylindrical divergence*) from a *line source*. For a *line source*, the sound pressure level SPL_1 at distance D_1 is related to the sound pressure level SPL_2 at a distance of D_2 by the equation:

$$SPL_1 - SPL_2 = 10 \log (D_1 / D_2)$$

Inverse Square - The lessening (increasing) of sound amplitude due to the process of *spherical divergence* (see *spherical divergence*) from a *point source*. For a *point source*, the sound pressure level SPL_1 at distance D_1 is related to the sound pressure level SPL_2 at a distance of D_2 by the equation:

$$SPL_1 - SPL_2 = 10 \log (D_1 / D_2)^2$$

kHz - abbreviation for kilo Hertz, or 1,000 Hertz; e.g. 3 kHz is 3,000 Hertz (see *Hertz*).

L_{dn} - Abbreviation for the Day-Night Level noise descriptor. It is the energy-average of the A-weighted sound levels occurring during a 24-hour period, with 10 dB added to the A-weighted sound levels occurring during the period from 10 p.m. to 7 a.m.

Leq - The equivalent steady state sound level which in a stated period of time would contain the same acoustical energy as the time-varying sound level during the same period.

Leq (h) - The energy-average of the A-weighted sound levels occurring during a one hour period, in decibels, i.e., a one hour Leq (see *Leq*).

Level - In acoustics, the value of a logarithm of the ratio (or ratio squared) of that quantity t a reference quantity of the same kind, in decibels. The base of the logarithm is commonly 10. The reference quantity and the kind of level must be specified, e.g., sound pressure *level* of 60 dB re: 20 μPa, sound power *level*, re: 10^{-12} W, etc.

Line of Sight - A straight line between the observer location and a specific noise source.

Line Source (of Noise) - A source of noise spread out into a line, such as approximated by the combined traffic on a roadway.

L_{max} - The highest sound pressure level in a specific time period.

Logarithm (Log) - A mathematical operation which, for values greater than 1, condenses these into smaller values by doing the reverse of y^x, where x is the number which is being operated on. Normally the base, or value of y, is taken as 10 (common log). If the base is not specified, its value is usually considered as 10. Thus, if $10^x = a$, then $x = \text{Log}_{10} a$ or Log a. If a > 1, x is positive; if a=1, x=0, and if 0<a<1, x is negative. Examples:

$10^2 = 100$; Log 100 = 2 (x=2, a=100)

$10^0 = 1$ Log 1 = 0 (x=0, a=1)

$10^{-2} = 0.01$ Log 0.01 = -2 (x=-2, a=0.01)

Note: *a* must never be 0!!

Loudness - The judgement of intensity of a sound in terms of which sounds may be ranked on a scale from soft to loud. On this scale, a doubling of a reference sound energy is barely perceptible to the human ear; a tripling of the sound energy is readily perceptible, and ten times the sound energy sounds about twice as loud. Decreasing the sound by the same factors has a reciprocal effect, i.e. reducing the reference sound energy to one tenth of the original energy the sound is perceived as half as loud. Although loudness depends primarily on the intensity of the sound, it also depends on the sound's frequency and wave form.

Loudness Level - Of a sound is defined as the median sound pressure level in a specified number of trials of a 1000 Hz tone that is judged equally loud to the listener as the sound in question. Described in units of phons.(See *phon*). NOTE: calculated loudness level, L in phons is related to loudness in *sones* (see *sone*) by the equation:

$L = 10 \log_2 n_s$,

where L is the loudness level in phons and n_s is loudness in sones (see *sone*)

(A twofold change in loudness corresponds to a n interval of 10 phons)

L_x (where x= 1-99; e.g. L_{10}, L_{50}) - The sound pressure level exceeded x percent of a specific time period. L_{10} is the level exceeded 10% of the time; L_{50} is the level exceeded 50% of the time.

Masking - The action of bringing one sound (audible when heard by itself) to inaudibility or to unintelligibility by the introduction of another sound.

Medium - A substance carrying a sound wave. For example: air, water, steel.

Medium Truck (MT) - A vehicle classification for the purpose of noise prediction modeling, defined as all vehicles with two axles and six wheels designed for transportation of cargo. Generally the gross weight is greater than 4,500 kg (10,000) lbs. and less than 12,000 kg (26,500 lbs.).

(Sound Level) Meter Response - Measure of the quickness with which the needle of an analog sound level meter, or the display of a digital sound level meter, follows changes in the actual sound level.

Microphone - An electroacoustic transducer that transforms sound waves into equivalent electric waves.

Natural Frequency - Frequency of free oscillation of a system, i.e. the frequency at which a system vibrates when given an initial excitation and then allowed to vibrate freely without constraints.

Near (Sound) Field - That part of a sound field, usually within about two wavelengths of the lowest sound frequency from a sound source, where the dimensions of the sound source have an important effect, and where there is no simple relationship between sound level and distance. For traffic noise, the near field usually exists within 7.5 m (25 ft) from the nearest traffic. Noise measurements or predictions should be avoided in the near field.

Noise - Sound that is loud, unpleasant, unexpected, or otherwise undesirable.

Noise Barrier - A generic term for any feature which blocks or diminishes sound in its path from the source to the receiver. Although the term can technically refer to any feature, man-made or natural, the two most common features included in noise barriers are *sound walls* and *earth berms* (see *sound walls; earth berms*). Almost all noise barriers in California are sound walls, and for this reason the terms noise barriers and sound walls are frequently interchanged, even though sound walls are a (albeit very large) sub set of noise barriers.

Noise Contour - An imaginary line shown on a plan along which sound levels are all equal.

Noise Floor - The level of noise (in dB) which represents the threshold of sensitivity for a sound level meter and below which the inherent, or the device's own noise, limits its detectability of low-level signals.

Noise Reduction Coefficient (NRC) - A value representing the arithmetic average of the absorption coefficients in four octave bands with respective center frequencies of 250, 500, 1000, and 2000 Hz.

Octave - The interval between two sounds having a frequency ratio of 1:2; e.g., 500 - 1,000 Hz; 440 - 880 Hz, etc.

Octave Band - A frequency band in which the interval between the upper and lower cut-off frequency is one octave. As is the case with all frequency bands, the octave band is usually described by its center frequency (See *frequency band).* Octave bands are centered by preferred frequencies described by ISO R 266. Example: the 500 Hz octave band.

One-Third (1/3) Octave (Also Third Octave) - The interval between two sounds having a frequency ratio of the cube root of 2 (approximately 1.26). Three contiguous one-third octaves cover the same frequency range as an octave.

One-Third (1/3) Octave Band - A frequency band in which the interval between the the upper and lower cut-off frequency is one third of an octave. As is the case with all frequency bands, the one-third octave band is usually described by its center frequency (See *frequency band).* Three contiguous octave bands make up one octave band. As is the case with octave bands, one-third octave bands are centered by preferred frequencies described by ISO R 266. Example: three one-third octave bands centered at 400, 500, and 630 Hz make up the 500 Hz octave band.

Overall (Noise) Level (Total Noise Level) - The sound pressure level which includes all the energy in all frequency bands of interest.

Pascal (Pa) - A unit of pressure (in acoustics, normally RMS sound pressure) equal to one Newton per square meter (N/m^2). A reference pressure for a sound pressure level of 0 dB is 20 µ Pa (20 micro Pascal, or 20×10^{-6} Pa).

Peak Sound (Noise) Level - (See *peak sound pressure level*).

Peak Sound Pressure - The maximum instantaneous (non-RMS) sound pressure for a transient or impulsive sound or short duration or in a specified time interval for a sound long duration. Unit is Pa.

Peak Sound Pressure Level - Level of peak sound pressure (see *peak sound pressure*). Peak sound pressure level may be frequency weighted (such as A-weighted). Note: sound pressure level should not be frequency weighted (see *sound pressure level*). Unit is dB with stated frequency weighting, if any.

Permanent Threshold Shift - Permanent hearing loss due to frequent exposures to noise of high intensities(see *temporary threshold shift*).

Phon - Unit of loudness, judged or calculated in definition of loudness level (see *loudness level*).

Pink Noise - Broadband noise that yields the same energy for each octave band over its entire range of frequencies. Since, going from low frequencies to high frequencies, each subsequent octave band contains twice the frequency range as the previous octave band, the energy decreases with increasing frequency to maintain equal energy per octave band. (Compare with *white noise*).

Point Source (of Noise) - A noise source essentially concentrated at a single point, from which noise propagates outward in all directions (see *spherical divergence, spreading*). A single vehicle observed from some distance can be approximated as a point source.

Propagation (of Sound, Noise) - The passage of sound energy from noise source to receiver through a medium (such as air).

Pure Tone - A sound wave whose waveform is that of a sine wave (single frequency).

Random Incidence (of Sound) - Refers to sound waves that strike the receiver randomly from all angles of incidence. Such waves are common in a diffuse sound field.

Random Noise - Noise that has random characteristics in both time and amplitude - that is, any occurrence of any amplitude is as likely to occur at any one moment as any other.

Rarefaction (of Sound Wave) - The portion of a sound wave in which the air molecules are rarefied or in a slight vacuum with respect to the barometric air pressure (opposite of compression).

Rate of Decay (of Sound) - The time rate at which a sound pressure level decreases at a given receiver after the sound source is turned off. The commonly used unit is decibels per second (dB/s). It is used in measuring reverberation time of a room. (See *reverberation* and *reverberation time)*.

(Noise) Receiver (Receptor) - Most basically, a receiver (receptor) is defined as any natural or artificial sensor that can perceive, register or be affected by sound, such as a human ear, or a microphone. The definition of receiver is usually extended to a three dimensional location where such receiver is likely to be present. In noise analysis, a receiver is any location of interest to the analyst. In noise measurement, a receiver is the location of the measurement, i.e. microphone. Frequently, one receiver is selected to represent a group of receivers in the same vicinity and with the same acoustical site characteristics.

Reference Energy Mean Emission Level (REMEL) - The speed-dependent, energy-averaged maximum pass-by noise level generated by a defined vehicle type, as measured by a sound level meter at 15 m (50 ft) from the centerline of travel, at a height of 1.5 m (5 ft).

Reference (Sound) Pressure - 1) Any sound pressure to which a test pressure is being compared on a decibel scale, e.g. in the following expression:

dB = 10 $\text{Log}_{10}\left(\frac{p_1}{p_0}\right)^2$,where P_0 is the reference pressure (usually defined as 20 μ Pa).

2) The sound pressure at 1000 Hz which normal young adults can just detect; taken as 20 μ Pa.

Reflection, Angle of - (See *angle of reflection*)

Reflection (of Noise, Sound) - Bouncing back of sound waves away from an object which is 1) larger in exposed section than the wavelengths and 2) of sufficient surface weight, density and stiffness to present a very large increase in impedance compared to the air surrounding it.

Reflective Ground - Opposite of absorptive ground (see *absorptive grounds*). Grounds that do not absorb sound energy and reflect back most of the energy. Examples are paved surfaces (asphalt, concrete) and hard-packed soils.

(Atmospheric) Refraction - The bending of sound waves in arcing curves, either downward or upward, due to different velocities of sound with respect to height above the ground. The sound velocity differences are caused either by differences in near-ground wind velocity due to wind shear, or vertical changes in temperature (sound velocity increases with air temperature). Downward refraction occurs for downwind sound propagation and also during near-ground temperature inversions (temperature increases with height), and is responsible for noise increases. Upward refraction occurs for upwind sound propagation and also during near-ground temperature lapses (temperature decreases with height), and is responsible for noise decreases.

Relative (Sound, Noise) Energy - The energy ratio between a sound level to that of a reference level. For example, the sound energy of 60 dB is 10^6, or 1,000,000 times larger than that of 0 dB; that of 67 dB $10^{6.7}$, or 5,011,872 times larger than that of 0 dB. To add or subtract sound levels, the (relative) energies (not the dB levels) may be added directly. So the total relative energy of 60 dB + 67 dB = 1,000,000 +5,011,872 = 6,011,872 (RE: 0 dB), or in decibels: 10 Log (6,011,872) = 67.8 dB. The same result would be obtained if a reference of 50 dB were selected. Then the addition would be set up as follows: Total sound level= 50 dB + 10 Log [$10^{(6-5)}$ + $10^{(6.7-5)}$ = 50 dB + 10Log[10^1 + $10^{1.7}$) = 50 dB + 10Log(60.12) = 50 dB + 17.8 = 67.8 dB.

Resonance - The relatively large amplitude of sound or vibration produced when the frequency of the source of the sound or vibration "matches" or synchronizes with the natural frequency (see *natural frequency*) of vibration of an object.

Resonator - A device that resounds or vibrates in sympathy with a source of sound and vibration, i.e. the source frequency matches the natural frequency of the resonator.

Reverberant Field - The region in a room where the reflected sound dominates, as opposed to the noise source where the direct sound dominates.

Reverberation - The persistence of sound in an enclosed space, as a result of multiple reflections, after the sound source has stopped.

Reverberation Room - A room having a long reverberation time, especially designed to make a sound field inside it as diffuse (homogeneous) as possible. Also called a live room. The opposite of an anechoic chamber (room). (see *anechoic chamber*).

Reverberation Time (RT) - The reverberation time of a room is the time taken for the sound energy (or sound intensity) to decrease to one millionth (10^{-6}) (corresponding to a drop of 60 dB in sound pressure level) of its steady-state value when the sound source is suddenly stopped. It is a measure of the persistence of an impulsive sound in a room and of acoustical absorption present inside the room.

Root Mean Square (RMS) Pressure (of Sound)- The square root of the mean (average) of the squares of a set of instantaneous positive, negative or zero (sound) pressure amplitudes. The RMS value is calculated by squaring the pressure values at each instant, adding them, dividing the total by the number of values, and taking the square root of the result. The squaring of both the positive and negative values ensures a positive result. An RMS sound pressure is directly correlated with sound energy. For a single frequency (pure tone) sound, or sine wave, there is a simple relationship between the peak sound pressure and RMS value:

$$\text{Peak} = \sqrt{2} \times \text{RMS} \approx 1.414 \times \text{RMS}$$

$$\text{RMS} = 1/\sqrt{2} \times \text{Peak} \approx 0.707 \times \text{Peak}$$

(Sound, Noise) Shadow Zone - The area behind a noise barrier that is blocked from direct view of the source of noise on the roadway.

Shielding - A noise reduction at the receiver due to to the placement or existence of natural or artificial barriers, such as walls, berms, rows of buildings, or, if thick and dense enough, trees.

Sine-Wave - A sound wave, audible as a pure tone, in which the sound pressure is a sinusoidal function of time.

Soft Site (- Ground) (See Absorptive Ground)

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

Sound (Noise, Acoustic) Energy - (See *Relative Energy*)

Sound Insulation - 1) The use of structures and materials designed to reduce the transmission of sound from one room or area to another or from the exterior to the interior of a building. 2) The degree by which sound transmission is reduced by means of sound insulating structures and materials.

Sound Intensity - The average rate of sound energy transmitted in a specified direction through a unit area normal to this direction at a point considered.

Sound Level (Noise Level) - Frequency-weighted sound pressure level measured using metering characteristics and frequency weighting, such as A,B, or C, specified in the American National Standards Institute Specification for Sound Level Meters, ANSI S1.4 - 1983.

Sound Level Meter - An instrument that is used for measuring sound levels in a specified manner. It generally comprises a microphone, an amplifier, an output display, and frequency weighting networks.

Sound Power - The total amount of energy radiated into the atmosphere per unit time by a source of sound.

Sound Power Level - The level of sound power, averaged over a period of time, the reference being 10^{-12} watts.

Sound Pressure Level (SPL) - Ten times the logarithm to the base ten of the ratio of the time mean-square pressure of a sound, in a stated frequency band (or range of frequencies) to the square of the reference sound pressure in gasses, of 20 μPa. SPL represent only un-weighted RMS levels (see *root mean square*). Unit is dB.

$$\text{SPL} = 10 \text{ Log}_{10} \left(\frac{p_1}{p_0}\right)^2$$

Where: P_0 is the reference pressure of 20 μ Pa

P_1 is the sound pressure

(Sound, Noise) Source - A general term designating the sound energy generator. In transportation, noise sources are classified as point and line sources (see *point source* and *line source*), which have different propagation characteristics.

(Sound, Noise) Source Heights - The effective acoustic (centroid) height of vehicle noise sources. These heigths have been determined from vehicle noise emission data, and are programmed in the appropriate computerized noise prediction models. The heights represent the energy average of all subsources, such as exhaust, tires and engine noise, and are most important in evaluating noise barrier attenuation.

Sound Transmission Class (STC) - A single figure rating system designed to give an estimate of sound insulation properties of a partition or a rank ordering of a series of partitions. It is intended for use primarily when speech and office noise constitutes the principal problem.

Spectrum - (See *frequency spectrum*)

Speed of Sound (in Air) - The speed of sound for standard temperature of dry air at 0° C and standard air pressure of 760 mm Hg standard is 331.4 m/s, or 1087.3 ft/sec. From these base values, the variation of speed of sound with temperature is described by the following equations:

Metric Units (m/s): $$c = 331.4\sqrt{1 + \frac{Tc}{273}}$$

English Units (ft/sec): $$c = 1051.3\sqrt{1 + \frac{Tf}{459}}$$

Where:
c = speed of sound in m/s (metric) or ft/sec (English)
Tc = Temperature in degrees Celcius (include minus sign for below zero)
Tf = Temperature in degrees Fahrenheit (include minus sign for below zero)

Spherical Divergence (- Spreading) - Sound waves generated by a point source, such as approximated by a single vehicle, tend to form spherical wave fronts that propagate by radiating outward from their original point source in spherical pressure waves of ever increasing areas. This process is referred to as spherical divergence or spreading. The same sound energy distributed over an ever-increasing spherical area is responsible of reducing the sound's energy per unit area (intensity) by one quarter for each doubling of distance. This corresponds with a noise level decrease of 6 dB per doubling of distance. (See also cylindrical divergence).

Spherical Wave - A sound wave in which the surfaces of constant phase are concentric spheres. A small (point) source radiating into an open space produces a free sound field of spherical waves.

Steady-State Sound - Sounds whose average characteristics remain constant in time. Examples are the sound of an air conditioner, fan, pump, etc.

Structureborne Sound - Sound that reaches the receiver, over at least part of its path, by vibration of a solid structure.

Temporary Threshold Shift - A temporary hearing loss, evidenced by an increase in the threshold of audibility (see *threshold of audibility*) occurring after exposure to noise of high intensity. After a given time (usually up to several hours), the ear recovers to almost normal, but not quite so. After an excessive number of exposures of high intensity a hearing loss, or permanent threshold shift develops gradually..

Threshold of Audibility (- of Detectabilty) - The minimum sound pressure level at which a person can hear a specific sound for a specified fraction of trials.

Transducer - A device capable of being actuated by waves from one or more transmission systems or media, and supplying related waves to one or more other transmission systems or media. Examples are microphones, loud speakers, accelerometers, and seismometers.

Transient Sound - Transient sounds are those, whose average properties do not remain constant over time. Examples are aircraft fly-over, a passing train, a sonic boom and a gun shot.

Transmission Loss (TL) - The "loss" in sound energy at a specific frequency, expressed in decibels as sound passes through a barrier or a wall. TL may be expressed mathematically as:

$$\text{TL} = 10 \times Log\left[\frac{E_1}{E_2}\right]$$

Where: E_1 is the sound energy leaving the back of the wall, and E_2 is the sound energy as it strikes the front of the wall.

Transmission Loss is not a reduction in total energy, only a transformation from sound energy into heat. Almost all highway noise barriers provide a TL of at least 25 dBA, which means that less than 1/3 percent of the sound energy travels through the wall.

Wave - In acoustics, a propagation wave is a cyclic pressure variation in air. The waves move at a characteristic speed (speed of sound) through the medium (air) as an elastic response to a pressure perturbation at a source.

Wave front - A portion of any wave (whether in compression or rarefaction state) which can be followed as it propagates throughout the medium, analogous to the crest of a tidal wave as it crosses the ocean. At all points on the wave front, the wave is of equal amplitude and phase.

Wavelength - For a non-periodic wave (such as sound in air), the normal distance between analogous points of any two successive waves. The wavelength of sound in air or in water is inversely proportional to the frequency of the sound. Thus the lower the frequency, the longer the wavelength.

White Noise - Broadband noise, the energy of which is constant over a wide range of frequencies, i.e. energy/Hz = constant. Since each octave band range increases by a factor of two, going from low to high frequencies, each subsequent octave band contains twice the acoustical energy as the previous one. This corresponds with an increase of 3 dB in energy for each subsequent octave band. (Compare with *pink noise*).

Ultrasonic - Pertaining to sound frequencies above the audible sound spectrum (in general higher than 20,000 Hz).

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