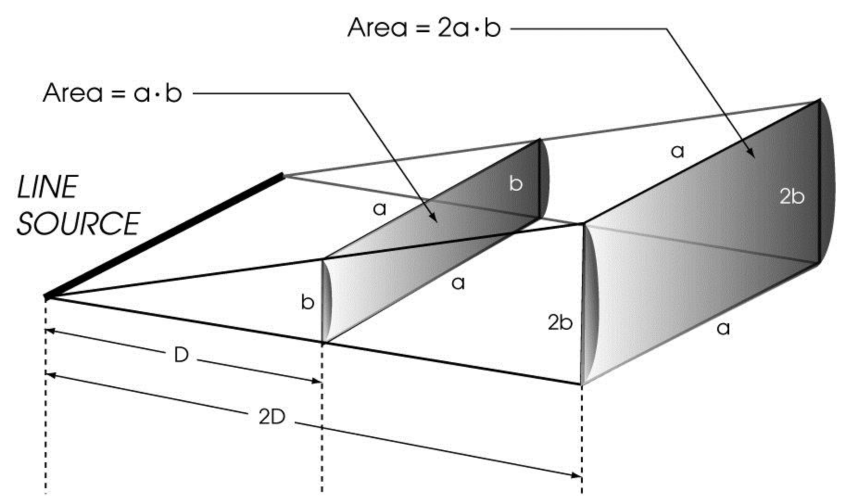

Figure 2-9. Line Source Propagation (Cylindrical Spreading)

2.1.4.2 Ground Absorption

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

The FHWA TNM is the model that is currently approved by FHWA for use in noise impact studies. The TNM has complex algorithms that directly calculate excess ground attenuation based on ground type and site geometry.

2.1.4.3 Atmospheric Effects and Refraction

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

Wind

The effects of wind on noise are mostly confined to noise paths close to the ground because of the wind shear phenomenon. Wind shear is caused by the slowing of wind in the vicinity of a ground plane because of surface friction. As the surface roughness of the ground increases, so does the friction between the ground and the air moving over it. As the wind slows with decreasing heights, it creates a sound velocity gradient (because of differential movement of the medium) with respect to the ground. This velocity gradient tends to bend sound waves downward in the same direction of the wind and upward in the opposite direction. The process, called refraction, creates a noise shadow (reduction) upwind of the source and a noise concentration (increase) downwind of the source. Figure 2-10 shows the effects of wind on noise. Wind effects on noise levels along a highway depend very much on wind angle, receiver distance, and site characteristics. A 6-mph cross wind can increase noise levels at 250 feet by about 3 dBA downwind and reduce noise by about the same amount upwind. Present policies and standards ignore the effects of wind on noise levels. Unless wind conditions are specifically identified, noise levels are always assumed to be for zero wind. Noise analyses are also always made for zero-wind conditions.

Wind also has another effect on noise measurements. Wind “rumble” caused by air movement over a microphone of a sound level meter can contaminate noise measurements even if a wind screen is placed over the microphone.

Limited measurements performed by Caltrans in 1987 showed that wind speeds of about 11 mph produce noise levels of about 45 dBA, using a ½-inch microphone with a wind screen. This means that noise measurements below 55 dBA are contaminated by wind speeds of 11 mph or more. A noise level of 55 dBA is about at the low end of the range of noise levels routinely measured near highways for noise analysis. FHWA’s *Measurement of Highway-Related Noise* (1996) recommends that highway noise measurements should not be made at wind speeds above 12 mph. An 11 mph criterion for maximum allowable wind speed for routine highway noise measurements seems reasonable and is therefore recommended. More information concerning wind/microphone contamination is provided in Section 3.

Wind Turbulence

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

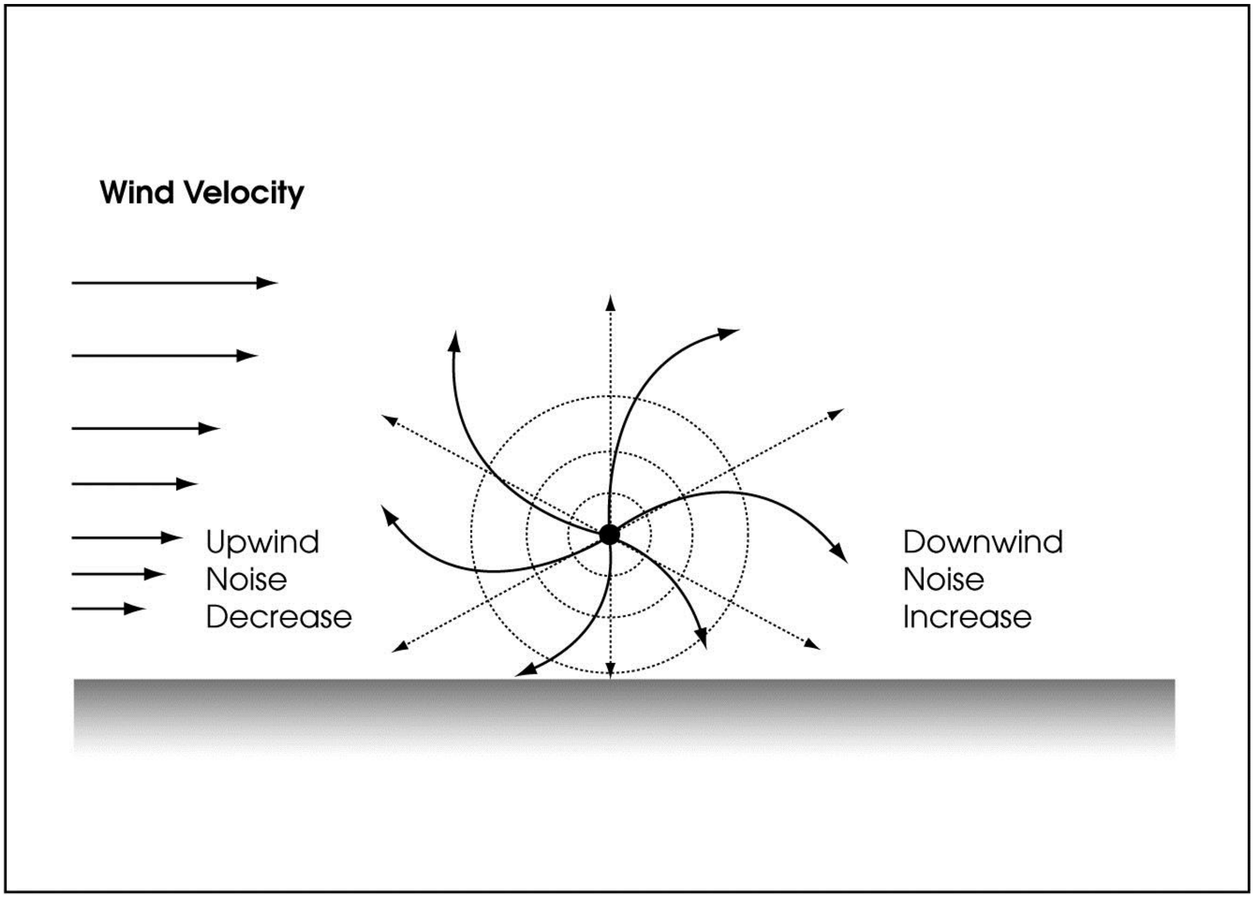

Figure 2-10. Wind Effects on Noise Levels

Temperature Gradients

Figure 2-11 shows the effects of temperature gradients on noise levels. Normally, air temperature decreases with height above the ground. This is called the normal lapse rate, which for dry air is about -5.5ºF per 1,000 feet. Because the speed of sound decreases as air temperature decreases, the resulting temperature gradient creates a sound velocity gradient with height. Slower speeds of sound higher above the ground tend to refract sound waves upward in the same manner as wind shear upwind from the source. The result is a decrease in noise. Under certain stable atmospheric conditions temperature profiles can become inverted (i.e., temperatures increase with height either from the ground up or at some altitude above the ground). This inversion results in speeds of sound that temporarily increase with altitude, causing noise refraction similar to that caused by wind shear downwind from a noise source. Also, once trapped within an elevated inversion layer, noise may be carried over long distances. Both ground and elevated temperature inversions have the effect of propagating noise with less than the usual attenuation rates and therefore increase noise. The effects of vertical temperature gradients are more important over longer distances.

Temperature and Humidity

Molecular absorption in air also reduces noise levels with distance. Although this process only accounts for about 1 dBA per 1,000 feet under average conditions of traffic noise in California, the process can cause significant longer-range effects. Air temperature and humidity affect molecular absorption differently depending on the frequency spectrum and can vary significantly over long distances in a complex manner.

Rain

Wet pavement results in an increase in tire noise and corresponding increase in frequencies of noise at the source. Wet pavement may increase vehicle noise emission levels relative to dry conditions in the range of 0 to 15 dBA (Sandberg and Ejsmont 2002). Because the propagation of noise is frequency-dependent, rain may also affect distance attenuation rates. However, traffic generally slows down during rain, decreasing noise levels and lowering frequencies. When wet, pavement types interact differently with tires than when they are dry. These factors make it very difficult to predict noise levels during rain. Therefore, no noise measurements or predictions should be made under rainy conditions. Noise abatement criteria (NAC) and standards in the FHWA noise regulation (23 CFR 772) are based on completely dry pavement.

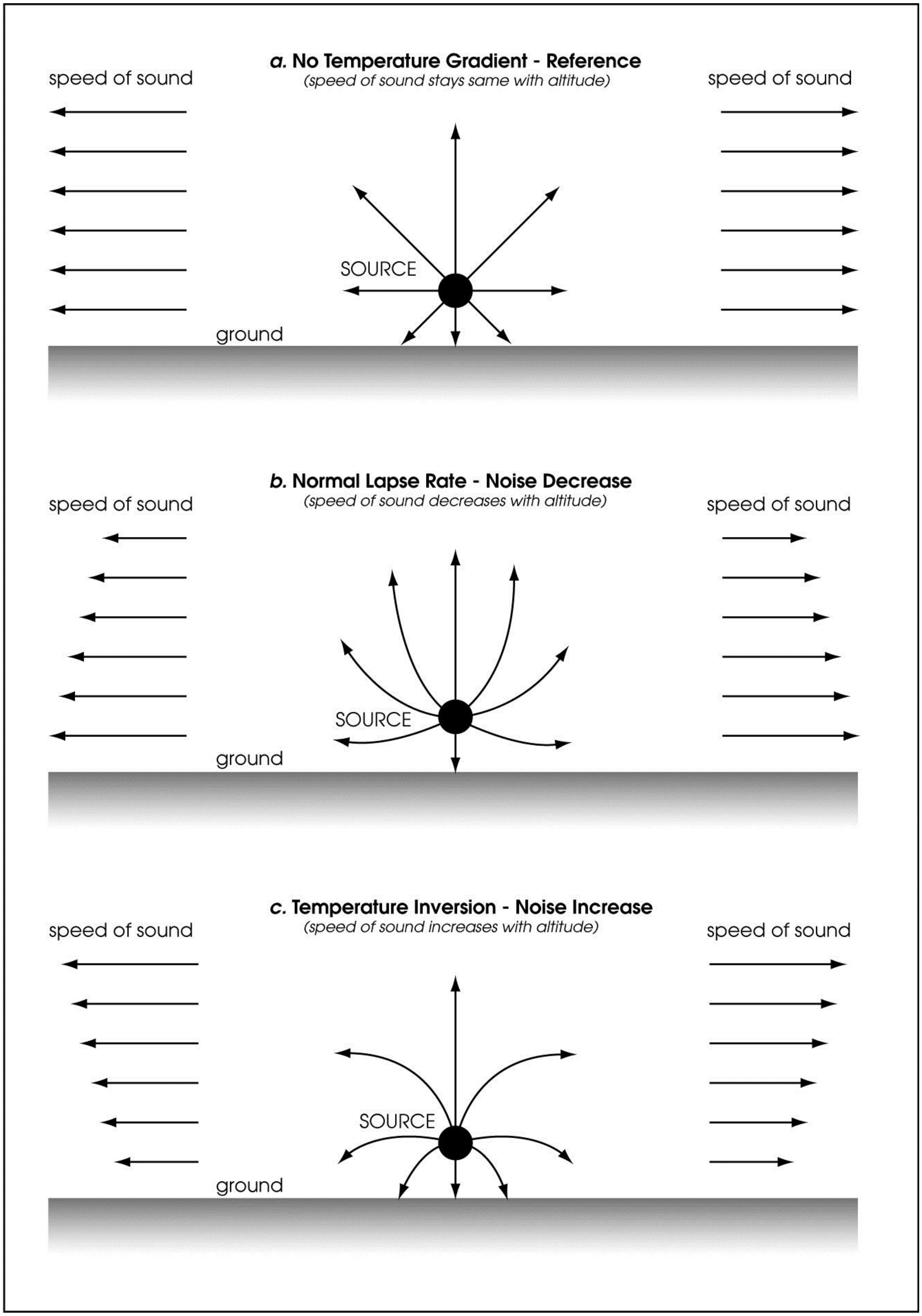

Figure 2-11. Effects of Temperature Gradients on Noise

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

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

Trees and Vegetation

It is uncommon for trees and vegetation to result in a noticeable reduction in noise. A vegetative strip must be very dense and wide for there to be any meaningful shielding effect. A heavily vegetated ground surface may increase ground absorption which can increase attenuation over distance.

Landscaping

Caltrans research (California Department of Transportation 1995) has shown that ordinary landscaping along a highway accounts for less than 1 dBA of reduction. Claims of increases in noise from removal of vegetation along highways are mostly spurred by the sudden visibility of the traffic source. There is evidence of a psychological effect (“out of sight, out of mind”) of vegetation on noise.

Buildings

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

Noise Barriers

Although any natural or manmade feature between source and receiver that reduces noise is technically a noise barrier, the term is generally reserved for a wall or berm specifically constructed for noise reduction. The acoustical design of noise barriers is addressed in Section 5. However, it is appropriate at this time to introduce the acoustical concepts associated with noise barriers. These principles apply loosely to any obstacle between the source and receiver.

As shown in Figure 2-12, when a noise barrier is inserted between a noise source and receiver, the direct noise path along the line of sight between the two is interrupted. Some of the acoustical energy will be transmitted through the barrier material and continue to the source, although at a reduced level. The amount of this reduction depends on the material's mass and rigidity, and is called the transmission loss (TL), which is expressed in decibels. Its mathematical expression is:

$$TL = 10\log_{10}(E_f/E_b) \qquad \textbf{(2-15)}$$

Where:

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

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

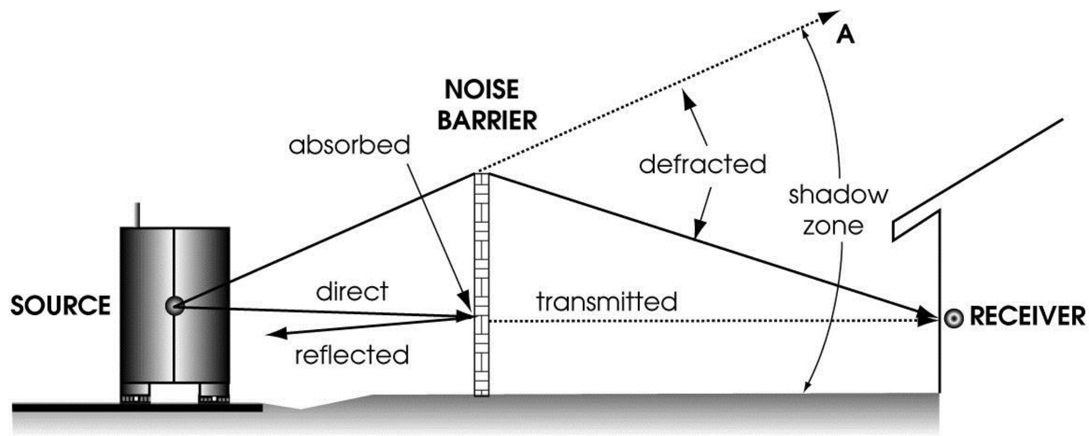

Figure 2-12. Alteration of Sound Paths after Inserting a Noise Barrier between Source and Receiver

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

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

If one wishes to calculate the noise increase from a partially absorptive wall, Equation 2-15 may be used. E_f is the noise energy striking the barrier, but E_b becomes the energy reflected back. For example, a barrier material with an α of 0.6 absorbs 60% of the direct noise energy and reflects back 40%. To calculate the increase in noise on the opposite side of the highway in this situation, the energy loss from the transformation of the total noise striking the barrier to the reflected noise energy component is $10\log_{10}(100/40)$= 4 dBA. In other words, the energy loss of the reflection is 4 dBA. If the direct noise level of the source at a receiver on the opposite side of the highway is 65 dBA, the reflective component (ignoring the difference in distances traveled) will be 61 dBA. The total noise level at the receiver is the sum of 65 and 61 dBA, slightly less than 66.5 dBA. The reflected noise caused an increase of 1.5 dBA at the receiver.

The transmitted, absorbed, and reflected noise paths shown in Figure 2-12 are variations of the direct noise path. Of these three paths, only transmitted noise reaches the receiver behind the barrier. However, there is one more path—the diffracted path—that reaches the receiver. The diffracted path is actually the most important path. With the barrier in place, sound energy traveling along this path is diffracted downward toward the receiver.

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

Because noise consists of many different frequencies that diffract by different amounts, it seems reasonable to expect that the greater the angle of diffraction, the more frequencies will be attenuated. In Figure 2-12, beginning with the top of the shadow zone and going down to the ground surface, the higher frequencies will be attenuated first, then the middle frequencies, and finally the lower ones. Please notice that the top of the shadow zone is defined by the extension of a straight line from the noise source (in this case represented at the noise centroid as a point source) to the top of the barrier. The diffraction angle is defined by the top of the shadow zone and the line from the top of the barrier to receiver. Therefore, the position of the source relative to the top of the barrier determines the extent of the shadow zone and the diffraction angle to the receiver. Similarly, the receiver location relative to the top of the barrier is also important in determining the diffraction angle.

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

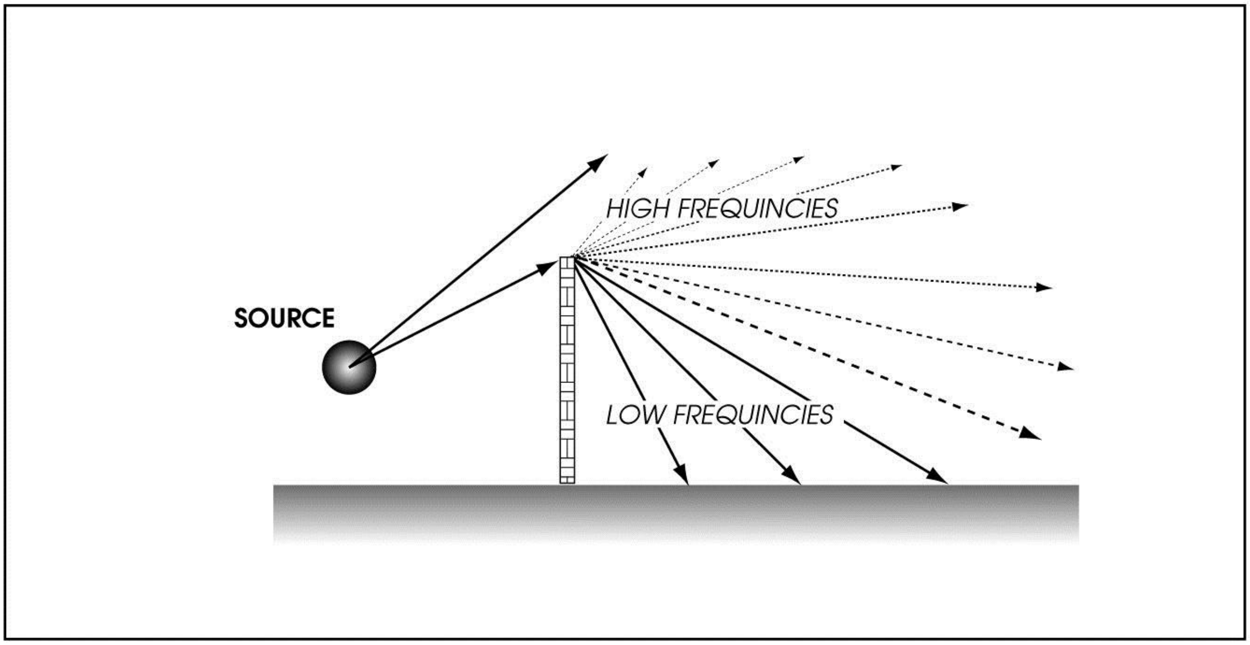

Figure 2-13. Diffraction of Sound Waves

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

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

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

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

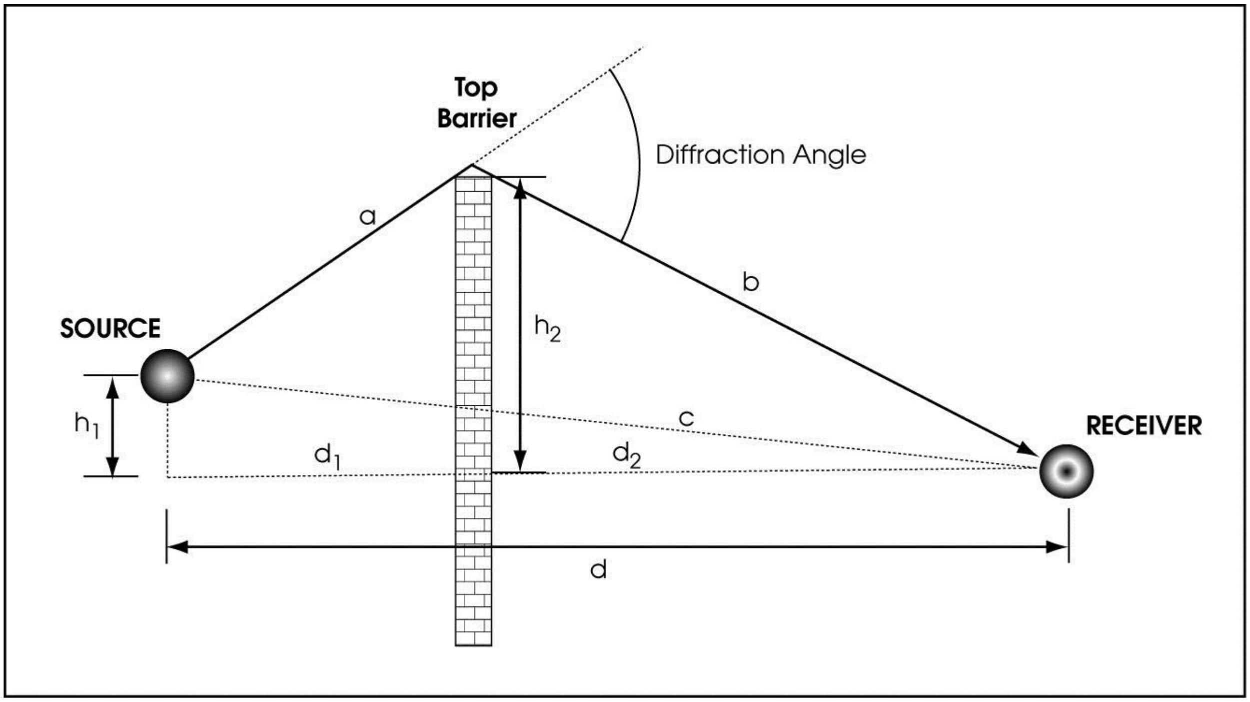

Figure 2-14. Path Length Difference between Direct and Diffracted Noise Paths

Highway noise prediction models use δ in barrier attenuation calculations. Section 5 addresses the subject in greater detail. However, it is appropriate to include the most basic relationship between δ and barrier attenuation through the Fresnel number (N_0). If the source is a line source (e.g., highway traffic) and the barrier is infinitely long, there is an infinite number of path length differences. The path length difference (δ_0) at the perpendicular line to the barrier is then of interest. Mathematically, N_0 is defined as follows:

$$N_0 = 2(\delta_0/\lambda) \quad \textbf{(2-16)}$$

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)

$\delta_0 =$ δ measured along perpendicular line to barrier

λ = wavelength of sound radiated by source

According to Equation 2-3, $\lambda = c/f$. Therefore, Equation 2-16 may be rewritten as follows:

$$N_0 = 2(f\delta_0/c) \tag{2-17}$$

Where:

f = frequency of sound radiated by source

c = speed of sound

Please note that these equations relate δ_0 to N_0. If one increases, so does the other, along with barrier attenuation. Similarly, if frequency increases, so will N_0 and barrier attenuation. Figure 2-15 shows the barrier attenuation Δ_B for an infinitely long barrier as a function of 550 Hz. It has been found that the attenuation of the A-weighted SPL of typical traffic is almost identical to the sound attenuation of 55 Hz frequency band. (Federal Highway Administration 1978)

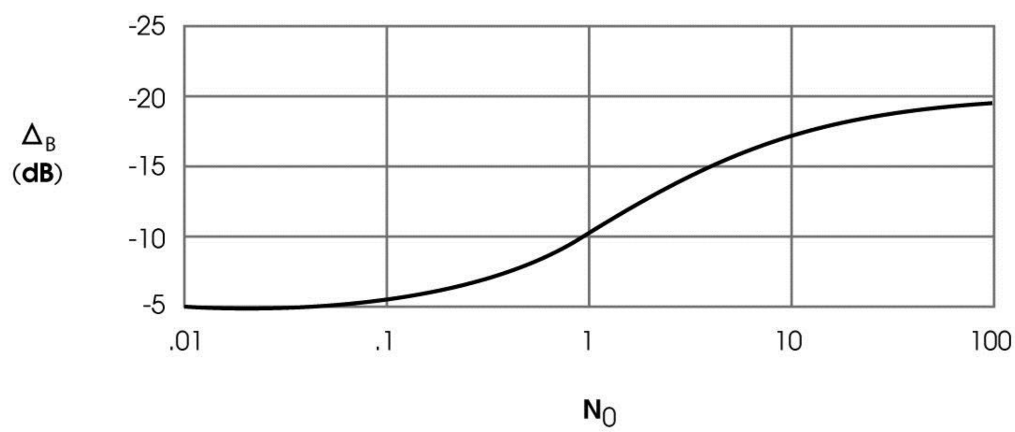

Figure 2-15. Barrier Attenuation (Δ_B) vs. Fresnel Number (N_0) for Infinitely Long Barriers

A barrier can be effective even when it does not completely block the line of sight between the source and the receiver. Figure 2-16 illustrates a special situation where the top of the barrier is just high enough to graze the direct noise path, or line of sight between the source and receiver. In this situation, a noise barrier provides about 5 dBA of attenuation.

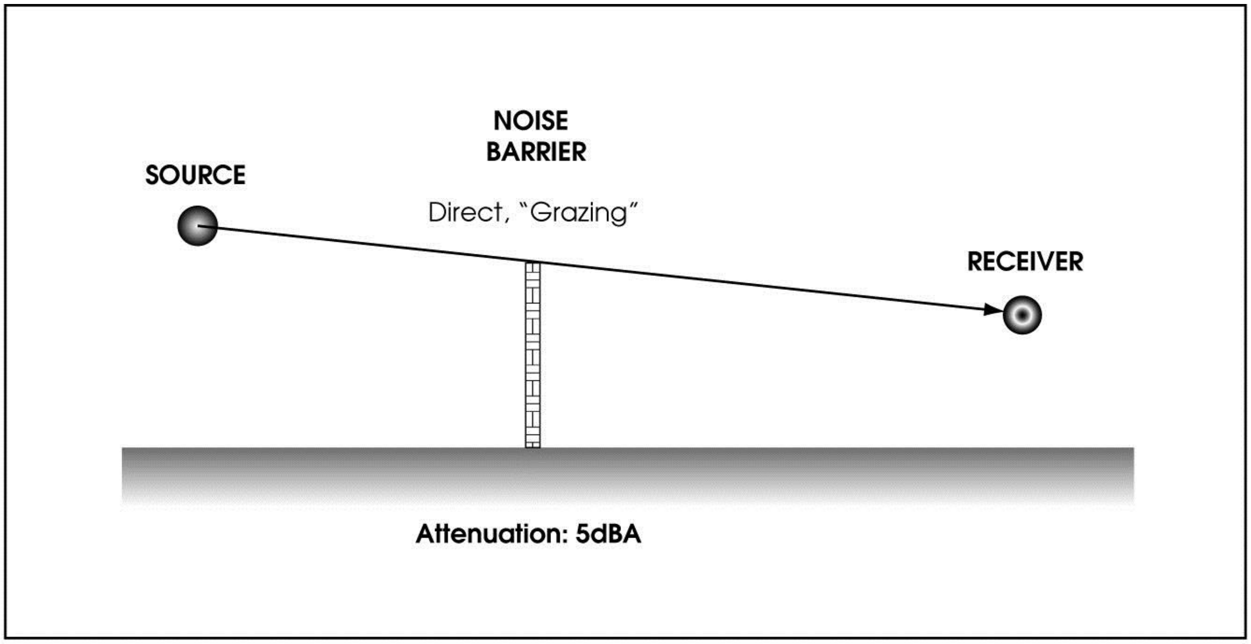

Figure 2-16. Direct Noise Path Grazing Top of Barrier, Resulting in 5 dBA of Attenuation

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

These principles of barriers apply loosely to terrain features (e.g., berms, low ridges, other significant manmade features). The principles are discussed in more detail in Section 5.

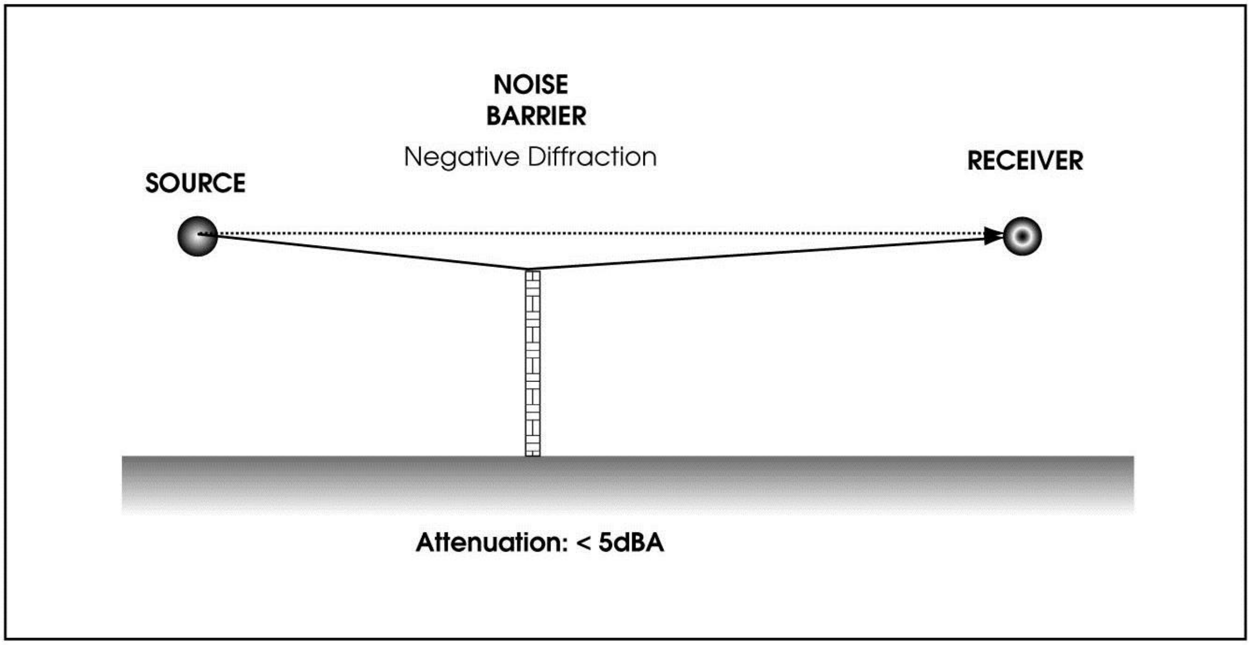

Figure 2-17. Negative Diffraction, Which Provides Some Noise Attenuation

2.2 Effects of Noise and Noise Descriptors

2.2.1 Human Reaction to Sound

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

- **Noise Level, Variability in Level (Dynamic Range), Duration, Frequency Spectrums, and Time Patterns:** Exposures to very high noise levels can damage hearing. A high level is more objectionable than a low-level noise. For example, intermittent truck peak noise levels are more objectionable than the continuous level of fan noise. Humans have better hearing sensitivities in the high frequency region than the low. This is reflected in the A-scale (Section 2.1.3.6), which deemphasizes the low-frequency sounds. Studies indicate that annoyance or disturbance correlates with the A-scale.
- **Amount of Background Noise Present before Intruding Noise:** People tend to compare an intruding noise with existing background noise. If the new noise is readily identifiable or considerably louder

than the background or ambient, it usually becomes objectionable. One example is an aircraft flying over a residential area.

- **Nature of Work or Living Activity Exposed to Noise Source:** Highway traffic noise might not be disturbing to workers in a factory or office, but it might be annoying or objectionable to people sleeping at home or studying in a library. An automobile horn at 2:00 a.m. is more disturbing than the same noise in traffic at 5:00 p.m.

2.2.1.1 Human Response to Changes in Noise Levels

Under controlled conditions in an acoustics laboratory, the trained healthy human ear is able to discern changes in sound levels of 1 dBA when exposed to steady single-frequency (pure tone) signals in the mid-frequency range. Outside such controlled conditions, the trained ear can detect changes of 2 dBA in normal environmental noise. It is generally accepted that the average healthy ear, however, can barely perceive a noise level change of 3 dBA. If changes to the character (i.e., frequency content) of a sound occur, level changes less than 3 dBA may be noticeable. Individuals who are exposed to continuous traffic noise may also be able to notice small changes in noise levels (i.e., less than 3 dBA).

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

It appears that the human perception of loudness is also not linear, either in terms of decibels or in terms of acoustical energy. As discussed, there is a mathematical relationship between decibels and relative energy. For example, if one source produces a noise level of 70 dBA, two of the same sources produce 73 dBA, three will produce about 75 dBA, and 10 will produce 80 dBA.

Human perception is complicated by the fact that it has no simple correlation with acoustical energy. Two noise sources do not sound twice as loud as one noise source. Based on studies conducted over the years some approximate relationships between changes in acoustical energy and corresponding human reaction have been charted. Table 2-10 shows the relationship between changes in acoustical energy, dBA, and human perception. The table shows the relationship between changes in dBA (ΔdBA), relative energy with respect to a reference of a ΔdBA of 0 (no change), and average human perception. The factor change in relative energy relates to the change in acoustic energy.

Table 2-10. Relationship between Noise Level Change, Factor Change in Relative Energy, and Perceived Change

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

Section 2.1.3.3 discusses that the rms value of the sound pressure ratio squared (P_1/P_2) is proportional to the energy content of sound waves (acoustic energy). Human perception is displayed in two columns: percentage and descriptive. The percentage of perceived change is based on the mathematical approximation that the factor change of human perception relates to ΔdBA as follows:

$$\text{Factor Change in Perceived Noise Levels} = 2^{\pm\Delta dBA/10} \qquad \textbf{(2-18)}$$

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

2.2.2 Describing Noise

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

2.2.2.1 Time Patterns

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

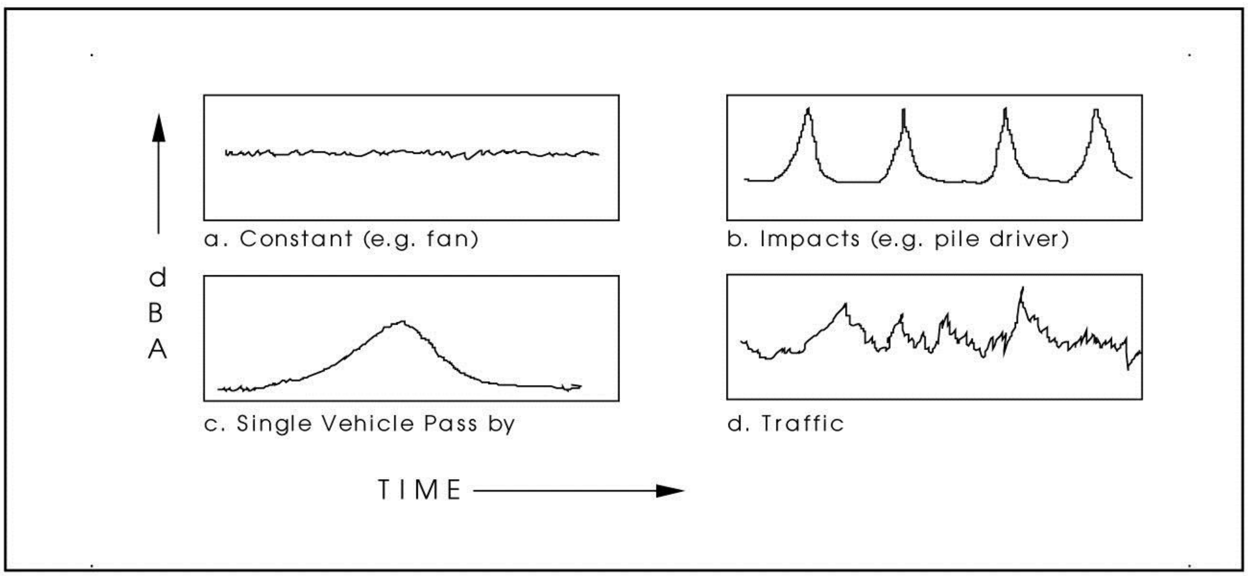

Figure 2-18. Different Noise Level vs. Time Patterns

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

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

2.2.2.2 Noise Descriptors

The proper noise descriptor to use in any given situation depends on the nature of the noise source. For example a high amplitude short duration event such as gunshot requires a different descriptor than a constant relatively low amplitude noise source such as traffic. The proper descriptor depends on the spatial distribution of noise sources, duration of the noise event, amount of fluctuation, and time patterns.

Dozens of descriptors and scales have been devised over the years to quantify community noise, aircraft flyovers, traffic noise, industrial noise, speech interference, etc. The descriptors shown in Table 2-11 are those encountered most often in traffic, community, and environmental noise. There are many more descriptors not discussed here. The word “Level,” abbreviated *L*, is frequently used whenever sound is expressed in decibels relative to the reference pressure. Therefore, all the descriptors shown in Table 2-11 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) as required under 23 CFR 772. If a noise analysis requires other descriptors to satisfy city or county requirements, see Section 2.2.3 for a discussion of descriptor conversions.

Table 2-11. Common Noise Descriptors

Noise Descriptor	Definition
Maximum noise level (L_{max})	The highest instantaneous noise level during a specified time period. This descriptor is sometimes referred to as "peak (noise) level." The use of term "peak level" should be discouraged because it may be interpreted as a non-rms noise signal (see Section 2.1.3.3 for difference between peak and rms).
Statistical descriptor (L_x)	The noise level exceeded *X* % of a specified time period. The value of *X* is commonly 10 (e.g., L_{10}). Other values such as 50 and 90 are used also.
Equivalent noise level (L_{eq}). Routinely used by Caltrans and FHWA to address the worst noise hour (L_{eq}[h]).	The equivalent steady-state noise level in a stated period of time that would contain the same acoustic energy as the time-varying noise level during the same period
Day-night noise level (L_{dn}). Used commonly for describing community noise levels.	A 24-hour L_{eq} with a "penalty" of 10 dBA added during the night hours (10 p.m. to 7 a.m.) because this time is normally used for sleep
Community noise equivalent level (CNEL). A common community noise descriptor, also used for airport noise.	Same as L_{dn} with an additional penalty of 4.77 dBA (or 10log3), for the hours 7 p.m. to 10 p.m., which are usually reserved for relaxation, television, reading, and conversation
Sound exposure level. Used mainly for aircraft noise, it enables comparing noise created by a loud but fast overflight with that of a quieter but slow overflight.	The acoustical energy during a single noise event, such as an aircraft overflight, compressed into a period of 1 second, expressed in decibels

2.2.2.3 Calculating Noise Descriptors

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

Statistical Descriptor

L_x, a statistical descriptor, signifies the noise level that is exceeded *X* % of the time. This descriptor was formerly used in highway noise, before L_{eq}. The most common value of *X* was 10, denoting the level that is exceeded 10% of the time. Therefore, the L_{10} descriptor is used as an example to represent the L_x family of calculations. The following instantaneous noise samples (Table 2-12) shown as a frequency distribution (dBA vs. number of occurrences) serve to illustrate the L_{10} calculation.

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

Table 2-12. Noise Samples for L_{10} Calculation

Noise Level (dBA)	Occurrences (Sampling Interval of 10 Seconds) (Each *X* Is One Occurrence)							Total Occurrences
80								0
79								0
78	X							1
77	X							1
76	X	X	X					3
75	X	X						2
74	X	X						2
73	X	X						2
72								0
71	X	X	X					3
70	X							1
69	X	X						2
68	X	X	X	X	X			5
67	X	X						2
66	X	X	X	X				4
65	X	X	X	X	X	X	X	7
64	X	X	X	X	X			5
63	X	X	X					3
62	X	X	X					3
61	X	X						2
60	X	X						2
Total samples								**50**

Equivalent Noise Level

L_{eq} is an energy average noise level. L_{eq} is also called an energy-mean noise level. The instant noise levels over a certain time period are energy-averaged by first converting all dBA values to relative energy values. Next, these values are added and the total divided by the number of values. The result is average (relative) energy. The final step is to convert the average energy value back to a decibel level. Equation 2-12 showed the method of adding the energy values. This equation can be expanded to yield L_{eq}:

$$L_{eq} = 10\log_{10}[(10^{SPL_1/10} + 10^{SPL_2/10} + \ldots 10^{SPL_n/10})/N] \quad \textbf{(2-19)}$$

Where:

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

N = number of noise level samples

Example

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

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

Using Equation 2-19:

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

Usually, longer time periods are preferred. Using the sampling data in Table 2-12, the following equation can be used to add the dBA levels for each set of equal noise levels:

$$SPL_{Total} = SPL_1 + 10\log_{10}(N) \quad \textbf{(2-20)}$$

Where:

SPL_1 = SPL of one source

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

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

$$SPL_{Total} = 10\log_{10}(10^{SPL_1/10} + 10^{SPL_2/10} + \ldots 10^{SPL_n/10}) \quad \textbf{(2-21)}$$

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

$$L_{eq} = 10\log_{10}(10^{SPL_{Total}/10}/N) \qquad \textbf{(2-22)}$$

Where:

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

The calculation procedures are shown in Table 2-13.

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

Noise Level (dBA)	Occurrences (N) (from Table 2-12)	Total Noise Levels [dBA + $10\log_{10}$(N)]
80	0	
79	0	
78	1	78
77	1	77
76	3	80.8
75	2	78
74	2	77
73	2	76
72	0	
71	3	75.8
70	1	70
69	2	72
68	5	75
67	2	70
66	4	72
65	7	73.5
64	5	71
63	3	67.8
62	3	66.8
61	2	64
60	2	63
Total	**50**	**87.5**
$\mathbf{L_{eq} = 10\log_{10}[(10^{8.75})/50] = 70.5}$ **dBA**		

Day-Night Noise Level

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

$$L_{dn} = 10\log_{10}\left[\left(\frac{1}{24}\right)\sum_{i=1}^{24} 10^{\,L_{eq}(h)_i + W_i/10}\right] \quad \textbf{(2-23)}$$

Where:

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

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

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

To calculate L_{dn} accurately, one must have 24 successive hourly L_{eq} values, representing one typical day. The hourly values between 10 p.m. and 7 a.m. (nine hourly values) must first be weighted by adding 10 dBA. An example is shown in Table 2-14.

The energy average calculated from the nine weighted and 15 unweighted hourly L_{eq} values is the L_{dn}. Once the hourly data is properly weighted, the L_{dn} can be calculated as an L_{eq} (in this case, a weighted 24-hour L_{eq}). Equation 2-19 can be used with the weighted data. The resulting L_{dn} is 65 dBA.

Table 2-14. Noise Samples for L_{dn} Calculations

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

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

Community Noise Equivalent Level

CNEL is the same as L_{dn} except for an additional weighting of almost 5 dBA for the evening hours between 7 p.m. and 10 p.m. The equation is essentially the same as Equation 2-23, with an additional definition of $W_i = 10\log_{10}(3)$, which is 4.77. Calculations for CNEL are similar to L_{dn}. The result is normally about 0.5 dBA higher than L_{dn} using the same 24-hour data. The equation for the CNEL is as follows:

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

Where:

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

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

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

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

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

Sound Exposure Level

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

$$SEL = L_{eq}(T) + 10\log_{10}(T) \quad \textbf{(2-25)}$$

$$L_{eq}(T) = SEL + 10\log_{10}(1/T) = SEL - 10\log_{10}(T) \quad \textbf{(2-26)}$$

Where:

T = duration of noise level in seconds

Example

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

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

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

$$L_{eq}(h) = SEL - 35.6 \quad \textbf{(2-27)}$$

$$SEL = L_{eq}(h) + 35.6 \quad \textbf{(2-28)}$$

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

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

First, all SELs are added:

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

Next, the SEL is expanded to 1 hour using Equation 2-28:

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

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

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

2.2.3 Conversion between Noise Descriptors

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

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

The previous section discussed that L_{dn} is defined as an energy-averaged 24-hour L_{eq} with a nighttime penalty of 10 dBA assessed to noise levels between 10 p.m. and 7 a.m. If traffic volumes, speeds, and mixes were to remain constant throughout the entire 24 hours and there were no nighttime penalty, there would be no peak hour and each hourly L_{eq} would equal the 24-hour L_{eq}. Hourly traffic volumes would then be 100/24, or 4.17% of ADT. Peak hour corrections would not be necessary in this case. (Let this be the reference condition.)

To convert peak hour L_{eq} to L_{dn}, at least two corrections must be made to the reference condition. First, one must make a correction for peak hour traffic volumes expressed as a percentage of ADT. Second, one must make a correction for the nighttime penalty of 10 dBA. For CNELs, a third correction needs to be made for the evening hour penalty. For this one must know what fractions of the ADT occur during the day and at night. Depending on the accuracy desired and information available, other corrections can be made for different day/night traffic mixes and speeds; these are not discussed in this section.

The first correction for peak hour can be expressed as:

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

Where:

P = peak hour volume as percent of ADT

The second correction for nighttime penalty of 10 dBA is:

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

Where:

D = day fraction of ADT

N = night fraction of ADT

D + N = 1

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

$$L_{dn} = L_{eq}(h)_{pk} + 10\log_{10}\frac{4.17}{P} + 10\log_{10}(D + 10N) \quad \textbf{(2-29)}$$

$$L_{eq}(h)_{pk} = L_{dn} - 10\log_{10}\frac{4.17}{P} - 10\log_{10}(D + 10N) \quad \textbf{(2-30)}$$

Where:

$L_{eq}(h)_{pk}$ = peak hour L_{eq}

P = peak hour volume % of ADT

D = daytime fraction of ADT

N = nighttime fraction of ADT

D + N = 1

<u>Example</u>

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

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

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

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

$$CNEL = L_{eq}(h)_{pk} + 10\log_{10}\frac{4.17}{P} + 10\log_{10}(d + 4.77e + 10N) \qquad \textbf{(2-31)}$$

$$L_{eq}(h)_{pk} = CNEL - 10\log_{10}\frac{4.17}{P} - 10\log_{10}(d + 4.77e + 10N) \qquad \textbf{(2-32)}$$

Where:

The variables *d* and *e* are further divisions of *D* shown in L_{dn} to account for day and evening hours. Please note that *d* + *e* = *D* (shown in Equations 2-31 and 2-32). The factor 4.77 comes from $10\log_{10}(3)$, which is the designated penalty for evening hours in the definition of CNEL. Although an evening hour penalty of 5 dBA is often used to calculate CNEL, the correct value is $10\log_{10}(3)$. The difference between using 4.77 and 5 is usually negligible.

Example

Using the data for the previous L_{dn} example and adding a further division of *D* into *d* = 0.80 and *e* = 0.05, the CNEL result using Equation 2-31 is 65.2 dBA, 0.3 dBA more than L_{dn}.

From Equations 2-31 and 2-32, the following equations can be derived in terms of CNEL and L_{dn}:

$$CNEL = L_{dn} + [10\log_{10}(d + 4.77e + 10N) - 10\log_{10}(d + e + 10N)] \qquad \textbf{(2-33)}$$

$$L_{dn} = CNEL - [10\log_{10}(d + 4.77e + 10N) - 10\log_{10}(d + e + 10N)] \qquad \textbf{(2-34)}$$

Example

Using the same example for which L_{dn} was 64.9 dBA, the CNEL in Equation 2-33 yields 65.2 dBA. Please note that CNEL is always larger than L_{dn}.

The values in Table 2-15 can also be used in Equations 2-29 and 2-30. Please notice that the peak hour percentage term of the equation always yields a negative value, while the weighted day/night split always yields a positive value. The difference between the two is the difference between $L_{eq}(h)_{pk}$ and L_{dn}.

Table 2-15. L_{eq}/L_{dn} Conversion Factors

Peak Hour, %	$10\log_{10}(4.17/P)$	Day	Night	$10\log_{10}(D+10N)$
5	-0.8	0.98	0.02	+0.7
6	-1.6	0.95	0.05	+1.6
7	-2.3	0.93	0.07	+2.1
8	-2.8	0.90	0.10	+2.8
9	-3.3	0.88	0.12	+3.2
10	-3.8	0.85	0.15	+3.7
11	-4.2	0.83	0.17	+4.0
12	-4.6	0.80	0.20	+4.5
13	-4.9	0.78	0.22	+4.7
14	-5.3	0.75	0.25	+5.1
15	-5.6	0.73	0.27	+5.4
17	-6.1	0.70	0.30	+5.7
20	-6.8	0.68	0.32	+5.9
		0.65	0.35	+6.2
		0.63	0.37	+6.4
		0.60	0.40	+6.6

Figure 2-19 illustrates the difference between $L_{eq}(h)_{pk}$ and L_{dn}. For example, if *P* is 10% and *D*/*N* = 0.85/0.15, $L_{dn} \approx L_{eq}(h)$.

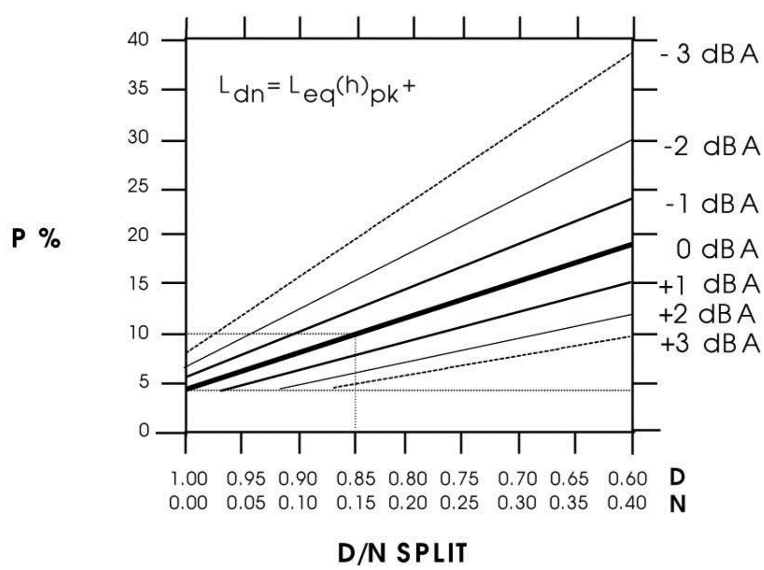

Figure 2-19. Relationship between L_{dn} and $L_{eq}(h)_{pk}$

If CNEL is desired, the L_{dn} to CNEL corrections (Δ) in Table 2-16 may be used. Please note that this table is only calculated for a common day/night volume spilt of 0.85/0.15. Because of the many possible combinations, other tables are not shown. For other D/N splits, use Equation 2-31 or 2-32 to calculate CNEL. This table is intended to be used when only an L_{dn} is given and CNEL is desired.

Table 2-16. L_{dn}/CNEL Corrections (Δ) (Must Be Added to L_{dn} to Obtain CNEL)

D = 0.85		Δ
D	E	(CNEL = L_{dn} + Δ)
0.80	0.05	0.3
0.79	0.06	0.4
0.78	0.07	0.5
0.77	0.08	0.5
0.76	0.09	0.6
0.75	0.10	0.7
0.74	0.11	0.7
0.73	0.12	0.8
0.72	0.13	0.8
0.71	0.14	0.9
0.70	0.15	0.9

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

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

2.2.4 Negative Effects on Humans

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

2.2.4.1 Hearing Damage

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

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

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

2.2.4.2 Interference with Activities

Activities most affected by noise include rest, relaxation, recreation, study, and communications. Although most interruptions by noise can be considered annoying, some may be considered dangerous, such as the inability to hear warning signals or verbal warnings in noisy industrial situations or situations involving workers next to a noisy freeway. Figure 2-20 gives an estimate of the speech communication that is possible at various noise levels and distances.

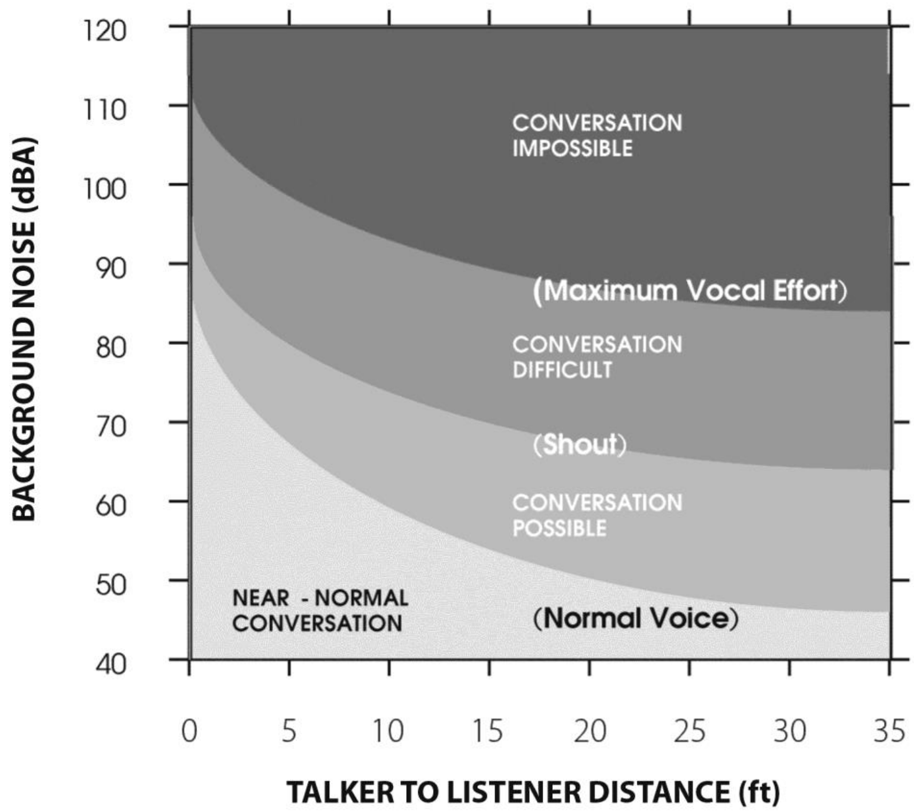

Figure 2-20. Interference of Conversation from Background Noise

For example, if the talker-to-listener distance is about 20 feet, normal conversation can be conducted with the background level at about 50 dBA. If the background level is increased to 60 dBA, the talker must either raise his or her voice or decrease the distance to the listener to about 10 feet.

2.2.4.3 Stress-Related Diseases

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

Section 3
Measurements and Instrumentation

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

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

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

3.1 Purposes of Noise Measurements

There are five major purposes for measuring transportation noise.

- Determine existing ambient and background noise levels.
- Calibrate noise prediction models.
- Monitor construction noise levels for compliance with standard specifications, special provisions, and local ordinances.
- Evaluate the effectiveness of abatement measures such as noise barriers.
- Perform special studies and research.

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

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

3.1.1 Ambient and Background Noise Levels

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

- To assess highway traffic noise impacts for new highway construction or reconstruction projects. Existing ambient noise levels provide a baseline for comparison to predicted future noise levels. The measurements are also used to describe the current noise environment in the area of the proposed project. This information is reported in appropriate environmental documents. Generally, the noise resulting from natural and mechanical sources and human activity considered usually to be present should be included in the measurements.
- To investigate citizens' traffic or construction noise complaints. Noise measurements are usually reported via memorandum to the interested party, with recommendations for further actions or reasons that further actions are not justified.

Background noise is considered to be the total noise in a specific region without the presence of noise sources of interest. Typically, this would be the noise generated within the community without the highway and is usually measured at acoustically representative locations away from the highway where highway noise does not contribute to the total noise level. Background noise levels are routinely measured to determine the feasibility of noise abatement and to ensure that noise reduction goals can be achieved. Noise abatement cannot reduce noise levels below background levels. Section 5.1.6 discusses the importance of background noise levels.

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

3.1.2 Model Validation/Calibration

Noise measurements near highways or other transportation corridors are routinely used to validate and, if necessary, calibrate the project-specific TNM model 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 4.3.3 and 4.4). Model calibration can only be performed on projects involving reconstruction of existing highways.

3.1.3 Construction Noise Levels

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

3.1.4 Performance of Abatement Measures

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

3.1.5 Special Studies and Research

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

3.2 Measurement Locations

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

Many tools are available in the search for quality noise measurement sites. Preliminary design maps, cross sections, aerial photographs, and field survey data are all helpful sources of information. However, noise measurement sites should only be selected after a thorough field review of the project area.

3.2.1 General Site Recommendations

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

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

3.2.2 Measurement Site Selection

For the purpose of this document, a distinction will be made between receivers and noise measurement sites. Receivers are all locations or sites of interest in the noise study area. Noise measurement sites are locations where noise levels are measured. Unless an extremely rare situation exists in which a noise measurement site is used for a specialized purpose, all noise measurement sites may be considered receivers. However, not all receivers are noise measurement sites. Additional information on receivers and noise measurement sites can be found in Section 4.3.

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

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

Factors that should be considered when selecting noise measurement sites are described in the next three sections.

3.2.2.1 Site Selection by Purpose of Measurement

Noise measurement sites should be selected according to the purpose of the measurement. For example, if the objective is to determine noise impacts of a highway project, sites should be selected in areas 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 and to document pre-project noise levels at distant receivers. Past controversies concerning reported increases in noise levels at distant receivers attributed to noise barriers could have been readily resolved if sufficient background noise measurements had been obtained prior to the project being built. (Refer to Section 3.1.1 for more information on background noise levels).

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

Model calibration measurements usually require sites to be near the highway, preferably at receivers or acoustical equivalents to the receivers (see Section 4.4 for additional details). Sites for construction noise monitoring are dictated by standard specifications, special provisions, and local ordinances, which detail maximum allowable noise levels at a reference distance (e.g., L_{max} of 86 dBA at 50 feet) and other requirements.

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

3.2.2.2 Site Selection by Acoustical Equivalence

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

The area under study may need to be divided into sub-areas in which acoustical equivalence can generally be maintained. Sub-area boundaries must be estimated by one or more of the previously mentioned acoustical parameters. Also, in cases where measurements are being taken for more than one purpose, separate sub-areas may be defined by each purpose. The areas of interest may vary in size. For example, noise abatement for a school may cover only the school itself, while a noise study for a large freeway project may range from a large area to many sub-areas.

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

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

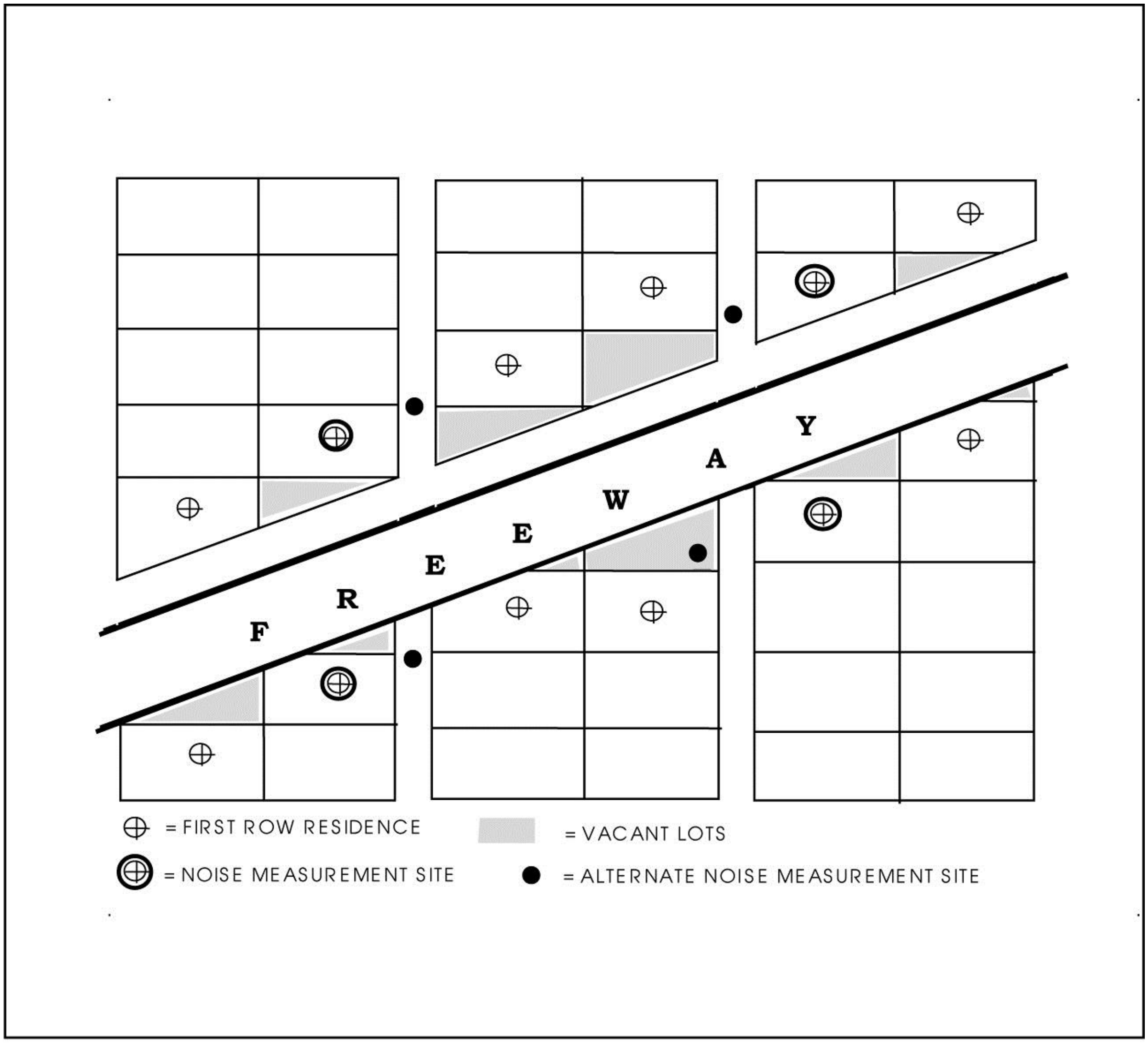

Figure 3-1. Typical Measurement Site Locations

3.2.2.3 Site Selection by Geometry

In addition to being an important consideration in determining acoustical equivalence, topography (site geometry) plays an important role in determining locations of worst exposure to highway noise. Receivers located farther from a highway may be exposed to higher noise levels, depending on the geometry of a site. One typical example is a highway on a high embankment, where the first-tier receivers may be partially shielded by the top of the fill. Unshielded second- or third-tier receivers may then be exposed to higher noise levels even though they are farther from the source. This concept is shown in Figure 3-2. Another common situation involves a receiver close to the source, shielded by the top of a highway embankment, and an unshielded receiver farther from the source. The attenuation provided by the embankment is often more than the distance effect, resulting in higher noise levels at the farther receiver.

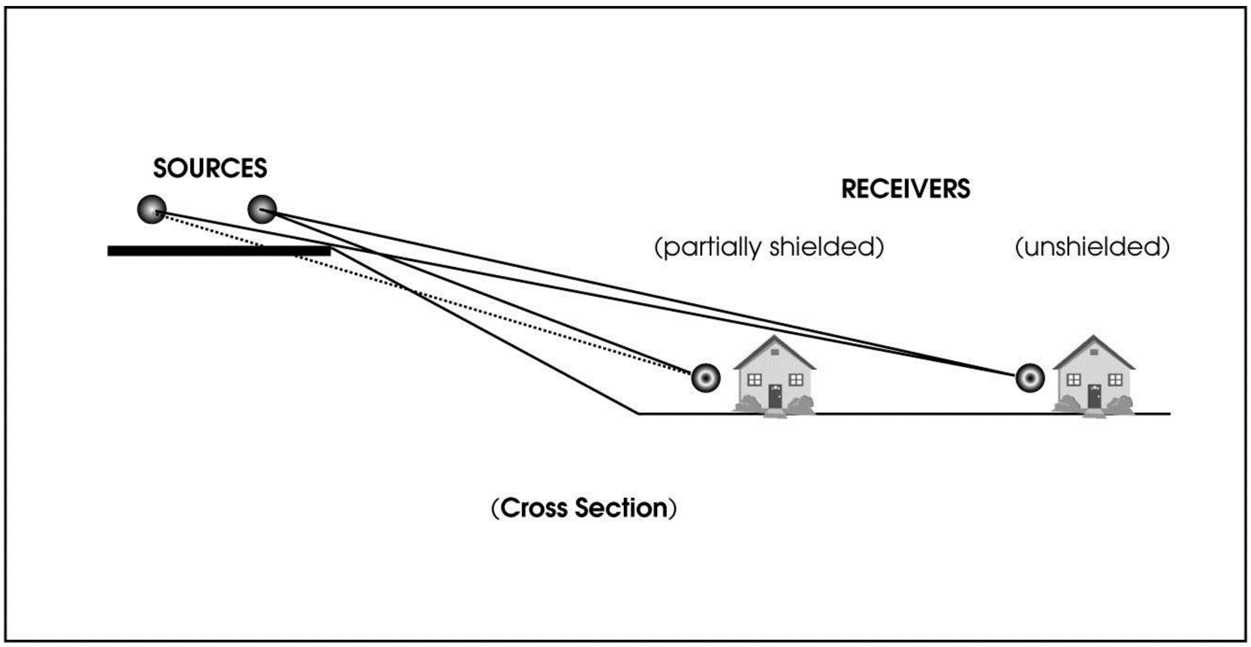

Figure 3-2. Typical Noise Measurement Site Locations

Figure 3-3 illustrates another example of the effects of site geometry on the selection of highest noise exposure. The unshielded Receiver 1 shows a higher noise level than Receiver 2 even though the latter is closer to the freeway. Other examples can be generated in which the nature of terrain and natural or artificial obstructions cause noise levels at receivers closer to the source to be lower than those farther away. This concept is an important consideration in impact analysis, where interest usually focuses on the noisiest locations.

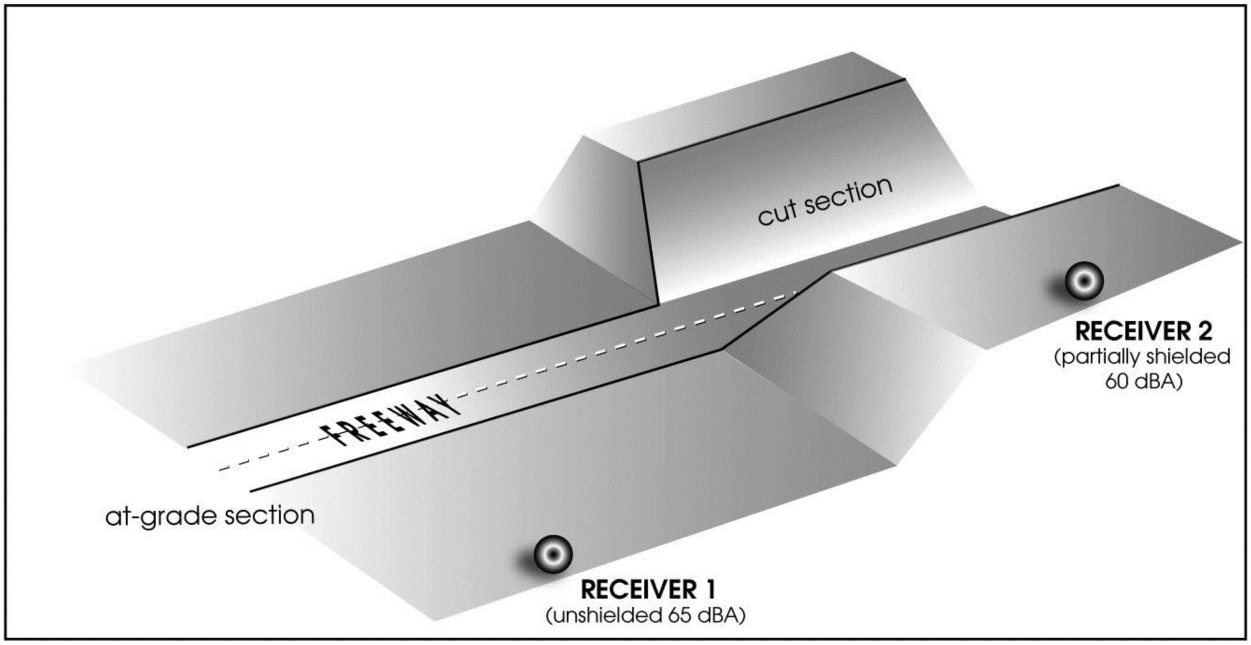

Figure 3-3. Receiver Partially Shielded by Top of Cut vs. Unshielded Receiver

3.3 Measuring Times, Duration, and Number of Repetitions

3.3.1 Measuring Times

23 CFR 772 requires that traffic characteristics that yield the worst hourly traffic noise impact on a regular basis be used for predicting noise levels and assessing noise impacts. Therefore, if the purpose of the noise measurements is to determine a future noise impact by comparing predicted noise with measured noise, the measurements must reflect the highest existing hourly noise level that occurs regularly. In some cases, weekly or seasonal variations need to be considered. In recreational areas, weekend traffic may be higher than on weekdays and may be heavily influenced by season, depending on the type of recreation. Measurements made for retrofit noise barrier projects also require noise measurements during the highest traffic noise hour.

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

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

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

Noise monitoring for investigating citizen complaints may need to be done at a time to which the parties mutually agree. Frequently, these measurements are taken before or after normal working hours, as dictated by the nature of the complaint.

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

Unless other times are of specific interest, before-and-after noise abatement (e.g., noise barrier) measurements to verify noise abatement performance should be done during the noisiest hour. Noise barriers are designed for noisiest hour traffic characteristics, which probably include highest truck percentages, and to minimize contamination by background noise. Traffic should be counted during these measurements. If before-and-after traffic conditions differ, measurements should be normalized or adjusted to the same conditions of traffic (see Section 3.3.1.2).

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

3.3.1.1 Noisiest Hour for Highway Traffic

The peak traffic hour is generally not the noisiest hour. During rush hour traffic, vehicle speeds and heavy truck volumes are often low. Free-flowing traffic conditions just before or after rush hour often yield higher noise levels. Preliminary noise measurements at various times of the day are sometimes necessary to determine the noisiest hour. If accurate traffic counts and speeds for various time periods are available, the noisiest hour may be determined by using TNM. Experience based on previous studies may also be valuable in determining the noisiest hour for a particular facility.

3.3.1.2 Adjusting Other-Than-Noisiest Hour

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

1. During each measurement, take noise measurements and count traffic simultaneously. Although lane-by-lane traffic counts yield the most accurate results, it is usually sufficient to count traffic by direction (e.g., east- and westbound). Separate vehicles into the five vehicle groups used by the model (autos, medium trucks, heavy trucks, buses, and motorcycles). Obtain average traffic speeds (both directions). These may be obtained by radar or driving a test vehicle through the project area at the prevailing traffic speed.
2. Expand vehicle counts for the measurement period to hourly values (e.g., if the measurement period was 15 minutes, multiply the vehicles counted in each group by 4). Section 3.3.2 discusses duration of measurement as a function of hourly vehicle volumes.
3. Enter the hourly traffic volumes and speeds from steps 1 and 2 into TNM. Also include the proper roadway and receiver geometry and site parameters. Run the model.
4. Enter the traffic volumes and speeds associated with the noisiest hour and the same roadway and receiver geometry and site parameters as used in step 3. Run the model.
5. Subtract results of step 3 from step 4. The step 4 results should always be larger than step 3.
6. Add the differences obtained in step 5 to the noise measurements of step 1.

Example

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

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

Calculated for noisiest hour (step 4) = 69 dBA

Difference (step 5) = 2 dBA

Measured noise level adjusted to noisiest hour (step 6) = 66 + 2 = 68 dBA

If 24-hour monitoring equipment is available, a histogram of 24 hourly noise measurements may be developed for an existing freeway. This information may then be used to adjust an off-peak hour noise level at any location along the freeway to a noisiest hour noise level. However, steps must be taken to reduce the chance of noise contamination from non-traffic sources. If hourly noise relationships are in agreement between the two monitors, there is reasonable assurance that neither was contaminated. There is, however, no assurance that regional contamination such as frequent aircraft flyovers did not take place. As such, measurements with remote noise monitoring equipment must be approached with extreme caution and only with at least some familiarity of nearby noise sources.

3.3.2 Measurement Duration

A noise measurement representing an hourly L_{eq} does not need to last the entire hour. As long as noise levels do not change significantly, a shorter time period will usually be sufficient to represent the entire hour of interest. The recommended length of measurements depends on how much the noise levels fluctuate—the higher the fluctuations, the longer the measurement must be. Vehicle spacing and differences in vehicle types are responsible for fluctuating noise levels. These fluctuations decline as traffic densities increase. Highway noise also becomes more constant as the distance from the highway increases because the rate of distance change between a moving vehicle and a receiver diminishes. The durations in Table 3-1 are recommended for highway traffic noise measurements as a function of number of vehicles per hour (vph) per lane.

Table 3-1. Suggested Measurement Durations

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

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

3.3.3 Number of Measurement Repetitions

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

- Change in traffic volumes, speeds, and/or mixes.
- Contamination from non-traffic noise sources, such as barking dogs, aircraft, nearby construction, and landscaping and road maintenance activities.
- Change in weather (e.g., wind speed, wind direction, temperature, and humidity).
- Changes in site conditions.
- Instrument, operator, or calibration error.
- Malfunctioning instruments.

Because of these potential variables and errors that may occur during a measurement, it is strongly recommended that a time-averaged measurement (e.g., the L_{eq} descriptor) be repeated at least once at each site. This procedure will reduce the chances of undetected errors. There are exceptions to this recommendation, however. Whenever three or more noise measurements are made in the same general area, simultaneously or in relatively rapid succession, one measurement at each site may be sufficient if the sites are acoustically equivalent (see Section 3.2.2.2). However, to determine whether a measurement at a particular site is acceptable, the measurement should be compared to those at the other sites and subjected to the same criteria for repeat measurements discussed later in this section.

The recommended minimum of two measurements should be taken independently (using two different setups and separate calibrations). However, the operator is not precluded from taking more than one measurement per setup and calibration. In fact, if time permits, multiple measurements during each setup are encouraged to improve accuracy. To save time concurrent measurements may be made at a single position with two separate instrument setups.

Repeat measurements should be compared with the original measurements under the same conditions of traffic, meteorology, and site. Noise contamination, instrument malfunction, operator error, or any other anomalies in the measurements can then readily be detected. To ensure that conditions are the same for all measurements, traffic counts and some basic meteorological measurements should be made during the noise measurements (see Sections 3.3.4 and 3.6). If the repeat measurements are not in reasonable agreement with the original measurements, additional measurement repetitions are recommended. For routine measurements, such as determining ambient noise levels or calibrating noise prediction models, the above-recommended minimum of two measurements normalized for differences in traffic mix and volumes should agree within 2 dBA. If more than one measurement is taken per setup, the mean noise levels for the two setups should agree within 2 dBA. Repetitive measurements for each setup should then be within about 1 dBA of the mean noise level of the setup.

The above criteria have been set empirically from many years of field experience with a variety of sound level meters approved for transportation noise measurements (American National Institute of Standards [ANSI] S1.4 1983, Types 1 and 2). Some examples illustrating these criteria are listed below and were purposely selected to show the extreme allowable limits. Usually, better agreement between setups and within setups can be expected. Examples 1 to 3 assume that all meteorological conditions, traffic conditions, and site conditions are the same throughout all measurements.

Example 1

Measurement 1

Setup 1: 74.5 dBA, L_{eq}

Setup 2: 76.5 dBA, L_{eq}

Mean: 75.5 dBA, L_{eq}

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

Example 2

Measurement 1

Setup 1: 69 dBA, L_{eq}

Setup 2: 71 dBA, L_{eq}

Measurement 2

Setup 1: 67 dBA, L_{eq}

Setup 2: 69 dBA, L_{eq}

Mean

Setup 1: 68 dBA, L_{eq}

Setup 2: 70 dBA, L_{eq}

Overall: 69 dBA, L_{eq}

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

Example 3

Measurement 1

Setup 1: 61.6 dBA, L_{eq}

Setup 2: 58.6 dBA, L_{eq}

Measurement 2

Setup 1: 59.6 dBA, L_{eq}

Setup 2: –

Mean

Setup 1: 60.6 dBA, L_{eq}

Setup 2: 58.6 dBA, L_{eq}

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

Conclusion: Measurements are acceptable.

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

Example 4

Measurement 1

Setup 1: 65.3 dBA, L_{eq}

Setup 2: 68.0 dBA, L_{eq}

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

After the second measurement, a decision should be made to either take another measurement during Setup 2 or break the setup and take a measurement for a new Setup 3. Either method will be acceptable, although if the decision is to take another measurement during Setup 2, and the agreement criteria still cannot be met, it is recommended to break Setup 2 and perform additional measurements with Setup 3. If agreement is reached between Setups 2 and 3, Setup 1 should be eliminated, as illustrated in Example 5:

Example 5

Measurement 1

Setup 1: 65.3 dBA, L_{eq}

Setup 2: 68.0 dBA, L_{eq}

Setup 3: 69.0 dBA, L_{eq}

Measurement 2

Setup 1: –

Setup 2: 68.5 dBA, L_{eq}

Setup 3: –

Mean

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

Conclusion: Setup 2 and 3 measurements are acceptable.

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

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

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

These examples illustrate some extreme cases; many other combinations are possible. Most measurements will show better agreement. The examples are intended to show how the recommended criteria may be applied in general. The analyst may need to rely more on individual judgment and experience in more complicated situations.

In some cases, more accuracy is required than the criteria allow. These cases apply mostly to special studies or research. However, they may also be applied to a few key noise measurement sites on a large project for the purpose of accurate model calibration. In these cases, a 95% confidence interval for the mean of several measurements (using a minimum of two setups) can be calculated. The 95% confidence interval should be specified to be no more than about 1 dBA. Table 3-2 shows the maximum allowable standard deviations (S_{max}) as a function of the number of samples (measurements). Although the table is calculated for up to 10 measurements, the criterion can be met by five or fewer measurements in most cases. A scientific calculator with statistical functions is essential when making calculations in the field.

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

Number of Measurements	Maximum Allowable Standard Deviations
2	0.11
3	0.40
4	0.63
5	0.81
6	0.95
7	1.08
8	1.20
9	1.30
10	1.40

Example

Measurement 1

Setup 1: 67.8 dBA, L_{eq}

Setup 2: 68.7 dBA, L_{eq}

Measurement 2

Setup 1: 66.9 dBA, L_{eq}

Setup 2: 67.9 dBA, L_{eq}

Measurement 3

Setup 1: –

Setup 2: 67.8 dBA, L_{eq}

Standard Deviation (Maximum)

Setups 1 and 2: 0.73 (0.63)

Setups 1 to 3: 0.64 (0.81)

Mean

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

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

The preceding examples assume that the previously mentioned site, traffic, and meteorological conditions remain the same during all measurements. Site conditions and contamination from other noise sources can be controlled by careful site selection. Noise contamination from intermittent sources can further be controlled by pausing the instruments during the contamination or by marking and editing recorded data.

Operator error and instrument malfunction usually cause larger errors that are easily detected. Instrument error is a function of equipment brand, type, and calibration. Instrument records of calibration, repair, performance, manufacturers' manuals, and accuracy standards (discussed later in Section 3.7) will give a good estimate of instrument error.

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

3.3.4 Normalizing Measurements for Differences in Traffic Mixes and Volumes

Before applying the criteria discussed in Section 3.3.3, repeated measurements must be adjusted for differences in traffic mix and volume. The effects of traffic differences can be calculated by the noise prediction models and compared with the actual differences in the measurements. However, a simple method to normalize measurements for differences in traffic mixes and volumes has been developed for optional use in the field.

This method involves field calculations that with practice can be carried out in a few minutes with a log function calculator as demonstrated in the discussion below. The repeated measurements are field-adjusted for the same traffic conditions as the first measurement. The adjusted (normalized) measurements may then be compared directly according to the criteria in Section 3.3.3.

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

- Average traffic speeds are not the same for each measurement. This is difficult to verify, but under free-flow conditions at a specific location, speeds generally will be constant.
- Truck speeds are significantly different (more than 5 mph) from auto speeds or truck percentages are significantly different (more than doubled).
- Speeds cannot be determined within 5 mph.

- The ratio of distances from the receiver to the centerline of the far (directional) lane group and the receiver to the centerline of the near (directional) lane group is more than 2:1. For most eight-lane urban freeways, this means that the receiver should not be closer than 45 feet from the edge of the traveled way.
- The directional split of traffic is different by more than 20% for each vehicle group between measurements. For example, if the directional split between heavy trucks during the first measurement is 60/40 and 80/20 or 40/60 during the next measurement, the method would be valid. However, a second split of 85/15 or 35/65 means that the method would be inaccurate. This criterion is usually met.

The method uses the concept of equivalent vehicles (V_E), which equates medium and heavy trucks to an acoustically equivalent number of autos. Based on the TNM Reference Energy Mean Emission Levels (REMELs) (Federal Highway Administration 1996b), one heavy truck traveling at 55 mph makes as much noise as approximately 10 autos cruising at the same speed. A medium truck at 55 mph is acoustically equivalent to approximately four autos passing at the same speed. These relationships are speed-dependent and the same for the maximum noise level ($L_{max)}$ and time-averaged noise levels (L_{eq}).

The relationships do not consider source heights and may not be used if the path from the source to the measurement site is intercepted by a barrier or natural terrain feature. Table 3-3 shows V_E for speeds from35 to 70 mph in 5-mph increments, based on the FHWA TNM REMELs for baseline conditions.

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

	Equivalent Vehicles		
Speed (mph)	1 Heavy Truck	1 Medium Truck	1 Automobile
35	19.1	7.1	1
40	15.1	5.8	1
45	12.9	5.0	1
50	11.5	4.5	1
55	10.4	4.1	1
60	9.6	3.7	1
65	8.9	3.5	1
70	8.3	3.2	1

Note: Based on FHWA TNM REMELs and vehicle definitions in Federal Highway Administration 1996a and 1996b (also see Section 4.5.2).

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

Given

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

Solution

76 heavy trucks = 76 x 10.4 = 790 V_E

34 medium trucks = 34 x 4.1 = 139 V_E

789 autos = 789 x 1 = 789 V_E

Total = 1,718 V$_E$

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

1. $L_{eq}(1)$ is the first noise measurement, which is used as the reference measurement. Convert the traffic count for $L_{eq}(1)$ to V_E, which is designated $V_E(1)$.
2. $L_{eq}(2)$ is the second noise measurement, which is to be normalized. Convert the traffic count for $L_{eq}(2)$ to $V_E = V_E(2)$.
3. *c* is the correction to be applied to $L_{eq}(2)$ for normalization to the traffic of $L_{eq}(1)$. The equation to compute *c* is $10\log_{10}[V_E(1)/V_E(2)]$. Note that *c* may be negative or positive.
4. $L_{eq}(2N)$ is the normalized $L_{eq}(2)$. The equation to compute $L_{eq}(2N)$ is $L_{eq}(2) + c$.
5. $L_{eq}(2N)$ may be directly compared to $L_{eq}(1)$ in the field to determine whether the agreement criteria discussed in Section 3.3.3 are met. If more than two measurements are made, the same procedure can be used for subsequent measurements. The same reference measurement must be used throughout the procedure.

Following is an example for determining in the field whether three 15-minute measurements for different traffic conditions meet the agreement criteria in Section 3.3.3 (for convenience the measurements have been numbered consecutively regardless of setup):

Given

		15-Minute L_{eq}					
Measurement	Setup	dBA	Heavy Trucks	Medium Trucks	Autos	Speed (mph)	Equivalent Vehicles (V_E)
1	1	74.4	100	50	1,275	55	2,520
2	1	75.5	150	100	850	55	2,820
3	2	74.0	60	30	1,700	55	2,447

Correction Calculations (Using Table 3-3)

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

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

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

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

Normalized Data Using Table 3-3

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

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

Average Energy of Measurements

74.5 dBA (report as 75 dBA)

Average 15-Minute Traffic Counts

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

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

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

Expand Average 15-Minute Traffic Counts to 1 Hour

Mean Heavy Trucks = 103.3 x 4 = 413

Mean Medium Trucks = 60.0 x 4 = 240

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

The expanded average traffic counts may be used in the prediction model to calculate the noise level. The result may be compared to the energy-averaged measurement. Section 4.4 explains how this comparison may be used for “calibrating” the prediction model.

An alternative more detailed approach to normalization is contained in American Association of State Highway and Transportation Officials (AASHTO) Draft Standard TP 99-12 (American Association of State Highway and Transportation Officials 2011).

3.3.5 Classroom Noise Measurements

These measurements meet the requirements of the California Streets and Highways Code Section 216 which is discussed in the Protocol. Under these provisions:

> [t]he noise level produced by traffic on, or by construction of, a state freeway shall be measured in the classrooms, libraries, multipurpose rooms, and spaces used for pupil personnel services of a public or private elementary or secondary school if the rooms or spaces are being used for the purpose for which they were constructed and they were constructed under any of the following circumstances: …

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

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

If the project involves a reconstruction of an existing freeway, simultaneous traffic noise measurements may be taken inside and outside the classroom. Microphones should be placed as shown in Figures 3-4 and 3-5.

Figure 3-4 shows the preferred setup where microphone 1 (Mic. 1) should be placed outside the classroom at approximately the same distance from the freeway as the center of the classroom. Care must be taken to place the microphone far enough away from the building to avoid significant shielding by the corner of the building. This can be accomplished by maintaining at least a 70º angle between a perpendicular line to the freeway and a line to the center of the building. Mic. 2 should be placed in the center of the classroom.

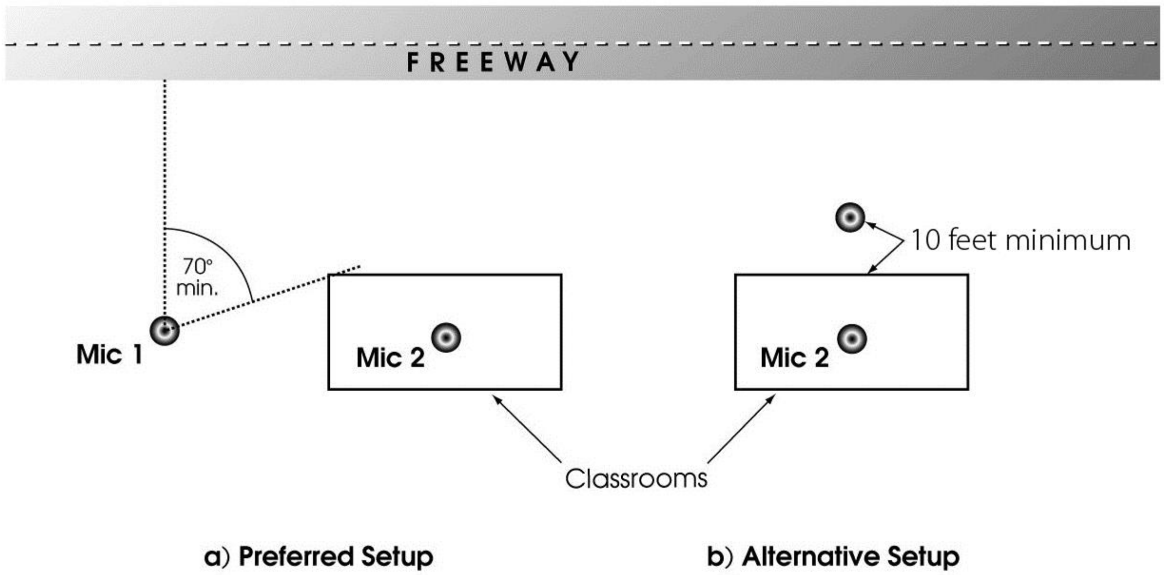

Figure 3-4. Classroom Noise Measurements (Reconstruction of Existing Freeway)

Figure 3-5 shows an alternate setup to be used if the setup shown in Figure 3-4 is not possible. Mic. 1 should be positioned at least 10 feet from the building to avoid noise reflections from the building. The disadvantage of this setup is that Mic. 1 and Mic. 2 are not equal distances from the freeway. If Mic. 1 is 200 feet or more from the freeway, the effects of unequal distances can usually be ignored. Assuming a 33-by-33-foot classroom, the error would be 0.5 dBA or less. Between 65 and 200 feet, a distance reduction of 1 dBA would have to be applied to Mic. 1 to normalize Mic. 1 to Mic. 2. If the distance from Mic. 1 to the freeway is less than 65 feet, a larger adjustment will be necessary. TNM may be used to calculate the adjustments.

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

If the project is on a new alignment or construction noise will be the dominant noise source, there is no existing traffic source that can be used to measure building attenuation. In that case, it is appropriate to use an artificial noise source to quantify building insertion loss (Figure 3-5).

Acceptable choices of an artificial source would be traffic noise audio recordings or an electronically generated noise spectrum that approximates typical traffic noise. This spectrum should be linear, from 31.5 to 500 Hz, and decrease at 6 dB per octave from 500 to 4,000 Hz. Amplification should be sufficient to produce A-weighted sound levels at least 10 dBA greater than background noise levels at exterior and interior microphone locations. A commercial-quality loudspeaker should be used with directional characteristics such that a 2,000-Hz signal measured at 45º from perpendicular to the face of the speaker is no more than 6 dB less than the level measured at the same distance on the perpendicular axis. The sound level output must be kept constant for inside and outside measurements.

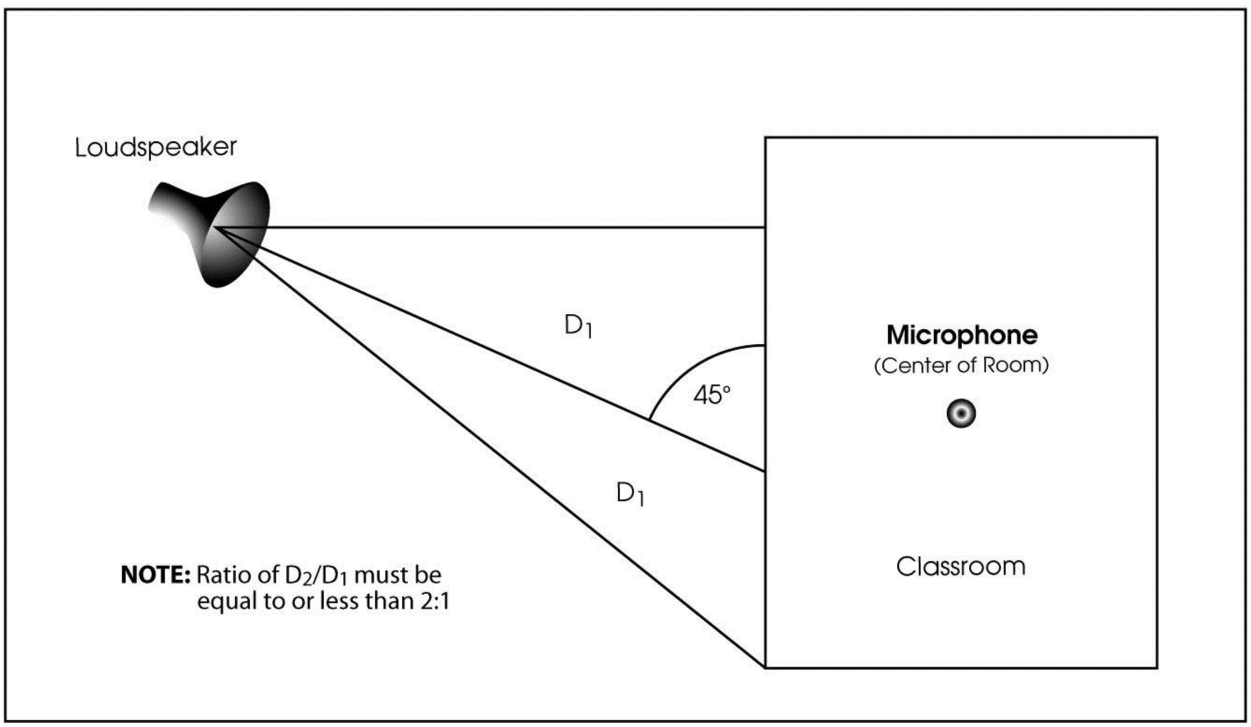

Figure 3-5. Classroom Noise Measurements (Project on New Alignment with Artificial Sound Source)

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 3-5 for the indoor noise measurements.

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

Once the indoor measurements are completed, outdoor measurements must be taken. For the outdoor noise measurements, the distance between the speaker to the outdoor microphone should be the same as the distance between the speaker and the indoor microphone. The sound level output of the artificial source must be the same for both indoor and outdoor measurements. The difference between the measured outdoor sound level and the indoor sound level indicates the sound level reduction provided by the building shell.

Section 7.4 discusses methods for evaluating interior noise for Activity Category D land use facilities (schools, hospitals, libraries, etc.). Under the 2011 revision to 23 CFR 772 interior noise abatement for residences is no longer a federally fundable form of noise abatement.

3.4 Instrumentation

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

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

3.4.1 Sound Level Meters

ANSI has established requirements for sound level meter 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 sound level meters.

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

The expected total allowable error for a Type 1 sound level meter in the field is about 1.5 dB; for a Type 2 sound level meter in the field, the allowable error is about 2.3 dB. These expected values of total allowable errors apply to an instrument selected at random. These errors may be reduced for a specific instrument through careful calibration and adjustment.

For each sound level meter 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 a sound level meter, such as impulse and peak measuring capabilities and wide ranges for the display of sound levels. All sound level meters used by Caltrans or its contractors shall be of any type described above (Types 0, 1, 2, with A-weighting). The type must be marked on the meter by the manufacturer. Although sound level meters are available in a variety of configurations, they all have the following general components.

- **Microphone System (Microphone and Preamplifier):** The microphone converts air pressure fluctuations into an electrical signal that is measured by instrumentation such as the sound level meter or a third-octave band spectrum analyzer. Most microphones can be detached from the body of the meter and connected to an extension cable. To satisfy a Type 0 or 1 requirement, the microphone may need to be separated from the meter body.

  Microphones come in various diameters. The 0.5-inch-diameter microphone is used most commonly. The air condenser microphone (most common) consists of a membrane and back plate separated by an air gap. The width of the air gap fluctuates as the membrane vibrates in a sound field, thereby changing the capacitance. Microphones of sound level meters complying with the type standards are omni-directional, have a flat frequency response, and are sensitive over a wide range of frequencies.

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

- **Wind Screen:** A spherically or cylindrically shaped screen, generally made of open-celled polyurethane. When placed over the microphone, it reduces wind noise (see Section 3.6). The wind screen should always be used, even in absence of wind, because it helps to protect the microphone against dust or mishaps.

- **Root Mean Square Detector:** Converts peak-to-peak signals to a rms signal. This measure is derived by squaring the signal at each instant, obtaining the average (mean) of the squared values, and taking the square root of this average.
- **Amplifier:** Amplifies the electrical signal.
- **Frequency Weighting Filters (A to C):** These filters are required by ANSI S1.4-1983 and ANSI S1.4-1985. The A-weighting is used internationally for environmental noise measurements (including transportation noise).
- **Slow or Fast Response Switch:** Refers to time-averaging characteristics of the sound level meter. On the slow setting, the averaging of sound levels takes place over 1-second increments. On the fast setting, the averaging time is 0.125 second. On a real-time display (digital or analog), the sound level fluctuations are easier to read on the slow setting. The fast setting, however, gives a better resolution of instantaneous sound levels.
- **Range Setting:** Allows setting of the correct range of sound levels to be measured.
- **Digital Display:** Displays instantaneous noise levels or integrated averages. Digital displays often have multi-function switches that allow the user to view various noise descriptors such as L_{eq} and L_{max}.
- **Battery Check Switch:** Allows user to check battery voltage.
- **Output:** For various recording devices.
- **Power On/Off Switch**.

Many sound level meters also have pause switches to interrupt data sampling, preset time switches that allow sampling over a predesignated time period, reset switches for starting a new sampling period, and other features.

3.4.2 Data Recording and Analysis

Professional sound level meters typically can log measured sound levels in the form of the various sound level descriptors including those described in Table 2-12. These logged values can then be downloaded to a computer for analysis using a computer spreadsheet or other analysis software.

Professional sound level meters will typically have an audio output that can be connected to an external audio recorder for recording the audio signal from the meter. Handheld solid state digital audio recorders are typically used as an external recording device. Recorders should be high-quality professional recorders with flat frequency response and high signal-to-noise ratios. Once the signal is recorded a digital signal analyzer can then be used to analyze the recorded signal using octave, one-third octave, or narrow band signal analysis equipment. Digital signal analyzers can be dedicated stand-alone units, computer software programs, or built into the sound level meter. Some sound level meters also have the ability to directly capture digital audio recordings.

3.4.3 Acoustical Calibrators

Acoustical calibrators are used to calibrate the sound level meter/recorder system in the field. The calibrator fits over the top of the microphone. 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 or 114 dB at 1,000 Hz. Modern sound level meters generally maintain calibration within about ±0.2 dB. If field calibration values fall outside this deviation, the meter should be checked and calibrated by a laboratory accredited to perform calibrations on specified instruments.

Acoustical calibrators and sound level meters should be periodically certified for proper calibration by an appropriate certified acoustic lab.

3.4.4 Meteorological and Other Non-Noise-Related Equipment

Basic meteorological data including wind speed, wind direction, temperature, and relative humidity should be collected concurrently with most noise measurements.

An anemometer is an instrument used to measure wind speed. For general-purpose measurements at relatively close distances to a noise source, i.e., within about 100 feet, a hand-held, wind-cup anemometer and an empirically observed estimation of wind direction are sufficient to document wind conditions. For all types of measurements, the anemometer should be located at a relatively exposed position and at an elevation approximately equal to that of the highest receiver position.

Other recommended equipment includes a radar gun to measure traffic speeds, tape measures, survey levels (or hand levels), and rods to survey the site and document microphone positions with reference to landmarks, as well as watches or stopwatches to time the measurements. Portable radios or cell phones may be helpful to maintain contact with traffic counting personnel and other field personnel. Traffic count logging equipment is also very useful. Traffic can be counted and classified in real time in the field or recorded with a video camera for subsequent counting and classification.

3.5 Noise Measurement Procedures

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

3.5.1 Instrumentation Setup

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

If the microphone is not separated from the sound level meter body, the sound level meter should be supported on a tripod. If the microphone is separated, it should be placed on a tripod or other stand.

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

3.5.2 Field Calibration

Acoustical calibrators are described under Section 3.4.3. Some calibrators provide a choice of several frequency settings. If the calibrator offers these choices, 1,000 Hz should be used for calibration. The sound level meter/recorder system can then be adjusted to this level. The procedures in manufacturers' user manuals should be followed.

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

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

$$\text{Data Adjustment} = C_R - [(C_I + C_F\}/2)] \qquad \textbf{(3-1)}$$

Example

C_R = 94.2 dB

C_I = 94.4 dB

C_F = 94.6 dB

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

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

The field calibration procedure is described below.

1. Adequate start-up of instruments should be allowed before calibration (at least 1 minute or as specified in the manufacturer's manual). The

analyst should check that all proper connections have been made and that batteries are fresh or adequately charged.

2. The calibrator should be placed carefully over the microphone and properly seated. Touching the calibrator during calibration should be avoided.
3. If necessary make calibration adjustments as indicated in the manufacturer's user manual.

3.5.3 Measurements

Following calibration of equipment, a wind screen should be placed over the microphone. The frequency weighting should be set on "A." The proper response setting should be set at "fast" or "slow." "Slow" is typically used for traffic noise measurements. The desired sampling time, sampling interval, and noise descriptor should be selected.

During the noise measurements, any noise contamination, such as barking dogs, local traffic, lawnmowers, train passbys and aircraft, should be noted. If the sound level meter is equipped with a "pause" or "standby" switch or button, the measurement should be temporarily interrupted until the noise contamination ceases. Notes on the start time and duration of the contaminating event should be taken.

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

If highway noise measurements are taken, traffic should be counted simultaneously with the noise measurements. At a minimum, directional traffic should be counted separately. Traffic counts by lane are best but often not practical because they are too labor-intensive. Traffic should be divided into heavy trucks, medium trucks, autos, buses, and motorcycles as defined in TNM. Definitions of these vehicle types are addressed in Section 4. Average speeds for each vehicle group and direction should be estimated using a radar gun (if available) or test runs with a vehicle in the flow of traffic during the noise measurements.

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

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

3.5.4 Documentation

Measurement data should be carefully recorded. If the data are read from a display and hand-copied on a form, the readings should be checked and confirmed by another person if possible. It is recommended that blank data logging and collection forms be printed in advance for noise data, meteorological data, traffic counts, and site data. The forms can easily be designed for various types of measurements or specific studies using word processing or spreadsheet software. Specifically, the following items should be documented:

- **Noise Measurement Sites:** A sketch should be made showing the microphone location in relation to natural or artificial landmarks. Distances should be shown to the nearest foot to such features as building corners, trees, street signs, curbs, and fences. Enough detail should be included on the sketch to enable anyone to reoccupy, at a later date, the three-dimensional (including height above ground) position of the microphone within 1 foot horizontally and 0.5 foot vertically. Accurate three-dimensional relationships between source and site should be shown. Cross sections should be obtained from accurate maps or field surveys. Sites should be located on maps showing all receivers used in the noise analysis. Global positioning system (GPS) coordinates should be noted at each position. Photo documentation is also recommended. Many digital cameras and smart phones are capable of taking pictures that are automatically geo-tagged. The district, county, route number, and post mile of the site should be included.
- **Noise Measurements:** All instruments used for the noise measurements should be recorded, including manufacturer, model number, and serial number. Also important are the calibrator make, model, serial number, reference level, frequency, and last calibration date. Names of instrument operators and persons recording the data should be shown. Pre- and post-calibration data should be shown. Site number, date, time, length of measurement, noise descriptor, pertinent settings on the sound level meter/recorder system, and noise data should be recorded. Remarks, notes of contamination, or anything that might have a possible effect on the measurement results should be included.

- **Meteorological Conditions:** Prevailing wind direction and speed during the noise measurements, temperature, relative humidity, and sky conditions should be noted. Approximate height, and location of measurements should be indicated. Date, time, site number, and name of observer should be shown also.
- **Traffic Counts:** The number of vehicles broken down by classification should be shown. It is important to indicate the location of traffic counts, number of lanes or lane groups counted, direction, length of time, time, district, county, route, post mile, names of personnel, and counts and speeds.

Care must be taken so that enough information to make necessary cross references between noise measurements, traffic counts, weather, and site information can be made later if necessary.

3.6 Meteorological Constraints on Noise Measurements

Meteorological conditions can affect noise measurements in several ways. At an ambient noise level of 40 to 45 dBA, wind speeds of more than 11 mph may begin to contaminate noise measurements with a rumbling noise because of frictional forces on a microphone covered with a wind screen. Without the screen, the effect would be present at a much lower wind speed.

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

Rain or snow on highway pavement can alter the levels and the frequencies of tire and pavement noise, causing it to vary in unpredictable ways from levels on dry pavements, on which vehicle noise source characteristics are based. Pavement should be dry when taking measurements. Refraction caused by wind shear or temperature gradients near the ground surface will also alter noise levels. The effects of refraction are discussed in Section 2.1.4.3. When noise levels are compared to determine the effects of a transportation project on the noise environment or to evaluate the effectiveness of a noise abatement measure, the before and after noise levels should be conducted under equivalent meteorological conditions.

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

3.6.1 Meteorological Criteria

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

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

3.6.2 Equivalent Meteorological Conditions

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

Studies by Caltrans and others have shown that this wind effect can affect noise measurements significantly even at relatively close distances to noise sources. Section 3.3.3 indicates that to compare noise measurements for agreement, all site, traffic, and meteorological conditions must be the same.

Noise measurement comparisons can therefore only be made for similar meteorological conditions. ANSI S12.8 - 1998 "Methods for Determination of Insertion Loss of Outdoor Noise Barriers" recommends that meteorological equivalence be based on wind, temperature, and cloud cover. The following criteria are recommended for atmospheric equivalence average wind velocities from the source position to the receiver position. In the case of highway noise, the wind component of interest is perpendicular to the highway. The standards recommended by ANSI may be used to define meteorological equivalency for the purposes of comparing noise levels for agreement with Section 3.3.3 or any time before and after noise measurements are performed on noise barriers.

3.6.2.1 Equivalent Wind Conditions

Wind conditions are equivalent for noise measurements if the following conditions exist.

- The wind class (Table 3-4) remains unchanged.
- The vector components of the average wind velocity from the source to receiver (perpendicular to the highway) do not differ by more than a certain limit.

This limit depends on the accuracy desired and the distance from the source to receiver. To keep the measurement accuracy due to atmospheric wind conditions to within about 1 dB, this limit should be 2.2 mph for distances less than 230 feet. If it is desired to keep this accuracy within about 0.5 dB for the same distance, the measurements to be compared should each be repeated at least four times. The 2.2 mph limit does not apply to the “calm” condition. By convention, the perpendicular wind component blowing from the highway to receiver (microphone position) is positive, while the same component blowing from the receiver to highway is negative.

Table 3-4. Classes of Wind Conditions

Wind Class	Vector Component of Wind Velocity, mph
Upwind	-2.2 to -11
Calm	-2.2 to +2.2
Downwind	+2.2 to +11

For example, two measurements may be compared when their respective wind components are 0 and -2.2 mph, -2.2 and -4.4mph, or -5.5 and -7.7 mph, but not when their respective components are 1.1 mph and 3.3 mph, because of the change in wind class. For the purposes of comparison with the results from the FHWA TNM, which has no provisions for wind inputs and therefore predicts noise levels for calm (no wind) conditions, the perpendicular wind component needs to be between -2.2 and +2.2 mph.

Please note that the actual wind velocity (direction and speed) needs to be resolved into two components, with directions parallel and perpendicular to the highway. Then, only the perpendicular component is considered (as long as the actual wind speed does not exceed 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 as follows.

- Monitoring wind velocity (speed and direction) throughout any period of acoustical measurements.

- Noting the average speed and direction.
- Computing from these averages the vector component of wind velocity from the source to receiver (perpendicular to the highway).

3.6.2.2 Equivalent Temperature and Cloud Cover

Measurements to be compared (e.g., before or after noise barrier measurements or repeat measurements) should be made for the same class of cloud cover, as determined from Table 3-5, and with the average air temperatures within 25°F of each other.

Table 3-5. Cloud Cover Classes

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

3.6.2.3 Equivalent Humidity

Although there are no strict guidelines for equivalence of humidity, an attempt should be made to pair measurements for similar conditions of humidity. For example, comparisons of measurements made under extremely dry conditions (e.g., less than 25%) with those made during humid conditions (e.g., more than 75%) should be avoided.

3.7 Quality Assurance

All sound level meters and acoustical calibrators should be periodically calibrated by the manufacturer, or by a laboratory accredited to perform calibrations on specified instruments. All calibrations should be traceable to the National Institute of Standards and Technology (NIST) in Washington, DC. For legal purposes instrument manuals and calibration and repair records should be kept on file in the office of the responsible party (e.g., District office, headquarters environmental unit). Historical data on the instrument performance may be useful in determining the reliability and accuracy of the equipment.

Section 4
Detailed Analysis for Traffic Noise Impacts

This section discusses the procedure for conducting a detailed analysis of traffic noise impacts. These procedures comply with analysis requirements of 23 CFR 772 and are consistent with standard acoustical practices.

4.1 Gathering Information

The first step in a technical noise analysis is to determine the level of detail necessary for the study, which depends on the size and nature of the project. Generally, as the size of the project, the complexity of terrain, and the population density increase, so does the amount of information and level of effort needed for an adequate noise analysis.

For the analysis, it is necessary to obtain adequate information and mapping showing project alternatives and their spatial relationships to potentially noise-sensitive areas. A "no build" alternative should be included. Early in the project, final design details usually are not available, and additional analyses may need to be performed as more details are introduced. Topographical information may also be limited in early stages of project design. Field reviews, recent aerial photographs, and online geographic data may be necessary to augment information shown on preliminary maps. Design-year traffic information for all project alternatives is also required for the analysis. Traffic count data for all state highways is available for downloading from the Caltrans website at:

http://www.dot.ca.gov/hq/traffops/saferesr/trafdata/index.htm

4.2 Identifying Existing and Future Land Use and Applicable Noise Abatement Criteria

Existing and reasonably expected future activities on all lands that may be affected by noise from the highway must be identified (see the Protocol for details on how various land use types are addressed). Existing activities, developed lands, and undeveloped lands which have been permitted for development that may be affected by noise from the highway must be identified. Land development is considered to be permitted on the date that the land use (subdivision, residences, schools, churches, hospitals, libraries, etc.) has received all final discretionary approvals from the local agency with jurisdiction, generally the date that the building permit or vesting tentative map is issued. This information is essential to determine which NAC apply for determining traffic noise impacts. The NAC are shown in Table 4-1.

Table 4-1. Activity Categories and Noise Abatement Criteria (23 CFR 772)

Activity Category	Activity $L_{eq}[h]$[a]	Evaluation Location	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[b]	67	Exterior	Residential.
C[b]	67	Exterior	Active sport areas, amphitheaters, auditoriums, campgrounds, cemeteries, day care centers, hospitals, libraries, medical facilities, parks, picnic areas, places of worship, playgrounds, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, recreation areas, Section 4(f) sites, schools, television studios, trails, and trail crossings.
D	52	Interior	Auditoriums, day care centers, hospitals, libraries, medical facilities, places of worship, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, schools, and television studios.
E	72	Exterior	Hotels, motels, offices, restaurants/bars, and other developed lands, properties, or activities not included in Activity Categories A–D or F.
F			Agriculture, airports, bus yards, emergency services, industrial, logging, maintenance facilities, manufacturing, mining, rail yards, retail facilities, shipyards, utilities (water resources, water treatment, electrical), and warehousing.
G			Undeveloped lands that are not permitted for development of a specific use.

[a] The $L_{eq}(h)$ activity criteria values are for impact determination only and are not design standards for noise abatement measures. All values are A-weighted decibels (dBA).

[b] Includes undeveloped lands permitted for this activity category.

23 CFR 772 requires that a minimum of one receiver be placed in all areas within a project area that are associated with Activity Categories A, B, C, D, and G. Undeveloped Activity Category

G areas are included because FHWA wants to provide a record of predicted future noise levels to local agencies so that these noise levels can be considered in future land use planning.

If there are no exterior use areas at an Activity Category E use it is not necessary to include a receiver in that area. Similarly, it is not necessary to include a receiver at an Activity Category F use. Receivers are not required for these areas because these uses are already developed and it is not necessary to inform local planning agencies about future noise levels in these areas.

4.3 Determining Existing Noise Levels

Existing noise levels may be determined at discrete locations in the project area by actual noise measurement (see Section 3) or using the TNM (see Section 4.5.1). The latter is usually the case. This section discusses how to select these locations, the methods used to determine existing noise levels, and how to "calibrate" the noise prediction model with measurements where appropriate.

4.3.1 Selecting Noise Receivers and Noise Measurement Sites

For the purposes of noise analysis, a noise receiver is any location included in the noise analysis. A noise measurement site is a location where noise measurements are taken to determine existing noise levels, and verify or calibrate the noise prediction model. Receivers and noise measurement sites may or may not coincide. Normally, there are more receivers than noise measurement sites. It is far less expensive to model (calculate) noise levels for receivers than to take noise measurements in the field. If the project involves the reconstruction of an existing facility, existing noise levels are measured at representative receivers and compared with modeled results for the conditions observed during the measurement. The difference between modeled and measured results may then be applied to the results for modeled future conditions. This process, called model calibration, is fully described in Section 4.4.

4.3.1.1 Receptors and Receivers

In the context of a 23 CFR 772 analysis the term *receptor* means a single dwelling unit or the equivalent of a single dwelling unit. A *receiver* is a single point in a noise model that can represent one receptor or multiple receptors. Within the identified land use activity categories adjacent to the project, there are typically numerous noise receptors that need to be analyzed for future noise impacts or benefits from noise abatement under consideration. It is not reasonable or possible to examine these factors at all receptors. Therefore, modeling receivers should be carefully selected to accurately represent one or more receptor locations. Some general recommendations for selecting receivers are listed below.

- Although noise impacts must be evaluated at all developed land uses, receiver locations should focus on areas of frequent human use (defined in the Protocol glossary).
- The TNM has been validated at distances within 500 feet of the highway. Receptors that are located beyond 500 feet from the project area do not need to be considered for analysis unless there is a reasonable expectation that noise impacts would extend beyond that boundary. This may require engineering judgment and supplemental noise measurements to determine impacts.
- Generally select receivers in locations that are receiving or are expected to receive the highest noise levels over the period covered by the analysis. Because in most cases impacts will be at receivers closest to the highway, most receivers should be in the first row of residences relative to the project alternative. Some common exceptions include the following.
    - Projects where realignment would move the noise sources toward receptors other than those adjacent to the existing alignment.
    - Projects involving geometry where the first row of homes is partially shielded and second-row homes actually may receive higher noise levels (e.g., roadways on high embankments).
    - Areas near the ends of proposed barriers where second- or third-row receptor sites may be needed to better define the barrier limits.
    - Projects that involve widening where additional right-of-way requirements may clear the first row of residences and turn the second row into the first.
- A noise measurement site should coincide with a modeling receiver whenever possible. However, this often may not be the case. The selected receiver location may not be a good or accessible location for setting up a sound level meter. In that case, a noise measurement site that is acoustically representative of the receiver should be selected in a more accessible location.
- Other noise-sensitive locations, such as libraries, churches, hospitals, and schools, should be included.
- Receivers that are acoustically equivalent of the area of concern should be chosen. The concept of acoustical equivalence incorporates equivalencies in noise sources (traffic), highway cross sections,

distance from the highway, topography of intervening terrain, shielding, and other pertinent factors. The region under study may need to be subdivided into subregions in which acoustical equivalence generally can be maintained. One or more of the previously mentioned acoustical factors should dictate boundaries of each subregion. The size of subregions may vary depending on the scope of the project.

- A minimum of two receivers should be selected for each acoustically equivalent region or subregion. The actual number necessary to define noise impacts depends not only on the type of project, but also on such influences as complexity of the highway profile and variability of the surrounding terrain. A highway with a straight grade or very shallow vertical curves in a relatively flat area with tract-type residential development that parallels the highway may need only a few receivers to adequately define the noise impacts. However, a project involving a major freeway that includes interchanges, cuts and fills in an area of rolling terrain, and non-tract mixed residential and commercial development is likely to need more receivers.
- Receivers are placed 5 feet above the ground elevation, unless dictated by unusual circumstances, special studies, or other requirements. Exceptions would include placing a receiver 5 feet above a wooden deck of a house situated on a steep slope, instead of 5 feet above the ground. Similar situations might be encountered where residential living areas are built above garages, where second-story levels would be more logical receiver locations.
- Noise should be evaluated at second-story elevations or at higher elevations in the case of multistory buildings when there are exterior areas of frequent human use at the higher elevations that could benefit from noise reduction. Examples include large patios or decks that are the primary outdoor use area in an apartment complex. Clearly, it will not be feasible or reasonable to construct a wall that protects a receiver location several stories above a freeway. There may, however, be situations where an upper story of a building is at the same elevation as the highway (i.e., the highway is on a fill section). In this case, it may be both feasible and reasonable to build a wall to reduce noise at the upper stories.
- To determine the number of benefited receptors (defined in the Protocol glossary), it is usually necessary to include receivers in the first, second, and third rows of residences (or beyond in some cases) in the noise analysis.

4.3.1.2 Noise Measurement Sites

The selection of noise measurement locations requires planning and foresight by the noise analyst. A fine balance should be achieved between a sufficient number of quality locations and the cost and availability of resources. Preliminary design maps, cross sections, aerial photographs, and field survey data are all helpful sources of information for selecting noise measurement sites, but the sites should be selected only after a thorough field review of the project area. Some recommended site characteristics common to all outside noise measurement sites are listed below.

- Sites should be clear of major obstructions. Reflecting surfaces such as walls of residences should be more than 10 feet from the microphone positions.
- Sites should be free of noise contamination by sources other than those of interest. Sites located near barking dogs, lawn mowers, pool pumps, air conditioners, etc. should be avoided unless it is the express intent to measure noise from these sources.
- Sites should be acoustically representative of areas and conditions of interest. They should either be located at or represent locations of frequent human use.

In addition to these general requirements, the selection of noise measurement sites is governed by the same general guidelines as those for selection of receivers in Section 4.3.1.1. Of particular importance is the concept of acoustical equivalence for representativeness of the area of concern. More detailed considerations are discussed in Section 3.2.

4.3.2 Measuring Existing Noise Levels

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

In the noise analysis for a project, the noise measurements are used to determine existing ambient and background noise levels, and to calibrate the noise prediction model when appropriate. Section 3 provides details of noise measurement methods.

4.3.3 Modeling Existing Noise Levels

Noise levels near existing facilities can also be determined by modeling. Although measurements are preferred, adverse environmental conditions, construction, unavailability of good measurement sites, or lack of time may make it necessary to calculate existing noise levels using TNM. However, this can only be done in areas where a defined highway source exists with minimal influence from traffic on other roads in the area 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 validation and 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 validation and calibration ensure that existing noise levels at the measured and modeled receptors are in reasonable agreement.

4.4 Validating/Calibrating the Prediction Model

The main purpose of modeling is to predict future noise levels. The computer model (TNM) and procedures used to predict future noise levels are discussed in Section 4.5. However, as mentioned in Section 4.3, TNM also can be used for modeling existing noise levels where measurements are not possible or undesirable because of lack of access or local environmental conditions. In both cases, the model should be validated with measurements and calibrated if necessary. This section, which discusses the model validation/calibration procedures that rely on measurements and modeling, should be used with Section 4.5. However, for convenience, all information needed except for running the model is contained in this section.

TNM cannot account for all the variables present in the real world. It uses relatively simple algorithms to approximate physical processes that are complex in nature. TNM for projects involving existing roadways should always be validated for accuracy by comparing measured sound levels to modeled sound levels using traffic data collected during the measurement. If modeled sound levels do not match measured sound levels within ±3 dB the model parameters should be reviewed and adjusted if necessary to ensure that they accurately represent actual site conditions. If the measurements and model results are still not in agreement, the model should be calibrated.

This section discusses the model calibration process. Section 4.4.1 addresses model calibrations that are routinely performed by Caltrans. The procedures for these are straightforward but rely on sound judgment and place a heavy burden on quality noise measurements.

4.4.1 Routine Model Calibration

4.4.1.1 Introduction

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

Model calibration is defined as the process of adjusting calculated future noise levels by algebraically adding a calibration constant derived from the difference between measured and calculated noise levels at representative sites. The difference—calibration constant, K-constant, or *K*—is defined as measured noise level *M* minus calculated noise level *C*, or $K = M - C$. Please note that *K* is positive when *M* is greater than *C*, and *K* is negative when *M* is less than *C*. In this section, a distinction will be made between calculated and predicted noise levels as follows:

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

4.4.1.2 Limitations

Highways constructed along new alignments and profiles do not lend themselves to model calibration. The site before project construction does not include the new highway. Ambient noise levels are generated by typical community noise sources, such as lawn mowers, air conditioners, and barking dogs, which cannot be modeled with TNM.

Highway reconstruction projects that significantly alter alignments and profiles of an existing highway are also poor candidates for model calibration. However, predictions of future noise levels for simple highway widening projects, design of retrofit noise barriers, or other improvements that do not significantly change highway alignment or profile are good candidates for model calibration as long as other site conditions do not change.

4.4.1.3 Pertinent Site Conditions

To determine whether the model can be calibrated successfully, the site conditions that are allowed to change between the present and the expected life of the project should be examined first. For this purpose, site conditions should be divided into two groups:

- **Group 1:** Site conditions that can be accounted for by the model, which include the following.
  - Traffic mix, speeds, and volumes.
  - Noise dropoff rates, terrain conditions, ground types, and distances.
  - Opaque barriers (noise transmission through barrier material may be ignored [i.e., high transmission loss]).
  - Roadway and barrier segment adjustments.
  - Receptor locations.
  - Grade corrections.
  - Pavement type.

  Note that FHWA policy requires the use of the "average" pavement type for design year traffic noise predictions. Alternative pavement types such as dense-graded asphaltic concrete (DGAC), Portland cement concrete (PCC), and open-graded asphaltic concrete (OGAC) can be used in the model validation process if actual existing pavements are one of these types of alternative pavements.

- **Group 2:** Site conditions that cannot be accounted for by the model and therefore are ignored, although they affect the local noise environment. These include the following.
  - Non-typical vehicle noise populations such as farm equipment, recreational vehicles, or vehicles with studded snow tires or aggressive tread (i.e., designed for mud and snow conditions).
  - Transparent shielding (noise transmission through material is significant [i.e., low transmission loss], and such materials include wood fences with shrinkage gaps [noise leaks] and areas of heavy brush or trees).
  - Reflections off nearby buildings and structures.
  - Meteorological conditions.

For the purposes of model validation and calibration, Group 1 site conditions are allowed to change somewhat. The degree to which conditions can change is a judgment call and is discussed further in

Section 4.4.1.5. Group 2 site conditions, however, are not allowed to change. These conditions affect noise levels to an unknown extent but are ignored by the model. As long as they remain constant during the entire analysis period, they may be corrected for with *K*. If they change at some point in the future, however, *K* also must change by an unknown amount, and model calibration becomes invalid.

Some cautions and challenges associated with Groups 1 and 2 site conditions are discussed in Section 4.4.1.5. First, however, the calibration procedures will be explained.

4.4.1.4 Procedures

The actual mechanics of model calibration are fairly straightforward.

1. Select locations along the existing highway that are representative of the area of interest.
2. Take noise measurements at these locations and count traffic, preferably during the peak noise hour. If this is not possible, select any other time during which traffic mix and speeds (not necessarily volumes) are roughly similar to the noisiest time. This may be estimated. Typically, this condition occurs during daytime whenever traffic is free-flowing.
3. Calculate the noise levels with the prediction model using the traffic counts (expanded to 1 hour), site geometry, and any other pertinent existing features.
4. Compare measured and calculated noise levels. If these values differ by more than 3 dB check traffic data and model parameters to ensure they represent actual site conditions. If the values continue to differ by more than 3 dB then calibrate the model using the difference. The difference, *K*, is determined as follows:

$$K = \text{Measured} - \text{Calculated, or } K = M - C \qquad \textbf{(4-1)}$$

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

$$P = C + K \qquad \textbf{(4-2)}$$

The following illustrates the mechanics of the calibration procedure with some typical values.

Example

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

$K = M – C_1 = 70 – 73 = -3$ dBA
$P_1 = C_2 + K = 75 + (-3) = 72$ dBA

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

4.4.1.5 Cautions and Challenges

Section 4.4.1.3 indicated that Group 1 conditions (those conditions that can be accounted for in the model) are allowed to vary. Experience has shown that significant changes in traffic volumes, speeds, and mix, as well as shielding by barriers more than 6 feet high and segment adjustments within the range normally encountered, can be accounted for adequately by the model. The main problem areas in Group 1 site conditions pertaining to model calibrations are differences in source-to-receiver distances and low barriers.

First, distances should be considered. No model can satisfy all conditions encountered in the real world. Therefore, *K* tends to be at least somewhat distance-dependent. This has two major implications for the calibration process.

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

The second Group 1 challenge relates to attenuation from low ground features or barriers. Although it is Caltrans' policy to build barriers that are at least 6 feet high, it is possible that the existing condition includes a low rise in terrain, a hinge point, or a low barrier. Because these features will result in some degree of attenuation, it is important to include these low ground features or barriers in the model if calibration is going to be conducted. Meteorology is one of the major challenges in Group 2 site conditions. The effects of wind speed and direction or temperature inversions on noise levels at a receiver can be substantial, even at relatively short distances from a highway. (Refer to Section 2.1.4.3 for more details on these effects.) Because the prediction model does not take weather into consideration, noise measurements should be taken under calm wind conditions. Strong temperature inversion conditions should be avoided as well. Temperature inversion conditions can occur during warm summer and fall months with cool morning conditions. Section 3.6 discussed the criteria for identifying calm winds. Any attempt to calibrate the model for a prevailing wind condition is only valid for that condition. Noise standards, however, are not linked to weather.

Finally, noise contamination from other sources not considered by the model cannot be corrected by model calibration, as illustrated in the following hypothetical case. In this case, at a calibration site, the existing measured noise level is 68 dBA. This freeway noise level is contaminated by nearby surface streets and other neighborhood noises and the freeway contribution and background noise cannot be separated from the measurement. It is not known that the freeway traffic and background noise contribute 65 dBA each, for a total of 68 dBA. The existing noise level from the freeway was calculated to be 65 dBA, which happens to agree with the actual freeway contribution. There is no reason to believe that the background noise will change in the future. Therefore, the model is incorrectly calibrated. The calculated future noise level is 70 dBA. However, the predicted future level must be determined. This problem is outlined below.

Existing Noise Levels	**Future Noise Levels**
Freeway: 65 dBA (unknown)	Freeway: 70 dBA (unknown)
Background: 65 dBA (unknown)	Background: 65 dBA (unknown)
Total: 68 dBA (measured)	Total: 71 dBA (actual)
Freeway: 65 dBA (calculated)	Freeway: 70 dBA (calculated)
K = M – C = 68 – 65 = 3	Freeway: ? dBA (predicted)

Predicted Freeway

$$P = C + K = 70 + 3 = 73 \text{ dBA}$$

(Compared with 71 dBA actual)

In this situation, the calibration process caused an overprediction of 2 dBA, although the background remained the same during the analysis period. Therefore, background noise high enough to contaminate the noise measurements cannot be considered a Group 1 or 2 site condition. In short, it represents a site condition that precludes the use of model calibration.

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 the sound level of an undesired noise source is within 10 dBA of the noise source of interest. A quick check for contamination can be performed by viewing the instantaneous sound level on a sound level meter. If the meter responds at all to fluctuations of the undesired source, the noise level likely will be contaminated.

4.4.1.6 Tolerances

Model accuracy is usually sufficient when the difference between measured and model sound levels is less than 3 dB. Because of the inherent uncertainties in the measurements and calibration procedures, model calibration should not be attempted when calculated and measured noise levels agree within 1 dBA. If there is great confidence in the accuracy and representativeness of the measurements, calibration may be attempted when calculated noise levels are within 2 dBA of the measured values. Differences of 3 to 4 dBA may routinely be calibrated unless the validity of the measurements is in serious doubt. Differences of 5 dBA or more should be approached with caution. The analyst should retake measurements, look for obvious causes for the differences (e.g., weather, pavement conditions, obstructions, reflections), check traffic and other model input parameters (and remember to expand traffic counted during the noise measurement to 1 hour), and confirm that the traffic speeds are accurate. If differences of 5 dBA or more still exist after confirming the measurements and input parameters, the decision about whether to calibrate the model should be made after determining whether any of the responsible Group 2 site conditions will change during the project life.

4.4.1.7 Common Dilemmas

The following hypothetical cases present some common dilemmas the noise analyst may need to resolve when selecting model calibration sites. In one case, a receiver was selected in a backyard abutting a freeway right-of-way. The only obstacle between the receiver and the freeway is a 6-foot-high wood fence running parallel to the freeway. The fence boards are standard ½ - by 6-inch boards with shrinkage gaps between them. The question is whether this receiver should be used for model calibration measurements.

There is no clear-cut answer. If the fence is new and expected to remain in good condition for about the next 20 years and no noise barrier is planned, this probably would be a good representative location to measure existing noise levels and predict model-calibrated future noise levels for all the backyards bordering the right-of-way.

In another case, the predicted (calibrated) noise level at this receiver is high enough to qualify for a noise wall. Before the wall is constructed, the existing fence provides transparent shielding, a Group 2 site condition. After the wall is constructed, however, any effect from the fence will be eliminated, regardless of whether the fence remains (i.e., the effects of a Group 2 site condition change). In this case, the location would be a bad choice for model calibration.

In many cases, it is uncertain whether noise levels are high enough to justify noise barriers until the noise is measured. There are also no assurances of the longevity of wooden backyard fences. In the preceding case (and for wooden privacy fences in general), it is good policy to pick for calibration purposes locations on the freeway side of the fence or on a side street that dead-ends at the freeway right-of-way. Similar situations may exist in areas of heavy shrubs or dense woods.

Shielding by a solid barrier such as by a masonry block wall of at least 6 feet in height, can be adequately addressed by the model and does not represent a problem in the calibration process.

4.5 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 whether any of the alternatives are predicted to result in traffic noise impacts. The traffic noise prediction procedures are specified in 23 CFR 772. FHWA requires that all new project noise studies be evaluated using the federally approved TNM. An exception to this requirement may occur for a reevaluation noise study of a project that was originally analyzed using an earlier noise model. Any decision to use an earlier noise model should be reviewed and approved by Caltrans headquarters noise staff. Refer to the 2009 version of TeNS for a detailed discussion of previous noise models.

4.5.1 FHWA TNM Overview

The FHWA TNM was released on March 30, 1998. FHWA mandated that all new federal-aid highway projects that begin after January 15, 2006, be evaluated using TNM. TNM Version 2.5 is the current version as of the publishing of this document. *Federal Highway Administration Traffic Noise Model* and *FHWA TNM* are a registered copyright and trademark. This provides FHWA with the exclusive right to use these names. The copyright and trademark encompass the user's guide, technical manual, software source, and executable codes.

The following sections provide a brief overview of TNM. For detailed information, the technical manual and user's guide should be consulted. Refer to the following FHWA website for current information and guidance on TNM:

http://www.fhwa.dot.gov/environment/noise/traffic_noise_model/tnm_v25

Additional detailed technical guidance from FHWA is available at the following website:

http://www.fhwa.dot.gov/environment/noise/regulations_and_guidance/

4.5.1.1 TNM Reference Energy Mean Emission Levels

TNM computes highway traffic noise at nearby receivers and aids in the design of noise barriers. The noise sources include an entirely new database of 1994–1995 REMELs that is detailed in *Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model (FHWA TNM), Version 1.0* (Fleming et al. 1995). The database includes speed-dependent emission levels for constant speeds on level roadways from idle to 80 mph, for the following vehicle types.

- **Automobiles:** all vehicles having two axels and four tires—designated primarily for transportation of nine or fewer passengers, i.e., automobiles, or for transportation of cargo, i.e., light trucks. Generally with gross vehicle weight less than 9,900 pounds.
- **Medium Trucks:** all cargo vehicles with two axles and six tires—generally gross vehicle weight is greater than 9,900 pounds but less than 26,400 pounds.
- **Heavy Trucks:** all cargo vehicles with three or more axles—generally with gross vehicle weight greater than 26,400 pounds.

- **Buses:** all vehicles having two or three axles and designed for transportation of nine or more passengers.
- **Motorcycles:** all vehicles with two or three tires with an open-air driver/passenger compartment.

TNM contains the following pavement types.

- DGAC.
- PCC.
- OGAC.
- Average: a combination of both DGAC and PCC pavements which is comprised of, on average, approximately 75% DGAC pavement and 25% PCC pavement.

TNM defaults to *average* for pavement type. The use of any other pavement type must be substantiated and approved by FHWA. Therefore, unless definite knowledge is available on the pavement type and condition and its noise-generating characteristics, no adjustments should be made for pavement type in the prediction of highway traffic noise levels.

In addition, the database includes data for the following.

- Vehicles on grades.
- Three different pavements (DGAC, OGAC, and PCC).
- Accelerating vehicles.
- Acoustic energy apportioned to two subsource heights above the pavement (0 feet and 5 feet for all vehicles, except for heavy trucks, where the subsource heights are 0 feet and 12 feet).
- Data stored in one-third-octave bands.

The TNM Baseline REMEL curves shown in Figure 4-1 were plotted from the following TNM Baseline equations:

$$\text{Speed} = 0 \text{ (idle)}: L(s_i) = 10\log_{10}(10^{C/10}) \quad \textbf{(4-3)}$$

$$L(s_i) = C \quad \textbf{(4-4)}$$

$$\text{Speed} > 0: L(s_i) = 10\log_{10}[(0.6214s_i)^{A/10} + 10^{B/10} + 10^{C/10}] \quad \textbf{(4-5)}$$

Where:

$L(s_i)$ = REMEL for vehicle type *i* at speed *s* in kilometers per hour

s_i = speed of vehicle type *i* in kilometers per hour

A, B, C are constants for each vehicle type, shown below (Table 4-2)

Note: For speeds in miles per hour omit 0.6214 in Equation 4-5.

Table 4-2. TNM Constants for Vehicle Types

	Constants		
Vehicle Type	A	B	C
Autos	41.740807	1.148546	50.128316
Medium trucks (two axles, dual wheels)	33.918713	20.591046	68.002978
Heavy trucks (three axles)	35.879850	21.019665	74.298135

Note: Baseline REMELs = REMELs for the following conditions.

- Average pavement (average for all pavements in the study, including PCC, DGAC, and OGAC).
- Level roadways (grades of 1.5% or less).
- Constant-flow traffic.
- A-weighted, total noise level at 50 feet.

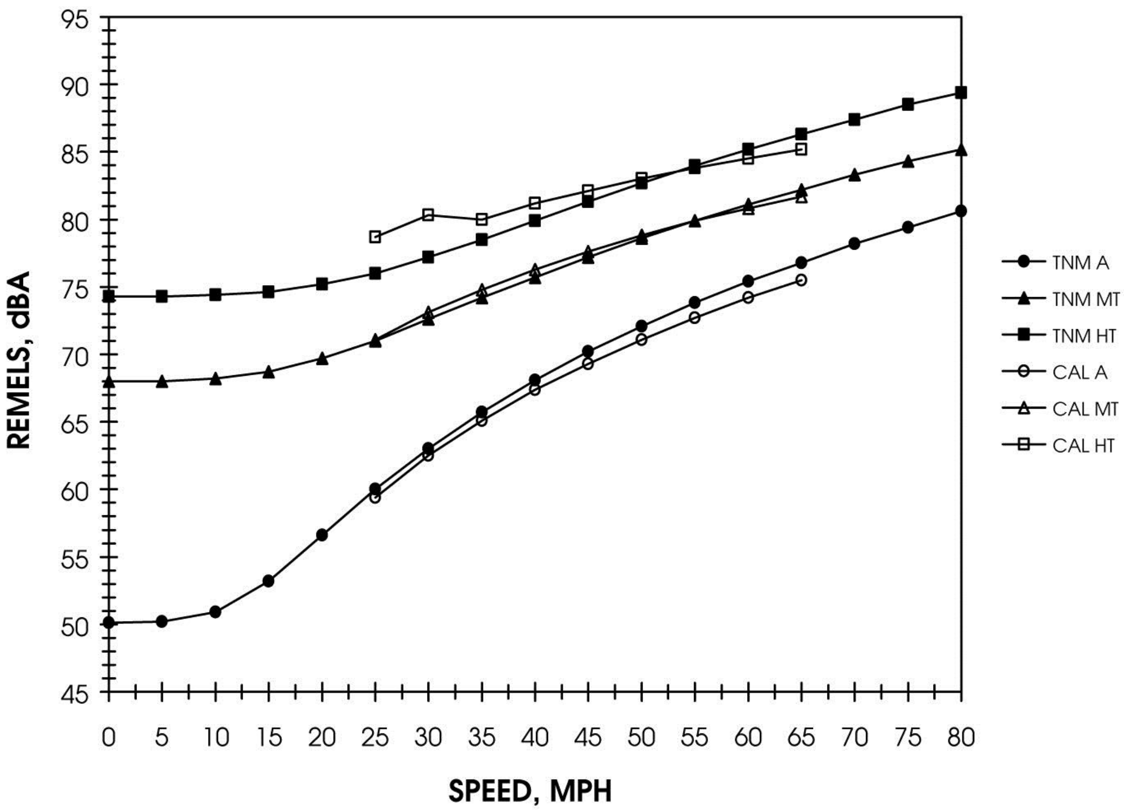

Figure 4-1. A-Weighted Baseline FHWA TNM REMEL Curves

4.5.1.2 Noise Level Computations

TNM calculations of noise levels include the following components.

- Three noise descriptors (L_{eq}[h], L_{dn}, and CNEL—see Section 2.2.2.2).
- Capability of inserting traffic control devices, including traffic signals, stop signs, tollbooths, and on-ramp start points (the TNM calculates vehicle speeds and emission levels, and noise levels accordingly).
- Computations performed in one-third-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.

4.5.1.3 Propagation, Shielding, and Ground Effects

The TNM incorporates sound propagation and shielding (e.g., noise barriers) algorithms, which are based on research of sound propagation over different ground types, atmospheric absorption, and shielding effects of noise barriers (including earth berms), ground, buildings, and trees. However, the 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. Source and receiver heights above the ground are important in noise propagation.
- Ground zones (x-y-z coordinates) define perimeters of selected ground types. Ground type may be selected from: a ground-type menu (e.g., lawn, field grass, pavement), 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 roadways 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 diffraction effect is computed from the most effective pair of barriers, berms, or ground points that intercept the source-to-receiver line of sight.

4.5.1.4 Parallel Barrier Analysis

TNM calculates the noise reduction provided by a barrier placed between a roadway and a receiver. If another barrier is placed on the opposite side of the roadway there is potential for multiple reflections between the two barriers to degrade the noise reduction provided by the original barrier at the receiver. (See Section 5.1.7.4 for a detailed discussion of this issue.)

TNM cannot directly calculate the degradation in barrier performance caused by parallel barriers. There is however a separate two-dimensional module in the program that can calculate the degradation caused by multiple reflections at a single receiver for a given parallel barrier configuration. This degradation, expressed in dB, is then applied to the TNM model results for that receiver.

4.6 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 Protocol. Examination of traffic noise impacts includes comparing the following for each project alternative when appropriate.

- Predicted noise levels with existing noise levels (for “substantial increase” impacts).
- Predicted noise levels with the appropriate NAC (for “approach or exceed” impacts).
- Predicted noise level of classroom interior with 52 dBA-L_{eq}(h) (as required by California Street and Highways code).

4.7 Evaluating Noise Abatement Options

If traffic noise impacts have been identified, noise abatement must be considered. Noise abatement measures may include those listed in the Protocol. These potential measures are based on avoiding impacts, interrupting noise paths, or protecting selected receptors. If the project alternative locations are flexible, alignments and profiles can be selected to avoid sensitive receptors or reduce the noise impacts. Most often, highway alignments and profiles are selected based on other overriding factors. The construction of noise barriers is usually the most common noise abatement option available. The consideration of noise abatement described in the Protocol requires at a minimum a preliminary design of the abatement. Section 5 provides guidance on the design considerations of noise barriers.

Section 5
Noise Barrier Design Considerations

The primary function of highway noise barriers is to shield receivers from excessive noise generated by highway traffic. Although there are other strategies for attenuating transportation-related noise, noise barriers are the most common noise attenuation option used by Caltrans.

Many factors need to be considered in the proper design of noise barriers. First, barriers must be acoustically adequate. They must reduce the noise as described by policies or standards. Acoustical design considerations include barrier material, 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 non-acoustical design considerations, is equally important. Noise barriers can have secondary effects related to security in surrounding areas, aesthetics, community continuity, and other non-acoustical factors. With appropriate planning and design these potential effects from noise barriers can be reduced or avoided.

The current edition of the *Highway Design Manual* Chapter 1100 should be consulted for specific noise barrier design criteria. Because these may change in the future, the discussion in this section will focus on general applications and consequences of the design criteria, not on the criteria themselves. The Caltrans Headquarters Division of Environmental Analysis should be consulted for the latest status.

The acoustical and non-acoustical design considerations in this section conform to the *FHWA Highway Noise Barrier Design Handbook* (Fleming et al. 2011).

5.1 Acoustical Design Considerations

The FHWA TNM described in Section 4 is 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 and any unshielded segments are considered. Therefore, the material of the barrier must be sufficiently dense or thick to ensure 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. The various effects associated with these factors are discussed in Sections 2 and 4.5.

Figure 5-1 is a simplified sketch showing what happens to vehicle noise when a noise barrier is placed between the source and receiver. The original straight path from the source to 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 toward the source. Another portion is absorbed by the material of the barrier, and another is transmitted through the barrier. The reflected (scattered) and absorbed noise paths never reach the receiver.

The transmitted noise continues on to the receiver with a loss of 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 the TL. The TL of a barrier depends on the barrier material, primarily 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 toward the receiver (Figure 5-2). This process also results in a loss of acoustical energy.

Therefore, the receiver is exposed to both 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.

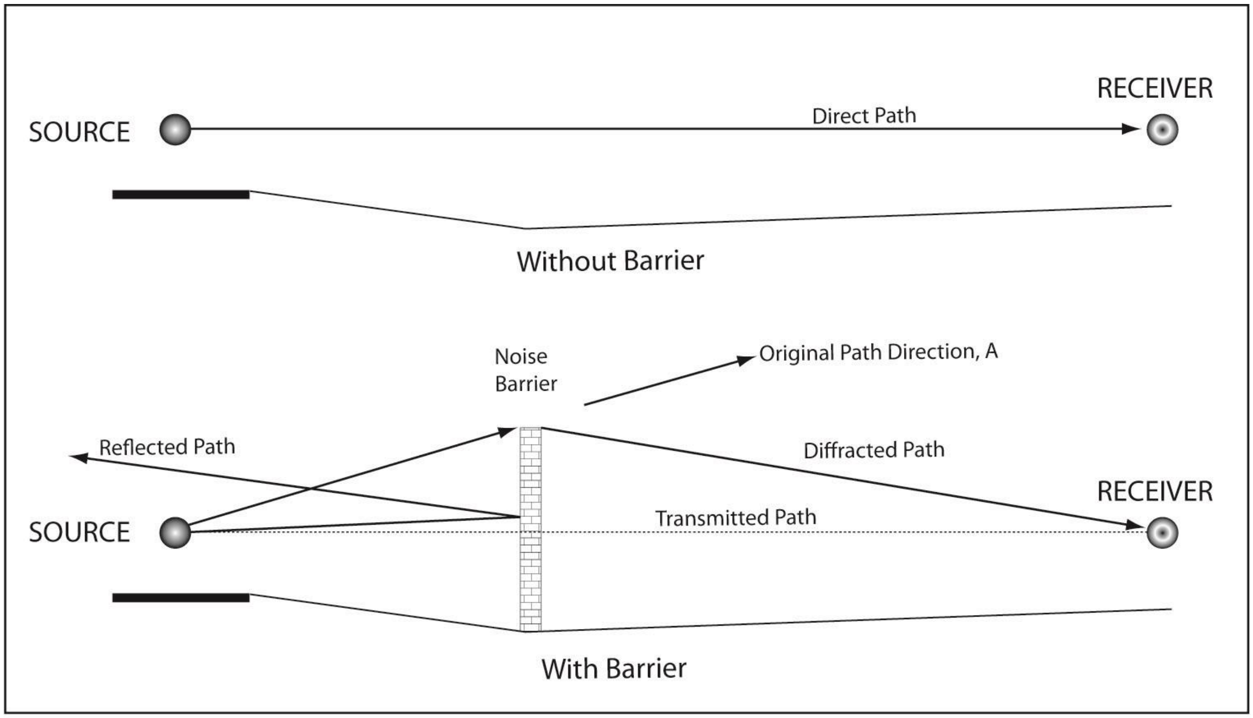

Figure 5-1. Alteration of Noise Paths by a Noise Barrier

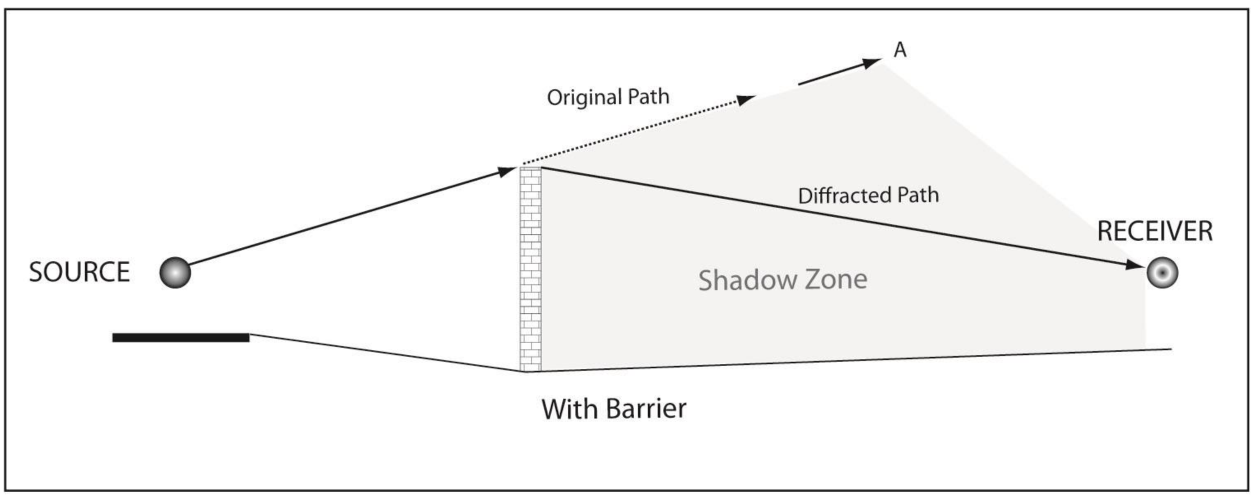

Figure 5-2. Barrier Diffraction

5.1.1 Barrier Material and 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 TL of at least 10 dBA more than the desired noise reduction. This ensures 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 more.

As a general rule, any material weighing 4 pounds per square foot 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. Please note that this weight can be attained by a variety of material types. The denser a material is, the thinner it may be. TL also depends on the stiffness of the barrier material and frequency of the source.

In general the maximum noise reduction that can be achieved from a barrier is about 20 dBA for thin screens (walls) and 23 dBA for berms. Therefore, a material that has a TL of 33 dBA (23 + 10) or more would be adequate for a noise barrier in most situations.

Table 5-1 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, material test reports by accredited laboratories should be consulted. These product specifications can usually be provided by the manufacturer.

Table 5-1. Approximate Transmission Loss Values for Common Materials

Material	Thickness (Inches)	Weight (Pounds per Square Foot)	Transmission Loss (dBA)
Concrete block, 8 by 8 by 16 inches, light weight	8	31	34
Dense concrete	4	50	40
Light concrete	6	50	39
Light concrete	4	33	36
Steel, 18 gage	0.050	2.00	25
Steel, 20 gage	0.0375	1.50	22
Steel, 22 gage	0.0312	1.25	20
Steel, 24 gage	0.025	1.00	18
Aluminum, sheet	0.0625	0.9	23
Aluminum, sheet	0.125	1.8	25
Aluminum, sheet	0.25	3.5	27
Wood, fir	0.5	1.7	18
Wood, fir	1	3.3	21
Wood, fir	2	6.7	24

Material	Thickness (Inches)	Weight (Pounds per Square Foot)	Transmission Loss (dBA)
Plywood	0.5	1.7	20
Plywood	1	3.3	23
Glass, safety	0.125	1.6	22
Plexiglas	0.25	1.5	22

Table 5-1 assumes no openings or gaps in the barrier material. However, some materials such as wood are prone to develop openings or gaps because of 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 TL of the material are known. The following formula can be used to calculate the transmission loss with the openings (TL_o):

$$TL_o = TL - 10\log_{10}(A_o * 10^{TL/10} + A_c) \qquad \textbf{(5-1)}$$

Where:

TL_o = transmission loss of material with openings

TL = transmission loss of material without openings

A_o = area of openings as a fraction of the total area of the barrier

A_c = area of closed portion as a fraction of the total area of the barrier = $1 - A_o$

This method of calculation assumes that the openings or gaps are distributed uniformly over the surface of a barrier. For example, a barrier made of 2-inch-thick fir planks has openings that make up about 5% of the total area and are about equally distributed. The transmission loss of the material with these gaps can then be determined. From Table 5-1, the TL for 2-inch fir is 24 dBA. A_o is 5%, or 0.05; A_c is 1 – 0.05 = 0.95. Therefore:

$$TL_o = 24 - 10\log_{10}(0.05 * 10^{2.4} + 0.95) = \textbf{12.7, or about 13 dBA}$$

The reduced TL could affect the barrier’s performance. For example, it is assumed that before the barrier the 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 was to be 75 – 24 = 51 dBA). The total noise level would have been 65 + 51 = 65 dBA. With the gaps, however, the transmitted noise is now 75 – 13 = 62 dBA, and the total noise level is 65 + 62 = 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 (e.g., paint) to be applied later. The wood also should have a low moisture content, requiring kiln drying after waterborne preservatives have been used. Wood planks should have tongue-and-groove deep enough to allow for shrinkage without gaps to maintain a high TL. Such tongue-and-groove is usually non-standard.

Several other ratings are used to express the ability of materials in specific construction configurations to resist sound transmission. Two of these are the Sound Transmission Class (STC) and Exterior Wall Noise Rating (EWNR). Both are most often used in conjunction with indoor acoustics.

STC is universally accepted by architects and engineers. The rating uses a standard contour against which the TL values in one-third-octave bands are compared in the frequency range between 125 and 4,000 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 one-third-octave center frequency is no more than 8 dB. The STC is the TL value of the standard contour at the 500-Hz center frequency.

The disadvantage of this rating scheme is that it is designed to rate noise reductions in frequencies of normal office and speech noises, not for the lower frequencies of highway traffic noise. The STC 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 more than the TL. For example, material with an STC rating of 35 has a TL of about 25 to 30 dBA for traffic noise.

The EWNR rating scheme is different from the STC in that it uses a standard contour developed from typical highway noise frequencies. Therefore, it agrees closely with the A-weighted TL for traffic noise. The FHWA *Highway Traffic Noise: Analysis and Abatement Guidance* (Federal Highway Administration 2011) provides further useful information for calculating outdoor to indoor traffic noise reductions.

5.1.2 Barrier Location

The previous section indicated that by selecting materials with sufficient TL, noise transmitted through a barrier may be ignored because its contribution to the total noise level is negligible. The only remaining noise of concern is diffracted noise. Sections 2 and 4 discuss 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 the source and receiver (source–receiver) and the diffracted path, described by the source, to top of the barrier, to the receiver (source–top of barrier–receiver). The greater this difference, the greater the barrier attenuation, to a limit of 20 dB for walls and 23 dB for berms. Figure 5-3 shows the PLD concept.

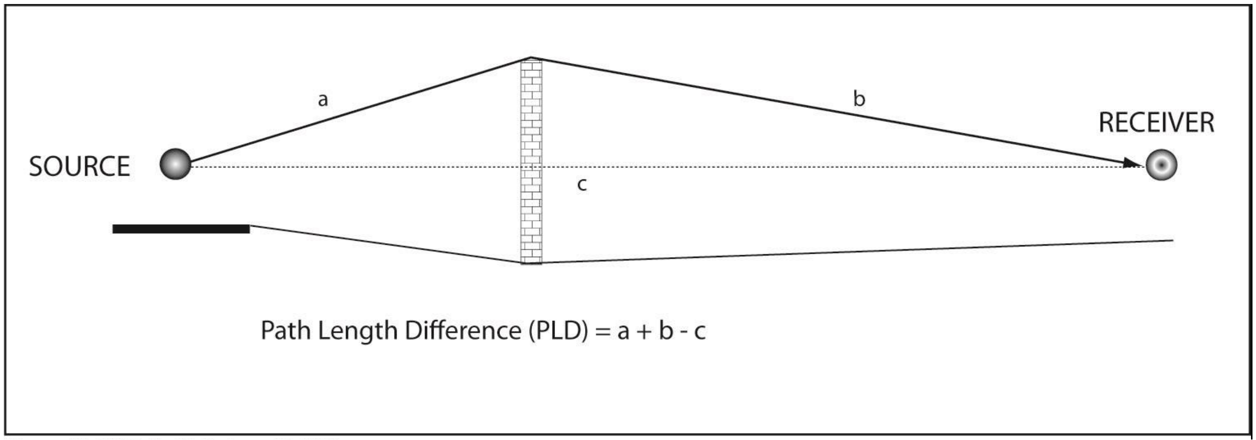

Figure 5-3. Path Length Difference

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 between the source and receiver. Figure 5-4 shows these situations for two source heights (autos and heavy trucks). Location *b* gives the lowest barrier attenuations for a given barrier height.

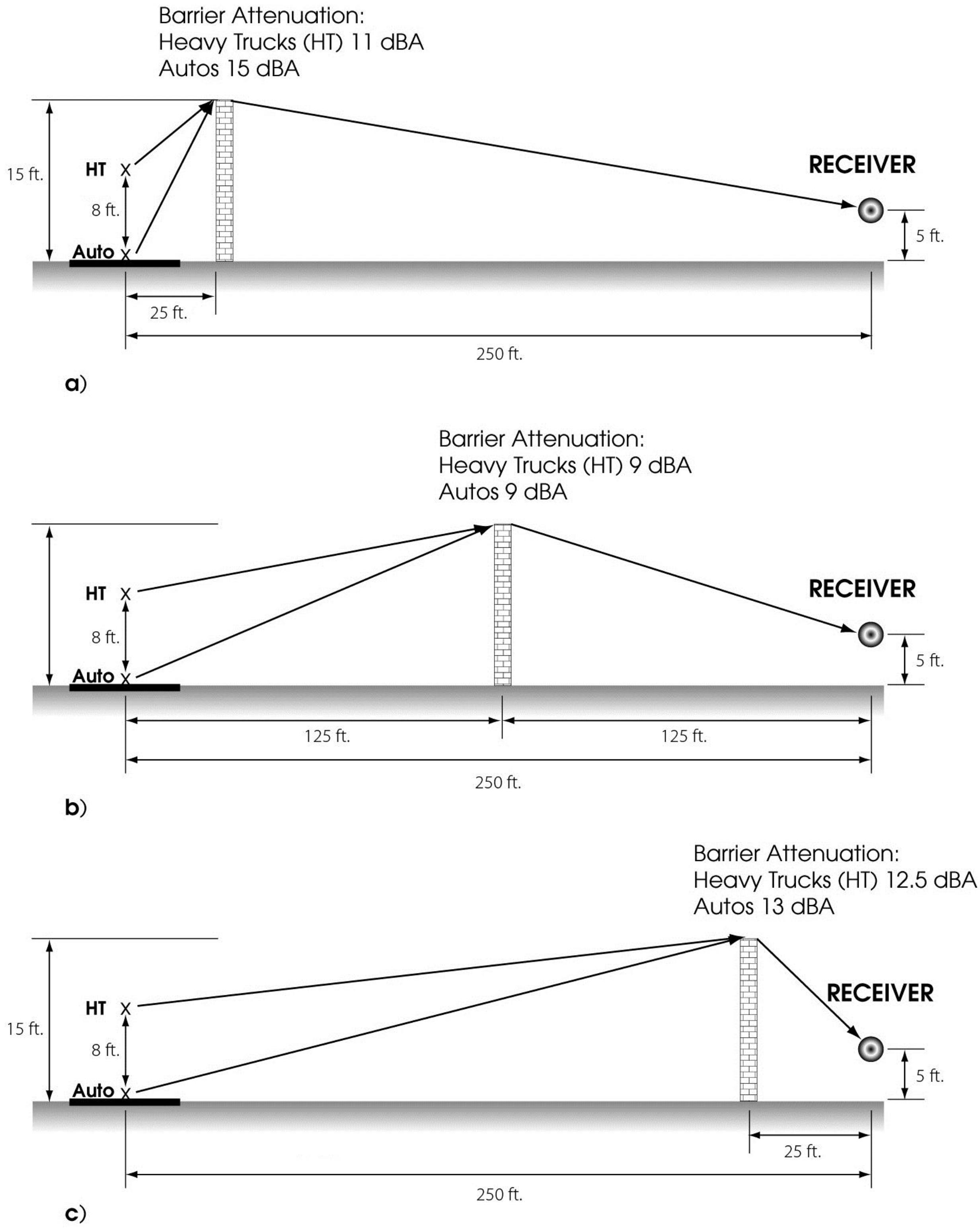

Figure 5-4. Barrier Attenuation as a Function of Location (At-Grade Highway)—Barrier Attenuation is Least When Barrier is Located Halfway between the Source and Receiver *b*; the Best Locations are Near the Source *a* or Receiver *c*

In depressed highway sections, the barrier is most effective near the receiver on top of the cut (Figure 5-5). Please note that the without-barrier path is generally not a straight path between the 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 line, and source–top of cut–receiver line. The barrier attenuation is then calculated from the difference in barrier attenuation provided by the top of cut and top of the noise barrier.

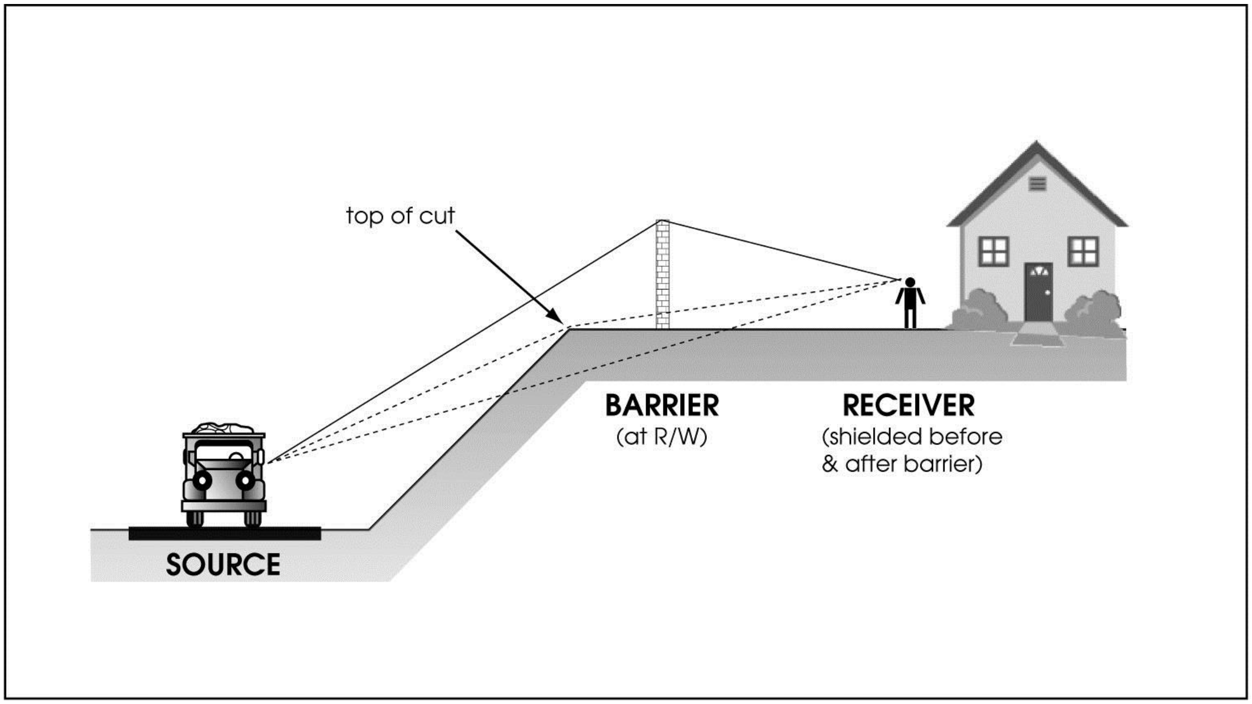

Figure 5-5. Typical Barrier Location for Depressed Highways

Because the attenuation per incremental increase in barrier height diminishes with the effective height of a barrier (see Section 5.1.3), this difference may be small. Noise barriers at the top of depressed highway sections are generally not very effective in reducing noise because the top-of-cut of the cut section by itself may already be providing substantial noise reduction.

The most effective location of noise barriers along highways on fills is on top of the embankment (Figure 5-6). Any attempt to place the barrier closer to the receivers will result in a higher barrier for the same or less attenuation. The same is true for elevated highways on structures. The most effective barrier location from an acoustical standpoint is on top of the structure.

The preceding 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:

- **Highway at Grade:** barrier location near the edge of shoulder or at the right-of-way (barrier is close to the noise source).
- **Highway in Depressed Section:** barrier at the right-of-way (barrier is close to the receiver).
- **Elevated Highway on Embankment or Structure:** barrier near edge of shoulder (barrier is close to the noise source).

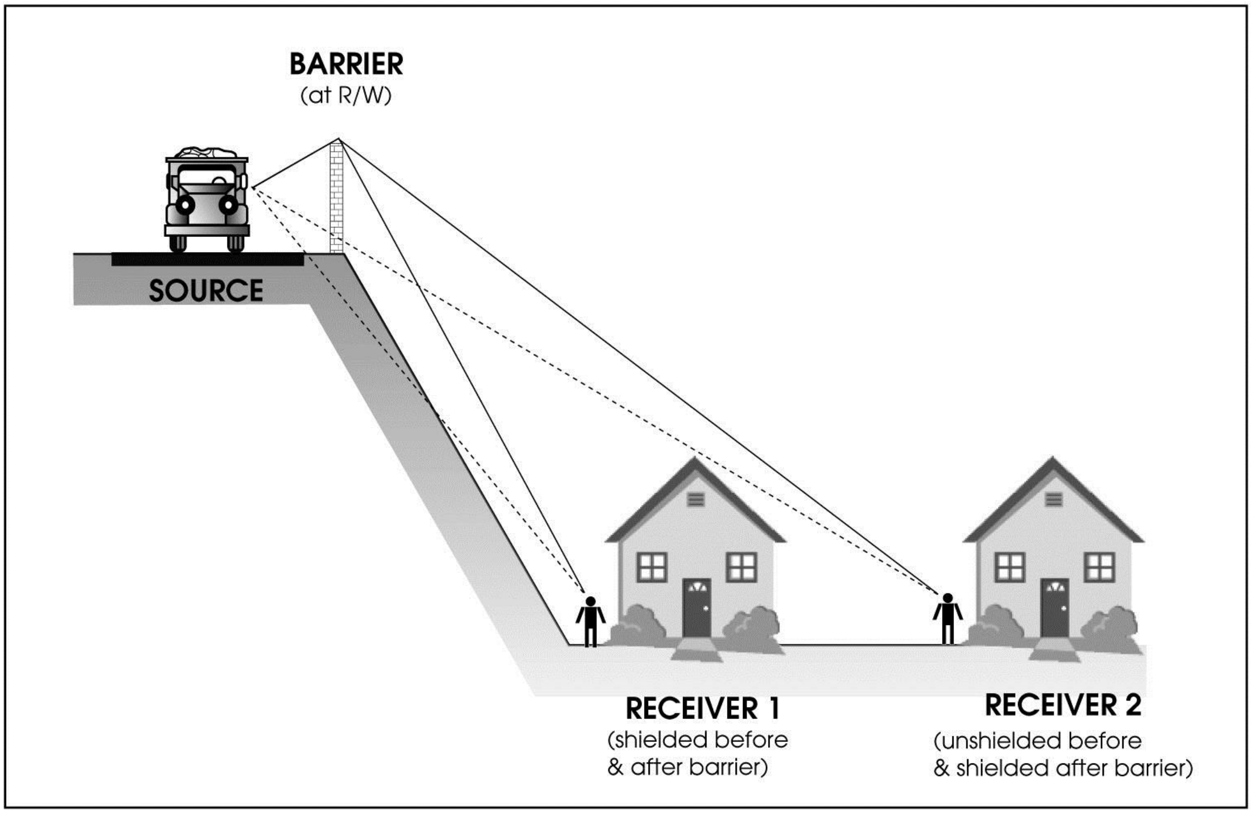

Figure 5-6. Typical Barrier Location for Elevated Highways

In some cases, however, the choices are not as simple. In more complex highway/receiver geometries, the best locations from an acoustical standpoint may need to be determined by using TNM for several barrier location alternatives.

Transitions between cuts and fills, ramps, and interchanges are some examples of cases that need careful consideration. Figures 5-7 to 5-9 show typical noise barrier locations in some of these transitional areas. Barrier overlaps are often necessary in these cases (Figures 5-7 and 5-8).

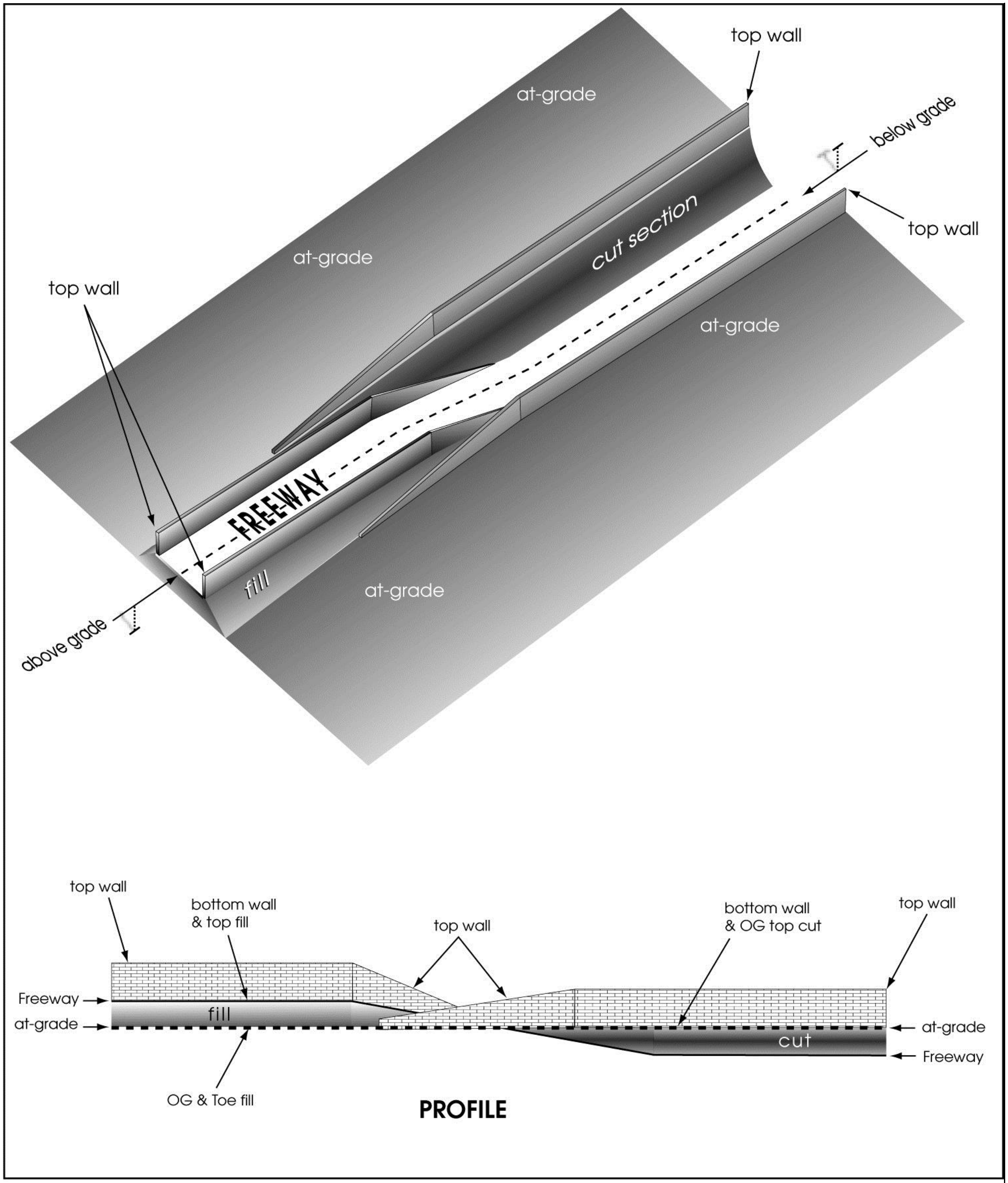

Figure 5-7. Barriers for Cut and Fill Transitions

One of the more common reasons for barrier overlaps is to provide maintenance access to the areas within the right-of-way that are on the receiver side of noise barriers (Figure 5-7). This will be discussed in more detail in the maintenance consideration portion of this section.

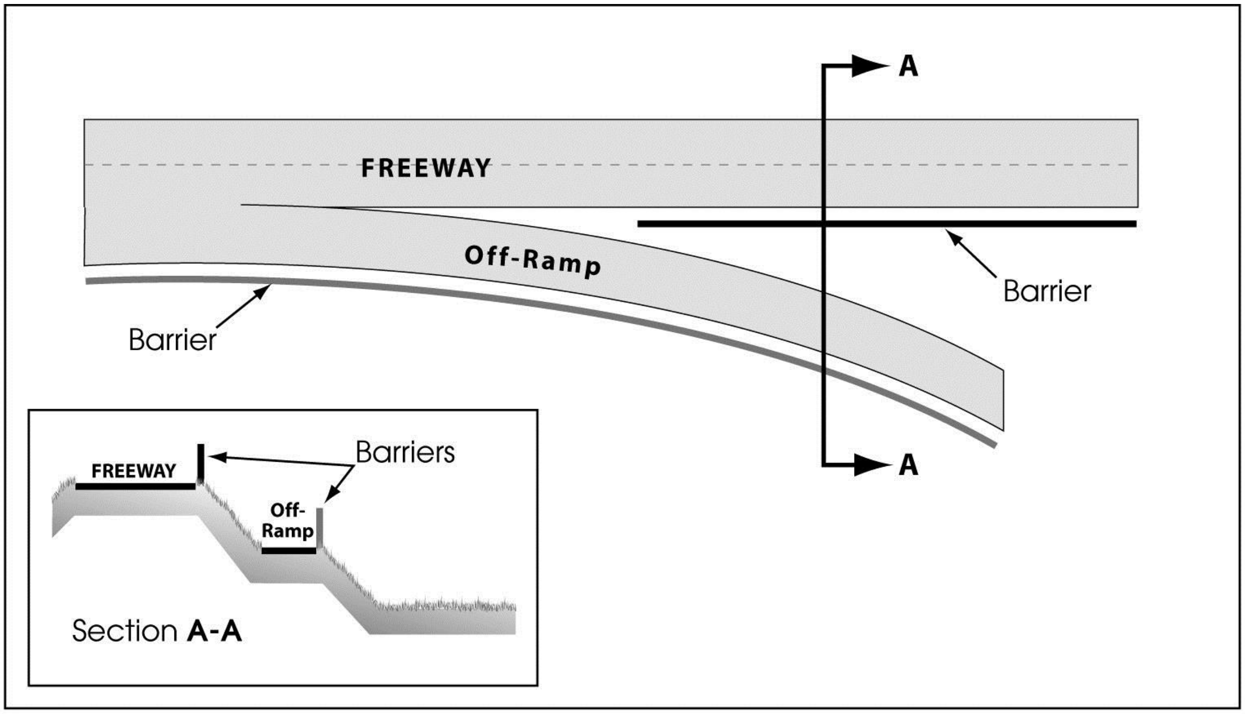

Figure 5-8. Barriers for Highway on Fill with Off-Ramp

Restrictions on lateral clearances, sight distances, and other safety considerations may also dictate final noise barrier locations. The current version of the Caltrans *Highway Design Manual* should always be consulted before finalizing alternate noise barrier alignments.

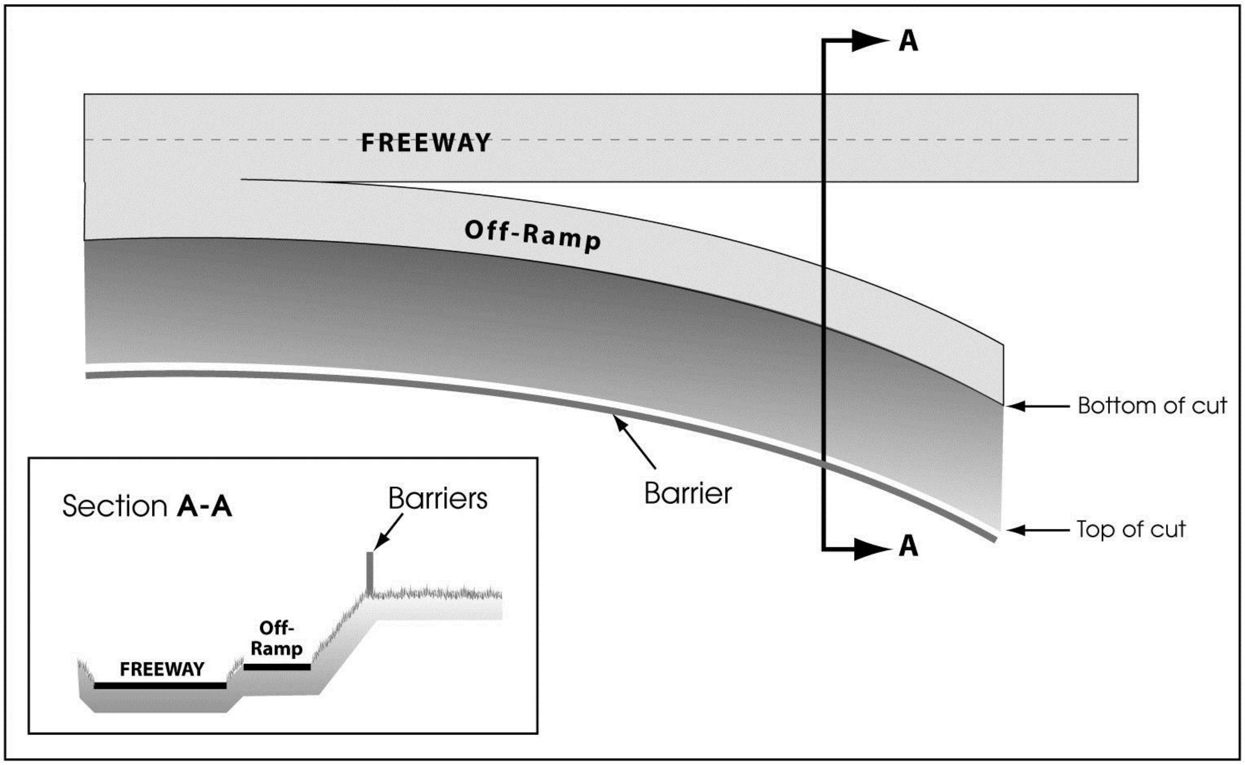

Figure 5-9. Barriers for Highway in Cut with Off-Ramp

5.1.3 Barrier Dimensions

Noise barrier dimensions depend largely on the freeway geometry, topography of the surrounding terrain, location of the noise barrier, and size of the area to be shielded by the barrier. Barrier attenuation depends on the path length difference between the direct (before-barrier) and diffracted (after-barrier) noise paths. Figure 5-3 reviews the concept. Because 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 5-10 illustrates this concept.

Similarly, the length of the barrier is governed by the extent of the area to be shielded and the site geometry and topography (Figure 5-11).

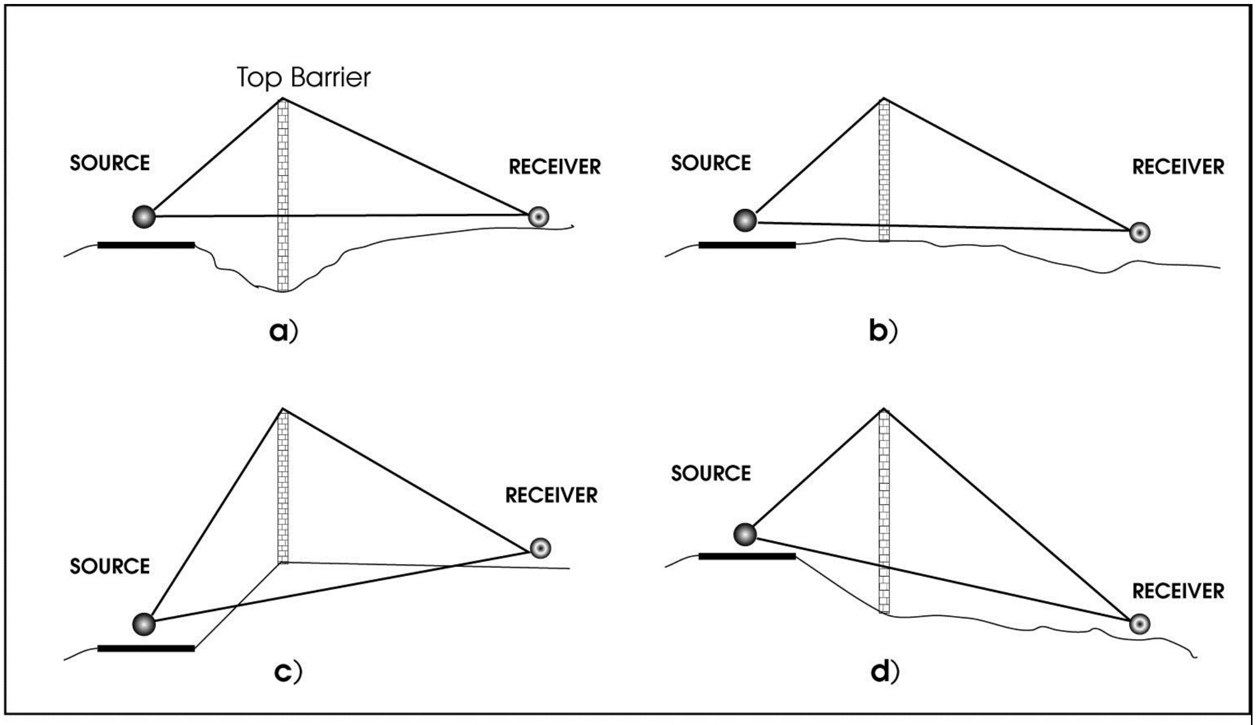

Figure 5-10. Actual Noise Barrier Height Depends on Site Geometry and Terrain Topography (Same Barrier Attenuation for *a*, *b*, *c*, and *d*)

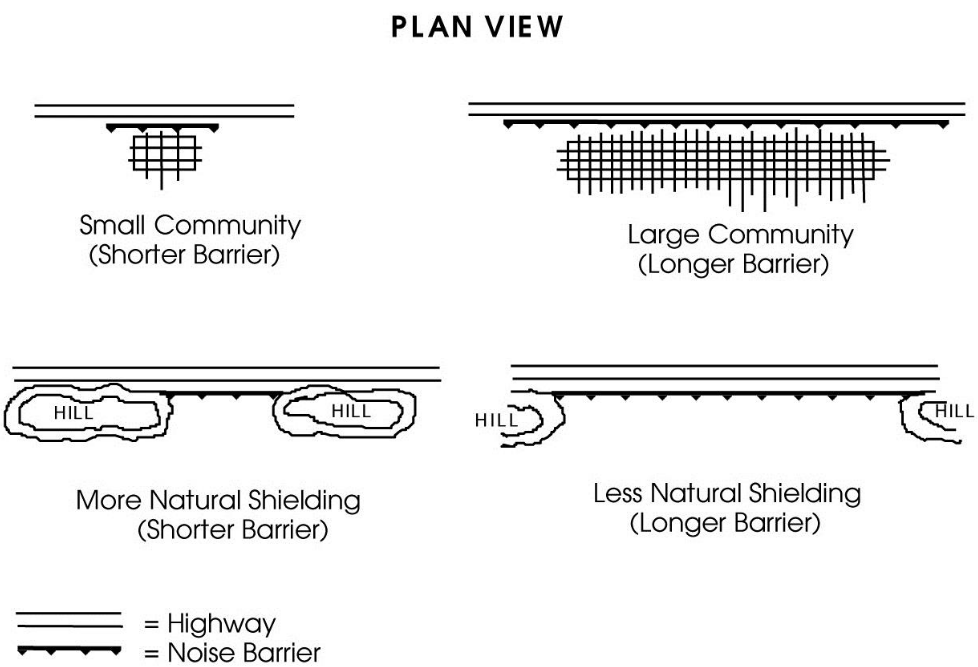

Figure 5-11. Noise Barrier Length Depends on Size of the Area to be Shielded and Site Geometry and Topography

5.1.3.1 Height

Barrier height generally has the most direct influence on the effectiveness of a noise barrier. Figure 5-3 reviews the PLD concept. An increase in height of a noise barrier will result in a greater PLD and therefore greater noise attenuation. This increase in noise attenuation is not linear with the increase in height.

Figure 5-12 shows the barrier attenuation as a function of wall height at a 5-foot-high receiver, 50 feet behind a soundwall located along the right-of-way of a typical urban at-grade eight-lane freeway. The traffic consists of 10% heavy trucks, 5% medium trucks, and 85% autos. Attenuations are plotted for wall heights from 6 to 16 feet, representing minimum and maximum heights identified in the Caltrans *Highway Design Manual* Chapter 1100. Also shown is the height at which the line of sight between an 11.5-foot truck stack and a 5-foot-high receiver is intercepted by the wall. For this particular highway/barrier/receiver geometry, the intercept height is 9 feet and the associated attenuation is 7.5 dB.

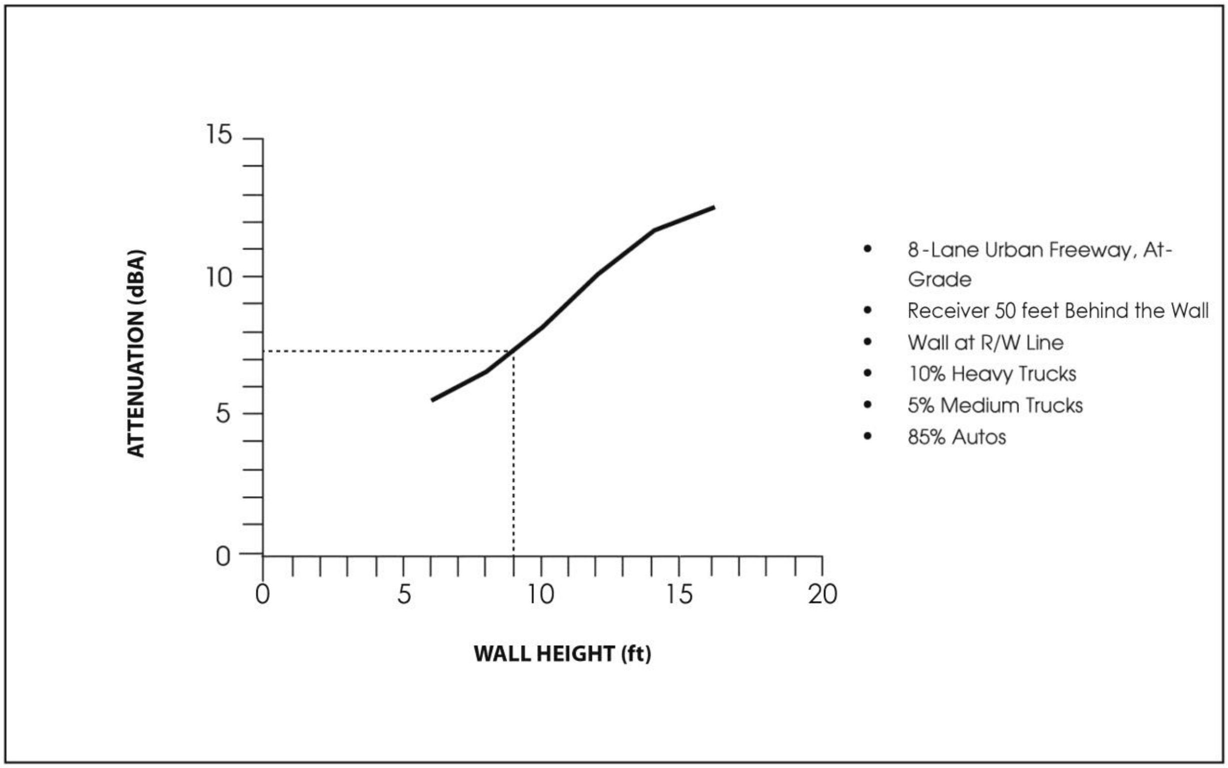

Figure 5-12. Soundwall Attenuation vs. Height for At-Grade Freeway

Please note that in this case the change in attenuation per incremental change in wall height is highest between wall heights of 9 and 11 feet, at 0.9 dBA per 1 foot. Above and below this range, the values are lower.

Once the optimum height has been reached, any further increases in noise barrier height results in diminishing returns in effectiveness. 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 the tops of cuts. In some cases, this top-of-cut shielding may not reduce noise levels enough to satisfy barrier design 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-barrier condition includes the shielding of the existing top of cut. Because of the 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 in an at-grade situation. The diminishing-returns effect, however, is not the only factor to consider.

In general a berm is more effective in reducing noise than a wall of the same height because of additional diffraction, ground absorption, and path length effects. The top of cut associated with a depressed freeway essentially acts like a berm in terms of noise attenuation. Figure 5-13 shows the barrier attenuation vs. height plots for a receiver 50 feet behind a barrier located on the right-of-way of a typical urban eight-lane freeway in a 25-foot-deep depressed section. The traffic mix is the same as that for Figure 5-12, 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 soundwall were built on top of an existing retaining wall (i.e., the top of cut would be the top of retaining wall).

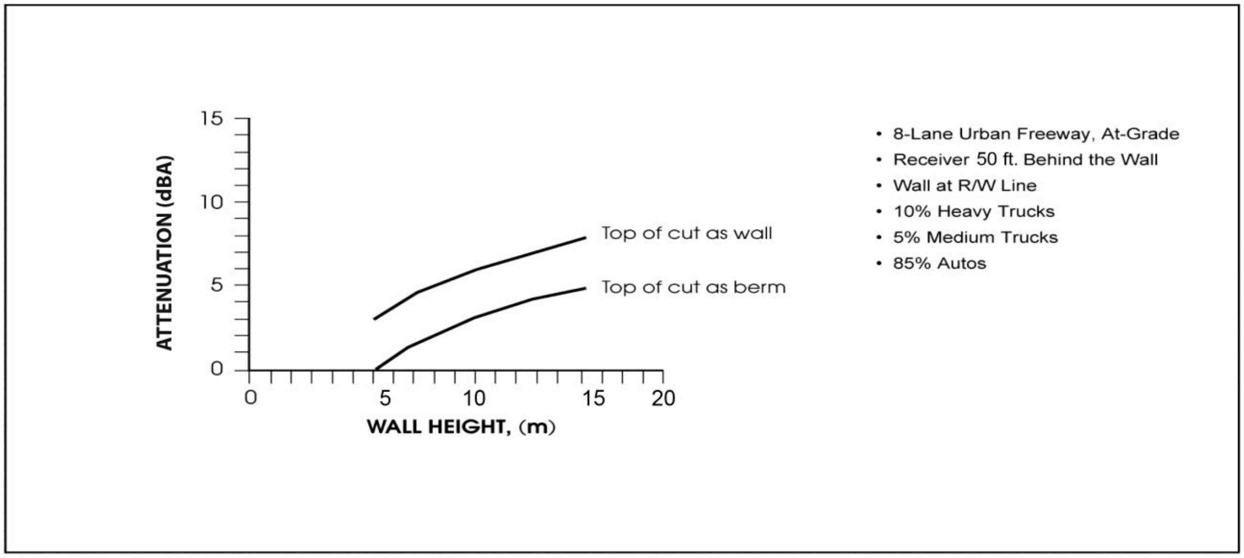

Figure 5-13. Soundwall Attenuation vs. Height for 25-Foot Depressed Freeway

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 the top of cut), the upper curve also would be a correct representation. The lower curve consists of attenuation differences between a soundwall 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 top of fill may be fully or partially shielded from traffic by the top of 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. Section 2.1.4 discusses hard- 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 receiver, the diffracted noise path is lifted higher off the ground, causing less noise absorption by the ground and a lower rate of noise attenuation with distance. Figure 5-14 illustrates this concept.

In "a," the before-barrier situation shows a noise attenuation rate of 4.5 dBA per doubling of distance. In "b," the after-barrier attenuation is 3 dBA per doubling of distance. The lower attenuation rate reduces the barrier's effectiveness.

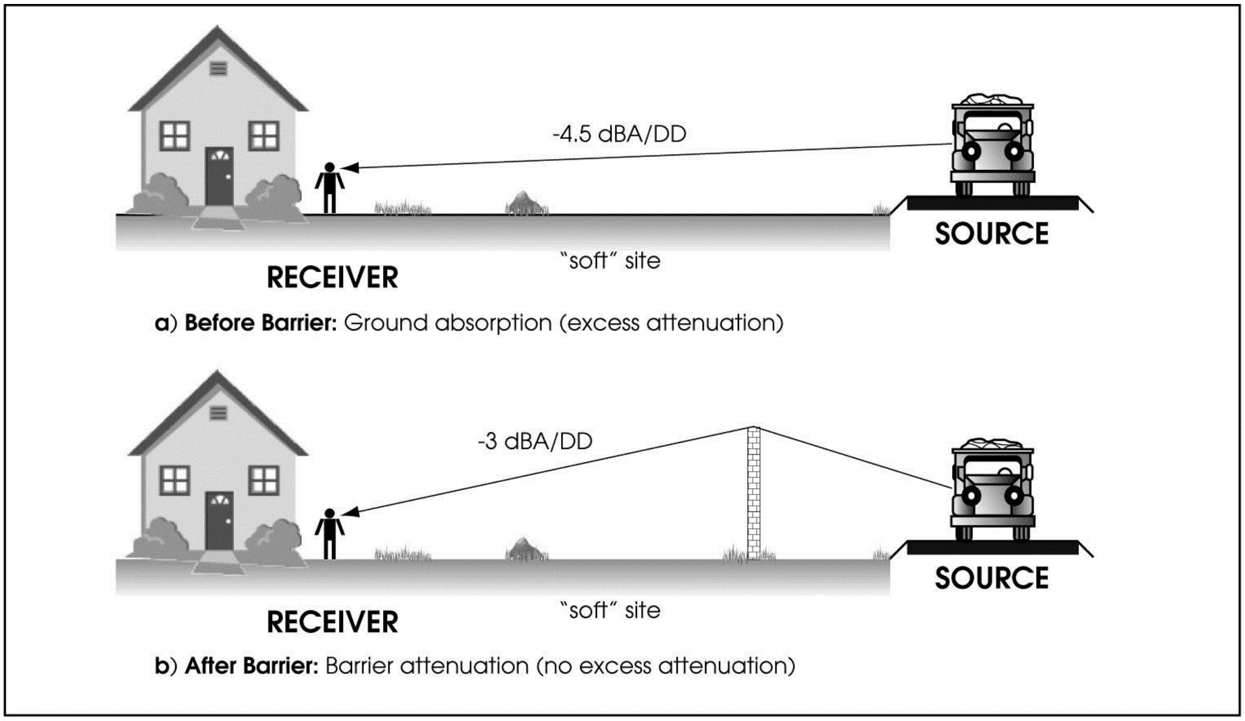

Figure 5-14. Loss of Soft-Site Characteristics from Constructing a Noise Barrier

The potential of a barrier to be less effective than indicated by barrier attenuation alone gave rise to the term insertion loss. Section 5.1.5 discusses the difference between barrier attenuation and insertion loss in detail. 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 height consideration in the acoustical design of noise barriers is Caltrans guidance to break the line of sight between an 11.5-foot-high truck exhaust stack and 5-foot-high receiver in the first row of houses. This guideline, detailed in *Highway Design Manual* Chapter 1100, is intended to reduce the visual and noise intrusiveness of truck exhaust stacks at the first-line receivers.

Barrier heights determined by TNM often satisfy the acoustical requirements without shielding high truck exhaust stacks. Although such barriers may reduce noise levels sufficiently to meet feasibility and design goal requirement, they have generated complaints from the public in the past when truck stacks were visible. The line of sight break criterion occasionally governs the height of a noise barrier.

The 11.5-foot height used for truck stacks was determined to be the average (50th-percentile) height of truck stacks in a 1979 District 7 study, including 1,000 heavy trucks measured at a truck inspection station along I-5. This means that the line-of-sight break will shield first-line receivers from the exhaust stacks of about half of the trucks on the highways.

The 11.5-foot dimension is not related to the noise source heights used for heavy trucks in TNM and therefore should not be used for noise predictions. Determining the line-of-sight break is a separate process from predicting noise and is completed with the line-of-sight module in TNM. Generally, it is desirable to calculate and plot the break profile along the barrier alignment before the acoustical design of the noise barrier. . If more than one barrier alignment is under consideration, the line-of-sight break must be calculated for each alignment alternative.

The line-of-sight break height depends on the three-dimensional locations of the 11.5-foot truck stack, receiver, and bottom of the barrier (interface between barrier and ground). To calculate the height for a certain source, barrier, and receiver combination, the designer needs to determine the critical truck stack lane, which is the lane in which the 11.5-foot truck stack creates the highest line-of-sight break. Figure 5-15 shows a quick method of determining which lane is critical. If the receiver is located above a baseline 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. When the receiver is on the line, either lane is critical. Please note that the line does not need to be horizontal or level.

Highway Design Manual Chapter 1100 does not give guidance on whether the entire barrier or only a portion of the barrier should break the line of sight for a certain receiver. On one extreme, a series of line-of-sight 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 the absence of an 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 = the distance from receiver to the lane). Also, it is recommended that the portion of the barrier evaluated be further constrained by a maximum distance from receiver to truck stack (D_t) of 500 feet. Figure 5-16 shows the recommended constraints.

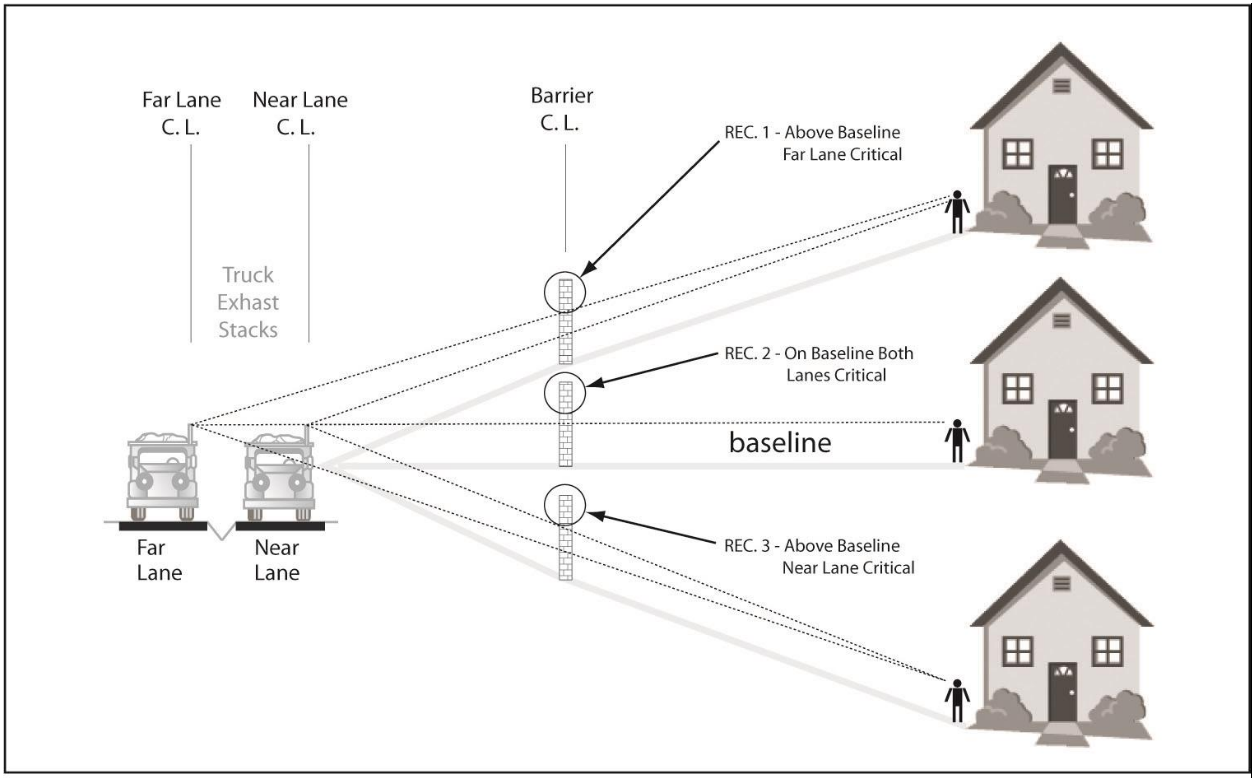

Figure 5-15. Determination of Critical Lane for Line-of-Sight Height

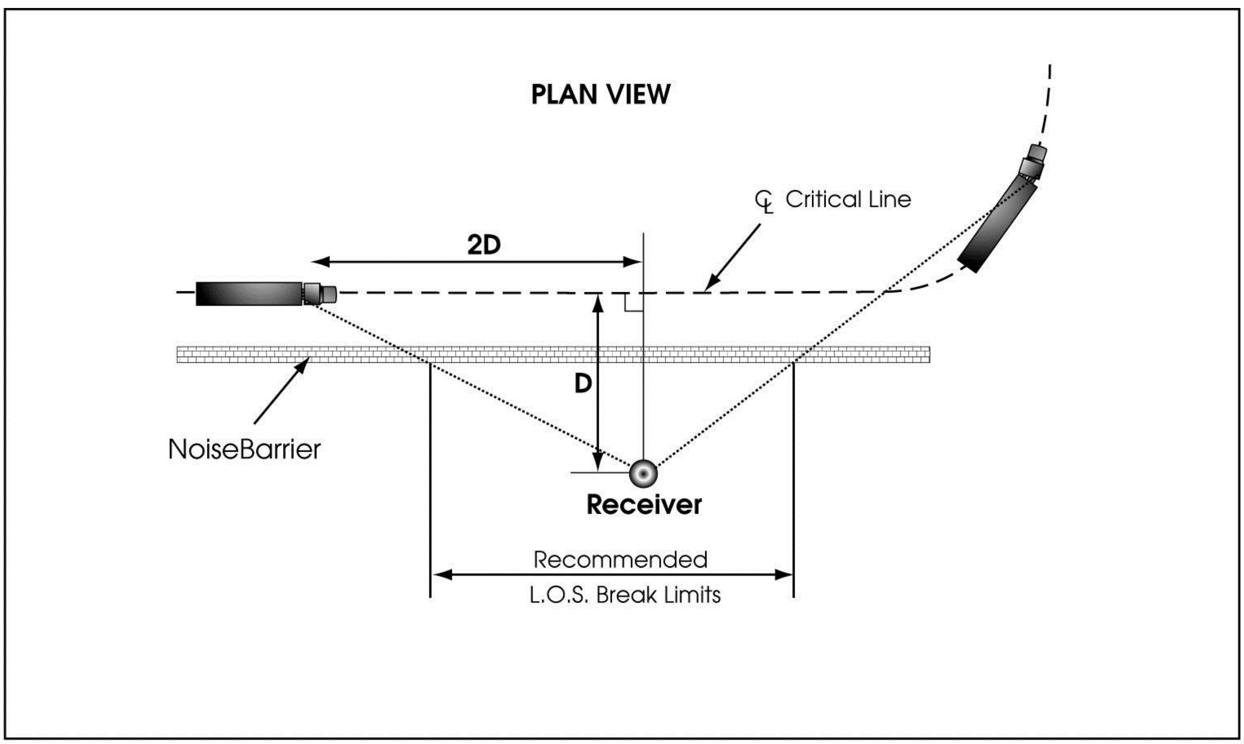

Figure 5-16. Recommended Line-of-Sight Break Limits

5.1.3.2 Length

A noise barrier should be sufficiently long to protect the end receivers (see Figure 5-17). If the barrier is not long enough, the exposed roadway segment will contribute a significant portion of noise energy received 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.

As a general rule, a noise barrier should extend at least 4D beyond the last receiver (where D = the perpendicular distance from barrier to receiver) (see Figure 5-18). The "4D rule," however, should be considered a starting point, and the FHWA TNM should be used to precisely locate the end of the barrier. Often, the critical end receivers are not in the first row of homes, but several rows farther from the highway (see Figure 5-17). As the barrier-to-receiver distance increases, highway noise becomes lower, but the barrier segment angle is also reduced, making a potential noise barrier less effective. The FHWA TNM is needed to resolve these opposing factors.

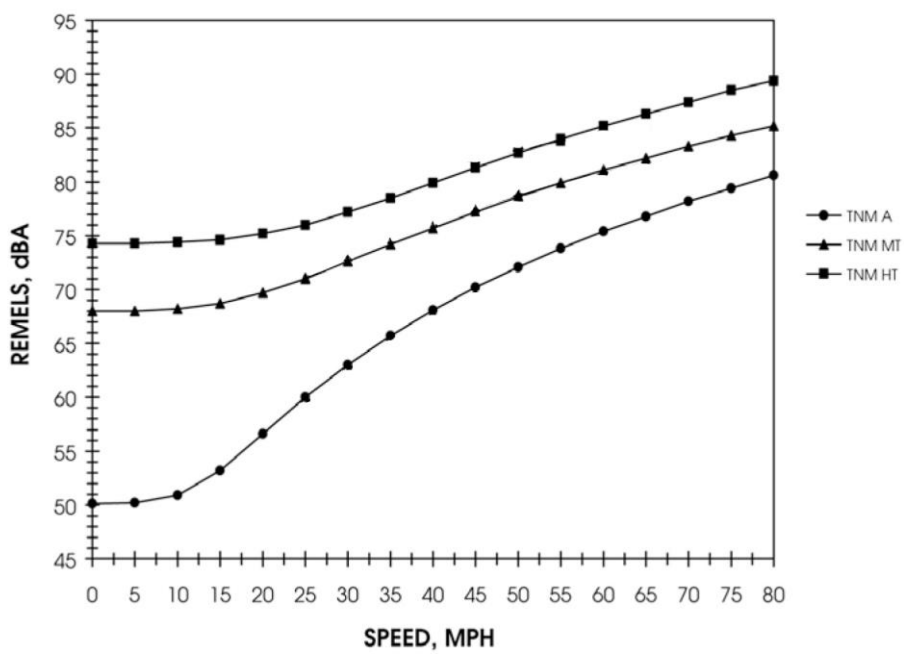

Figure 5-17. Barrier Extended Far Enough to Protect End Receivers

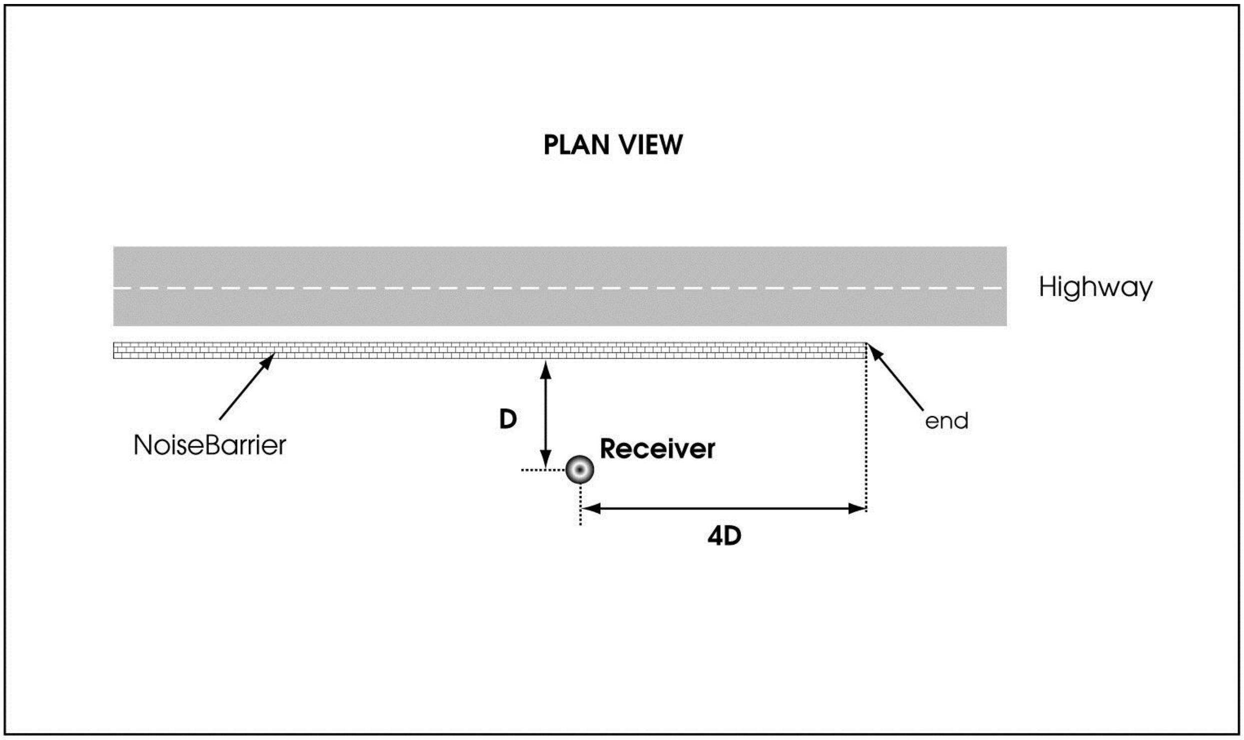

Figure 5-18. 4D Rule

Another way of addressing end receivers is shown in Figure 5-19. The barrier is “hooked” around the critical receivers. The obvious advantage of this design is the shorter barrier length compared to the normal barrier extension. The disadvantage is the need for legal agreements between Caltrans and the private property owners concerning construction easements, barrier maintenance, and responsibilities.

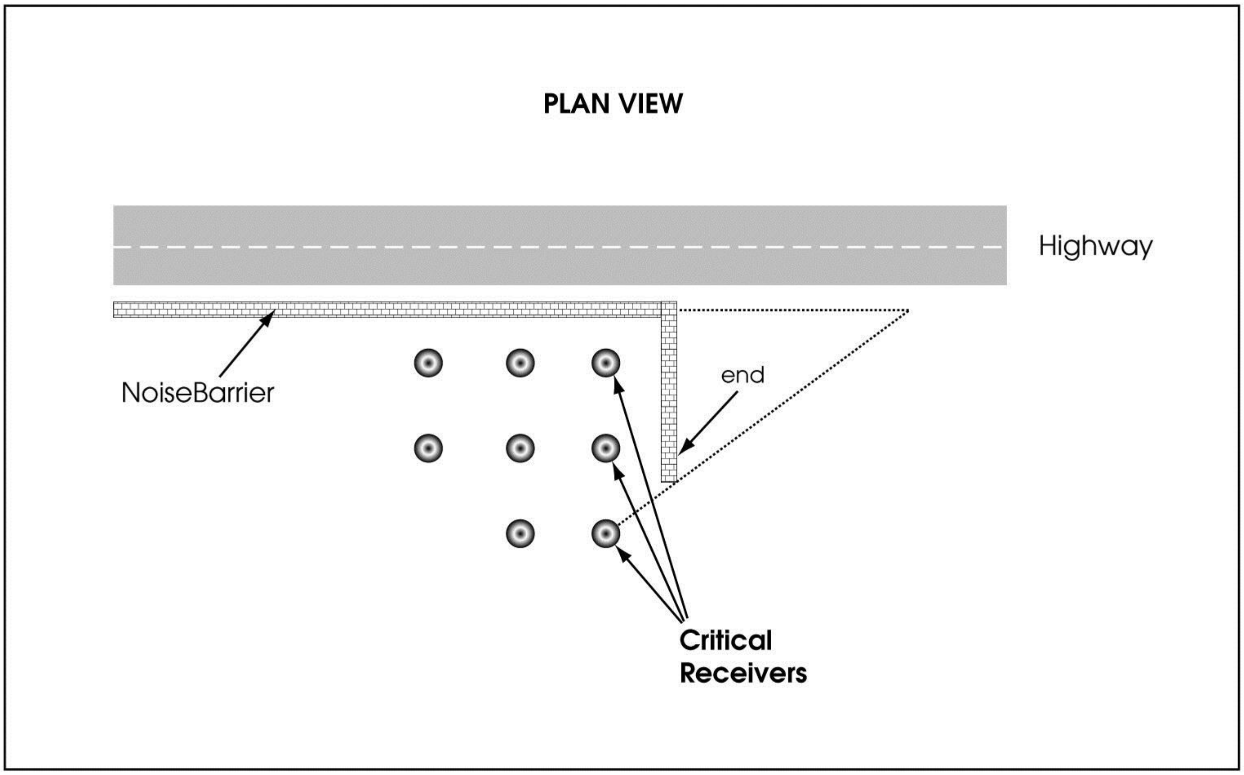

Figure 5-19. Barrier Wrapped around End Receivers, an Effective Alternative

5.1.4 Barrier Shape

Section 4.5.1 indicates that the FHWA TNM distinguishes between two noise barrier shapes: thin screen (wedge) and earth berm. Figure 5-20 shows representations of the two barrier shapes.

Given the same site cross section, distance between source and receiver, and barrier height, a berm allows greater barrier attenuation than the thin screen (wedge), such as a soundwall. In general the actual extra attenuation associated with a berm is somewhere between 1 and 3 dBA.

There are several probable causes for the extra 3-dBA attenuation for a berm. The flat top of the berm allows a double diffraction, resulting in a longer path-length difference. Also, the noise path is closer to the ground (berm surface) than for a thin screen, allowing more ground absorption.

Other barrier shapes have been researched, including “T-tops,” “Y-tops,” pear-shaped tops, and curved walls. Given the same total wall height, these do little to improve barrier attenuation, usually only about 1 or 2 dBA at most. Figure 5-21 shows some different shapes. The added cost of constructing and complexity of these shapes usually does not justify the small acoustical benefit.