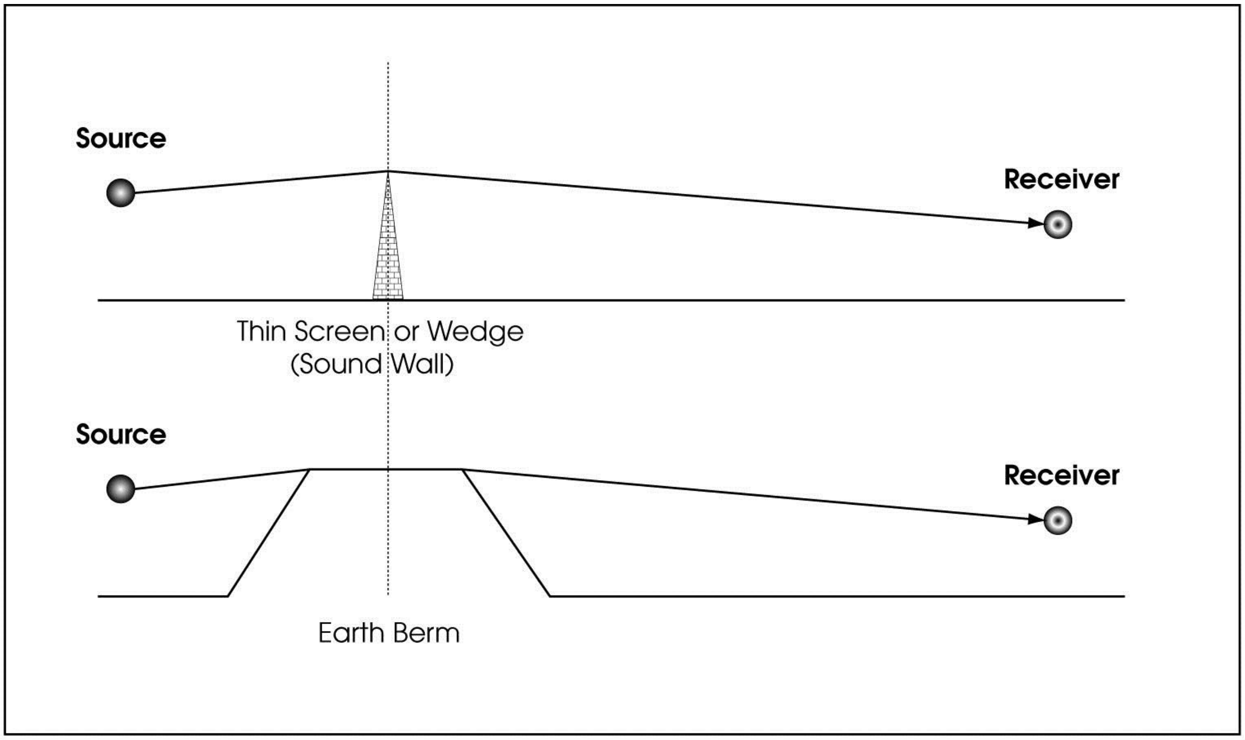

Figure 5-20. Thin Screen vs. Berm (Berm Gives More Barrier Attenuation)

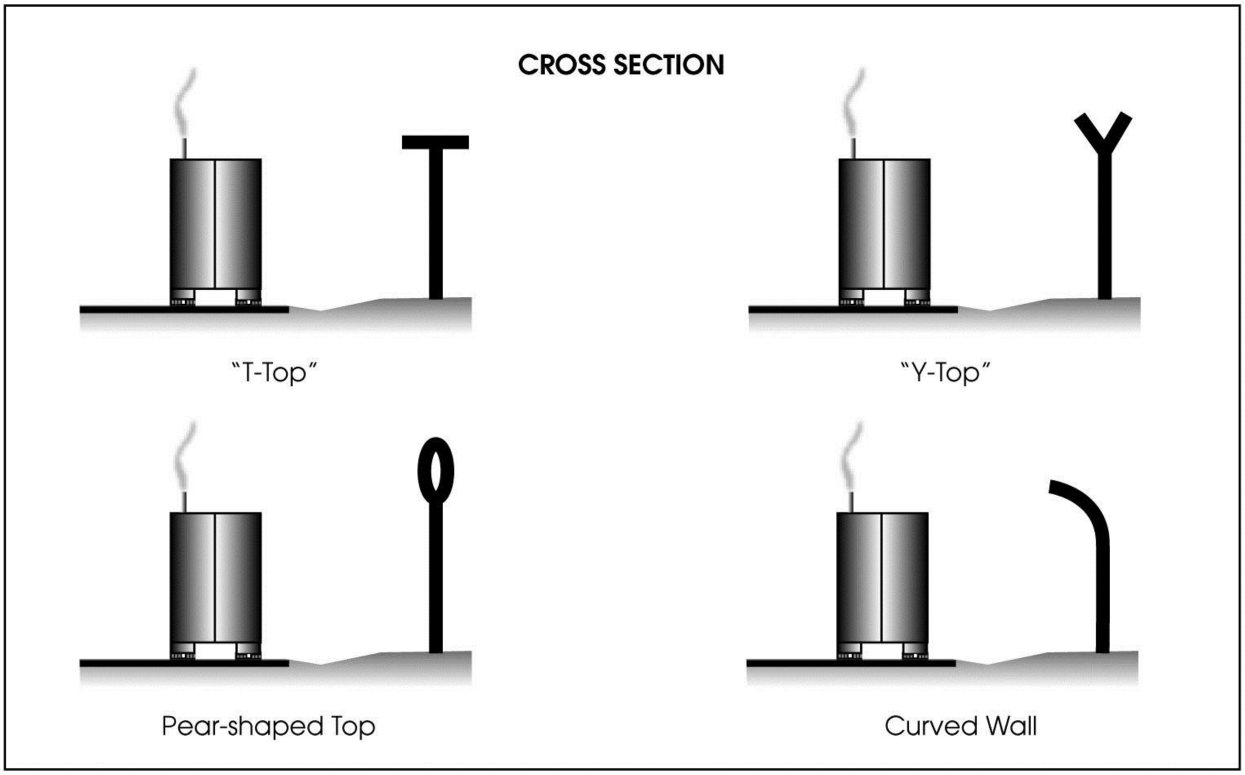

Figure 5-21. Various Wall Shapes (Minimal Benefit for Extra Cost)

There is also a question of jeopardizing safety with any overhang, especially when the barrier is constructed near the edge of the shoulder.

5.1.5 Barrier Insertion Loss vs. Attenuation

In simple terms, barrier insertion loss is the difference in noise levels before and after a barrier is constructed. It accounts for barrier attenuation, contributions from unshielded roadway segments, changes in dropoff rates, and interaction with existing barriers (e.g., reflections or additional shielding).

Figure 5-22 illustrates the difference between barrier insertion loss and attenuation. Barrier attenuation only accounts for noise attenuated from noise barrier diffraction, integrated over the length of the noise barrier. Barrier insertion loss is the net noise reduction and includes barrier attenuation, changes in noise path heights and associated changes in ground effects, flanking noise, and other noise sources. When designing noise barriers, barrier insertion loss is the primary factor of interest.

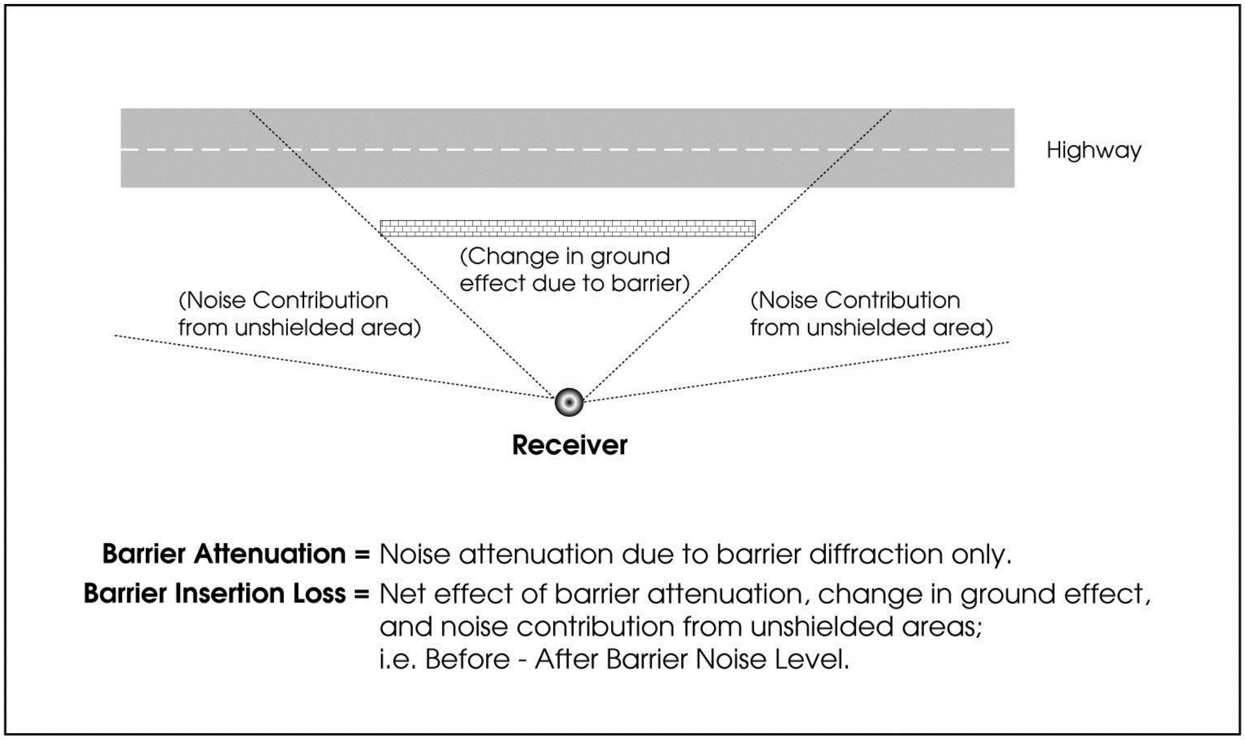

Figure 5-22. Barrier Insertion Loss vs. Attenuation

5.1.6 Background Noise Levels

One important factor to be considered but often overlooked in noise barrier design is the background noise level within a community. A noise barrier cannot reduce noise levels below the noise level generated by local traffic on surface streets. For instance, if the background level (without the highway) is 65 dBA at the target receivers, and a proposed project will raise this level to 68 dBA, a noise barrier will not be able to reduce the noise level to less than 65 dBA. Therefore, the community background noise level always should be added into the predicted noise levels and considered in the noise abatement design process. Only if it is obvious that the background noise from local sources will not influence the noise barrier's insertion loss (i.e., is at least 10 dBA less than the predicted noise level with the noise barrier) can the background noise be ignored.

The following is an example of how background noise levels can influence noise barrier calculations.

<u>Given</u>

Background noise level: 60 dBA at receivers

New facility (without background): 68 dBA at receivers

Total predicted: 69 dBA at receivers

The goal of this exercise is to design a noise barrier that will reduce the total noise level at the receiver by at least 5 dBA. The model predicts traffic noise levels without the background noise level. However, the background noise level should be accounted for in the total noise attenuation. Therefore, the predicted noise level needed to reduce the total predicted noise level at the receiver to 64 dBA must be calculated.

<u>Calculation</u>

If the barrier reduces the noise from the new facility by 5 dB the facility noise level would be 64 dBA. When the background noise is considered the resulting sound level would be 65 dBA (60 dBA + 64 dBA). This is only a 4 dB reduction from the total predicted noise level of 69 dBA. Additional attenuation is needed to provide at least 5 dB of noise reduction relative to the total predicted noise level.

The goal is for the background sound level plus the new facility noise level behind the barrier to be 64 dBA (5 dBA below the total predicted noise level of 69).

background (B) + new facility noise level behind barrier (N) = 64 dBA

$B + N = 64$ dBA

$60 + N = 64$ dBA

$N = 64 – 60$

$N = 10\log(10^{(64/10)} – 10^{(60/10)}$

$N = 61.8 \approx 62$ dBA.

Therefore the barrier must provide a total noise reduction of 7 dB and result in a noise level of 62 dBA behind the barrier for the net noise reduction to be at least 5 dBA.

5.1.7 Reflected Noise and Noise Barriers

5.1.7.1 Noise Reflection

The reflection of noise from barriers can be a source of concern for residences in the vicinity of a barrier. A barrier that reduces noise at receivers on one side of the highway could potentially alter the noise at receivers on the other side. The complex nature of noise barrier reflections, difficulties in measuring them, and controversy surrounding the significance of their impacts deserve detailed discussion.

More noise barriers have been constructed in California than in any other state, in many different configurations of alignment, profile, and height. These barriers are located along one or both sides of highways of different widths; along ramps, connectors, and interchanges; and in urban, suburban, and, rural regions under varying traffic conditions. The receivers for which they were designed are located in many different types of terrain, topography, and climate. The combinations and permutations associated with the vast variety of conditions inevitably increase the possibility of creating controversies over the extent of noise reflections by barriers. Therefore, it is only natural that noise reflection issues are on the rise in California, especially because almost all noise barriers here are made of noise-reflective material with hard, smooth surfaces, such as masonry and concrete. In most cases, the noise increases from reflections are so small that most people do not notice them. The people who do perceive increases in noise are usually suddenly made aware of freeway noise by an event that triggers that awareness (e.g., construction of the noise barrier). Measured increases from noise reflections of more than 2 dBA have never been measured by Caltrans, but claims of 10 and even 20 dBA increases have been made occasionally.

Many complaints of large increases in noise came from residents living far from the highway and were actually from changes in meteorology. Atmospheric refraction from wind shear and temperature gradients can account for 10- to 15-dBA variations when the same sources are measured from distances of approximately 1 to 2 miles. To measure the effects of noise reflections, before- and after-barrier noise measurements need to be carefully matched by wind speed, wind direction, temperature gradients, air temperature, humidity, and sky cover. Likewise, if a person perceives a noticeable increase in noise levels from a reflective noise barrier, he or she must be able to compare it mentally with a before-barrier condition that included the same meteorology. Of course, this process is very unreliable. The effects of noise barriers on distant receivers are discussed in Section 7.

This section addresses various aspects of noise reflection concerns in detail. The following classifications of reflective noise with respect to noise barriers and other structures will be discussed.

- Single barriers (on one side of the highway).
- Parallel barriers (on both sides of the highway).
- Structures and canyon effects.

Compared with reflections measured under similar conditions, results of theoretically modeled noise reflections normally show higher values. This overprediction of reflection models has been attributed to the inability of models to accurately account for all the variables, such as interactions with atmospheric effects and the unknown degree to which traffic streams interfere with reflections.

Reflective noise is not peculiar to noise barriers. Retaining walls and other structures reflect noise in the same manner as noise barriers. The principles discussed in this section can be applied to reflective barriers, reflective retaining walls, or any other smooth, continuous, hard surfaces.

5.1.7.2 Single Barriers

Simple Terrain

Figure 5-23 is the simplest two-dimensional representation of single-barrier reflections. The presence of a reflective barrier on the opposite side of an at-grade highway essentially doubles the acoustic energy at the receiver. In addition to the direct noise ray “d,” the barrier reflects a noise ray “r” of roughly the same acoustic energy (actually, “r” is longer than “d” and will result in slightly less acoustical energy). Theoretically, only one reflective ray reaches the receiver because the angle of incidence equals the angle of reflection (both depicted as θ in Figure 5-23). Therefore, even if they are equal, “r” and “d” cause a doubling of energy that increases the noise level by 3 dB at the receiver.

Figure 5-24 shows that for an infinite line source and noise barrier the reflections are also an infinite line source. At each point along the highway, there is only one reflection ray that reaches the receiver and for which the angle of incidence equals the angle of reflection.

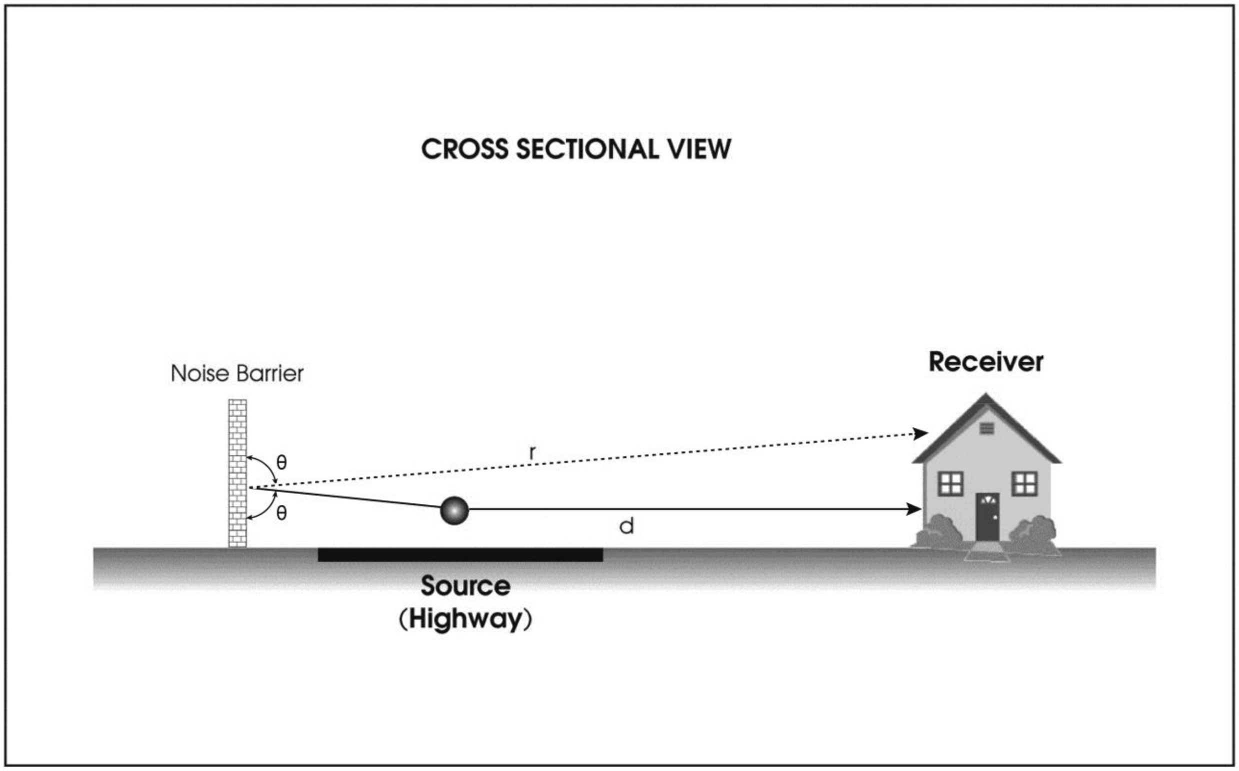

Figure 5-23. Single-Barrier Reflection (Simplest Representation)

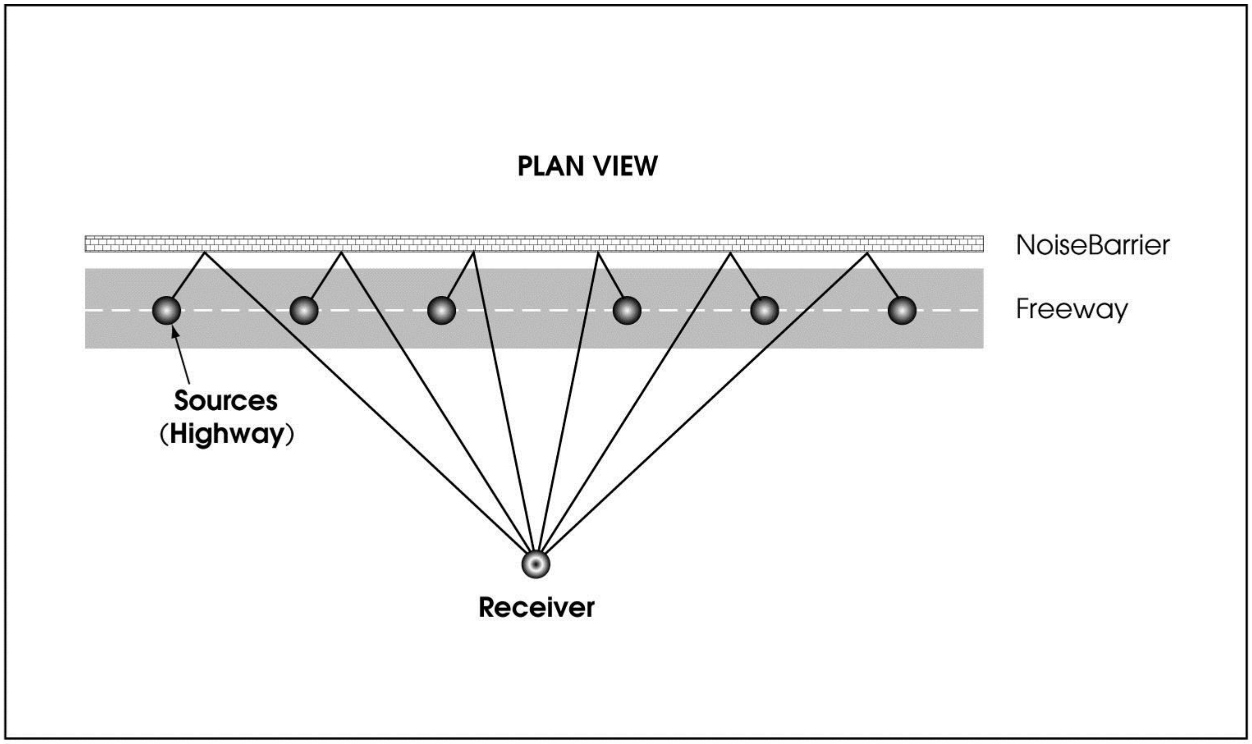

Figure 5-24. Single-Barrier Reflections (Infinite Line Source and Noise Barrier)

Figure 5-25 is a more realistic depiction, which includes pavement reflections. Please note, however, that a noise barrier on the opposite side still increases the noise level by 3 dB, although the before and after noise levels are 3 dB higher (because of pavement reflections) than in Figures 5-23 and 5-24. In plan view, the pavement reflections would also be shown to be a line source. The reflection point R_1 (Figure 5-25) may fall off the pavement on absorptive ground, reducing the before-barrier noise levels at the receiver. The pavement reflection point R_2, however, which is significant only after building the barrier, usually will be on the pavement. Therefore, the difference between before- and after-barrier noise levels could in theory slightly exceed 3 dBA.

The effects of single-barrier reflections are distance-dependent. At distant receivers, the ratios of direct/reflected noise path lengths and those for near- and far-lane distances approach 1. When this is the case, contributions of direct and reflected noise from each lane contribute roughly the same energy (there will always remain a slight loss of acoustical energy because of imperfect reflections). The result would be an increase that approaches 3 dBA for distant receivers. For receivers close to the highway, however, the distance ratios become less than 1, and the noise at the receiver is dominated by direct noise from the near lanes. The result is less contribution from reflected noise.

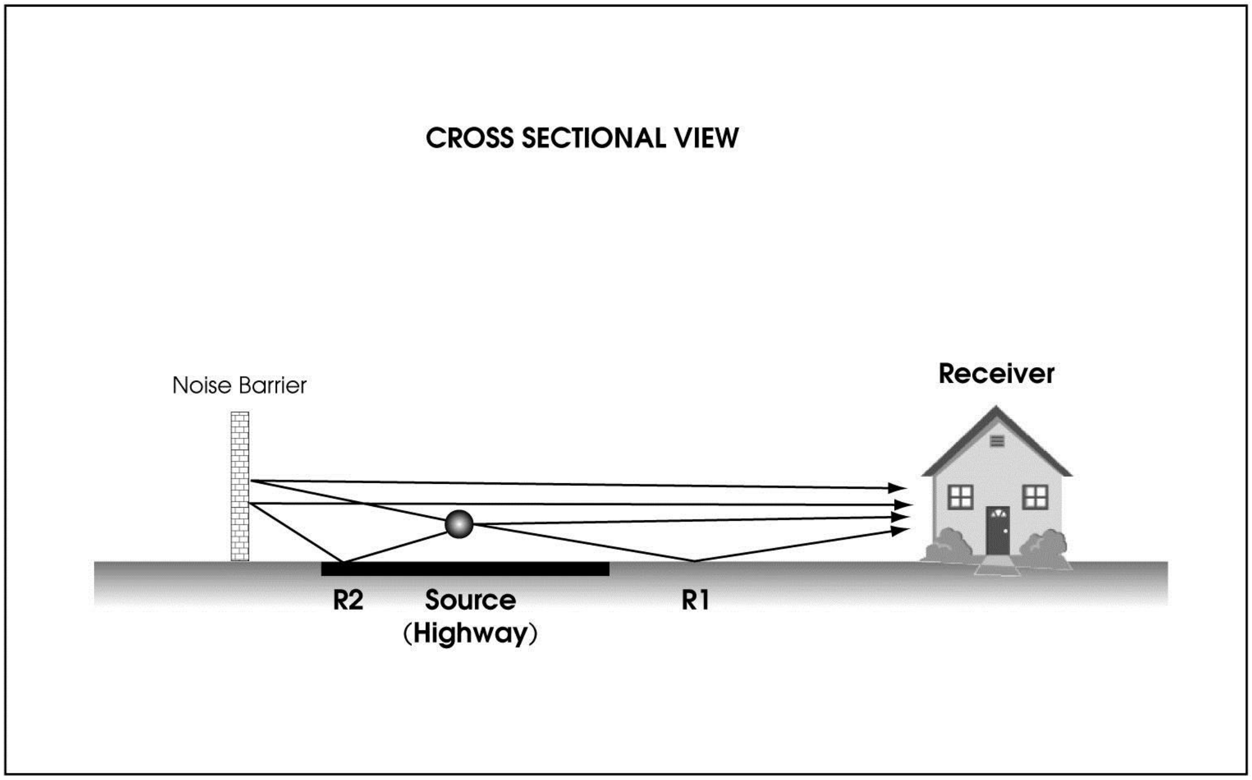

Figure 5-25. Single-Barrier Reflection (More Accurate Representation)

Figure 5-26 shows the distance dependency of the noise increases from barrier reflections for a typical eight-lane at-grade freeway. At 50 feet from the edge of the traveled way, the increase is only 1.3 dBA, at 200 feet it is 2.0 dBA, and at 400 feet it is 2.4 dBA. The increases were calculated assuming equal noise source distributions in the near and far (eastbound and westbound) lanes and hard-site propagation.

Real-world situations are far more complicated than shown in Figures 5-23 to 5-26. The noise sources are distributed over the width of the highway, the paths of the barrier noise reflections are always longer than the direct noise paths, reflective barriers are not perfect reflectors, and the traffic stream likely interferes with the reflections. Because of these factors, reflected noise contributions are less than those of direct noise and seldom increase noise levels by more than 1 or 2 dB.

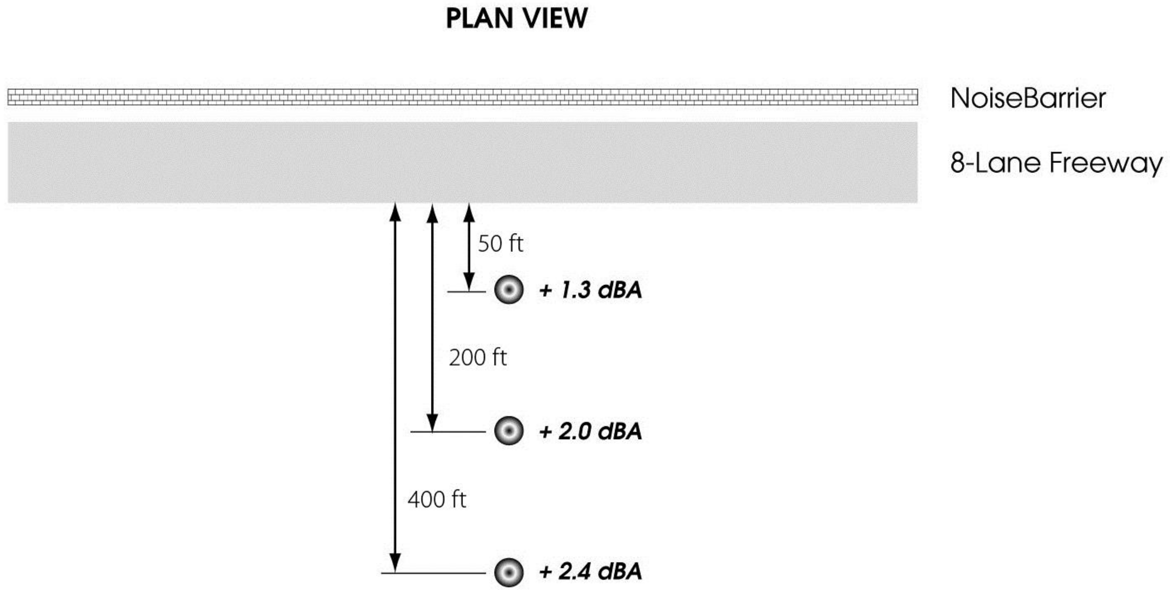

Figure 5-26. Noise Increases from Single-Barrier Reflections

Complex Terrain

In more complex terrain there are instances when single-barrier reflected noise could increase noise levels perceptibly at a receiver. One such case is shown in Figure 5-27, which depicts a receiver that is effectively shielded by terrain or the top of a depressed highway cut. If a noise barrier or retaining wall were constructed on the opposite side of the highway, unshielded reflected noise ray “r” could contain significantly more acoustical energy than the shielded direct ray “d,” causing a noticeable increase in noise at the receiver. However, real-world situations are far more complex than illustrated. Some of the noise sources or noise paths may be shielded, while others may not. In general, if most of the traffic cannot be seen from the receiver while most of the noise barrier is visible, it is possible that the barrier noticeably increased noise levels at the receiver.

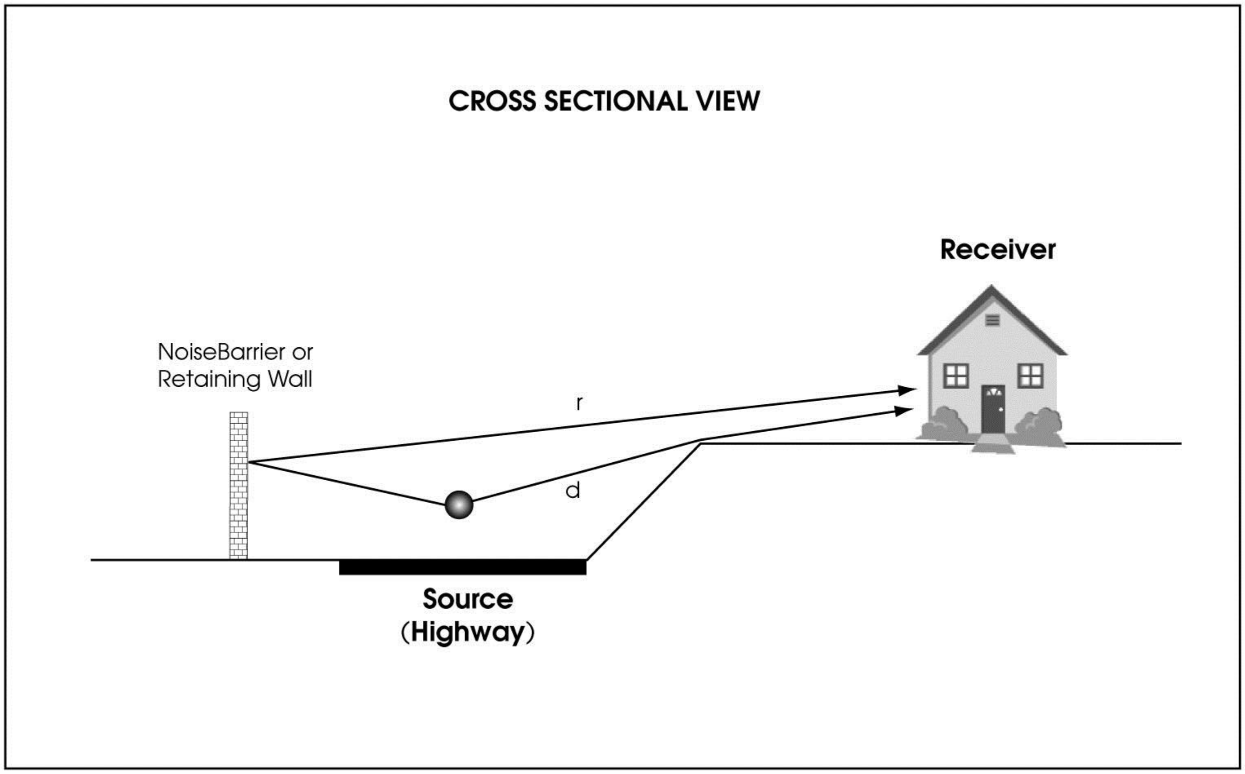

Figure 5-27. Single-Barrier Reflection (Direct Noise Shielded, Reflected Noise Not Shielded)

Reflections off single barriers located at the top of cut (Figure 5-28) generally are directed over a 5-foot-high receiver on the opposite side and therefore are usually not a concern for low receivers. However, higher receivers— the second floor of a residence or receivers located on a higher hill behind the front receivers—still may be affected by the reflections if the direct noise is shielded.

Situations depicted in Figures 5-27 and 5-28 (high receivers only) may increase noise levels by 3 to 5 dBA, depending on the angle of reflections and the height and length of the reflective barrier.

Single barriers on the top of fills (Figure 5-29) generally do not present any reflection issues. The reflected noise ray is usually well above the receiver.

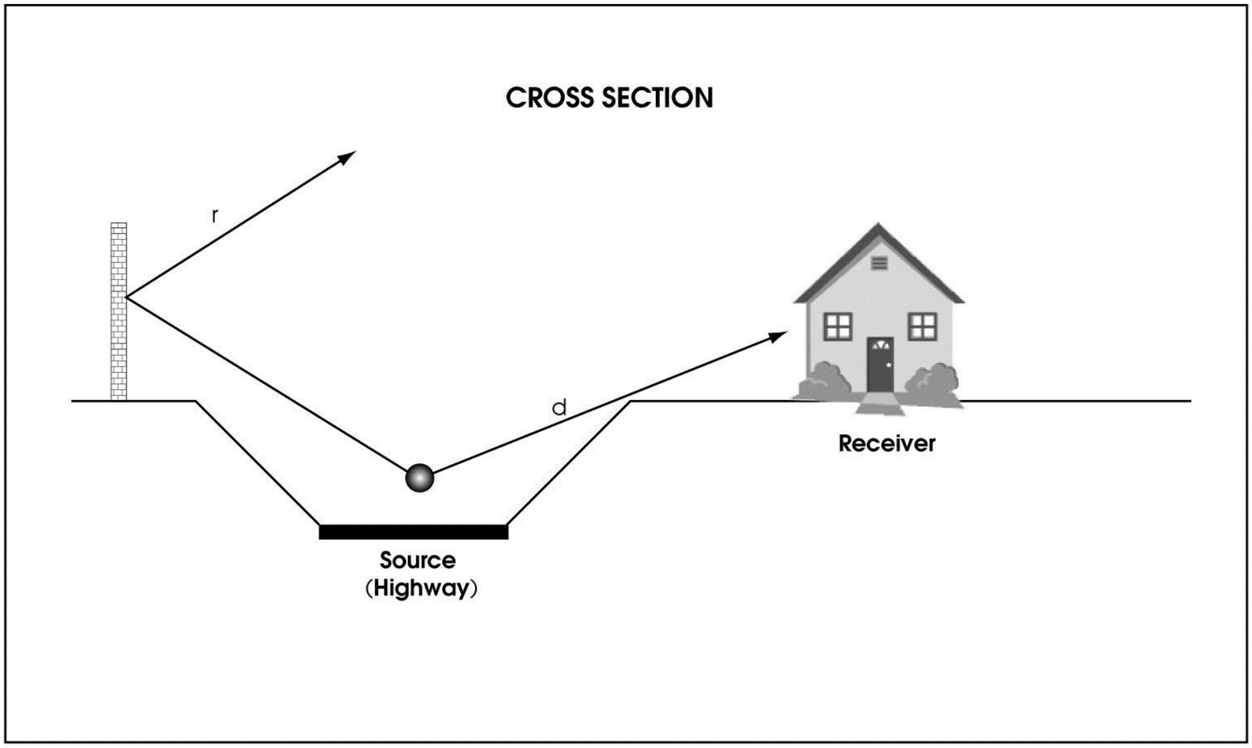

Figure 5-28. Single-Barrier Reflection (Noise Barrier on Top of Opposite Cut)

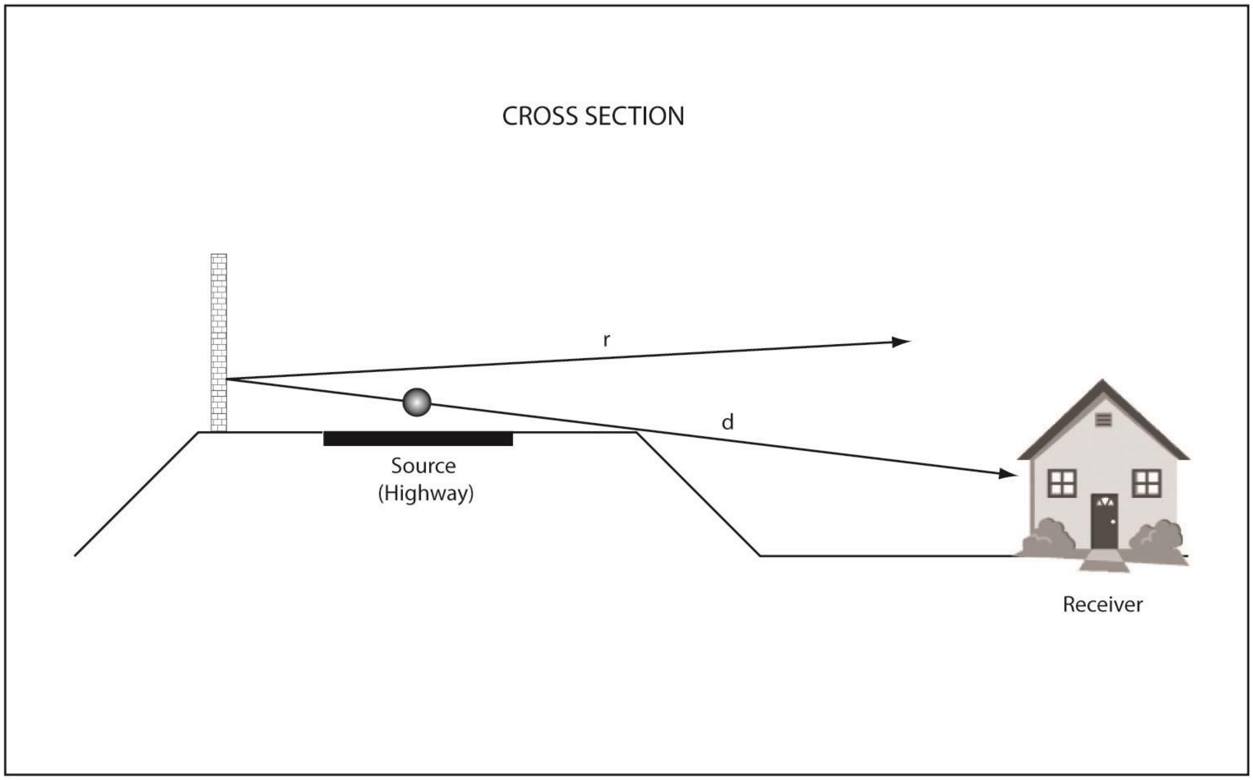

Figure 5-29. Highway and Noise Barrier on Fill

5.1.7.3 Modeling Single Barrier Reflections

TNM currently has no provisions for calculating single barrier reflections. In the future, however, it is planned to have that capability.

For simple situations, the effects of reflections can be evaluated in TNM using image sources. Figures 5-30 and 5-31 illustrate these concepts in cross section and plan views.

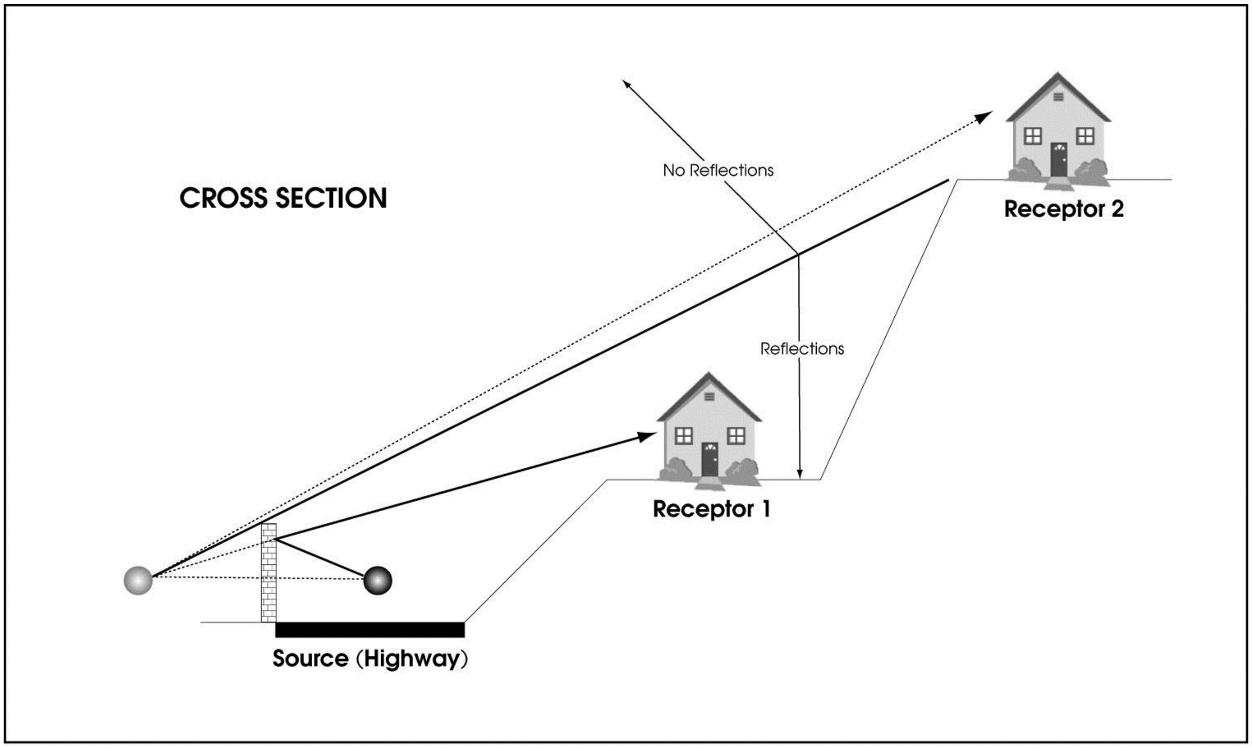

Figure 5-30. Placement of Image Sources (Cross Sectional View)

Figure 5-30 illustrates the placement of an image source in cross section by drawing a line perpendicular to the reflective wall (or its vertical extension) that passes through the real source. The image source is positioned on that line at the same distance from the wall as the real source but on the opposite side. The image source is analogous to a mirror image of the real source, with the wall acting as the mirror.

It is important to point out that just as mirror images cannot be seen from all angles, not all image sources necessarily contribute to reflections. A straight line drawn from the image source to the receiver must pass through the wall before the image source can contribute to the noise at the receiver. Please note that Receptor 1 lies in the "zone of reflections," while Receptor 2 does not experience reflective noise. In some cases, there are reflections from cars but not heavy trucks, or vice versa, depending on the site geometry. In other cases, only traffic noise from certain lanes will be reflected, while noise from others will not. Accurate site cross sections will reveal which image sources are relevant.

Figure 5-31 illustrates how an image source can be created in a plan view. A general case is shown with a finite wall that is not parallel to the roadway. Examination of Figure 5-31 reveals that for the purposes of creating an image source a finite wall creates a unique finite image line source for a particular receiver on the opposite side of a highway.

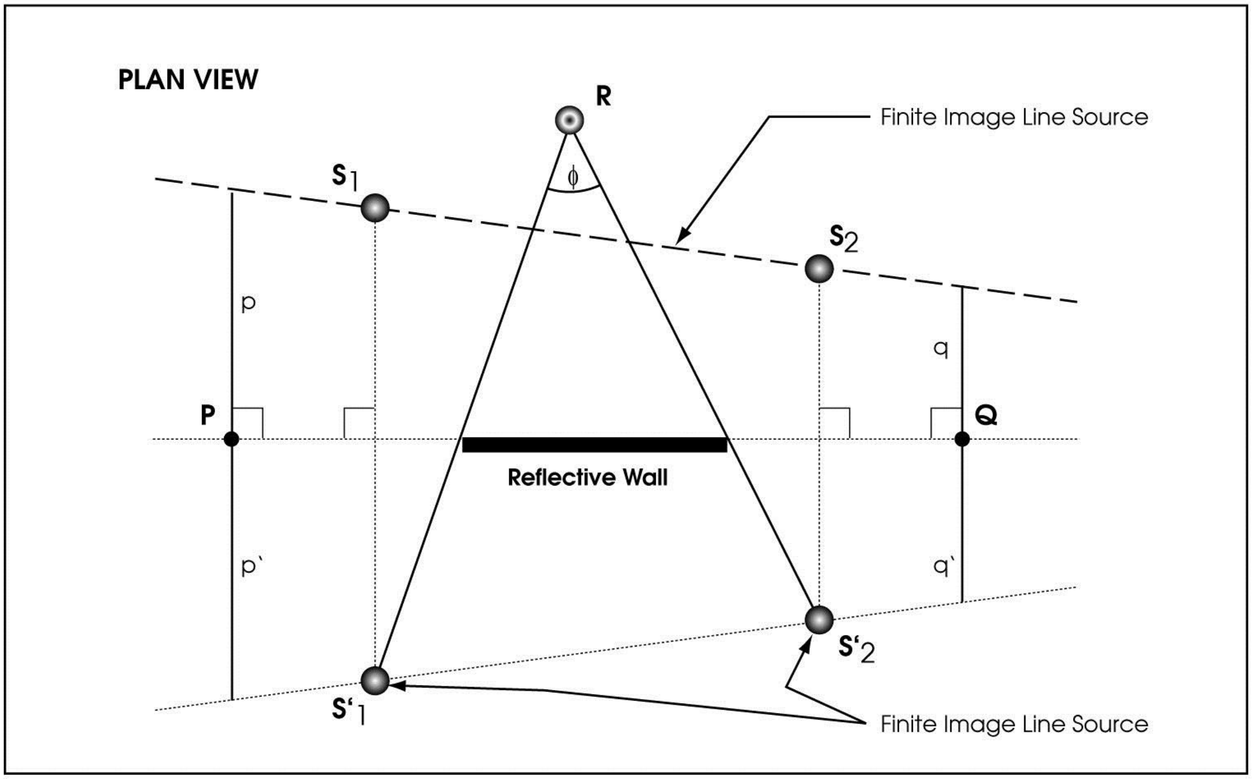

Figure 5-31. Placement of Image Sources (Plan View)

To construct the finite image line source, lines perpendicular to the wall or its extensions at two random locations (e.g., *P* and *Q*) can be drawn. Along these lines, distances *p* and *q* from the wall to the roadway line L, at *P* and *Q*, respectively, can be measured and reconstructed on the image side of the wall ($p = p'$, $q = q'$). A line L' connecting the two points defined by distances p' and q' establishes the direction of the image line source. Next, the termini of the infinite image line source can be determined by the intersections of line L' with two lines from the receiver *R* through both end points of the wall. S'_1 and S'_2 are now the end points of the finite image line source and represent image sources of real sources S_1 and S_2. To correctly account for the reflections at *R*, the finite image source S'_1 –

S'_2 must be input along with the infinite real line source L. Because the reflective wall does not shield R, it must not be included in the analysis.

Please note that for a given source and noise barrier length, the locations S'_1 and S'_2 will be receiver-dependent. For each receiver location, the finite image source $S'_1 - S'_2$ will have a different length unless both the real line source and reflective wall are deemed infinite. When analyzing the effects of the reflections from the wall, each receiver must be analyzed and modeled separately unless both the line source and reflective wall are infinitely long. However, where receiver locations do not change the length of $S'_1 - S'_2$ significantly, the length may be averaged and applied to these receivers.

Only primary reflections should be considered when employing the above methods. Further, because each receiver is affected by a different set of reflections, the number of receivers modeled should be minimized. Even in that case, however, modeling of reflective noise can be very cumbersome. TNM does not currently have provisions for reflection calculations except for the parallel barrier analysis module discussed in the next section.

5.1.7.4 Parallel Barriers

Multiple reflections between reflective parallel noise barriers can potentially reduce the acoustical performance of each individual barrier. Figure 5-32 shows a simple illustration of only five of the many possible reflective paths in addition to the direct path to the top of the barrier. Theoretically, there are an infinite number of possible reflective noise paths. Each reflection essentially becomes a new source, which may add to the noise diffracted by the barrier nearest to the receiver. This in turn may reduce the barrier's effectiveness.

However, Figure 5-32 clearly shows that as the number of reflections for each possible path increases, the path length becomes significantly longer. However, in all instances the barrier-to-receiver distance is the same. Only the path lengths from source to receiver that are located between the barriers change. For the direct path, this distance is defined as $W - S$, where W is the separation distance between the two barriers and S is the distance from the far barrier to the source.

For the first reflective path, the distance is approximately $W + S$. For the second reflective path, it is approximately $3W - S$. Further examination of Figure 5-32 shows that the path length difference between the first reflective path and the direct path is $2S$. The difference between the second and first reflective paths is $2(W - S)$. The pattern repeats itself for subsequent reflections. These increases in path length distances for each subsequent reflection soon make their contribution to the total diffracted noise insignificant (only the first few reflections are important).

For example, for the special case where $W = 2S$ (source halfway between the barriers), each subsequent reflective path increases by W. Assuming that the distance between the source and receiver $D = W$ (a fairly typical situation) and the Noise Reduction Coefficient (NRC) is 0.05 (95% of energy reflected at each reflection point), the contribution of each subsequent reflection decreases rapidly because of increasing path length, as shown in Table 5-2. The table assumes only the effects of increasing distances and a slight absorption by the walls (5% at each reflection point), and does not include the effects of the location of the final point of reflection with respect to the source location. This affects the amount of diffraction by the wall on the receiver side, which will be different for each reflective path. Pavement reflections, constructive and destructive interference of sound waves, frequency shifts, effects of the traffic mix, traffic stream, and lane distribution are ignored also.

Noise contributions from parallel barrier reflections obviously depend on the source-to-receiver distance. For a fixed W, the relative distance attenuation for each reflective path decreases as D increases. The contribution of each reflection also increases as W decreases in relation to D (Figure 5-32).

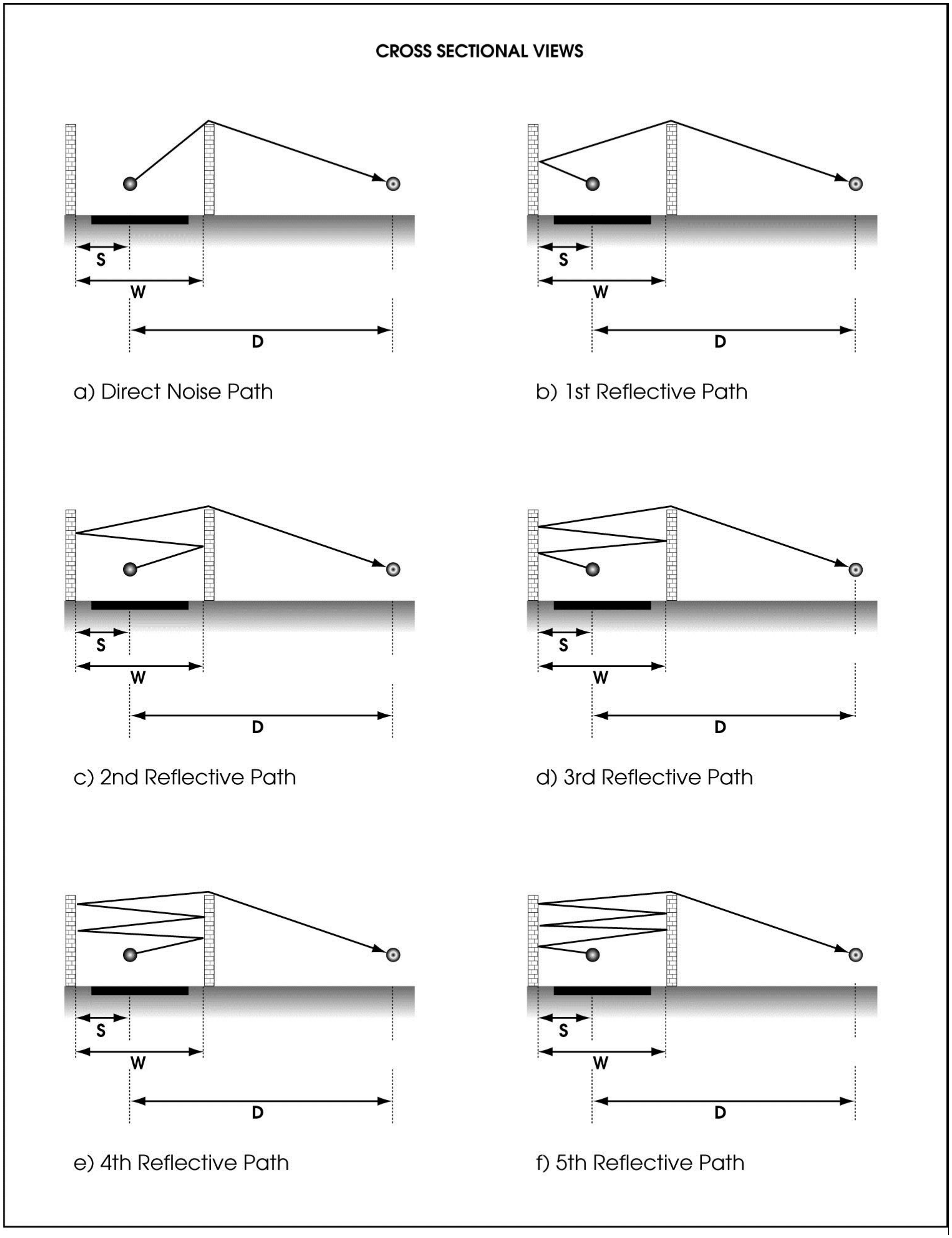

Figure 5-32. Various Reflective Noise Paths for Parallel Noise Barriers

Table 5-2. Contribution of Reflections for Special Case Where W = 2S, D = W, and NRC = 0.05

Noise Path	Distance, (Source to Receiver of Reflected Paths)	(1) Distance Adjustment (Direct to Reflective Path) 10log(W / NW) (where N = 2 through 11) (dBA)	(2) Absorbed (NRC = 0.05) (dBA)	(1 + 2) Contribution (RE: Direct) (dBA)	Cumulative Total Noise Level (RE: Direct) (dBA) (Direct + 1st Reflective + 2nd Reflective, etc.)
Direct	W	0 (Ref.)	0	0 (Ref.)	0 (Ref.)
1st reflective	2W	-3.0	-0.2	-3.2	+1.7
2nd reflective	3W	-4.8	-0.45	-5.25	+2.5
3rd reflective	4W	-6.0	-0.7	-6.7	+3.0
4th reflective	5W	-7.0	-0.9	-7.9	+3.3
5th reflective	6W	-7.8	-1.1	-8.9	+3.6
6th reflective	7W	-8.5	-1.3	-9.8	+3.8
7th reflective	8W	-9.0	-1.6	-10.6	+3.9
8th reflective	9W	-9.5	-1.8	-11.3	+4.1
9th reflective	10W	-10.0	-2.0	-12.0	+4.2
10th reflective	11W	-10.4	-2.2	-12.6	+4.3

Noise contributions of reflections between parallel barriers degrade the performance (insertion loss) of each noise barrier. The amount of degradation that takes place depends on the site geometry and barrier configurations. In addition to the factors shown in Figure 5-32 and Table 5-2, there is another important relationship between the ratio of the separation between two parallel barriers (W) and their average height (H_{AVG}), and the amount of insertion loss degradation. As a rule, if the W / H_{AVG} ratio is 10:1 or more, the insertion loss degradation is less than 3 dBA. This has been supported by research done by Caltrans and others (California Department of Transportation 1991 and Federal Highway Administration 1990). Because of suggested noise barrier height limits in the *Highway Design Manual*, parallel noise barriers in California typically have a W / H_{AVG} ratio of 10:1 or more. Although there have been claims to this effect, there are no known instances in which reflective parallel noise barriers in any configuration have ever measurably increased noise levels over those without noise barriers. The W / H_{AVG} guideline applies not only to noise barriers, but also to retaining walls or combinations of both. Figure 5-33 illustrates these concepts.

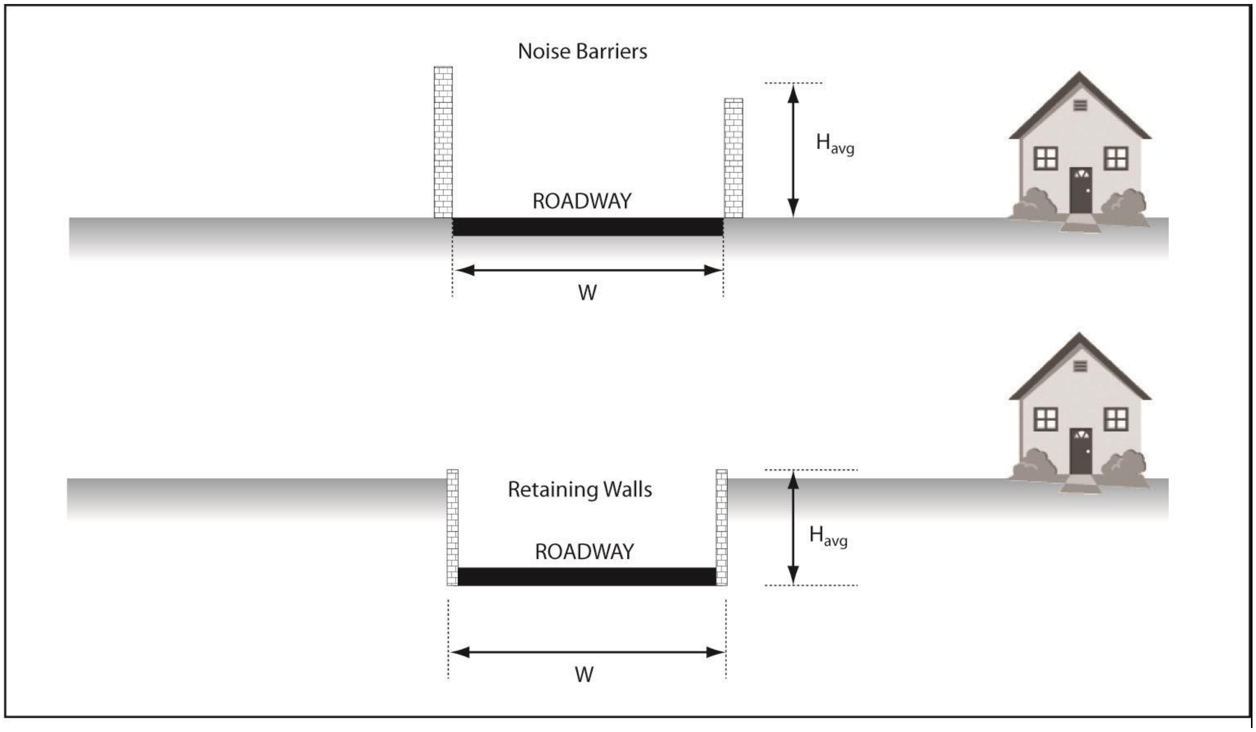

Figure 5-33. *W* / H_{AVG} Ratio Should be 10:1 or Greater

5.1.7.5 Reflections off Structures and Canyon Effects

Generally, the same rules that apply to reflections off noise barriers also apply to those off retaining walls. Because the height limitations to noise barriers do not pertain to retaining walls, there is more potential for noise reflections, especially when the retaining walls are along stretches of depressed freeways. However, no noise barriers in this configuration have ever been shown objectively and conclusively to result in higher noise levels than those of a similar at-grade freeway because of reflective noise.

Complex multi-level highway interchanges can present some challenges in noise abatement design. The widespread spatial distributions of traffic noise sources and receivers make it difficult to design noise barriers that interrupt all direct noise paths between the many source-to-receiver combinations. Additionally, reflective surfaces of concrete structural components create many opportunities for noise reflections to circumvent noise barriers. Figure 5-34 shows one example of a potential complication created by the interaction of structures and noise barriers.

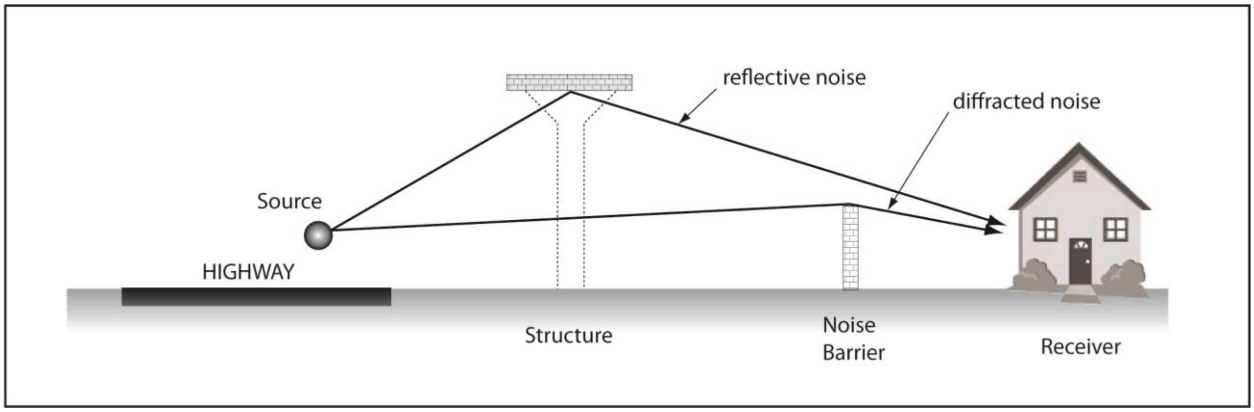

Figure 5-34. Noise Reflection off Structure

The structure in the illustration provides a point (or line) of reflection off the structure's soffit. This essentially creates a new line source with respect to the receiver shown. Unlike the highway noise sources that are shielded from the receiver by the noise barrier, the reflected noise (new source) is not shielded.

High median barriers (e.g., 5-foot-high concrete glare screens) are typically not considered an issue. Because of the barriers' limited height, reflections most likely are scattered and interrupted by the traffic stream.

The effects of reflections near tunnel portals can substantially increase noise at receptors near the portal. A study conducted in Germany (Woehner 1992) provides guidance on how to reduce noise at tunnel portals by applying acoustical absorption to the tunnel walls near the opening. The report indicates that the depth of treatment into the tunnel should be 2 to 3 times the diameter of the tunnel opening.

To date, Caltrans measurements have yet to conclusively reveal issues associated with the interaction between structures and noise barriers. The effects of reflections off structures would be limited because of the small reflecting surface and therefore affect only a relatively small group of receivers because of the small reflecting surface.

Studies of highways through canyons typically have shown noise increases of less than 3 dBA from canyon effects. Noise increases generated from highways in narrow canyons with steep side slopes theoretically could be more than 3 dBA, depending on groundcover and the steepness and smoothness of side slopes. The canyon walls, to some extent, act as parallel soundwalls with respect to multiple reflections. However, unless the slopes are perfectly vertical, buildup of reflections will be more limited because of the slope angles.

Highways on hillsides with nearly vertical rock cuts are somewhat similar to the single barrier situation discussed previously. No perceptible noise increases are expected. Because of the angle of the cut slope, reflections are directed skyward, while receivers would likely be below the highway.

5.1.7.6 Double-Deck Bridge Reflections

A special case of multiple noise reflections is a double-deck bridge. Frequently, noise measurements taken at receivers near such a structure differ substantially from those modeled for the same conditions because of the model’s inability to account for the noise contributions generated by lower-deck traffic, and reflecting between the lower road deck and the bottom (soffit) of the upper deck. An example of how to calculate the contributions of these reflections manually will be shown in this section.

In Figure 5-35, the noise levels at the receiver are determined by the direct diffracted path from the lower deck traffic (sources S_1 and S_2), traffic from the upper deck, and contributions from reflections between the lower deck and the soffit of the upper deck. The direct noise levels from the lower and upper decks can be modeled in the TNM. The contributions of the multiple reflections between the decks, however, cannot be modeled in TNM and require manual calculations that can be added to the results of TNM. To accomplish this, ignore the contributions of the upper-deck traffic and begin by modeling the geometry of the lower deck, the receiver, and the associated traffic at S_1 and S_2. In Figure 5-35, the direct paths from S_1 and S_2 are diffracted by the barrier at the edge of the lower deck.

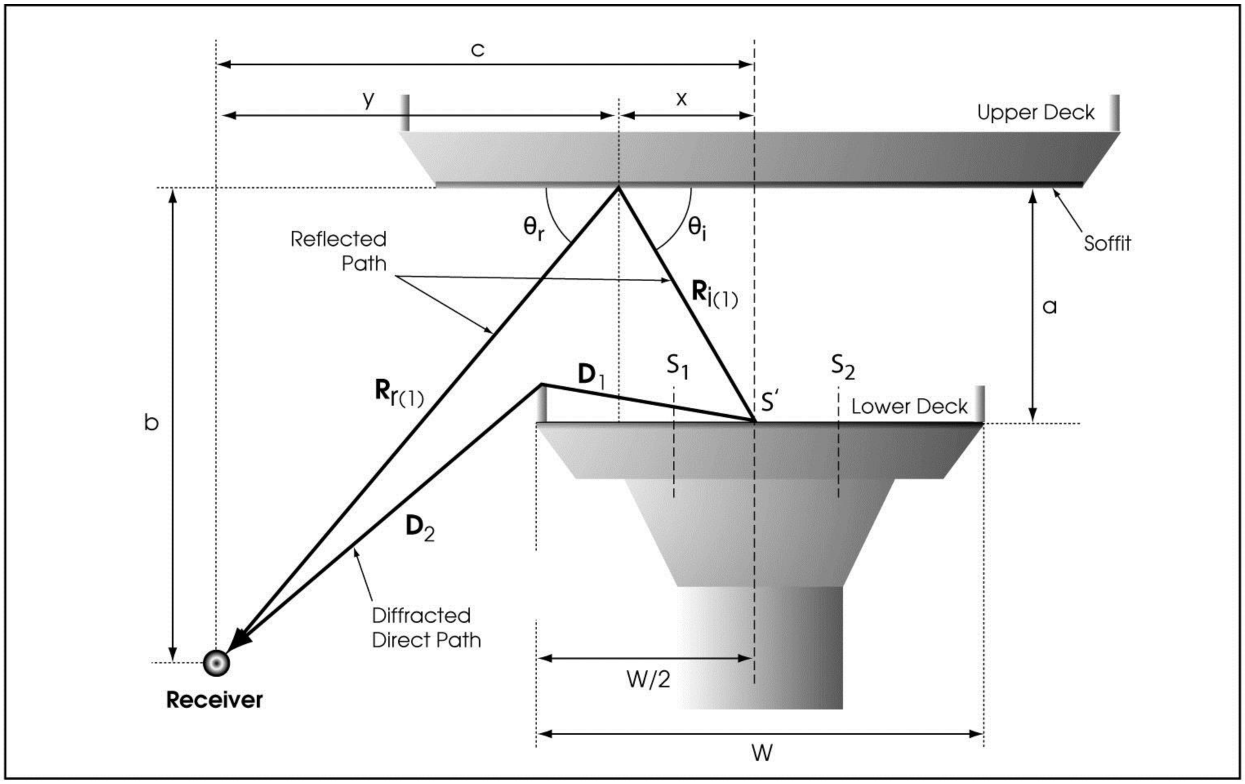

Figure 5-35. Double-Deck Structure Reflections, First Reflective Path

Contribution of Primary Reflection

Begin by analyzing only the primary (first) reflective path, $R_{(1),}$ as shown in Figure 5-35. Subsequent reflections will be analyzed similarly and will be discussed later in this section. $R_{(1)}$, consisting of the incident path $R_{i(1)}$ and path after first reflection $R_{r(1)}$, is not diffracted by the edge of the bridge. For simplicity, one path originating from S' is shown to represent an average of the primary reflective paths from both S_1 and S_2. The direct diffracted paths from S_1 and S_2 are similarly shown as one average path originating at S'. This approximation will yield results that are sufficiently accurate. Please note that all the sources depicted in Figure 5-35 are actually lines shown on end (disappearing into the paper). Therefore, all the direct and reflected paths are actually planes and propagate as line sources.

If the path lengths of both the direct diffracted and reflected paths are known, the line-source noise contribution of the reflective path relative to the direct path can be calculated as follows:

$$10\log(D/R_{(1)}) \quad \textbf{(5-2)}$$

Where:

D = direct path length ($D_1 + D_2$)

$R_{(1)}$ = primary reflected path length ($R_{i(1)} + R_{r(1)}$)

However, this would be true only if D would be undiffracted. Any calculated reflected noise contributions would be relative to the undiffracted noise level originating from S_1 and S_2. These contributions could then be added to the diffracted noise level at the receiver. The difference between the undiffracted and diffracted noise levels can be calculated from modeled results.

The diffracted noise level at the receiver can be modeled with the geometry shown in Figure 5-35, eliminating the upper deck. The required dimensions are all given: the line source locations S_1 and S_2; the location of the edge of the bridge deck, including a jersey or other barrier; and the dimensions a to c.

The undiffracted noise level requires relocation of the receiver while keeping the distance of the diffracted path length, and raising the receiver high enough to not be influenced by the barrier at the edge of the bridge deck. This requires the straight-line path of the receiver to be at least 5 feet higher than the top of the (jersey) barrier. The difference between the diffracted and undiffracted noise level at the receiver can now be expressed relative to the undiffracted noise level. For instance, if the diffracted noise level is 60 dBA and the undiffracted noise level is 70 dBA, the latter is the reference, and the former becomes -10 dBA.

The contribution of the primary reflections (simplified by a single path representing both paths from S_1 and S_2) can now be calculated using Equation 5-2. Using Figure 5-35, calculate the lengths of D and $R_{(1)}$. D can be calculated as described below:

$$D = D_1 + D_2 \quad \textbf{(5-3)}$$

Where:

$D_1 \approx W/2$

$D_2 = \sqrt{[(b-a)^2 + (c - W/2)^2]}$

The calculation of $R_{(1)}$ requires additional manipulation. First, it is known the primary reflective path consists of $R_{i(1)}$ and $R_{r(1)}$, and the angle of incidence (θ_i) equals the angle of reflection (θ_r). It is also known that the primary reflective path must originate at S' and end at the receiver. Within these constraints, the location of the point of reflection, which lies on the soffit of the upper deck, a distance *x* from S' and a horizontal distance *y* from the receiver, which in turn lies a horizontal distance of *c* from S’, can be calculated as described below. (It should be emphasized that the point of reflection and the source at S’ are actually lines.)

Because $\theta_i = \theta_r$, x/y = a/b (sides of proportional triangles)
Therefore, x = y(a/b) and y = x(b/a)
In c = x + y (given), substitute y(a/b) for x
Therefore, c = y(a/b) + y = y[(a/b) + 1] and y = [c/(a/b) + 1] = bc/(a + b)
Similarly, x(b/a) can be substituted for y
By the above process, x = ac/(a + b)

Because a, b, and c are given, x and y can be readily calculated.

$R_{i(1)} = \sqrt{}(x^2 + a^2)$ and $R_{r(1)} = \sqrt{}(y^2 + b^2)$.
$R_{(1)} = R_{i(1)} + R_{r(1)}$

The noise contribution of R_1 relative to the undiffracted noise level at the receiver now can be calculated.

Example 1
Given
a = 30 feet
b = 50 feet
c = 60 feet = x + y
W = 66 feet
Undiffracted noise level from lower deck at image receiver = 70 dBA, L_{eq}(h)
Diffracted noise from lower deck is 60 dBA, L_{eq}(h)

Calculate
1. Contribution of primary reflection
2. Total noise level from lower deck at receiver (including primary reflection)

Step 1: Compute D
$D = D_1 + D_2$
$D_1 = W / 2 = 66 / 2 = 33$ feet
$D_2 = \sqrt{}[(b – a)^2 + (c – W / 2)^2] = \sqrt{}[(50 – 30)^2 + (60 – 33)^2] = 33.6$ feet
D = 33 + 33.6 = **66.6 feet**

Step 2: Compute $R_{(1)}$

$R_{(1)} = R_{i(1)} + R_{r(1)}$

$R_{i(1)} = \sqrt{[x^2 + a^2)}$

$R_{r(1)} = \sqrt{[y^2 + b^2)}$

a and b are given

$x = ac / (a + b)$

$y = bc / (a + b)$

$x = (30 * 60) / (30 + 50) = 22.5$ feet

$y = (50 * 60) / (30 + 50) = 37.5$ feet

$R_{i(1)} = \sqrt{[22.5^2 + 30^2)} = 37.5$ feet

$R_{r(1)} = \sqrt{[y^2 + b^2)} = \sqrt{[37.5^2 + 50^2)} = 62.5$ feet

$R_{(1)} = 37.5$ feet + 62.5 feet = 100 feet

From Equation 5-2, the contribution of the primary reflective path is 10log(D / $R_{(1)}$), or 10log(66.6 / 100) = -1.8 dBA (RE: undiffracted noise level). The total noise level (RE: undiffracted noise level) is -10 dBA (diffracted noise level from lower deck) plus -1.8 dBA (from primary reflection), or $10\log(10^{-10/10} + 10^{-1.8/10}) = -1.2$ dBA. This means that because of the undiffracted primary reflection, the noise level from the lower deck at the receiver rose from (70 – 10) = 60 dBA to (70 – 1.2) = 68.8 dBA.

At this point, a discussion of the geometry and characteristics of the upper deck soffit surface is appropriate. In Figure 5-35, the point of reflection of the primary reflective path falls on the soffit. This may not always be the case, however, depending on the width of the upper deck and locations of the traffic sources and receivers. Each reflection must begin at the source and end at the receiver and the angles of incidence and reflection must be equal. If any of the constraints are not met, the reflection will not contribute. To determine whether the reflection contributes, *x* must be calculated first. The upper bridge deck must be sufficiently wide for the point of reflection to fall on the soffit surface, as determined by the distance *x* in Figure 5-35. If it does not, the reflection will not be a noise contributor. Similarly, the orientation of the upper deck relative to the lower deck must be accurately known. In Figure 5-35, the two decks are assumed to be parallel. If they are not, additional angle complications will be encountered in determining the reflective paths.

Other factors have been ignored so far. The soffit surface seldom is a perfect reflector (i.e., less than 100% of the incident sound energy is reflected back) at each point of reflection. If the sound absorptive characteristics of the soffit are known, Equation 5-2 can be expanded to include the fraction of incident noise energy that is reflected at each reflection point.

The equation can then be written as follows:

$$10\log[(D / R_{(1)})(1 - \alpha), \text{ or } (1 - \text{NRC})] \qquad \textbf{(5-4)}$$

Where:
α or NRC = fraction of noise energy absorbed by soffit material
$(1 - \alpha)$ or $(1 - \text{NRC})$ = fraction being reflected
If α or NRC = 1, all noise energy is absorbed; none is reflected.
If α or NRC = 0, no noise energy is absorbed; all is reflected
Difference between α and NRC is discussed in Section 5.1.7.7 below.

For example, the NRC for a concrete surface is frequently given as 0.05. In Example 1, the contribution of the primary reflective noise path would be 10log[(66.6 / 100)(1 – 0.05)] = -2.0 dBA, instead of -1.8 dBA for a 100% reflection of noise energy. The difference between perfect reflection (NRC = 0) and NRC = 0.05 is 0.2 dBA. This difference is independent of distance and cumulative for each reflection point.

Contributions of Subsequent Reflective Paths

Figure 5-36 shows additional reflective noise paths from S’ to the receiver. The second reflective path is almost identical to the primary noise path and consists of two reflection points, the first at S’ on the pavement and the second almost coinciding with the primary reflection point.

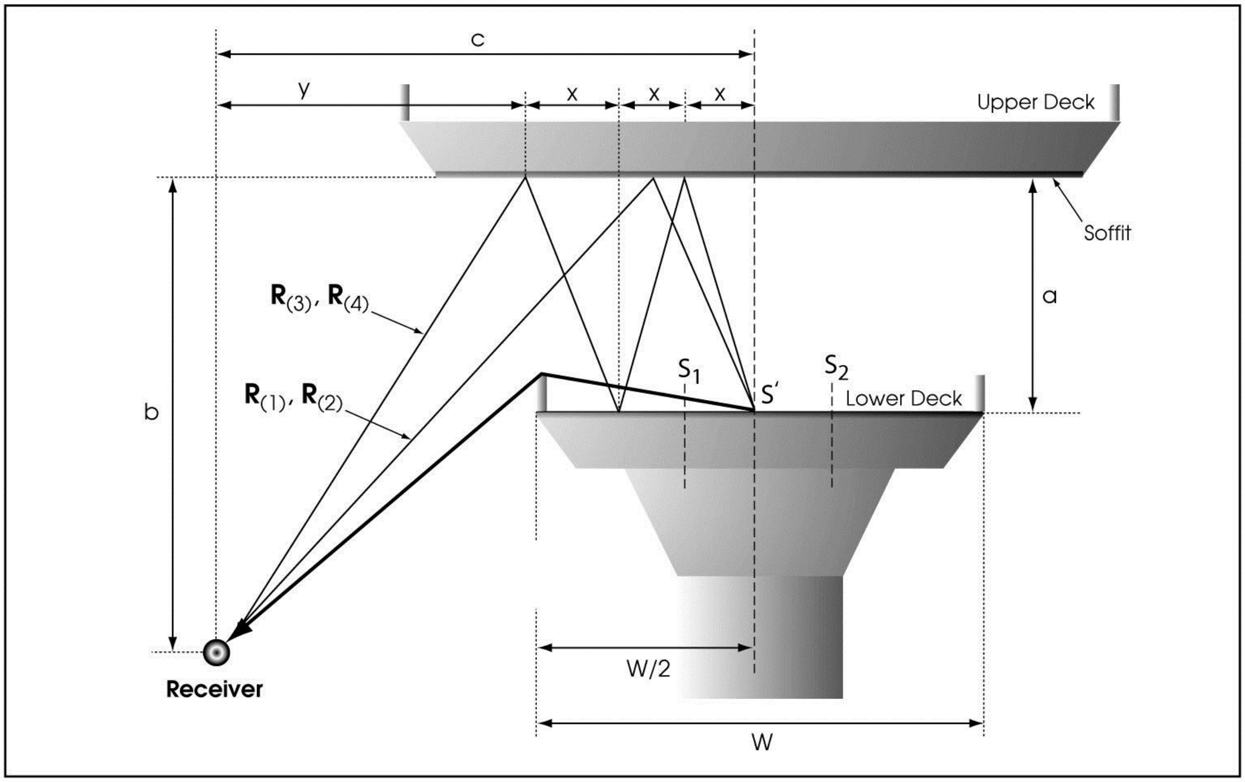

Figure 5-36. Multiple Reflective Paths

The difference between the primary and secondary noise paths is very small; therefore, they can be assumed to be the same. However, its contribution must be accounted for separately. The same is true for any even-numbered reflective path (e.g., the fourth reflective path almost coincides with the third reflective path). As discussed before, the number of possible reflective paths is limited to the following restrictions.

- Each reflective path must start at S' and end at the receiver.
- For each reflective path, the angles of incidence and reflection must be equal.
- For the *n*th reflective path, the last upper reflection point at distance $(n)x$ must fall on the soffit surface.
- The last lower reflection point at distance $(n - 1)x$ must fall on the lower deck surface.

For each reflective path, the distance x can be calculated as shown for the primary path. For the *n*th reflective path, $c = y + (n)x$. Therefore, $x = ac / [(n)a + b)$ and $y = bc / [(n)a + b)$. Also, $y = c - nx$. Actually, n refers to the odd-numbered reflective paths only. Each even-numbered reflective path is approximately equal to the previous odd-numbered one. Therefore, the noise contributions for the even-numbered reflective paths are also approximately the same as the previous odd-numbered reflective path (i.e., the noise contribution of $R_{(2)}$ equals $R_{(1)}$, and the contribution of $R_{(4)}$ equals $R_{(3)}$). The reflective path lengths can be calculated as shown in Example 1.

Using the same data as Example 1, the contributions of the remainder reflections can be determined. As stated, $R_{(2)} \approx R_{(1)}$, and the contributions are equal. $R_{(3)}$, which consists of three short incident/reflection paths (Figure 5-36) and a final long reflective path to the receiver, and its contribution can be calculated as follows.

Example 2

$x = ac / (3a + b) = (30)(60)/(90 + 50) = 12.9$ feet

$y = c – 3x = 60 – 3(12.9) = 21.3$ feet

Also, $y = bc / (3a + b)$, which can serve as a check:

$y = (50)(60) / (90 + 50) = 21.4$ feet

(Slight difference in results of y is because of rounding.)

Three short paths (all equal) = $\sqrt{(x^2 + a^2)} = \sqrt{(12.9^2 + 30^2)} = 32.7$ feet

Final reflective path = $\sqrt{(y^2 + b^2)} = \sqrt{(21.3^2 + 50^2)} = 54.3$ feet

$R_{(3)} = 3(32.7) + 54.3 = 152.4$ feet

$R_{(3)}$ contribution = $10\log(D / R_{(3)}) = 10\log(66.6 / 152.4) = -3.6$ dBA

$R_{(4)}$ contribution = $R_{(3)}$ contribution = -3.6 dBA

Close examination of Figure 5-36 indicates that the number of possible reflective paths is limited by *x* and the smaller of the half-widths of the soffit or lower deck. By comparing the half-widths of both the soffit and lower deck with calculated *n*(*x*), where *n* is each whole interval of *x*, the number of reflection points will become apparent. However, it should be noted that the final reflective path is the *n*th + 1 reflective path (in this case, *n* + 1 = 4).

Finally, the results from Examples 1 and 2 can be tabulated in summary form. An example of this format is shown in Table 5-3. All the reflective noise contributions shown are referenced to the undiffracted noise level at the receiver, but at the distance of the diffracted path. Because the reflective contributions are all without diffractions but the noise at the receiver (without reflections) is diffracted, all contributions to the undiffracted noise at the receiver must be normalized. As indicated in the discussion of primary reflection, undiffracted noise can be modeled by placing the receiver in such a position that no diffraction takes place. The previous discussion used undiffracted noise of 70 dBA and diffracted noise (without including reflections) of 60 dBA. The results table reuses these values. In that case, the reference is 70 dBA and all other values are relative to this reference. Also included is the correction for non-perfect reflections (assumed NRC = 0.05 [Equation 5-4] at each reflection point). Please note that reflective paths 2 and 4 actually have two and four reflection points very close to the source and therefore will be corrected for NRC 0.05.

Table 5-3. Summary of Reflective Noise Contributions and Cumulative Noise Levels

(1) Reflective Path Number $R_{(n)}$	(2) Contribution Relative to Ref.[a] [10log(D / $R_{(n)}$)]	(3) Correction for NRC = 0.05(n) 10log(1 – 0.05)	(4) [(2) + (3)] Adjusted Contribution (AC_n) Re: Ref.[a]	(5) Cumulative Noise Level (L_n)[b] Re: Ref.[a]	(6) [(5) + Ref.[a]] Absolute Noise Level
None	-10 dBA	None	0	L= -10 dBA (Given)	60 dBA (Given)
1	-1.8 dBA	-0.2 dBA	AC_1 = -2.0 dBA	L_1 = -1.4 dBA	68.6 dBA
2	-1.8 dBA	-0.4 dBA	AC_2 = -2.2 dBA	L_2 =+1.2 dBA	71.2 dBA
3	-3.6 dBA	-0.7 dBA	AC_3 = -4.3 dBA	L_3 = +2.3 dBA	72.3 dBA
4	-3.6 dBA	-0.9 dBA	AC_4= -4.5 dBA	L_4 = +3.2 dBA	73.2 dBA

[a] Ref. = reference of 70 dBA.

[b] Cumulative noise levels in column 5 are calculated as follows:

$L_1 = 10\log(10^{L/10} + 10^{AC1/10})$ $L_2 = 10\log(10^{L1/10} + 10^{AC2/10})$

$L_3 = 10\log(10^{L2/10} + 10^{AC3/10})$ $L_4 = 10\log(10^{L3/10} + 10^{AC4/10})$

5.1.7.7 Minimizing Reflections

When designing reflective parallel noise barriers, it is recommended that a minimum 10:1 W / H_{AVG} ratio is maintained between the two barriers to avoid perceivable barrier performance degradations. Earth berm noise barriers are not reflective and therefore not affected by W/H_{AVG} ratios of less than 10:1.

Sound absorption has been promoted as a solution for noise reflection issues. As part of an ongoing program, Caltrans considers a variety of proprietary noise barrier products and systems, some of which have sound-absorptive characteristics. . For more information on barrier materials and new products, the designer should check with the Caltrans Headquarters Office of Design and Local Programs for availability of approved materials, and the Division of Structures Design to determine which materials have been approved for use on noise barriers. Sound-absorptive materials can be an inherent property of the barrier or added on to an existing barrier (retrofit). The Caltrans new products webpage lists approved noise barrier products. These barrier products include reflective, absorptive, transparent, and bridge-rail-mounted options. The new products webpage is available here:

http://www.dot.ca.gov/hq/esc/approved_products_list/

The amount of noise absorption of the materials is rated by a noise absorption coefficient α. The coefficient is defined as the ratio of the acoustical energy absorbed by the material to the total energy incident on that material. For any particular material, α is frequency-dependent, and its value for each specific frequency ranges from 0 (perfect reflector) to 1 (perfect absorber). To rate the overall absorptive characteristics of the material, a measure of the average α over the frequency range of interest is useful. For traffic noise frequencies, an appropriate measure is the NRC, which is the arithmetic average of α in four octave bands with center frequencies of 250, 500, 1,000, and 2,000 Hz, calculated as follows:

$$\mathrm{NRC} = (\alpha_{250} + \alpha_{500} + \alpha_{1,000} + \alpha_{2,000})/4 \qquad \textbf{(5-5)}$$

If approved absorptive materials are considered, a minimum NRC of 0.85 should be used as a criterion. This value means that 85% of the incident noise energy is absorbed and 15% reflected. For a single reflection, this can only add a maximum of 0.6 dBA to the direct noise level, instead of the theoretical 3 dBA for a perfect reflector (NRC = 0).

5.1.8 Miscellaneous Acoustical Design Considerations

There are various other factors that can affect the acoustical performance of noise barriers. Some (maintenance access, emergency access, and drainage openings) are discussed in *Highway Design Manual* Chapter 1100. The criteria in Chapter 1100 are based on actual noise measurements performed by the TransLab in the 1980s. Although the information is mostly useful to the designer of the noise barrier, it is repeated here for the noise analysts because they often need to field questions about the acoustical integrity of the noise barrier’s design features. Refer to the Caltrans website for the latest version of the *Highway Design Manual*.

5.1.8.1 Maintenance Access behind Noise Barriers

Noise barriers placed within the area between the shoulder and right-of-way line complicate the ongoing maintenance operations behind the noise barrier. From a maintenance perspective, it would be best to place the noise barrier on the right-of-way line, which would avoid access issues and the need of a chain link fence. However, this location may not be preferable for acoustical reasons, as discussed in Section 5.1.2. If the right-of-way line borders a frontage road or other public easement, access to the strip of land between the barrier and the right-of-way can be provided through gates in the chain link right-of-way fence. If not, access may be provided by offsets in the barrier (Figure 5-37). The acoustical integrity of the noise barrier can be maintained by either providing a solid gate of appropriate material and transmission loss (see Section 5.1.1) to close the opening between the two barriers, or by providing a barrier overlap of two-and-a-half to three times the offset distance without closing the opening (Figure 5-38).

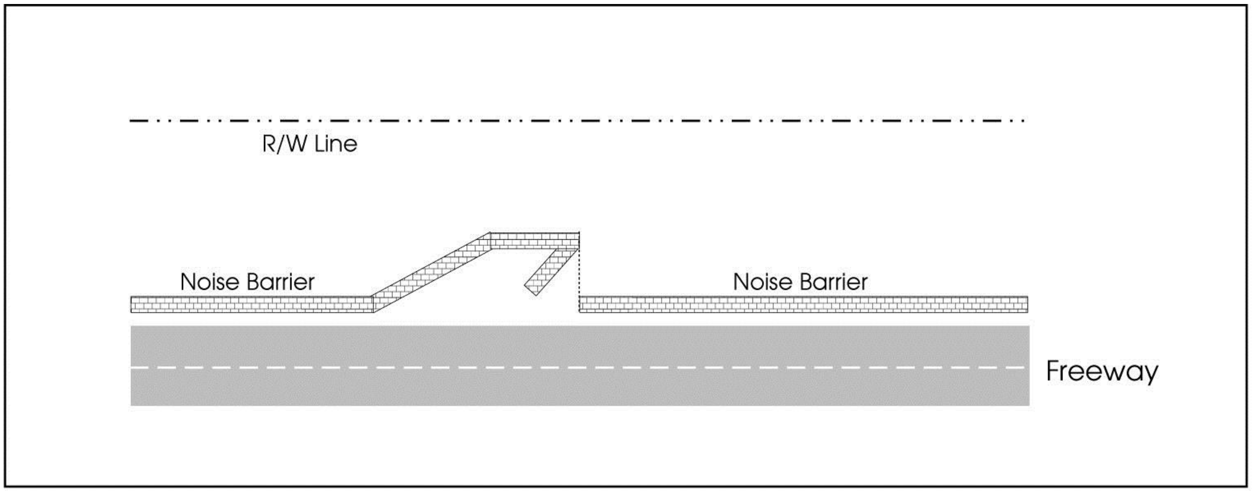

Figure 5-37. Barrier Offset with Solid Gate

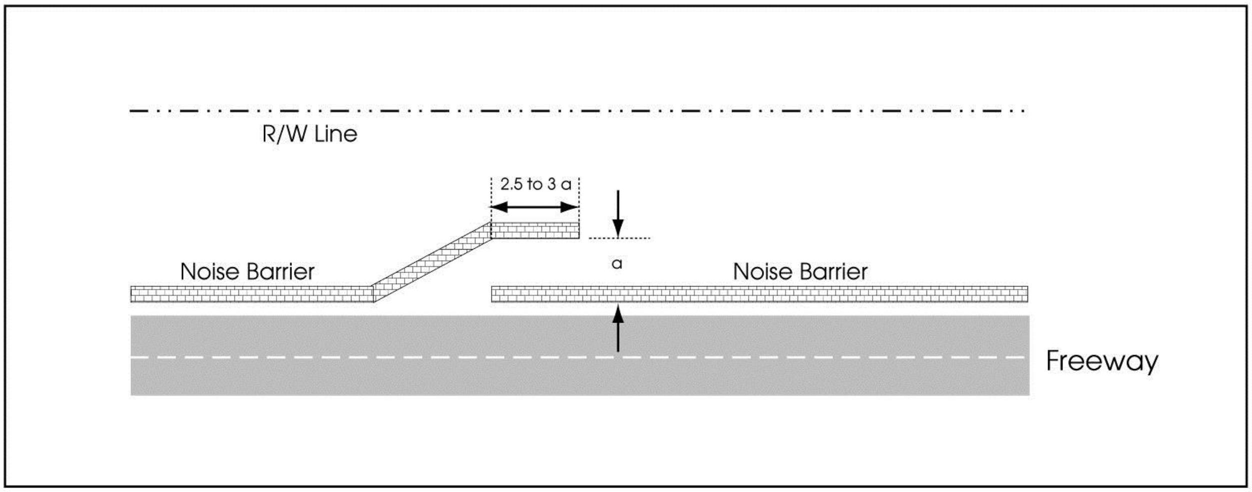

Figure 5-38. Barrier Overlap Offset 2.5 to 3 Times the Width of the Access Opening

5.1.8.2 Emergency Access Gates in Noise Barriers

In addition to access gates and openings in noise barriers for routine maintenance, emergency access gates may be constructed to provide access to a freeway when emergency vehicles cannot reach the scene of an accident. The gates are not intended to provide alternate emergency access to adjacent neighborhoods. Small openings in the noise barrier may also be provided to allow fire hoses to be passed through. The number of gates should be minimized, and the gates should be at least 1,000 feet apart. Where possible, the maintenance openings and emergency access gates should be combined in one location. The Division of Structures Design has incorporated the design of the gates in the soundwall details. The fire hose openings should be located as close as possible to the fire hydrants on the local streets. The size and spacing of the openings normally do not compromise the acoustical performance of a noise barrier. Design details of these openings are available from the Division of Structures Design.

5.1.8.3 Drainage Openings in Noise Barriers

Drainage through noise barriers is sometimes required for various site conditions. Depending on size and spacing, small unshielded openings at ground level can be provided in the barriers to allow drainage without compromising the acoustical performance of the barrier. This can be accomplished if the following size and spacing criteria are observed.

- Openings of 8 by 8 inches or smaller if the openings are spaced at least 10 feet on center.
- Openings of 8 by 16 inches or smaller if the openings are spaced at least 20 feet on center and the noise receiver is at least 10 feet from the nearest opening.

The location and size of drainage openings need to be designed based on the hydraulics of the area. The designer should also consider possible erosion that may occur at the drainage openings.

Where drainage requirements dictate openings that do not conform to these criteria, shielding of the opening may be necessary to uphold the acoustical performance of the noise barrier in the vicinity of a receiver. Shield design should be done with consultation of the district hydraulics unit and noise analyst.

5.1.8.4 Vegetation as Noise Barriers

In spite of a general perception of its effectiveness in lowering noise levels, shielding by shrubbery and trees typically used in landscaping along highways provides an imperceptible amount of noise reduction (less than 1 dB) (California Department of Transportation 1995). Such plantings are not effective for reducing highway noise. A possible explanation for the contradiction of objectively measured noise with general perception is that shrubs shielding traffic from the receiver reduce the visual awareness of the traffic. In such cases, the reduction in visual awareness of the traffic is commonly accompanied by a reduction in auditory awareness of the traffic. The role of landscaping and planting in enhancing the aesthetics of a noise barrier and combating graffiti are addressed in the next section.

5.2 Non-Acoustical Considerations

Final selections of materials, locations, heights, lengths, and shapes of noise barriers include non-acoustical considerations such as safety and aesthetics. Although the noise analyst is normally not involved with these decisions, the analyst should be aware that recommended acoustical designs of noise barriers are sometimes altered because of non-acoustical considerations.

5.2.1 Safety

Safety considerations include lateral clearances, sight distance requirements, and guardrail or safety-shaped barrier requirements. These safety considerations are addressed in *Highway Design Manual* Chapter 1100.

The Division of Structure Design has developed standard plans for noise barriers (soundwalls). Standard plans for soundwalls can be downloaded from the Caltrans website:

http://www.dot.ca.gov/hq/esc/oe/construction_standards.html

Other designs, retrofit treatments, and alterations to noise barriers should be approved by the Office of Structure Design. Approved commercial noise barrier products including absorptive barriers are listed on the Caltrans website:

http://www.dot.ca.gov/hq/esc/approved_products_list/pdf/noise_barrier_systems.pdf

The standard plans also include designs for gates that provide emergency access to community fire hydrants, emergency access for stranded motorists, and rapid access to accidents, as discussed in Section 5.1.8.

A minimum height criterion of 6 feet for soundwalls in *Highway Design Manual* Chapter 1100 was partially designed to control pedestrian access to the freeway. The online version of the *Highway Design Manual* at the Caltrans website should be checked for the latest changes and referrals.

5.2.2 Aesthetics

The visual impact of noise barriers on adjoining communities and motorists is a major consideration in the design of noise barriers. A high noise barrier placed close to single-story residences could result in a visual effect. A high barrier also can create shadows, impede natural airflows, or block panoramic views. *Highway Design Manual* Chapter 1100 outlines maximum recommended heights for noise barriers located at distances of 15 feet or less and more than 15 feet from the traveled way.

In general, visual dominance of high walls near residences is reduced when the soundwall is located at least two to four times its height from the nearest receiver. The visual impact is further softened with berms and landscaping (Figure 5-39). Landscaped earth berms are aesthetically superior to soundwalls and acoustically perform equally or slightly better. However, in many locations, they are not suitable because of space limitations.

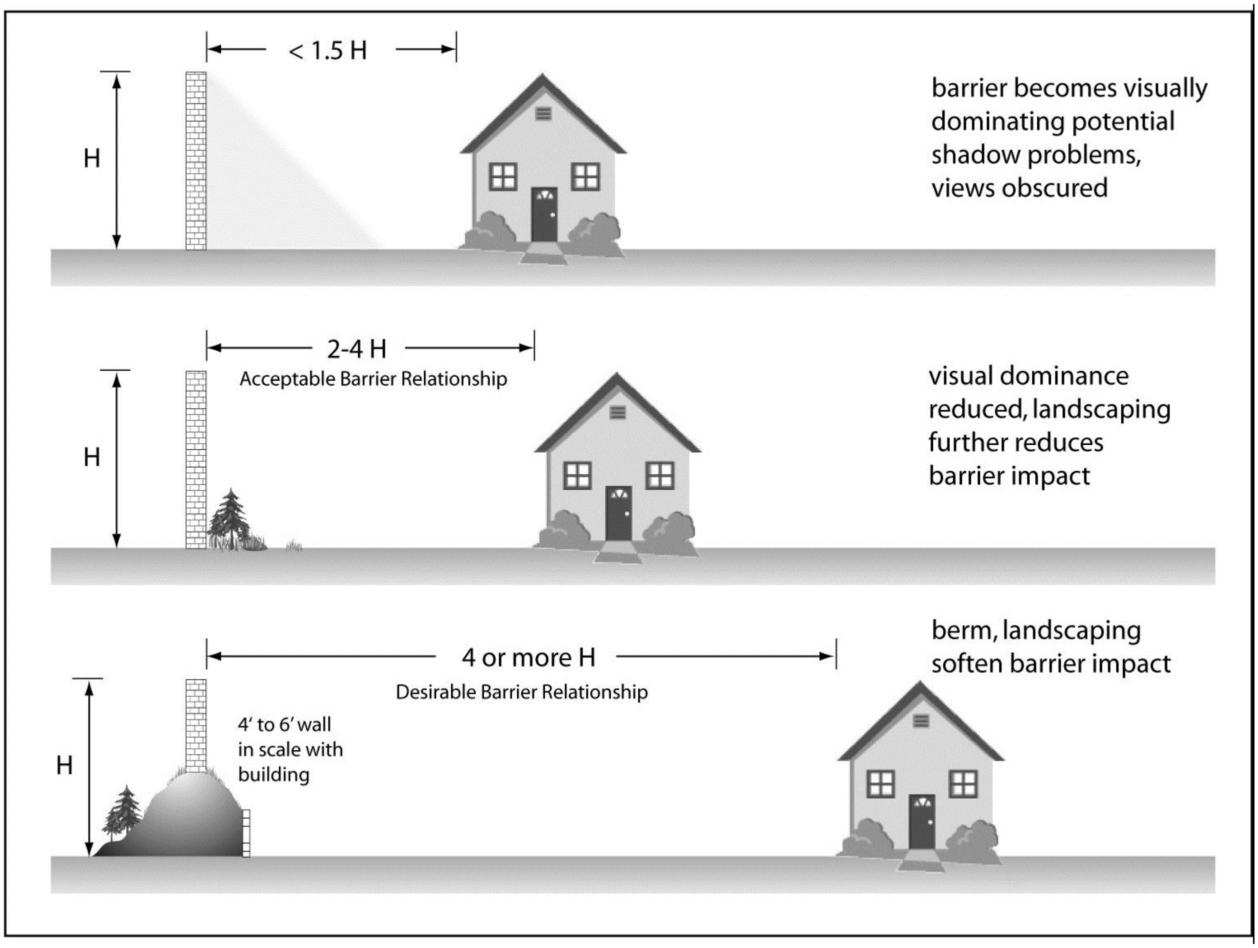

Figure 5-39. Spatial Relationship of Barrier to Adjoining Land Use

Soundwalls should not have abrupt beginnings or endings; they should be tapered or stepped. Aesthetic treatments are normally developed by the Division of Landscaping. If landscaping is to be placed adjacent to the soundwall where it eventually will screen a substantial portion of the wall, only minimal aesthetic treatment is justified.

Walls should reflect the character of the surroundings as much as possible. In cases where the general architecture of a community has a certain character, soundwall material, texture, and color should fit this character at the community side of the wall. Ideally, the community should have some input in the aesthetic design of noise barriers.

On the motorist side of the wall, the emphasis should be on the overall form, color, and texture of the wall. Visual effects on the driver from brick patterns and other forms and shapes should be considered when designing soundwalls. Small details will not be noticed at normal highway speeds. Instead, the emphasis should be on avoiding a tunnel effect through various forms, and visual treatments. Landscaping can be used effectively to accomplish this goal. As discussed, shrubs and trees used for landscaping along a highway do not provide effective shielding by themselves, but they can enhance the aesthetics of a noise barrier and combat graffiti by denying access to a large smooth surface and reducing its visibility from the highway or community side.

Further guidance on aesthetics can be found in *Highway Design Manual* Chapter 1100. Another useful reference on all aspects of noise barrier design and extensive coverage of aesthetics is the *FHWA Noise Barrier Design Handbook* (Fleming et al. 2011).

Section 6
Noise Study Reports

The primary function of a noise study report is to present the methods and results of a traffic noise analysis, as well as the data supporting the conclusions, to a target audience that includes both laypersons and technical noise analysts. To satisfy both audiences, the author can provide a summary for laypersons and decision-makers, and a technical report for experienced readers who desire more detail than what is provided in the summary.

The summary should briefly describe the existing land use and noise environment, project alternatives, future noise environment, traffic noise impacts, and noise abatement and mitigation considered. The technical report needs to fully support the conclusions that are incorporated into the environmental document and should satisfy technical reviewers who wish to assess the validity of the noise study, including methods and assumptions. Sufficient information should be presented to allow any trained noise analyst to reach the same conclusions.

As with all technical environmental studies, the level of effort to be spent on the noise study report needs to correspond to the size and complexity of the project, and degree of controversy surrounding it.

After completion of the noise study report, the noise abatement decision report (NADR) is prepared. The NADR is a design responsibility and is prepared to compile information from several sources. These sources include the noise study report, other relevant environmental studies, and design information. The NADR brings this information together into a single, comprehensive document that is completed before public review of the project. The NADR is prepared before publication of the draft environmental document.

The draft environmental document is the primary means of conveying information on noise impacts and abatement to the public, and reflects conclusions and information contained in the noise study report and NADR.

6.1 Outline

Table 6-1 shows an outline for a typical noise study report. Not all reports will need this level of detail. Others may require more because of special circumstances. An annotated noise study report outline has been prepared by Caltrans and is available: <http://www.dot.ca.gov/ser/forms.htm>. This outline provide guidance on the contents of noise study reports and provides a template with standard language that can be used a starting point for those who are preparing noise study reports.

Table 6-1. Noise Study Report Outline

Summary (or Executive Summary)

Purpose of Noise Report
Brief Description of the Project
Brief Description of the Land Use and Terrain
Existing Noise Levels (Ambient and Background)
Future Predicted Noise Levels
Traffic Noise Impacts (if Any)
Noise Abatement/Mitigation Considered (Range of Heights, Lengths, Insertion Losses, and Number of Benefited Receivers)
Reasonable Monetary Allowances per Benefited Receiver for Abatement Considered
Areas Where Abatement/Mitigation Is Not Feasible
Construction Noise

Chapter 1. Introduction

1. Purpose of Report
2. Background

Chapter 2. Project Description

1. Detailed Description of All Project Alternatives
2. Maps Showing Alignment and Profiles

Chapter 3. Fundamentals of Traffic Noise

1. Decibels and Frequency
2. Noise Source Characteristics (Vehicles and Roadways)
3. Noise Propagation
4. Perception at the Receiver, A-Weighting, and Noise Descriptors
5. Decibel Scale

Chapter 4. Federal and State Policies and Procedures

1. Traffic Noise Analysis Protocol
2. Technical Noise Supplement

Chapter 5. Study Methods and Procedures

1. Selection of Receivers and Measurement Sites
2. Field Measurement Procedures (Note: Field Data in Appendices):
   a. Instrumentation and Setups
   b. Noise Measurements
   c. Traffic Counts and Speeds
   d. Meteorology
   e. Data Reduction
3. Noise Prediction Method Used: TNM as mandated in 23 CFR 772

Chapter 6. Existing Noise Environment

1. Detailed Description of Noise-Sensitive Land Use
2. Maps Showing Receivers and Noise Measurement Sites
3. Table Showing Existing Noise Levels at Receivers:
   a. Field-Measured Results (Ambient and Background)
   b. Modeled Results
4. Discussion on Model Calibration (if Appropriate) for Adjusting Modeled Noise Levels (Existing or Future)

Chapter 7. Future Noise Environment, Impacts, and Considered Abatement/ Mitigation

1. Discuss Future Traffic Data Assumptions and Site Geometry
2. Table Showing Predicted Noise Levels and Identification of Traffic Noise Impacts, if Any
3. Discussion of Noise Abatement Options
4. Table Showing Future Noise Levels and Insertion Losses (Noise Reduction) for Various Noise Barrier Heights, Lengths, and Locations
5. Table showing top-of-wall elevations as a function of station number
6. Table Summarizing Data Necessary for “Reasonableness” Determination
7. Discussion of Areas Where Abatement/Mitigation Is Not Feasible

Chapter 8. Construction Noise

Chapter 9. References

Appendix A. Traffic Data

Appendix B. Predicted Future Noise Levels and Noise Barrier Analysis

Appendix C. Noise Barrier Reasonableness Analysis Worksheets

Appendix D. Noise Barrier Analysis

Appendix E. Supplemental Data

1. Instrumentation, Manufacturer, Model, Type, Serial Number, and Calibration
2. Measurement Site Details and Instrument Setups
3. Measurement Procedures, Duration, and Number of Repetitions
4. Measured Noise Data, Dates, and Times
5. Meteorological Conditions
6. Traffic Counts
7. Data Reduction and Measurement Results
8. Details of Computer Modeling Assumptions, Inputs, and Outputs

6.2 Summary

The noise study findings and conclusions should be presented near the front of the noise study report in the form of a summary (sometimes called *Executive Summary*). The summary is extracted from the technical portion of the noise study report. This requires the technical portion to be written first.

The summary should target laypersons and managers who are interested in the findings and conclusions of the noise study but not concerned about all of the technical details. Because the author of the noise study report is usually not the author of the project's environmental document, the summary should be written in such a manner that it can be copied into the environmental document. This will help to reduce misinterpretations, inconsistencies, loss of vital information, and numerical transpositions. The summary should be short, usually no longer than a few pages. The elements mentioned in Table 6-1 should be described briefly. A table listing receivers, existing noise levels, future noise levels without noise barriers, future noise levels with noise barriers (various heights), and insertion loss should be sufficient to summarize the results of the noise study.

6.3 Noise Impact Technical Study

The noise impact technical study is the main body of the noise study report. It contains detailed descriptions of why and how the noise study was performed and how the conclusions were reached. Sufficient detail is needed for someone to be able to duplicate the study from the information included in report.

6.3.1 Introduction

The introduction should include the purpose of the noise study report, study objectives, background information such as the need for the project and study, and any other general information useful to the understanding of the noise study report.

6.3.2 Project Description

The project description should include a detailed description of all project alternatives. There should be enough information for the reader to understand the project and how it fits into the transportation system of the area. An appropriate location map that shows the alternative alignments studied and their spatial relationship with noise-sensitive receivers such as residences, schools, hospitals, churches, and parks should be included.

6.3.3 Fundamentals of Traffic Noise

A short review of the physical principles of traffic noise at the source and its propagation, as well as subjective human perception, will provide a link for laypersons to understand the technical information. The contents of this section may be in a standard format or tailored to specific studies.

The noise characteristics of vehicles should be described briefly. Vehicle noise emissions increase with speed, and increased traffic volumes increase traffic noise, but it takes a doubling of traffic to increase noise levels by only 3 dB.

Noise propagation (line vs. point source) over acoustically hard and soft ground, effects by meteorological factors such as wind and temperature gradients, and shielding by terrain or noise barriers should be discussed.

Human perception of noise is frequency-dependent, which leads to a discussion on A-weighting, its purpose, and its use. If the character of the noise is unchanged sound level increases or decreases generally are perceived as follows: 3 dBA as barely perceptible, 5 dBA as readily perceptible, and 10 dBA as a doubling or halving of noise. This should be followed with a discussion on commonly used noise descriptors, such as L_{eq}(h).

Inclusion of a decibel scale that shows a link between everyday activities and associated noise levels will provide the reader with a scale by which to evaluate the severity of traffic noise.

This discussion does not need to be restricted to the above items. Other topics may be included as appropriate, some of which may be specifically tailored to the nature of the noise study. The information presented in this TeNS may be beneficial in explaining various phenomena. For instance, where controversies surrounding parallel or single noise barrier noise reflections are an issue, it may prove beneficial to include relevant selected text from Section 5.1.7 or 7.1. Text from Section 7.1 may be similarly useful in addressing concerns about the effects of noise barriers on distant receivers.

6.3.4 Federal and State Standards and Policies

This section addresses the applicable federal and state standards and policies. Caltrans noise analysis policies are in the Protocol and *Highway Design Manual*. Federal requirements are identified in 23 CFR 772. State requirements are contained in Streets and Highways Code Section 216. Terms used in the policies and standards should be mentioned in this section including the NAC, definitions of appropriate noise descriptors, and traffic noise impact criteria.

6.3.5 Study Methods and Procedures

Study methods and procedures followed should be identified in the noise study report. This section should describe selecting receivers, noise measurement sites, field measurement procedures, and noise prediction methods (see Sections 3 and 4).

The discussion of selecting the receivers and noise measurement sites should focus on the reasons they were selected. Selections are based on expectations of worst noise impacts, geometry of the project, representativeness, acoustical equivalence, and human use (see Sections 3.2 and 4.3.1). The importance of selecting receivers outside the area of project influence must not be overlooked. These receivers are extremely useful for documenting background noise levels and, after the project is built, guarding against unsubstantiated public claims that noise barriers constructed as part of the project increased noise levels at distant receivers (see Section 7.1.1).

The discussion on field measurement procedures (see Section 3) should include descriptions of instrumentation, setups, noise measurement procedures, traffic counts and speeds, meteorological observations, and data reduction methods. Model calibration procedures (see Section 4.4) should also be discussed.

The appendices to the noise report should indicate the measurement equipment used, calibration information, dates and times of measurements, measured noise data, traffic counts and speeds, meteorological conditions, site topography, and detailed measurement locations. (As a general rule, the microphone locations should be retraceable within 3 feet horizontally, and 1 foot vertically.) If measurements were taken at a time different from the worst noise hour, the adjustment and procedure used (see Section 3.3.1.2), any receivers modeled and calibrated, and any inputs should be shown.

Noise level predictions must be based on the methodology in the FHWA Traffic Noise Model. These and other documents pertinent to the noise study should be referenced as appropriate.

6.3.6 Existing Noise Environment

Before traffic noise impacts can be evaluated, detailed knowledge of the existing noise environment is required. A description of the project's surrounding land use (e.g., residential, commercial, undeveloped land, farmland) should be included in this section. The number and types of receptors involved should be reported so that the reader understands the size and characteristics of the area under study. Particularly sensitive land uses should also be pointed out. For undeveloped land, future uses should be included if they are known. For reporting purposes the Protocol requires that at least one receiver be included in an area that is undeveloped. The presence of any other stationary or mobile noise sources (e.g. arterials, airports, railyards) should also be noted.

The general topography surrounding the project and any issues in noise measurements or modeling should be pointed out in this section, especially for complicated or unusual situations. A discussion on background noise levels (i.e., noise levels unaffected by the existing highway) is also appropriate as well as a general description of traffic flow conditions (i.e., traffic level of service). The importance of selecting measurement sites to document background noise levels is discussed in Section 3.1.1.

For each receiver selected for the noise impact analysis, the following should be shown.

- Location or address.
- Type of development.
- Number of units represented by the receiver.
- Land use activity category and NAC.
- Existing noise level results (data logs should be included in the appendices).
- State whether existing noise level was measured or modeled (predicted).
    - If measured, whether measurement was adjusted to worst hour noise (see Section 3.3.1.2).

- ☐ If predicted, whether prediction included model calibration (see Section 4.4) (details of the calibration, such as the calibration constant and explanations of why they were excessively large, should be in the appendices).

Table 6-2 suggests how the information might be displayed in tabular form. The format shown is only an example. The information may be presented in other ways as long as the result is clear, concise, and effective.

This section should only show a summary of the results. It is important to mention whether the existing noise levels reflect the worst noise hour or other time periods. The text should include brief discussions of meteorological conditions during measurements and meteorological criteria. Noise measurement data, traffic counts, speeds, meteorological conditions, site locations, and topography should be included in the appendices.

6.3.7 Future Noise Environment, Impacts, and Considered Abatement

This section of the noise study report addresses the future noise environment. A discussion of the assumptions and data used to model predicted noise levels is appropriate. The source of predicted future traffic volumes (e.g., traffic models, assumed level of service [LOS] C or D, design-hour traffic), vehicle mix, and speeds should be included. The actual input and output data should be presented in the appendices.

The predicted results for future noise levels, traffic noise impacts, and considered abatement, if any, should be presented clearly and concisely. It is usually best to display summary information in tables. Examples of presenting predicted noise levels and impacts are shown in Tables 6-3 and 6-4. The table shows receivers, receiver type, location or address, existing noise levels, predicted noise levels, noise increase or decrease, activity category, NAC, and impact type. A project map showing receivers and approximate locations of noise barrier locations considered should be included.

The table showing predicted noise and impact results provides information for discrete receivers. The information must be expanded to include the entire study area. Table 6-2 shows how many units were represented by each selected receiver. This information can be used to identify areas of traffic noise impacts and the acoustical design of noise barriers (e.g., insertion loss, length, and height). For projects where traffic noise impacts have been identified, heights and lengths of all feasible noise barriers or other abatement measures should be shown, as well as enough information to determine the reasonable noise abatement allowance per benefited residence for each noise barrier and height considered. This allowance is necessary to determine whether abatement measure costs are reasonable. Although noise barriers are normally considered for abatement, other measures may also be considered (see the Protocol) and in some instances might be a better option.

If noise barriers are be considered for the project, the future noise levels and noise insertion losses for various barrier heights or alternate locations should be provided in tabular form. As stated in Section 1102.3 of the Caltrans *Highway Design Manual* a noise barrier should intercept the line of sight from the exhaust stack of a truck to the receptor. The truck stack height is assumed to be 11.5 feet above the pavement. The receptor is assumed to be 5 feet above the ground and located 5 feet from the living unit nearest the roadway. Table 6-4 provides an example of how this information can be reported.

The procedures for determining the preliminary reasonableness of noise abatement (see the Protocol) require various inputs, most of which have been discussed. Table 6-5 is an example of how this information may be displayed. The fact that barrier heights and locations are preliminary and subject to change should be mentioned.

If appropriate, it should be mentioned that noise barriers under consideration can create their own impacts. Barriers may interfere with the passage of air, interrupt scenic views, or create shadows. They can also create maintenance access challenges, make it difficult to maintain landscaping, create drainage or snow removal issues, and provide pockets for trash to accumulate. In certain circumstances, they may raise concerns about safety by blocking areas from the view of patrolling police. Noise barriers can also raise concerns about traffic safety by reducing stopping or merging sight distance or by reducing errant vehicle recovery room.

It is not uncommon for roadway geometries to change between the time the noise study report is completed and final design. Because calculated barrier attenuation values are directly tied to the geometric relationship between the roadway, barrier, and receivers, it is important to document the top and bottom elevations of noise barriers relative to the elevation of the roadway. Then if geometries change in the final design, an assessment can be made as to the significance of the geometric change relative to calculated barrier attenuation. If the geometric change is large enough it may be necessary to re-run the noise model with the new geometries to ensure that predicted attenuation values are maintained or to re-assess cost reasonableness if attenuation values change significantly.

To document the elevations used in the noise analysis a top-of-wall profile should be provided for each noise barrier evaluated. The elevation profile should be provided for the minimum height wall that breaks the truck stack line-of-sight and the wall height that meets the reasonableness design goal (7 dB noise reduction at one or more benefited receiver). It may also be useful to include the elevation of the base of the barrier and outside travel lane. Table 6-6 is an example of how roadway and barrier elevations can be reported.

6.3.8 Construction Noise

Construction noise impacts and likely abatement measures (if necessary) should be discussed briefly. Unless the project involves construction activities that are likely to generate unusually high noise levels such as pile driving or pavement breaking, the discussion should be concise. Detailed discussions of typical construction equipment noise levels are probably not necessary unless the project involves unusually sensitive receptors or nighttime work or if the project is controversial. Caltrans Standard Specification Section 14-8 should be discussed. It states the following.

- Do not exceed 86 dBA L_{max} at 50 feet from the job site activities from 9 p.m. to 6 a.m.
- Equip an internal combustion engine with the manufacturer-recommended muffler. Do not operate an internal combustion engine on the job site without the appropriate muffler.

Procedures for analysis, monitoring, and abatement of construction noise can be found in Section 7.5.

6.3.9 References

Typical references may include 23 CFR 772, *FHWA Highway Traffic Noise: Analysis and Abatement Guidance* (December 2011), the Protocol, *Highway Design Manual* Chapter 1100, FHWA-PD-96-009 and -010, DOT-VNTSC-FHWA-98-1 and -2, and other appropriate documents.

Table 6-2. Existing Noise Levels (Example)

Receiver	Location or Address	Type of Development	Units Represented	Noise Abatement Category and Criterion	Existing Worst Hour Noise Level, (dBA-L_{eq}[h])	Noise Level Measured[a] or Modeled[b]?
1	1234 Elm Street, backyard, center of patio (first-row residence)	Residential	15	B (67)	74	Measured
2	4321 Main Street, 5 feet from façade (first-row residence)	Residential	9	B (67)	75	Measured
3	2336 Elm Street, center of backyard (first-row residence)	Residential	24	B (67)	73	Modeled
4	3538 Elm Street, center of backyard (first-row residence)	Residential	18	B (67)	74	Modeled
5	1212 Church Street, 10 feet north of bottom front step	Church	1	C (67)	68	Measured
6	1723 Oak Street, center of front lawn (0.25 mile from the freeway, background noise level)	Residential	24	B (67)	56	Measured
7	1052 Sycamore Drive, middle of cul-de-sac, (0.25 mile from the freeway, background noise level)	Residential	30	B (67)	55	Measured

[a] Unless otherwise indicated, all measurements shown reflect worst hour noise levels (i.e., they were either measured during the noisiest hour [see Section 3.3.1.1] or were adjusted to worst hour traffic characteristics [see Section 3.3.1.2]).

[b] Unless otherwise indicated, modeled receivers include a calibration constant (see Sections 3.1.2, 4.3.3, and 4.4).

Table 6-3. Predicted Traffic Noise Impacts (Example)

Receiver	Type, Location, or Address	Existing Noise Level (dBA-L_{eq}[h])	Predicted Noise Level (dBA-L_{eq}[h])	Noise Increase (+) or Decrease (–)	Activity Category and NAC, (L_{eq}[h])	Impact Type[a]
1	1234 Elm Street, backyard, center of patio (first-row residence)	74	75	+1	B (67)	A/E
2	4321 Main Street, 5 feet from façade (first-row residence)	75	76	+1	B (67)	A/E
3	2336 Elm Street, center of backyard (first-row residence)	73	74	+1	B (67)	A/E
4	3538 Elm Street, center of backyard (first-row residence)	74	75	+1	B (67)	A/E
5	1212 Church Street, 10 feet north of bottom front step	68	69	+1	C (67)	A/E
6	1723 Oak Street, center of front lawn (0.25 mile from freeway, background noise level)	56	56	0	B (67)	None
7	1052 Sycamore Drive, middle of cul-de-sac (0.25 mile from freeway, background noise level)	55	55	0	B (67)	None

Table 6-4. Noise Abatement Predicted Noise Levels and Insertion Loss (dBA) for Soundwall 1 at Right-of-Way (Example)

		With Wall											
		Height = 6 feet		Height = 8 feet		Height = 10 feet[a]		Height = 12 feet		Height = 14 feet		Height = 16 feet	
Receiver	Without Wall	L_{eq}(h)	Ins. Loss	L_{eq}(h)	Ins. Loss	L_{eq}(h)	Ins. Loss	L_{eq}(h)	Ins. Loss	L_{eq}(h)	Ins. Loss	L_{eq}(h)	Ins. Loss
1	75	70	5	69	6	68[a]	7	66	9	65	10	64	11
2	76	70	6	69	7	68[a]	8	67	9	65	11	64	12
3	74	70	4	69	5	68[a]	6	66	8	65	9	63	11
4	75	70	5	69	6	68[a]	7	66	9	65	10	64	11
5	69	65	4	64	5	63[a]	6	61	8	60	9	59	10
6	56	56	NA[b]	56	NA[b]	56	NA[b]	56	NA[b]	56	NA[b]	56	NA[b]
7	55	55	NA[b]	55	NA[b]	55	NA[b]	55	NA[b]	55	NA[b]	55	NA[b]

[a] Breaks line of sight between 11.5-foot truck stack and 5-foot-high receiver per Section 1102.3 of the *Highway Design Manual*..

[b] NA = not applicable (no barrier considered).

Table 6-5. Data for Reasonableness Determination (Example)

	Predicted without Soundwall[a]	
Soundwall	Absolute Noise Level (L_{eq}[h], dBA)	Build vs. No Build (dBA)
SW-1	75	+1
SW-2	74	+1

[a] At critical receivers.

	Predicted with Soundwall[a]					
Soundwall	Height = 6 feet	Height = 8 feet	Height = 10 feet	Height = 12 feet	Height = 14 feet	Height = 16 feet
SW-1						
Insertion Loss (dBA)	5	6	7	9	10	11
Benefited Residences	24	24	24	48	72	96
Reasonable Allowance Per Benefited Residence	$55,000	$55,000	$55,000	$55,000	$55,000	$55,000
SW-2						
Insertion Loss (dBA)	4	5	6	8	9	11
Benefited Residences	0	24	24	48	48	96
Reasonable Allowance Per Benefited Residence	Not Feasible	$55,000	$55,000	$55,000	$55,000	$55,000

[a] At critical receivers.

Table 6-6. Roadway and Barrier Geometries (Example)

Barrier ID	Station	Elevation of Outside Lane (feet)	Elevation of Wall Base (feet)_	Elevation of Top of 6 ft Wall	Elevation of Top of 8 ft Wall	Elevation of Top of 10 ft Wall[a]	Elevation of Top of 12 ft Wall	Elevation of Top of 14 ft Wall	Elevation of Top of 16 ft Wall
SW-1	100+00	1255	1258	1264	1266	1268	1270	1272	1274
	100+25	1256	1259	1265	1267	1269	1271	1273	1275
	100+50	1258	1261	1267	1269	1271	1273	1275	1277
	100+75	1257	1260	1266	1268	1270	1272	1274	1276
	200+00	1255	1258	1264	1266	1268	1270	1272	1274
	200+25	1254	1257	1263	1265	1267	1269	1271	1273
	200+50	1252	1255	1261	1263	1265	1267	1269	1271
	200+75	1251	1254	1260	1262	1264	1266	1268	1270
SW-2	300+00	1251	1252	1258	1260	1262	1264	1266	1268
	300+25	1253	1254	1260	1262	1264	1266	1268	1270
	300+50	1254	1255	1261	1263	1265	1267	1269	1271
	300+75	1255	1256	1262	1264	1266	1268	1270	1272
	300+00	1256	1257	1263	1265	1267	1269	1271	1273
	300+25	1255	1256	1262	1264	1266	1268	1270	1272
	300+50	1254	1255	1261	1263	1265	1267	1269	1271
	300+75	1253	1254	1260	1262	1264	1266	1268	1270

[a] Breaks line of sight between 11.5-foot truck stack and 5-foot-high receiver per Section 1102.3 of the *Highway Design Manual*.

6.4 Appendices

Any details that would support the conclusions of the noise study report should be included in the appendices, such as instrumentation used, calibration data, field measurement data (e.g., noise, traffic, weather, dates, times, personnel), site details (e.g., plan views, cross sections), computer modeling inputs, and model results. If the analysis includes model calibrations (see Section 4.4), they should be shown in simple table form (see Table 6-7 for an example). The appendices should fill in all details that are not in the main report so the analysis could be repeated by an independent analyst.

Table 6-7. Model Calibration (Example)

Receiver	Measured Noise Level (dBA-L_{eq}[h])	Calculated Noise Level* (dBA-L_{eq}[h])	Calibration Constant (dBA)
1	68	70	-2
2	66	69	-3
3	70	71	-1
4	69	72	-3

*Calculated noise level = noise model result (see Section 4.4.1.1)

If measurements were taken at a time different than the worst noise hour, the adjustment and procedure used (see Section 3.3.1.2), any receivers modeled and calibrated, and any inputs should be shown.

The appendices are a good place to describe issues encountered during the noise study, such as difficulties of site accessibility (include a map of the access route) or contaminating noise sources, such as barking dogs, air conditioners, pool equipment, children’s playgrounds, nearby construction, and aircraft. Such information may be useful if additional study or analysis is required.

Section 7

Non-Routine Considerations and Issues

Sections 2 to 6 address the routine phases of Caltrans highway noise fieldwork and analyses. The subjects in this section are considered non-routine. Because Caltrans is occasionally involved in these special situations, they are included to round out the knowledge base of the Caltrans noise analysts or other interested party. The subjects addressed in this section are listed below.

- 7.1: Noise Barrier Issues
- 7.2: Sound Intensity and Power
- 7.3: Pavement Noise
- 7.4: Insulating Facilities from Highway Noise
- 7.5: Construction Noise Analysis, Monitoring, and Abatement
- 7.6: Earthborne Vibrations
- 7.7: OSHA Noise Standards
- 7.8: Effects of Transportation and Construction Noise on Marine Life and Wildlife (Bioacoustics)

7.1 Noise Barrier Issues

This section discusses some challenging issues and non-routine considerations related to noise barriers. Noise barriers are generally considered beneficial for residents near a freeway. However, there have been claims about perceived noise increases at distances farther than those for which the noise barriers were designed. This issue involves complex relationships between highway and barrier configurations, intervening terrain, receiver location, and atmospheric influences. This section discusses what Caltrans and others have found about this issue and suggests ways to study the effects of noise barriers on distant receivers. Some elements of this discussion involve routine considerations addressed in Section 5.

The effectiveness of vegetation typically used in highway landscaping in reducing noise is also discussed. This issue occasionally surfaces when trimming or removal of shrubs and trees by Caltrans maintenance personnel triggers complaints of perceived noise increases.

7.1.1 Effects of Noise Barriers on Distant Receivers

The public and media in California have on occasion raised concerns that noise barriers increase noise levels at distances of up to 3 miles. The alleged increases were attributed to certain site geometries, noise barrier configurations, intervening terrain, and interacting meteorology. Continuing research by Caltrans and others has provided some answers to these concerns. However, there is a continued need for field research to verify prediction algorithms in prediction models for distances more than 500 feet, alter them if needed, and investigate conditions that lead to any newly identified concerns. This section discusses what Caltrans and others have found.

7.1.1.1 Background

Normally, noise barriers are designed for residences and noise-sensitive receptors located adjacent to a highway, and their effects are generally limited to receivers within about 500 feet of the highway. With few exceptions, there is little disagreement that properly designed noise barriers reduce highway noise within this distance, except for the limited conditions described in Section 5.1.7. Noise prediction models have not been adequately validated for distances beyond 500 feet. Caltrans' *Distance Limits for Traffic Noise Prediction Models* (2002) discusses the reasons for the distance limits. However, if there is a reasonable expectation that noise impacts would extend beyond 500 feet those impacts must be evaluated. This may require engineering judgment and supplemental noise measurements to determine impacts.

With the proliferation of noise barriers in California, public concern has emerged that under certain conditions of topography and meteorology noise barriers can increase noise levels at receivers located from 0.25 to 2 miles from freeways. To date, the concerns have been based on subjective perception only. No objective evidence based on noise measurements has been advanced that noise barriers increase noise levels at any distance or under any conditions other than under the limited conditions described in Section 5.1.7. As indicated, present noise prediction models are not reliable to accommodate distances more than

500 feet. In addition, noise prediction models are unable to predict meteorological effects, which play an increasingly important role in observed noise levels with distance, independent of the nature and strength of their source.

The concerns raised by the public, primarily in the San Francisco Bay Area and Los Angeles area, include all three possible categories of source, barrier, and receiver configurations.

- Reflective noise barriers on the sides of highways opposite from those of the receivers (i.e., highways between barriers and receivers).
- Parallel reflective noise barriers on each side of highways.
- Noise barriers between highways and receivers.

The first two issues involve reflective noise of single and parallel barriers, discussed in Section 5.1.7. The third, however, deals with diffracted noise. All three issues of concern involve long noise propagation distances, which are difficult to study because of the numerous variables in topography and meteorology. Caltrans' experience has been that atmospheric conditions can cause measured noise levels at those distances to fluctuate by more than 10 dBA, with or without noise barriers.

Atmospheric refraction is the principal atmospheric process responsible for these fluctuations. A vertical gradient of either temperature or wind velocity produces a corresponding vertical gradient of sound velocity. This causes sound waves to refract (bend) upward or downward. Upward refraction occurs during sound propagation in an upwind direction or temperature lapse conditions (air temperatures decreasing with height). This tends to send noise skyward, leaving a noise shadow near the ground and thereby reducing noise levels. Downward refraction occurs during sound propagation in a downwind direction or in temperature inversions (temperature increasing with height above the ground). Downward refraction tends to send skyward noise down, concentrating noise near the ground, thereby increasing noise levels. Both upward and downward refraction occurs with and without noise barriers. Atmospheric refraction of sound waves is discussed in Section 2.1.4.3.

7.1.1.2 Results of Completed Studies

Caltrans and its consultants and others have performed elaborate research-level studies concerning noise from highways at adjacent and distant receivers, with and without noise barriers for the three barrier configurations mentioned in Section 7.1.1.1 above. It is not the intent of this section to discuss these studies in detail, only to mention their combined results. The studies were performed along the following routes: Interstate (I-) 405 in Los Angeles, various locations on I-680 and I-80 in the Bay Area, and one along State Route (SR) 99 in Sacramento. These studies followed the general guidelines and criteria outlined in Caltrans' *General Guidelines for Studying the Effects of Noise Barriers on Distant Receivers* (1998). The John A. Volpe National Transportation Systems Center (VNTSC) in Cambridge, Massachusetts, performed two similar studies at Dulles International Airport near Washington, DC, and along I-495 near Baltimore for parallel noise barriers. In addition to the research studies, Caltrans has gathered numerous anecdotal data during routine project studies.

In each research study, before– and after–noise barrier measurements were carefully matched by wind speed, wind direction, temperature, relative humidity, and temperature gradients with height above the ground. All measurements were also normalized for traffic variations. Brief summaries of results of the studies are provided below.

Study Results for Single Barrier on the Opposite Side

The results of studies involving noise level increases for single barriers on the opposite side of a highway in simple terrain, as discussed in Section 5.1.7.2, agreed remarkably with the theoretical calculations shown in the same section, particularly in Figure 5-26. For distances of 50 to 100 feet, the increases were generally 0 to 1 dBA. At 400 feet, the measured results were a 2.4-dBA increase as calculated. For longer distances, the increases were difficult to discern with accuracy but never more than 3 dBA, even in complex terrain as discussed in Section 5.1.7.2.

Study Results for Parallel Barriers

The results of studies involving parallel noise barriers (i.e., one on each side of the highway), as discussed in Section 5.1.7.4, showed degradations in performance of each barrier because of multiple reflections between two reflective barriers. The degradations appeared to increase with distance from and height above the highway/barrier configuration. Degradations also appeared to be a function of the W/H ratio, discussed in Section 5.1.7.4 and depicted in Figure 5-33. The VNTSC study at Dulles International Airport concluded that the maximum degradation at a 6:1 W/H ratio was 6 dBA at distances for which noise barriers are typically designed. At another location near Baltimore, a maximum degradation of 2.8 dBA was measured by VNTSC for a 9:1 W/H ratio. Caltrans measured a maximum degradation of 1.4 dBA for a W/H ratio of 15:1 along SR 99.

Almost all parallel barrier configurations in California have a W/H ratio of at least 10:1, and most are about 15:1. Based on the studies by VNTSC and Caltrans, Caltrans Highway Design Manual Chapter 1100 advises a minimum W/H ratio of 10:1 or more to avoid degradations of 3 dBA or more. Please note that degradation in barrier performance does not indicate an increase in noise level above that without a noise barrier. Instead, it reduces the effectiveness of each barrier on each side of the highway.

Studies along I-680 and I-80 in the Bay Area also showed no measurable noise increase at receivers 0.25 to 2 miles from the highway and barriers.

Study Results for Receiver behind Single Barrier

For receivers behind a single barrier, field studies indicate that barriers are effective within about 330 feet of a highway. Caltrans has collected an abundance of data in research and routine studies over the years to substantiate this claim.

Caltrans has also experienced, in the course of many measurements, that beyond 330 feet or so from a highway, traffic noise levels often approach background levels (the noise levels associated with normal day-to-day activities in the community). Although soundwalls cannot attenuate noise below these levels, Caltrans has never experienced noise increases (above no-barrier noise levels) at any distance behind noise barriers. However, some people continue to believe that noise barriers will increase noise levels at distant receivers behind a barrier.

Explanations have sometimes centered on noise waves “going over the wall and coming back to the ground.” This is called diffraction and is actually responsible for noise attenuation, rather than an increase in noise, when compared to the direct noise received without a noise barrier, as explained in Sections 2, 4, and 5.

Another popular “explanation” for perceived noise increase from soundwalls is that the soundwall “lifts” the noise over tiers of homes that normally would shield the receiver. A soundwall will elevate the noise source over tiers of homes no more than the intervening homes do. Soundwalls in California are generally limited in height to 16 feet, approximately equal to the average height of residential development.

There generally is a loss of “ground effect” behind a noise barrier. Without a noise barrier, the direct path of the traffic noise to the receiver travels closer to the ground than after a noise barrier is built. Noise waves close to the ground are subject to excess attenuation because of absorption by the ground. Therefore, when a noise barrier is built, there is a trade-off between barrier attenuation (a decrease in noise) and a loss of excess attenuation.

The net reduction of noise from barrier attenuation and loss of excess attenuation is called barrier insertion loss (see Section 5.1.5). Close to a barrier, the barrier attenuation benefit far outweighs the loss of excess attenuation. At farther distances, however, barrier attenuation diminishes while the cumulative effects of the loss of excess attenuation increase. Caltrans acoustical design procedures for noise barriers take these factors into consideration by applying different noise dropoff rates to with– and without–noise barrier cases. If these drop-off rates were kept constant and applied to long distances, there would be a distance at which the loss in ground effect would eventually exceed the barrier attenuation.

Extensive amounts of field data gathered during a Caltrans noise propagation research project show that differences between excess attenuation rates of elevated sources (e.g., truck stacks, noise diffracted over a noise barrier) and those close to the ground (e.g., tire noise) diminish after few hundred feet or so. The findings can be applied to noise barriers, which in essence “elevate” the source. The cumulative effect of decreasing differences in elevated and near-ground excess attenuation rates with distance appear to be at a maximum at about 200 to 300 feet behind the barrier, where the effect of the differences is the greatest. At greater distances, the differences in elevated and near-ground noise levels appear to become smaller until they disappear at some distance beyond about 400 feet.

Questions have also been raised at times about whether noise “redirected” by noise barriers “bounces off” temperature inversion layers. Redirections on the scale being discussed involve a maximum of 16-foot-high noise barriers and a distance of 0.25 mile or more, are less than 1 degree, and therefore are negligible. Studies under these conditions have confirmed that the difference between barrier and no barrier was not measurable although the noise levels were considerably higher.

After years of research and field measurements under controlled conditions, Caltrans has found no objective evidence that noise levels increase perceptibly because of noise barriers. It is widely accepted by acousticians that normal human ears can barely perceive 3-dBA changes in traffic noise levels when the frequency content of the noise has not changed. Such an increase in noise levels from noise barriers has never been measured.

7.1.1.3 Studying the Effects of Noise Barriers on Distant Receivers

Allegations of noise barriers increasing noise levels at distant receivers based on perception only are unreliable at best. With possible noise fluctuations of more than 10 dBA from meteorological factors alone, people making such claims must not only remember the noise levels before the barrier, but also have knowledge of the meteorological conditions associated with those noise levels. To confirm whether noise barriers do increase noise levels in some instances, a complex before- and after-barrier field study must be undertaken.

Before– and after–noise barrier noise measurements do not adequately address the previous issues unless the measurements are carefully matched by before- and after-barrier conditions of meteorology, traffic, and topography. These types of studies are not routine. Technical Advisory, Noise, TAN-98-01-R9701 *General Guidelines for the Effects of Noise Barriers on Distant Receivers*, November 30, 1998, provides guidelines and criteria for conducting such studies. The advisory is available on the website of Caltrans Division of Environmental Analysis, Noise and Vibration Studies (http://www.dot.ca.gov/hq/env/noise/index.htm).

Procedures for measuring the performance of noise barriers including parallel barriers are provided in the 2009 version of TeNS.

7.1.2 Shielding Provided by Vegetation

No discussion on noise barriers is complete without mentioning the shielding effectiveness of trees, shrubs, and other vegetation typically used for landscaping along highways. Caltrans research on the shielding effectiveness of such vegetation at three different sites in late 1980s and early 1990s concluded that the mean noise reduction was less than 1 dBA, and ranged from 0 dBA to less than 3 dBA (California Department of Transportation 1995). The research further concluded that such vegetative barriers were not an effective measure to reduce highway traffic noise on a routine basis.

However, Caltrans receives complaints of noise increases when Caltrans maintenance personnel trim shrubs and bushes along highways. The most likely explanation for the increase in noise complaints is more related to visual aspects than noise. When shrubs shield traffic from the view of residences, the awareness of the traffic is reduced (i.e., “out of sight, out of mind”). When the vegetation is trimmed or eliminated, the adjacent residents will be able to see the traffic and will be reminded of the noise.

In some cases, residents complaining about ineffective noise barriers have been satisfied when noise barriers have been combined with trees, shrubs, or ivy. Although noise did not noticeably decrease in those cases, the aesthetics of the barriers were improved. Early community acceptance studies have indicated a correlation between barrier acceptance and perceived effectiveness in reducing noise. Therefore, the use of vegetation with noise barriers can be beneficial by improving community acceptance and perceived effectiveness.

As discussed above wind can cause sound waves to refract (bend) upward or downward. When wind is blowing from a source to a receiver downward refraction can increase the sound energy received at the receiver. When a barrier is located between the source and the receiver downward wind refraction can reduce the affective noise reduction provided by the barrier. Research conducted by University Ghent in Belgium (Renterghem and Botteldooren 2008) studied how a tree canopy between the barrier and the receiver affects the degredation of barrier performance from downwind refraction. The study concluded that the presences of a row of trees between a barrier and receiver can provide an important improvement in downwind noise barrier performance up to a distance of 30 times the noise barrier height. Coniferous trees were found to the most effective in this regard. Other references indicate that 100 horizontal feet of tall grass and thick shrubbery can provide up to 5 dB of additional attenuation and 100 feet of dense woods can provide up to 2 dB of additional attenuation (Hoover & Keith 2000).

7.2 Sound Intensity and Power

This document has consistently described the amplitude of sound at a specific location in terms of sound pressure level or noise level. This is also the case for all noise standards, criteria, and descriptors mentioned in this document. In fact, SPL is used in virtually all environmental noise studies for two primary reasons: 1) it is easiest to measure, and 2) it best describes the impact at the receiver.

However, it is important for the noise analyst to know that there are other ways to express sound amplitude. Although considerably more difficult to measure, sound intensity and sound power often provide more useful information about noise sources than sound pressure level. Caltrans has begun using sound intensity in pavement noise studies, and future plans call for other uses to locate and map specific locations of vehicle noise subsources. This section briefly discusses sound power and intensity to broaden the knowledge of noise analysts who may in the future be involved with sound intensity or sound power studies.

7.2.1 Sound Power

Sound pressure level describes a local condition. When the noise from a certain source is measured, such as a truck, in terms of sound pressure level, the information is incomplete without knowing the distance, nature, and radiation pattern of the source, intervening terrain, obstacles, reflections, and atmospheric conditions. A change in one or more of these factors will probably change the sound pressure level.

Sound power is a property of the noise source and is independent of the factors influencing sound pressure. Knowing the sound power of a noise source, the sound pressure level can be calculated under a variety of conditions and at different locations. The sound power of a source is a constant. Power is a rate of energy, or the amount of energy produced each second. Energy is force times distance, most commonly expressed as newton meters (Nm), with newton (N) being the unit of force. A force of 1 N is the force required to accelerate 1 kilogram 1 meter per second per second. If sound power is the rate of energy flow, the units are Nm/s, or watts (W).

Sound power may be visualized as the wattage of a light bulb and sound pressure level as the amount of light received by a reader in a room. The latter would depend on many factors, such as the power of the light bulb, distance from the light bulb, shadows from obstacles between the light bulb and reader, and reflections from walls.

From Section 2.1.3.2, sound pressure level is expressed in decibels, and 1 dB is defined as follows:

$$10\log_{10}(P_1 / P_0)^2 \qquad \textbf{(7-1)}$$

Where:

P_1 = the sound pressure

P_0 = a reference pressure of 20 μPa

Pascal is the unit of pressure (force per unit area); 1 Pa = 1 N/m^2. Sound power may similarly be expressed in decibels. The definition of a sound power level (L_W) is:

$$L_W = 10\log_{10}(W_1 / W_0) \qquad \textbf{(7-2)}$$

Where:
$W_0 = 10^{-12}$ W
W_1 = total acoustic power
L_W = sound power level in decibels

Sound pressure level should actually be referred to as $L_{P,}$ although in environmental noise just L (e.g., L_{eq}) has normally been used. Using decibels in both sound power and sound pressure levels can be confusing. To avoid confusion, the international standard ISO 9296 requires documentation of sound power ratings in units of bels (B) rather than decibels. However, in the United States, decibels are often also used for sound power levels. In any case, the descriptors should be clearly noted whether they are sound power level or sound pressure level units. If a quantity is expressed in bels, 1 B = 10 dB.

Sound power cannot be measured directly. However, it can be calculated from sound intensity, which can be measured. One practical use of sound power level is rating product noise from hair dryers to refrigerators.

7.2.2 Sound Intensity

Sound intensity is a measure of a directional rate of energy flowing through a unit of area. The units of sound intensity are watts per square meter (W/m^2) and can be expressed in decibels RE: 1 picowatt (pW) per m^2 (1 pW = 10^{-12} W). This implies that if the entire measurement area around a source is known, its sound power can be calculated if the mean sound intensity for the measurement area is known. The measurement area (usually hemispherical) around a source increases with distance, and because sound intensity decreases with increasing area, sound power remains constant at any distance. To reduce the influence of background noise, sound intensity measurements are taken close to the source. Caltrans commonly uses on-board sound intensity (OBSI) measurements to characterize sound generated by various types of pavement. OBSI measurements are discussed in more detail in Section 7.3 below.

The sound intensity level (L_I) is calculated as follows:

$$L_I = 10\log_{10}(I_1 / I_0) \qquad \textbf{(7-3)}$$

Where:

L_I = sound intensity level in decibels

I_1 = sound intensity of interest in W/m^2

I_0 = reference intensity of 10^{-12} W/m^2

The sound intensity of interest (I_1) in W/m^2 can be calculated as follows:

$$I_1 = I_0 * 10^{(L_I/10)} \qquad \textbf{(7-4)}$$

Sound intensity (I) is the product of sound pressure (P) and particle velocity (v):

$$I = P * v \qquad \textbf{(7-5)}$$

Sound pressure is measured in pascals (N/m^2). Particle velocity is measured in meters per second (m/s). Therefore, the product of sound pressure and particle velocity yields W/m^2 (N/m^2 * m/s). In Section 2.1.3.1, it is explained briefly that particle velocity is the (back and forth) movement of air molecules. In Figure 2-2, it was shown that the motion is 90° out of phase with the fluctuating sound pressure. When the sound pressure is 0, the particle velocity is at its maximum either in a positive (away from the source) or negative (toward the source) direction.

A sound field includes both sound pressure and particle velocity and is therefore described by sound intensity, which includes amplitude and direction. Where sound pressure fluctuations are easy to measure with a sound level meter, the measurement of particle velocity requires more sophisticated instrumentation.

Sound intensity is most commonly measured with a pair of phase-matched microphones facing each other at a fixed distance apart (Figure 7-1). This two-microphone sound intensity probe measures only the total sound intensity traveling parallel to the microphones' axis and is therefore highly directional. If the probe is pointed at the source (Microphone 1 toward the source and Microphone 2 away from the source) the sound intensity is positive. If the probe is pointed away from the source, the sound intensity will be negative. Because of this directional characteristic, sound intensity is useful in measuring and mapping sound fields around sound sources. The reference point of a sound intensity probe is halfway between the diaphragms of the two microphones facing each other, and the reference direction is along the axis of the microphones.

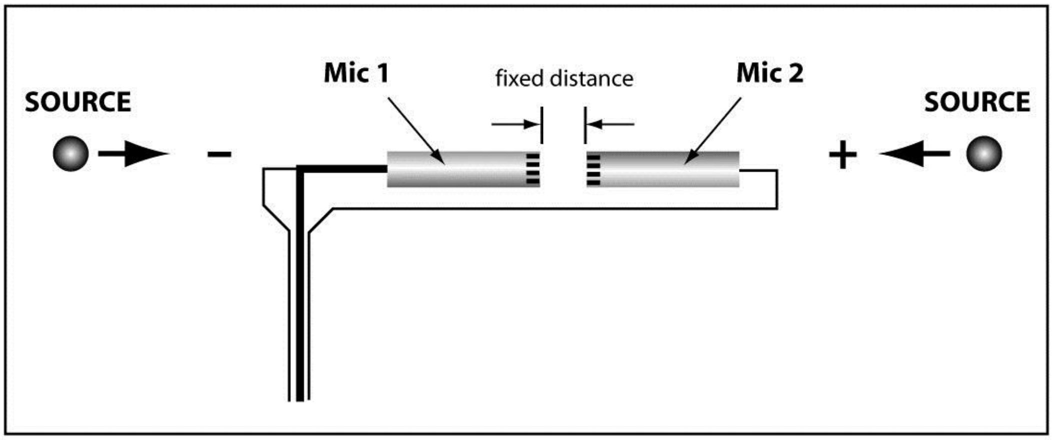

Figure 7-1. Schematic of a Sound Intensity Probe

Other sound intensity probes include a two-microphone, side-by-side system. This type of probe is aimed at 90° to the source and relies on "grazing" type microphones, which are sensitive to sound pressures directed parallel to the membranes, instead of perpendicular (Figure 7-2).

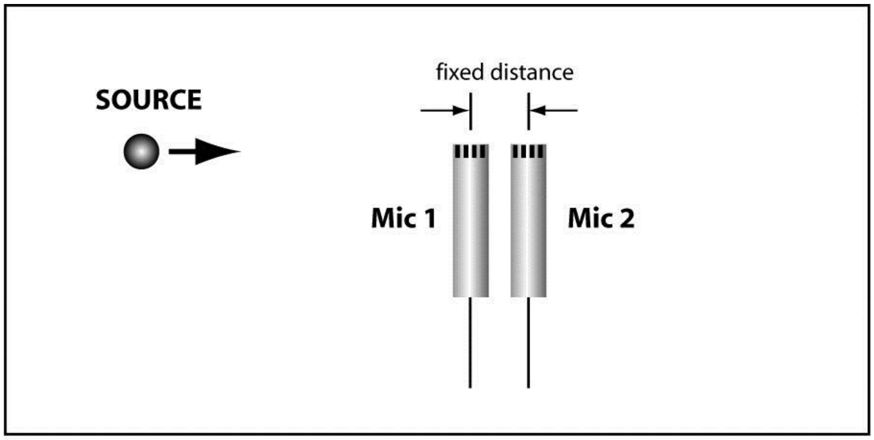

Figure 7-2. Side-by-Side Microphone Probe

To determine the total sound power of a source in watts, the sound intensity (I_k) must be first measured perpendicular to the unit area (A_k) (Figure 7-3). The power for that unit area (W_k) is then the product of I_k and A_k. Therefore, the total power (W_{total}) is calculated as follows:

$$W_{total} = \sum_1^K (A_k \text{ x } I_k) \qquad \textbf{(7-6)}$$

The result in units of decibel can be calculated from Equation 7-2, or shown in B by dividing the decibel result by 10.

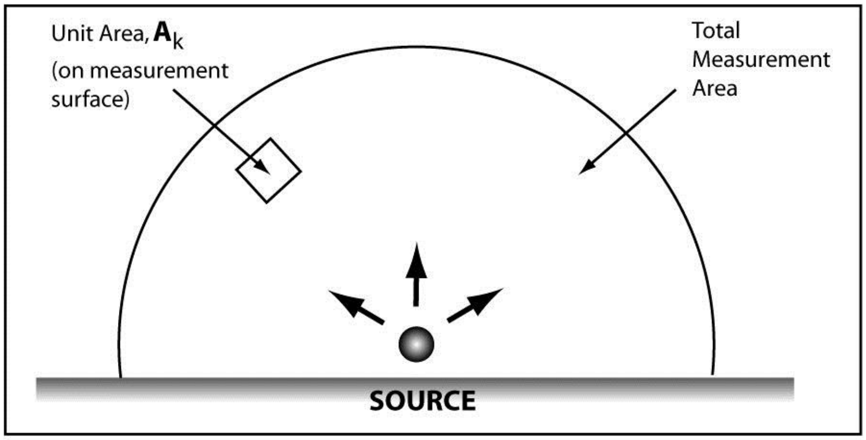

Figure 7-3. Sound Power Measurement Area

7.3 Tire/Pavement Noise

In Section 2, noise is discussed in terms of source, path, and receiver. All three components must be present before noise impacts can occur. Strategies involving quieting the source, disrupting the path, or insulating the receiver may conceptually be used to achieve noise abatement. Using a common analogy of a loud stereo set in a room, there are three options open to lowering the sound to a listener in an adjacent room. The first is lowering the volume at the stereo, quieting the source. The second option is to close the door between the two rooms, disrupting the path. As a third option, the listener can wear earplugs, insulating the receiver.

Although quieting the source would conceptually be the simplest and most effective method of noise abatement, Caltrans has so far dealt with noise abatement by disrupting the path by constructing noise barriers between the highway source and resident receivers. This approach is used because Caltrans has limited options at quieting the highway noise source. For instance, Caltrans has no control over quieting vehicles. This has been the responsibility of the U.S. Environmental Protection Agency, which over the years, through regulatory and legislative action, has mandated stricter new vehicle noise standards, especially for trucks. The only control Caltrans has at the source is highway design. Highway alignments could be selected away from sensitive receivers, and new highways could be depressed. Unfortunately, many factors other than noise dictate highway design. In addition, new development often occurs along existing highways, further limiting noise abatement options.

One detail of highway design that affects noise at the source is the type and texture of pavement used. There are two major types of pavement:

flexible asphalt concrete (AC) which is black in color and rigid PCC which is white in color. Historically, new AC generally tends to be quieter than new PCC, but aggregate size, surface texture, and age/condition can cause wide variations in tire pavement noise levels. The differences in noise reducing characteristics between AC and PCC are narrowing as new construction techniques are being developed. It has been well known for at least a decade that OGAC produces less noise from tire/pavement interaction than DGAC. It is also known that longitudinal (parallel to direction of travel) texturing, tining, or grooving in PCC is much less noisy than transverse (perpendicular to direction of travel) texturing, tining, or grooving. What is least understood is the longevity of the lower noise benefits associated with “quieter” pavement. There are many regional variables that affect pavement performance, such as road base condition, environment, traffic loads, mix design, and quality of construction material and methods. In general as pavements age and wear, the acoustic characteristics change and tire/pavement noise becomes louder.

Caltrans has gathered increasing evidence that OGAC retains its noise reduction benefits throughout the years in typical applications at lower elevations on snow-free highways. The longest-running quiet pavement noise study to date, being conducted on I-80 near Davis, California, demonstrates that after over 13years of operation, OGAC continues to yield 4- to 5-dBA lower noise levels than the previous DGAC pavement. Other studies have shown the same trend. The pavement noise results are based on actual traffic streams, wayside noise measurements carefully controlled for the effects of meteorology, and supplemental OBSI measurements.

Studies using innovative approaches such as sound-intensity measurements of tire/pavement interactions have been employed to study the relative noise benefits of various pavement mixes and textures. In all cases, the sound-intensity measurements are augmented and correlated with wayside noise measurements. This is important because vehicle noise consists of four primary subsources: mechanical noise, exhaust noise (stack exhaust on heavy trucks), tire/pavement noise, and aerodynamic noise (at high speeds). The stricter EPA standards initiated in the 1970s have lowered mechanical and exhaust noise subsources. At highway speeds, tire/pavement noise affects total vehicle noise to a greater extent than all the other vehicle noise subsources combined. Tire/pavement noise on a passenger car operating at a steady freeway speed may account for as much as 75% to 90% of the vehicle noise energy, but these percentages may not be the same on louder, more acoustically complex heavy trucks. It is possible to perceptively lower overall traffic noise levels by careful pavement selection and design. Future Caltrans-sponsored research will include the relative contribution of subsources of vehicles to help confirm the validity of the importance of tire/pavement noise through the use of complex microphone arrays and multi-channel signal processors.

FHWA policy does not allow quieter pavement to be considered as a noise abatement measure. Caltrans practice of calibrating noise prediction models allows for optional calibration adjustments for various pavement types (California Department of Transportation 2003). This practice does not mean that quieter pavement is to be used as a noise abatement measure. Rather, the process is used to account for an otherwise unexplained portion of differences between measured and predicted noise results. Without the adjustment for pavement, this difference would have been added anyway, without explaining the cause.

The following studies and reports provide useful and relevant information related to tire/pavement noise.

> *Determining End Limits of Quieter Pavement Projects* (Rymer and Donavan 2011).
>
> *Standard Method of Test for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method* (American Association of State Highway and Transportation Officials 2012)
>
> *I-80 Davis OGAC Pavement Noise Study* (Illingworth & Rodkin 2011a)
>
> *Eight Year Evaluation of the Noise Performance of the Caltrans Asphalt Research Pavements on LA 138* (Illingworth & Rodkin 2011b)
>
> *Initial and Long-Term Evaluation of the Tire-Pavement Noise Produced by Various Portland Cement Concrete Surface Textures Measurements on the State Route KN 58 Mojave Bypass 2003 to 2010* (Illingworth & Rodkin 2011c)
>
> *Comparative Measurements of Tire/Pavement Noise in Europe and the United States Noise Intensity Testing in Europe (NITE) Study* (Illingworth & Rodkin 2006)
>
> *Caltrans Thin Lift Study: Effects of Asphalt Pavements on Wayside Noise* (Rochat et al. 2010)
>
> Caltrans Memorandum—Quieter Pavement Bulletin (Shatnawi 2009)

NCHRP Report 635 Acoustic Beamforming: Mapping Sources of Truck Noise (National Cooperative Highway Research Program 2009)

NCHRP Project 1-44: Measuring Tire-Pavement Noise at the Source (National Cooperative Highway Research Program 2011a)

NCHRP Project 1-44 (1) Measuring Tire-Pavement Noise at the Source: Precision and Bias Statement (National Cooperative Highway Research Program 2011b)

The Little Book of Quieter Pavement (Federal Highway Administration 2007)

Rumble strips and expansion joints can be the source of impulse noise when vehicle tires strike the strips or joints. Locations of rumble strips or expansion joints relative to noise sensitive receptors should be considered to minimize community noise impacts. Alternative rumble strip and expansion joint designs that reduce noise are currently being explored by Caltrans.

7.4 Insulating Facilities from Highway Noise

Revisions to 23 CFR 772 that occurred in 2011 eliminated the interior noise abatement criterion for residential uses and eliminated noise insulation of private residences as a fundable form of noise abatement. 23 CFR 772 does however include an interior noise abatement criterion for Activity Category D land use facilities (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.) Noise insulation of Activity Category D land use facilities is listed in 23 CFR 772 as a fundable form of noise abatement.

If a situation arises where interior noise at Activity Category D land use facilities must be evaluated as part of a noise study report, the normal procedure is to determine exterior noise levels using standard modeling methods and then to apply building noise reduction factors recommended by FHWA based on the building construction type and window condition. Table 7-1 summarizes building noise reduction factors recommended by FHWA (Federal Highway Administration 2011).

Table 7-1. FHWA Building Noise Reduction Factors

Building Type	Window Condition	Noise Reduction Due to Exterior of Building
All	Open	10 dB
Light Frame	Ordinary Sash (closed)	20 dB
	Storm Windows	25 dB
Masonry	Single Glazed	25 dB
	Double Glazed	30 dB
The windows shall be considered open unless there is firm knowledge that the windows are in fact kept closed almost every day of the year.		

Source: Federal Highway Administration 2011.

If interior noise impacts are identified the first course of action is to consider the use of an exterior barrier to reduce noise. If an exterior barrier is not feasible or does not provide sufficient noise reduction, insulation of the facility can be considered. This would require a detailed evaluation of existing building noise reduction and potential methods for improving the noise reduction. The 2009 version of TeNS provides detailed methods for measuring existing building noise reduction which are consistent with ASTM E966-02, “Standard Guide for Field Measurements of Airborne Sound Insulation of Building Facades and Façade Elements.”

7.5 Construction Noise Analysis, Monitoring, and Abatement

Construction noise is usually a concern only in exceptional cases, such as when pile driving and crack-and-seat pavement rehabilitation operations are planned. Ground vibration generated by pile driving and crack-and-seat operation also increase concern by the public. Caltrans Standard Specifications Sections 14-8 and the Caltrans Standard Special Provisions Section 5-1 discuss construction noise levels. Caltrans Standard Specifications are applied to all construction projects. The Standard

Special Provisions provide a menu of special provisions that can be selectively applied to a project based on the specific needs of the project.

Section 14-8 of the Caltrans standard specifications addresses noise and states:

> Do not exceed 86 dBA L_{max} at 50 feet from the job site activities from 9 p.m. to 6 a.m.
>
> Equip an internal combustion engine with the manufacturer-recommended muffler. Do not operate an internal combustion engine on the job site without the appropriate muffler.

Section 5-1, *Noise Control*, of the Standard Special Provisions states the following.

General

This section applies to equipment on the project or associated with the project, including trucks, transit mixers, stationary equipment, and transient equipment. Do not exceed 86 dBA L_{max} at 50 feet from the job site activities from _____ p.m. to _____ a.m. except you may perform the following activities during the hours and for the days shown in the following table:

Noise Restriction Exceptions

Activity	Hours		Days	
	From	To	From	Through

Do not operate construction equipment or run the equipment engines from 7:00 p.m. to 7:00 a.m. or on Sundays except you may operate equipment within the project limits during these hours to:

1. Service traffic control facilities.
2. Service construction equipment.

Noise Monitoring

Provide one Type 1 sound level meter and one acoustic calibrator to be used by the Department until contract acceptance. Provide training by a person trained in noise monitoring to one Department employee designated by the Engineer. The sound level meter must be calibrated and certified by the manufacturer or other independent acoustical laboratory before delivery to the Department. Provide annual recalibration by the manufacturer or other independent acoustical laboratory. The sound level meter must be capable of taking measurements using the A-weighting network and the slow response settings. The measurement microphone must be fitted with a windscreen. The Department returns the equipment to you at contract acceptance. Use if a sound meter is required. The contract lump sum price paid for noise monitoring includes full compensation for furnishing all labor, materials, tools, equipment and incidentals and for doing all work involved in noise monitoring.

As a state agency, Caltrans is not required to comply with local noise ordinances. However, as a matter of practice, it is Caltrans' intent to comply with 23 CFR 771.105 which states that it is FHWA policy that:

> [t]o the fullest extent possible all environmental investigations, reviews, and consultation be coordinated as a single process, and compliance with all applicable environmental requirements shall be reflected in the environmental documentation.

If construction noise on any highway project is anticipated to be a substantial concern, further analysis is recommended. The following items are to be examined.

- Land uses or activities that may be affected by construction noise.
- Level, timing (scheduling), and duration of construction.
- Measures to reduce adverse construction noise impacts on the community that could be included in the project's plans and specifications.

Caltrans does not routinely analyze construction noise during the project development phase. However, as is discussed in Section 6.3.2, construction noise impacts and likely abatement measures (if necessary) should be discussed briefly in the noise study report for all projects. Generally, Caltrans will only consider construction noise and its abatement in greater detail during the project impact analysis if the project is large, is controversial, or has a prolonged construction phase with extensive pile driving or other loud operations. Construction noise impacts on wildlife may also need to be considered in some special situations. An example would be where pile driving will occur near nesting birds that are on the endangered species list. The effects of noise on wildlife are discussed in more detail in Section 7.8.

Caltrans construction or environmental personnel are sometimes asked to monitor construction noise levels during the construction phase to ensure the contractor's compliance with the Caltrans Standard Specifications, project-specific Special Provisions, or other construction noise limits that may be imposed on the project. The monitoring is usually performed in response to complaints from adjacent residents, but there may also be situations where the contractor must demonstrate compliance with a specific limit on noise.

In January 2006, the FHWA published the FHWA Roadway Construction Noise Model Users guide, which provides guidance on how to use the

FHWA Windows-based construction noise model. It provides useful information on construction noise analysis, equipment noise source levels, and impact criteria.

In addition to noise, construction activities can potentially generate earthborne vibrations that may disturb, damage, or interfere with activities at vibration-sensitive receivers. Section 7.6 briefly discusses earthborne vibrations.

7.5.1 Consideration of Construction Noise during Project Development Phase

If the project is large, is controversial, or has a prolonged construction phase with extensive pile driving or other loud operations, construction noise should be analyzed during the project development phase, along with routine noise analyses, and the analysis should be included in the environmental documentation. Details of construction operations are frequently lacking or minimal in this phase. Therefore, the analysis will usually be qualitative rather than quantitative, and addressed in the environmental document only in general terms, with references to the Standard Specification, Standard Special Provisions, and other appropriate directives. A qualitative discussion may include information on the following topics.

- Residences or land use activities to be impacted most by construction noise.
- Principal types of equipment to be used.
- Noise characteristics (impact noise, continuous noise, etc.) and range of noise levels of equipment used at reference distances.
- Duration of construction and the loudest operations.
- Appropriate specifications, special provisions, and regulations by which the contractor must abide.
- Noise monitoring for compliance during construction.
- Abatement strategies that can potentially be provided, such as one or more of the following.
    - ☐ Temporary walls, earth berms, or noise curtains.
    - ☐ Alternative, less noisy construction methods.
    - ☐ Restricted hours of operation.
    - ☐ Planning and routing haul roads away from residences.

- ❑ Building soundwalls required for traffic noise abatement for the project first.

If some details about the types and numbers of construction equipment, types of operations, duration, and scheduling are available during the project development phase, a quantitative analysis may be performed. A quantitative analysis may include all of the factors for the qualitative analysis and the following.

- ■ Calculating expected noise levels at the affected receivers or at a standard distance (usually 50 feet) as dictated by criteria.
- ■ Comparisons of calculated noise levels to specifications, special provisions, and other pertinent criteria.

Caltrans construction noise criteria are typically expressed using the L_{max} descriptor at a reference distance. As stated above, an L_{max} of 86 dBA at 50 feet is commonly used by Caltrans as a maximum construction noise limit. Equipment and operations are usually at or less than that level, except for blasting, pile drivers (impact or vibratory), hoe rams, pavement breakers for crack-and-seat operations, and other impact equipment. Table 7-2 summarizes typical construction noise levels identified in the FHWA Roadway Construction Noise Model User's Guide (Federal Highway Administration 2006). These noise levels come directly from data developed during the construction of the Central Artery Tunnel Project in Boston completed December 2007.

Table 7-2. Typical Construction Equipment Noise

Equipment Description	L_{max} Noise Limit at 50 feet, dB, Slow	Usage Factor	Impact Device?
All other equipment more than 5 horsepower	85	50	No
Auger drill rig	85	20	No
Backhoe	80	40	No
Bar bender	80	20	No
Blasting	94	N/A	Yes
Boring jack power unit	80	50	No
Chain saw	85	20	No
Clam shovel	93	20	Yes
Compactor (ground)	80	20	No
Compressor (air)	80	40	No
Concrete batch plant	83	15	No
Concrete mixer truck	85	40	No
Concrete pump truck	82	20	No
Concrete saw	90	20	No

Equipment Description	L_{max} Noise Limit at 50 feet, dB, Slow	Usage Factor	Impact Device?
Crane (mobile or stationary)	85	16	No
Dozer	85	40	No
Dump truck	84	40	No
Excavator	85	40	No
Flat bed truck	84	40	No
Front end loader	80	40	No
Generator (25 kilovolt-amperes [kVA] or less)	70	50	No
Generator (more than 25 kVA)	82	50	No
Gradall	85	40	No
Grader	85	40	No
Horizontal boring hydraulic jack	80	25	No
Hydra break ram	90	10	Yes
Impact pile driver (diesel or drop)	95	20	Yes
Jackhammer	85	20	Yes
Mounted impact hammer (hoe ram)	90	20	Yes
Paver	85	50	No
Pickup truck	55	40	No
Pneumatic tools	85	50	No
Pumps	77	50	No
Rock drill	85	20	No
Scraper	85	40	No
Slurry plant	78	100	No
Slurry trenching machine	82	50	No
Soil mix drill rig	80	50	No
Tractor	84	40	No
Vacuum street sweeper	80	10	No
Vibratory concrete mixer	80	20	No
Vibratory pile driver	95	20	No
Welder/Torch	73	40	No

Source: Federal Highway Administration 2006.

Table 7-2 also provides a typical usage factor for each equipment type. The usage factor is an estimate of the fraction of time each piece of equipment operates at full power. The usage factor can be used to estimate L_{eq} from the L_{max} values listed in Table 7-2 in those cases where the impact criteria is expressed in terms of L_{eq}. Equation 7-10 can used to estimate L_{eq} from L_{max}. It also includes a term for estimating noise at distances other than 50 feet.

$$L_{eq}(h), \text{dBA} = L_{max} \text{ at 50 feet} - 20\log(D / 50) + 10\log(UF) \qquad \textbf{(7-7)}$$

Where:

L_{max} at 50 feet can be looked up in Table 7-2 or similar table

D = distance of interest

UF = usage factor or fraction of time period of interest equipment is in use

If more than one piece of equipment is in operation in the same location, Equation 7-7 can be used for each piece of equipment and the results can be summed to give a combined noise level at the location of interest. Typically, only noise levels from the two or three loudest pieces of equipment are summed. The FHWA Roadway Construction Noise Model automates most of this process.

7.5.2 Noise Monitoring during Construction

Construction noise monitoring may be part of a program called for in the environmental document, in regulatory permits, or in response to noise complaints. Noise monitoring requirements may be in response to effects on both humans and wildlife. Refer to Section 7.8 for more discussion on the effects of construction noise on wildlife. In most cases, the noise measurements are used to ensure compliance with the appropriate criteria specified in construction contract specifications or other applicable regulations. In the case of complaints, measurements may be conducted to identify the source of the complaints and to develop solutions for reducing the noise. As discussed above, Caltrans is not required to comply with local noise ordinances. However, as a matter of practice, it is Caltrans intent to comply with all applicable environmental requirements per 23 CFR 771.105.

If construction noise monitoring is necessary, the districts' environmental units or trained construction personnel will usually perform the measurements. In some cases, the contractor or subcontractor may perform noise monitoring as part of the construction contract.

The manner in which construction noise measurements are taken depends on the applicable criteria. If the criterion calls for a certain L_{max} at a reference distance, the sound level meter must be placed at the requested distance from stationary equipment and the noise measured in the L_{max} mode during full operation of the equipment. Ideally, the noise level should be measured from four different directions, approximately 90° from each other (Figure 7-4). This may not be possible, however, and perhaps only two or three directions can be measured. A sufficient time period in each of the microphone positions should be allowed to permit the

L_{max} to occur. Sound level meters usually have an L_{max}-hold button. In this mode, the recorded L_{max} only changes when a higher noise level than the previous maximum is recorded. If the noise is relatively constant and the L_{max}-hold does not change for 30 seconds, the measurement is completed. If the noise is not constant, such as with pile driving, a longer time period of at least 2 minutes is recommended.

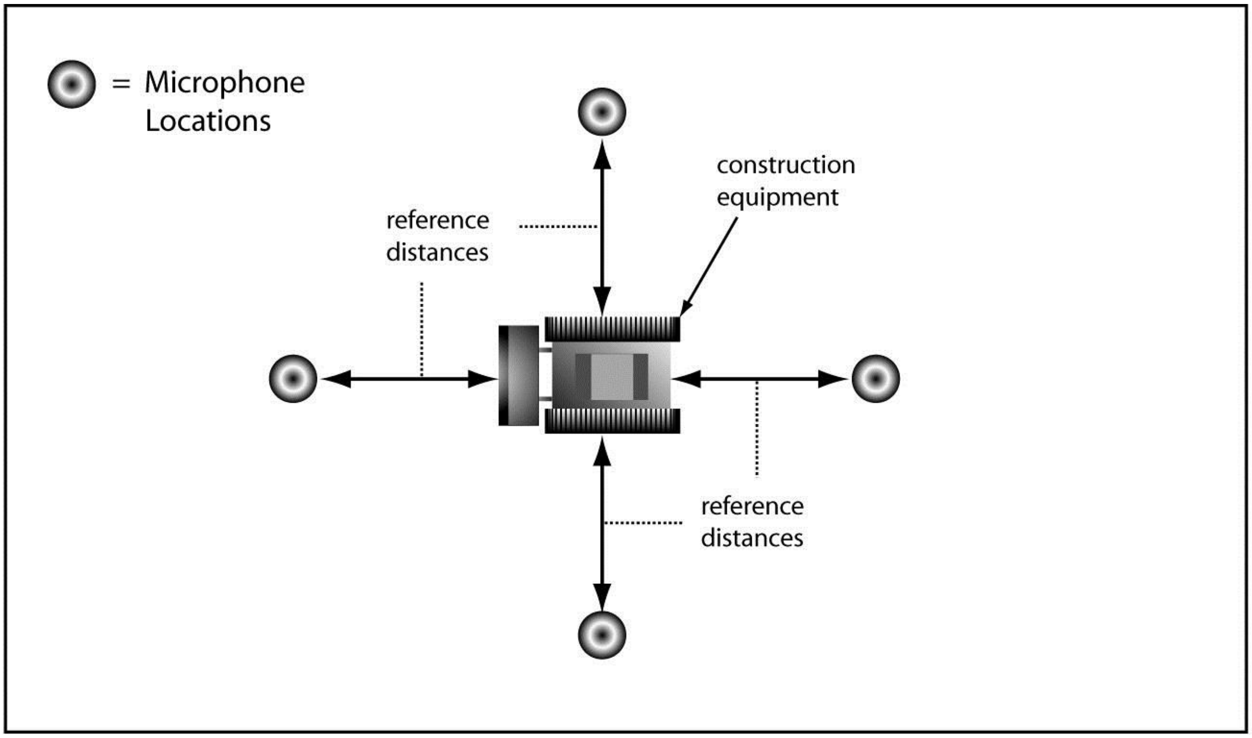

Figure 7-4. Measuring One Piece of Equipment

If more than one piece of stationary construction equipment is involved in the same operation, the reference distance should be measured from the nearest piece of equipment, preferably from various directions (Figure 7-5).

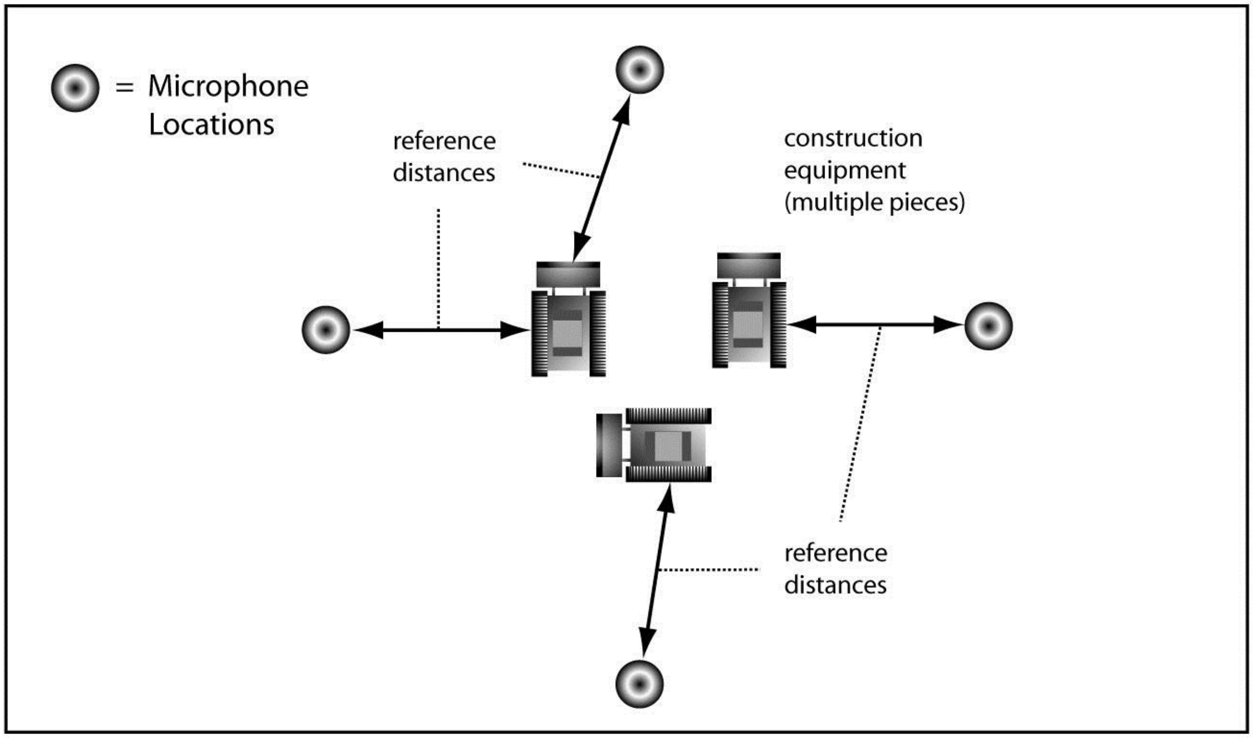

Figure 7-5. Measuring Multiple Pieces of Equipment Operating in Same Area

For mobile equipment, the reference distance is the closest distance at the point of passby. The equipment should be measured from two directions—equipment moving from left to right and from right to left.

If the response time setting of the meter is not specified in the criteria, the slow setting should be used for equipment producing continuous noise. For impact noise, such as pile driving, the response setting should be switched to impulse. In all cases, a minimum of three measurements should be taken at each microphone position. The highest L_{max} should be used for comparison with applicable standards or criteria.

In the less frequent cases where a construction noise criterion may call for a certain noise level at the project right-of-way line or a residence, the microphone locations must coincide with the locations called for in the criterion. In the event a criterion calls for a descriptor different from L_{max}, such as L_{eq}, the proper descriptor must be measured by the sound level meter. All previously mentioned provisions are applicable. Section 3 should be consulted for general noise measurement provisions.

Additional information on construction noise measurements can be found in “Measurement of Highway-Related Noise,” Report FHWA-PD-96-046, May 1996, available through the National Technical Information Service in Springfield, Virginia, and in the FHWA Construction Noise Handbook which is available:

http://www.fhwa.dot.gov/environment/noise/construction_noise/handbook

7.5.3 Construction Noise Abatement

In the event that construction noise exceeds or is expected to exceed applicable standards and criteria, the following options are open to abate the noise at the source, in the path, and at the receiver.

7.5.3.1 Abatement at Source

Noise control at the source is the most sensible approach because it does not limit abatement for a single source-receiver pair, but instead lowers construction noise at all receivers. Caltrans Standard Specifications require all construction equipment to have adequate mufflers and be well maintained. If these specifications are not enough to reduce noise levels to less than the standards and criteria, other options can be used, including one or more of the following.

- Reroute haul routes away from residences.
- Require modern equipment.
- Plan noisiest operations for times of day when people are less sensitive to noise.
- Plan operations to minimize the use of backup warning devices.
- Set backup warning devices to lowest level without jeopardizing safety.
- Operate equipment at minimum power.
- Use quieter alternate methods or equipment.

7.5.3.2 Abatement in Path

There are several options open to abate construction noise in the source-to-receiver noise path. These usually include temporary enclosures around stationary equipment, temporary barriers, and noise curtains. If permanent noise barriers are part of the project, their construction should be scheduled first. Other strategies include effective use of temporary earth mounds as barriers, creating buffer zones between equipment and residences, or making use of existing structures as barriers.

7.5.3.3 Abatement at Receiver

Abatement at the residence is usually done as a last resort. Strategies include window treatment or other insulation techniques. This is usually only cost-effective if relatively few residences are involved. Another strategy is temporary relocation of residents.

7.5.3.4 Community Awareness

Community awareness may be the most effective approach to reduce complaints of construction noise. Residents' tolerance toward construction noise is greatly increased if they are informed that the noise is temporary, that they have a telephone number to call for more information and to report specific noise concern, and that every effort will be made to address those concerns. Door-to-door personal contacts are the most effective, but this may be time-consuming. Other ways to relate the information are hotlines, project websites, automated phone calls, frequent community meetings, letters to the impacted residences, and local news coverage.

If construction noise is anticipated to be a major issue, the community should have an opportunity to provide considerable input early in the project development stage. It is essential that communication channels between the Caltrans resident engineer and the community stay open during the construction phase as well. A real time monitoring and reporting system with posting of measured noise levels on a website can be an effective way to keep the public informed on the project noise conditions associated with large, long-term projects. Responsibilities for addressing noise complaints should be included in the construction contract documents.

7.6 Earthborne Vibration

Caltrans has been involved with vibration studies since 1958. Until 1992, the Caltrans Transportation Laboratory in Sacramento conducted all vibration studies. Since then, most vibration studies have been contracted out. However, the Caltrans Division of Environmental Analysis does perform some vibration monitoring to investigate complaints.

Earthborne vibrations generated by construction activities or by traffic once a transportation facility is in operation can under certain circumstances be a serious concern. This section emphasizes the awareness and early recognition of potential vibration issues. When vibration-sensitive receptors or activities are located near a proposed new alignment or near an existing facility scheduled for heavy reconstruction, potential vibration impacts should be addressed during the project development phase with assistance of the Caltrans Division of Environmental Analysis. Caltrans' *Transportation- and Construction-Induced Vibration Guidance Manual* (2004) provides a wealth of information on vibration, including summaries of Caltrans experiences, and should be consulted.

During construction, pile driving, pavement breaking for crack-and-seat operations, demolition of old structures, and blasting are among the worst vibration offenders. Concerns may include annoyance, interference with activities, and structural damage. Therefore, construction activities involving generation of high-level vibrations must be carefully planned.

Although construction activities potentially generate the highest vibration levels and most damage, they are temporary in nature. Long-term effects of vibration may be caused by the transportation facility after it is completed. Normally, highway traffic does not generate high enough levels to cause damage to residences or other structures, even at very close distances. However, vibrations caused by heavy trucks can interfere with vibration-sensitive activities or equipment. Laboratories using sensitive electronic equipment, laser surgery, or close-tolerance machining are a few examples of operations that can be affected by nearby highway traffic.

In addition trains can produce some of the highest vibrations on a transportation facility. Caltrans has needed to consider cases involving train vibrations where a new highway or light-rail facility necessitated realignment of railroad tracks closer to residences or sensitive operations.

Potential vibration issues should be recognized as early as possible, and strategies to address the concerns should be coordinated with the Caltrans Division of Environmental Analysis. Potentially impacted vibration-sensitive receptors should be considered early in the design development process so that effective mitigation design strategies can be identified.

7.7 Occupational Hearing Loss and OSHA Noise Standards

This section does not pertain to environmental noise standards or NAC. Occupational hearing loss is a concern in certain occupations where workers are exposed to high noise levels. These occupations could be relevant to Caltrans operations, such as construction, maintenance, and materials laboratories. OSHA has set standards for permissible noise exposures. When the limits of these permissible exposures are approached, OSHA requires the employer “to administer a continuing, effective hearing conservation program” to prevent hearing loss. When the maximum allowable noise exposure is exceeded, the employer must take certain steps to control the noise. OSHA occupational noise exposure standards are addressed by 29 CFR 1910.95 and should be consulted if excessive noise exposure is suspected. For general reference, the most relevant information in 29 CFR 1910.95 is summarized below.

7.7.1 Noise-Induced Hearing Loss

Occupational noise-induced hearing loss develops slowly over a period of time when exposed to high continuous or intermittent noise levels. This should not be confused with traumatic hearing loss, which is caused by a single transient high-level noise event, such as a gunshot or explosion. The most important aspects of occupational noise-induced hearing loss are listed below.

- It is always sensory-neural (affects the hair cells in the inner ear).
- It typically affects both ears equally.
- The first sign of hearing loss is a *notching*, or reduced hearing sensitivity at 3,000, 4,000, or 6,000 Hz, with normal sensitivity in higher or lower frequencies. This is in contrast to age-related hearing loss, which also begins at 3,000 to 6,000 Hz but continues into higher frequencies.
- Noise-induced hearing loss due to chronic noise exposure is greatest during the first 10 years or so of exposure and slows down afterward. Age-related hearing loss, however, accelerates over time.
- Noise-exposed ears are not more sensitive to future noise exposure and do not progress beyond the added normal age-related hearing loss once the noise exposure is discontinued.

7.7.2 OSHA Noise Standards

Occasionally, the exposure of Caltrans personnel or contractors to noise is a concern. 29 CFR 1910.95(a) requires the employer to protect the employee against the effects of noise exposure when the permissible noise exposures in Table 7-3 are exceeded. The noise levels must be measured on the A-scale with the sound level meter at slow response.

29 CFR 1910.95(b)(1) requires that when the permissible noise exposure levels are exceeded, “feasible administrative or engineering controls shall be utilized. If such controls fail to reduce sound levels within the levels of

Table [7-3], personal protective equipment shall be provided and used to reduce sound levels within the levels of the table."

29 CFR 1910.95(b)(2) considers variations in noise level involving maxima at intervals of 1 second or less to be continuous.

Table 7-3. Table G-16 Permissible Noise Exposure

Duration per Day (Hours)	Sound Level (dBA, Slow Response)
8	90
6	92
4	95
3	97
2	100
1.5	102
1	105
0.5	110
0.25 or less	115

Notes: When the daily noise exposure is composed of two or more periods of noise exposure of different levels, their combined effect should be considered, rather than the individual effect of each. If the sum of the following fractions [C(1) / T(1)] + [C(2) / T(2)] + ……[C(n) / T(n)] exceeds 1, the mixed exposure should be considered to exceed the limit value. C(1), C(2), etc. indicate the times of exposure at a specific noise level. T(1), T(2), etc. indicate the times permissible for that specific exposure. Exposure to impulsive or impact noise should not exceed 140 dB peak (as opposed to rms) sound pressure level.

Two simple examples of the calculation shown in the footnote of the above table are provided below.

- C(1) = 3 hours at 95 dBA and C(2) = 5 hours at 90 dBA. The corresponding T(1) and T(2) values from the permissible noise exposure table are T(1) = 4 hours and T(2) = 8 hours. Using the calculation in the footnote, the exposure is:

  3/4 + 5/8 = 0.75 + 0.625 = **1.375 (>1)**.

  The maximum allowable exposure has been exceeded.

- C(1) = 1 hour at 100 dBA and C(2) = 3 hours at 90 dBA. The corresponding T(1) and T(2) values from the permissible noise exposure table are T(1) = 2 hours and T(2) = 8 hours. Using the calculation in the footnote, the exposure is:

  1/2 + 3/8 = 0.50 + 0.375 = **0.875 (<1).**

  The maximum allowable exposure has not been exceeded.

The fractions may also be expressed as percentages, with 100% the maximum allowable exposure level. The first example would result in 137.5% and the second in 87.5%.

29 CFR 1910.95(c)(1–2) requires the employer to "administer a continuing, effective hearing conservation program…whenever employee noise exposures equal or exceed an 8-hour time-weighted average sound level…of 85 decibels, measured on the A-scale (slow response). Or equivalently, a dose of fifty percent." The 85-dBA noise level or dose of 50% is also referred to as the action level. The hearing conservation program is fully described in 29 CFR 1910.95(c–o).

7.8 Effects of Transportation and Construction Noise on Marine Life and Wildlife (Bioacoustics)

The effects of highway and construction noise on marine life and wildlife is generally referred to as bioacoustics. Concerns regarding these effects generally arise in response to requirements of the federal Endangered Species Act, National Marine Fisheries Service, U.S. Fish and Wildlife Service, California Department of Fish and Wildlife, and other resource agencies that have jurisdiction in the project area.

Caltrans biologists routinely address environmental issues related to all of the effects of transportation and construction on animals. Noise is only one of the issues, but it can be an important factor in the overall impact assessment. Underwater noise from pile driving can affect some fish within close range. In the San Diego area, Caltrans has built earth berms and soundwalls to protect nesting areas for Least Bell's Vireo, an endangered bird species. The task of addressing noise impacts on marine and terrestrial wildlife rests primarily with the biologists. However, noise analysts provide a supporting role to the biologists in providing technical noise expertise. Accordingly, it is critical that biologists coordinate directly with the project noise analyst when evaluating noise impacts on wildlife.

Addressing the effects of noise on marine and terrestrial animal species provides an exceptionally difficult challenge and requires specialized expertise. With marine life, the acoustical environment is vastly different than on land. In both marine and terrestrial environments, there is a great variety of animal species, each with different tolerances to noise. The nature of the adverse effects on the different species can also differ. On land, some birds may be flushed from their nesting areas, which may interfere with reproduction. Songbirds, which depend on their songs to find a mate, may be unable to communicate with each other in a noisy environment, therefore missing the opportunity to reproduce. Other animals may be temporarily or permanently driven from their habitat. The hearing frequency response to noise is also different in each species. For example the hearing range for humans is 20 to 20kHz whereas the hearing range for bats is 10 Hz to 200 kHz and the range for birds is 1KHz to 5 KHz. Accordingly, the use of the human response A-scale when evaluating noise impacts on other species may not be appropriate in some cases.

The Caltrans' document *Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish* (Guidance Manual) provides detailed guidance on the process for evaluating underwater noise impacts on fish from pile driving (2009). This document is available:
<http://www.dot.ca.gov/hq/env/bio/fisheries_bioacoustics.htm>.

National Cooperative Highway Research Program Research Results Digest 363- Hydroacoustic Impacts on Fish from Pile Installation (National Cooperative Highway Research Program 2011c) provides additional on pile driving noise impacts on fish. This document is available:
<http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rrd_363.pdf>.

Specific guidance on how to address airborne noise effects on terrestrial wildlife has not yet been developed by Caltrans. Caltrans has however commissioned a report entitled *The Effects of Highway Noise on Birds* (Dooling and Popper 2007) which provides background on the effects of noise on birds and provides recommended criteria for impact assessment. This document is available:
<http://www.dot.ca.gov/hq/env/bio/avian_bioacoustics.htm>

Another useful resource is the FHWA document *Synthesis of Noise Effects on Wildlife Populations* (Federal Highway Administration 2004).

Section 8

Glossary

The terms and definitions in this glossary are either used in this TeNS or are commonly found in environmental noise literature. To make this glossary more useful to the highway traffic noise analyst, these definitions are generally oriented toward highway traffic noise and abatement, not general acoustics.

Absorption: The attenuation of sound caused by conversion of sound energy into other forms of energy, usually heat, within a medium. Absorption is a property of the medium. In noise barrier material, absorption can be considered the complement of reflection. A perfectly absorptive material does not reflect any sound energy, and a non-absorptive (i.e., reflective) material reflects almost all sound energy. In either case, a small portion of sound energy is transmitted through the barrier and continues in roughly the same direction as the incident noise propagation. In typical highway traffic noise barriers, the sound energy passing through is less than 1% of the incident noise energy. See also "Transmission Loss."

Absorption Coefficient: A term that approximately equals the ratio of sound energy absorbed by a material to the energy incident on the material. Absorption coefficients range from 0 (no absorption) to 1 (perfect absorption). In highway noise barriers, material with an absorption coefficient of 0 will reflect back almost all incident noise energy, and material with a coefficient of 1 will not reflect back any sound energy. The absorption coefficient depends on material, sound frequency, and angle of incidence.

Absorptive Grounds: Types of ground, such as normal earth and most grounds with vegetation, that are absorptive to sound energy and that reverse the phase of reflected energy at grazing angles of incidence. See also "Soft Sites" and "Ground Effects."

Acoustics: The broad field of science that deals with the production, propagation, reception, effects, and control of sound, both audible and inaudible to the human ear, and occurring in all media.

Airborne Sound: Sound that reaches the point of interest primarily by propagation through the air.

Ambient Noise: All-encompassing noise at a given place and time. This is usually a composite of sounds from all sources near and far, including any specific sources of interest.

Amplitude: The strength or magnitude of the pressure of a sound wave.

Anechoic Chamber: A room that has boundaries designed to absorb nearly all of the sound incident on them, producing a test room that is essentially free from reflected sound, and simulates free field conditions for the limited space defined by the room's boundaries.

Angle of Diffraction: The angle through which sound energy is diffracted as it passes over the top of a noise barrier and proceeds toward the receiver. Receivers deeper into the shadow zone have larger angles of diffraction and therefore higher barrier attenuation. See also "Diffraction" and "Shadow Zone."

Angle of Incidence: The angle formed by the radial line of sound waves striking a surface at a specific location and the plane of that surface. See also "Angle of Reflection."

Angle of Reflection: The angle formed by the radial line of sound waves reflecting off a surface at a specific location and the plane of that surface. See also "Angle of Incidence."

Atmospheric Effects: Sound absorption by air molecules and water vapor, sound refraction caused by temperature and near-ground wind gradients, and air turbulence are collectively called atmospheric effects. Although atmospheric effects are mostly responsible for substantial noise fluctuations at distant receivers, they also can have a significant effect at distances within 330 feet.

Audible Spectrum: The frequency range normally associated with human hearing, usually considered between 16 and 20,000 Hz. For noise control purposes, the audible spectrum of interest usually lies between 20 and 10,000 Hz.

Audiogram: A graph showing hearing loss as a function of frequency.

Audiometer: An instrument for measuring hearing sensitivity or loss.

Automobile: A vehicle classification for the purpose of noise prediction modeling, defined as all vehicles with two axles and four wheels designed primarily for transportation of nine or fewer passengers (automobiles) or transportation of cargo (light trucks). Generally, the gross weight is less than 10,000 pounds.

Average Level: Typically the energy-averaged noise level in decibels, wherein the contributing levels are first converted to relative energies or energy ratios, and added and divided by the number of contributing levels. The result is then converted back to decibels.

A-Weighted Sound Level: Expressed in dBA or dB(A). Frequency-weighted sound pressure level approximating the frequency response of the human ear. It is defined as the sound level in decibels measured with a sound level meter having the metering characteristics and a frequency weighting specified in the American National Standards Institute Specification for Sound Level Meters, ANSI S 1.4–1983. The A-weighting de-emphasizes lower frequency sound sounds below 1,000 Hz (1 kHz) and higher frequency sounds above 4 kHz. It emphasizes sounds between 1 and 4 kHz. A-weighting is the most commonly used measure for traffic and environmental noise throughout the world.

Background Noise: The total noise in a system or situation independent of the presence of (i.e., without) the noise source of interest.

Baffle: A shielding structure or series of partitions used to increase the effective external transmission path length between two points in an acoustic system.

Band: See “Frequency Band.”

Band Center Frequency: The designated geometric mean frequency of a band of noise.

Band Pressure Level: The SPL contained within a specified band.

Barrier Attenuation: The noise reduction from barrier diffraction only.

Broadband Noise: Noise with components over a wide range of frequencies.

Calibrator: A device used to calibrate or properly adjust for valid measurement results a sound level meter and microphone system. Calibration must be performed before and after the sound level measurement sequence.

Community Noise Equivalent Level: A noise level that accounts for all the A-weighted noise energy from a source during 24 hours, and weights the evening (7 p.m. to 10 p.m.) and night (10 p.m. to 7 a.m.) noise by adding 5 and 10 dBA, respectively, during these periods.

Compression: The portion of a sound wave in which the air molecules are slightly compressed with respect to the barometric air pressure. The opposite of rarefaction.

Cylindrical Divergence: Sound waves generated by a line source, such as approximated by a highway, tend to form cylindrical wavefronts that propagate by radiating outward from their original line source in cylindrical pressure waves of ever-increasing areas. This process is referred to as cylindrical divergence or spreading. The same sound energy distributed over an ever-increasing cylindrical area is responsible for reducing the sound's energy per unit area (i.e., intensity) by half for each doubling of distance. This corresponds with a noise level decrease of 3 dB per doubling of distance.

Cycles per Second: See "Hertz."

Day-Night Level: See "L_{dn}."

Decibel: A decibel is one-tenth of a bel. It is a measure on a logarithmic scale that indicates the squared ratio of sound pressure to a reference sound pressure (unit for sound pressure level) or the ratio of sound power to a reference sound power (unit for sound power level). See also "Sound Pressure Level" and "Sound Power Level."

Descriptor: A generic term for a noise indicator such as L_{eq}, L_{max}, or L_{dn}.

Diffuse Sound Field: A sound field in which the time average of the mean square sound pressure is the same everywhere and the flow of acoustic energy in all directions is equally probable. For example, a sound source in a reverberation room, where many reflected sound waves are present and the sound level is equal at any location in the room.

Diffraction: The bending of sound pressure waves around an obstacle. The ease with which the pressure waves diffract around an obstacle depends on the ratio of wavelength to the size of the obstacle. Pressure waves with a given wavelength diffract more readily around a small object than a large one. Pressure waves with longer wavelengths diffract more easily around an object of a given size than pressure waves with a shorter wavelength. Because of the above principles, highway traffic noise barriers provide a more defined noise "shadow" behind the barrier and more noise attenuation for higher-frequency noise than lower-frequency noise. See also "Angle of Diffraction" and "Shadow Zone."

Doppler Effect: The change in observed frequency of a sound wave caused by a time rate of change in the effective path length between the sound source and receiver. If the path length rate of change causes the source and receiver to approach each other, the observed frequency shifts upward. If the source and receiver recede relative to each other, the frequency shifts downward. The frequency shift is called the Doppler shift, and the unit is hertz.

Dosimeter: An instrument measuring noise exposure for compliance with OSHA standards.

Dynamic Range: The range in sound levels, in decibels, through which a source or receiver can emit or receive sound. For example, the dynamic range of a sound level meter typically ranges from 20 to 140 dB.

Emission Level: A measure of the noise output of a single vehicle. It is the maximum noise level, in dBA, observed during a passby of the vehicle at 50 feet. See also “Reference Energy Mean Emission Level.”

Energy Average: The result of energy averaging or a method of averaging various SPLs based on their squared pressures. This method involves the conversion of decibels to equivalent relative energy or energy ratios, averaging the values, and changing the values back to decibels.

Energy Ratio: See “Relative Energy.”

Equivalent Distance: The distance to a specific receiver from an imaginary single lane that acoustically represents a multilane highway or a group of lanes, such as directional lanes.

Equivalent Level: See “L_{eq}.”

Excess Attenuation: Sound attenuation in addition to that caused by geometric spreading. It is usually meant to be the attenuation from ground effects and sometimes atmospheric effects. See also “Geometric Spreading,” “Ground Effects,” and “Atmospheric Effects.”

Existing Noise Levels: The noise resulting from the natural and mechanical sources and human activity considered to be usually present in a particular area.

Far Field: The region beyond the near field, where the effects of source dimensions are less important and noise propagates with a simple relationship between sound level and distance.

Filter: A device for separating components of a signal based on their frequency. It allows components in one or more frequency bands to pass relatively unattenuated and attenuates components in other frequency bands.

Flanking Noise: Refers to noise energy that arrives at an observer by an unexpected or unexamined pathway. For example, in the design of noise barriers, the calculations predict the energy that diffracts over the top of the barrier. If significant amounts of noise energy reach the observer by passing around its ends far up and down the roadway, this energy has flanked the barrier along unexpected "flanking paths."

Flow Resistivity: A measure of the acoustical absorption of the ground located between a sound source and receiver. As applied in the FHWA TNM the units of flow resistivity are cgs rayls. Water and hard pavement are highly acoustically reflective and are assigned a flow resistivity value of 20,000 cgs rayls. At the other extreme is power snow which is assigned a value of 10 cgs rayls.

Free Field: A sound field that is free from enclosures or boundaries, and in which there are no reflections and accompanying interference and reverberation effects such as found in auditoriums.

Frequency: The number of oscillations per second of a periodic wave sound and of a vibrating solid, expressed in units of hertz, formerly cycles per second (cps). 1 Hz = 1 cps = 1 oscillation per second. The value is the reciprocal (1/x) of the period of oscillations in seconds. The symbol for frequency is *f*.

Frequency Band: An interval of the frequency spectrum defined between an upper and lower cutoff frequency. The band may be described in terms of these two frequencies or (preferably) by the width of the band and the geometric mean frequency of the upper and lower cutoff frequencies (e.g., an octave band "centered" at 500 Hz).

Frequency Response: The response to an oscillating phenomenon (e.g., sound pressure) by an object (e.g., microphone or ear) measured in decibels as a function of frequency. For example, the A-weighting curve corresponds closely to the frequency response of human hearing at a certain constant level of sound energy. See also "A-Weighted Sound Level."

Frequency Spectrum: The description of a sound wave's resolution into components of different frequency and usually different amplitude and phase.

Fresnel Number: A dimensionless value used in predicting the attenuation of a noise barrier located between a noise source and receiver. In its simplest mathematical form, $N = 2\delta / \lambda$, where δ is the path length difference between the sound path from the source to receiver via the top of the barrier and the straight line between the source and receiver, and λ is the wavelength of the sound (the units of δ and λ must be the same). Generally, the larger the value of N, the greater the attenuation.

Fundamental Frequency: The frequency with which a periodic function (e.g., sound wave) reproduces itself, sometimes called the first harmonic. See also “Harmonic.”

Geometric Divergence: Refers to the shape of sound pressure wavefronts and the manner in which they propagate. Geometric divergence or spreading is a generic term used for specific types of divergence, such as cylindrical or spherical divergence. See also “Cylindrical Divergence” and “Spherical Divergence.”

Gradient: Variation of speed of sound, temperature, and wind velocity with height above the ground surface. A gradient in speed of sound can be caused by differences in temperature with height above the ground or differences in wind velocities with height above the ground. The speed of sound gradient in turn causes atmospheric refraction of sound which can create noise “shadows” (i.e., decreases) in certain areas and noise concentrations (i.e., increases) in others. See also “(Atmospheric) Refraction.”

Ground Effects: The effects of sound grazing absorptive ground. See also “Absorptive Grounds.”

Hard Site: Term used for reflective characteristics of the ground surface between a noise source and receiver. The term is most often used in traffic noise prediction models, where it is associated with a 3 dB per doubling of distance line source attenuation (because of geometric spreading only, without excess attenuation).

Harmonic: A sinusoidal (i.e., pure-tone) component whose frequency is a whole-number multiple of the fundamental frequency of the wave. If a component has a frequency twice that of the fundamental frequency, it is called the second harmonic.

Heavy Truck: A vehicle type for the purpose of noise prediction modeling defined as all vehicles with three or more axles designed for transportation of cargo. Generally, the gross weight is more than 26,500 pounds.

Hertz: Unit of frequency, formerly called cycles per second. 1 Hz = 1 cps. See also “Frequency.”

Hourly Equivalent Sound Level: See “L_{eq}(h).”

Incident Sound: Direct sound striking a surface. See also “Angle of Incidence.”

Infrasound: A sound with a frequency less than the audible sound spectrum (i.e., generally lower than 16 to 20 Hz).

Insertion Loss: The actual noise level reduction at a specific receiver from construction of a noise barrier between the noise source (e.g., traffic) and the receiver. Generally, it is the net effect of the barrier attenuation and loss of ground effects.

Inverse First Power: The increasing of sound amplitude from the process of cylindrical divergence from a line source. See also “Cylindrical Divergence.” For a line source, the sound pressure level SPL_1 at distance D_1 is related to the sound pressure level SPL_2 at a distance of D_2 as follows:

$$SPL_1 – SPL_2 = 10\log(D_1 / D_2)$$

Inverse Square: The increasing of sound amplitude from the process of spherical divergence from a point source. See also “Spherical Divergence.” For a point source, the sound pressure level SPL_1 at distance D_1 is related to the sound pressure level SPL_2 at a distance of D_2 as follows:

$$SPL_1 – SPL_2 = 10\log(D_1 / D_2)^2$$

kHz: Abbreviation for kilohertz, or 1,000 Hz. See also “Hertz.”

L_{dn}: Abbreviation for the day-night level noise descriptor. It is the energy average of the A-weighted sound levels occurring during a 24-hour period, with 10 dB added to the A-weighted sound levels occurring from 10 p.m. to 7 a.m.

L_{eq}: The equivalent steady-state sound level that in a stated period of time would contain the same acoustical energy as the time-varying sound level during the same period.

L_{eq}(h): The energy-average of the A-weighted sound levels occurring during a 1-hour period in decibels (i.e., a 1-hour L_{eq}). See also “L_{eq}.”

Level: In acoustics, the value of a logarithm of the ratio or ratio squared of that quantity *t* a reference quantity of the same kind in decibels. The base of the logarithm is commonly 10. The reference quantity and kind of level must be specified (e.g., sound pressure level of 60 dB RE: 20 μPa, sound power level RE: 10^{-12} W).

Line of Sight: A straight line between the observer's location and a specific noise source.

Line Source: A source of noise spread out into a line, such as approximated by the combined traffic on a roadway.

L_{max}: The highest SPL in a specific time period.

Logarithm: A mathematical operation that, for values more than 1, condenses these values into smaller values through the reverse of y^x, where x is the number being operated on. Normally, the base, or value of y, is taken as 10 (common log). If the base is not specified, its value is usually considered 10. Therefore, if $10^x = a$, then $x = \log_{10}a$, or log a. If $a > 1$, x is positive. If $a = 1$, $x = 0$. If $0 < a < 1$, x is negative. Please note that *a* must never be 0. For example:

$10^2 = 100$; $\log 100 = 2$; $x = 2$, $a = 100$
$10^0 = 1$; $\log 1 = 0$; $x = 0$, $a = 1$
$10^{-2} = 0.01$; $\log 0.01 = -2$; $x = -2$, $a = 0.01$

Loudness: The judgment of intensity of a sound in terms of which sounds may be ranked on a scale from soft to loud. On this scale, a doubling of a reference sound energy is barely perceptible to the human ear, a tripling of the sound energy is readily perceptible, and 10 times the sound energy is about twice as loud. Decreasing the sound by the same factors has a reciprocal effect—reducing the reference sound energy to one-tenth of the original energy the sound is perceived as half as loud. Although loudness depends primarily on the intensity of the sound, it also depends on the sound's frequency and wave form.

Loudness Level: Defined as the median SPL in a specified number of trials of a 1,000-Hz tone that is judged equally loud to the listener as the sound in question. Described in units of phons. Please note that the calculated loudness level, *L*, in phons is related to loudness in sones as follows:

$$L = 10\log_2 n_s$$

Where:

L = the loudness level in phons

n_s = loudness in sones

A twofold change in loudness corresponds to an interval of 10 phons. See also “Phon” and “Sone.”

L_x: The sound pressure level exceeded *x* percent of a specific time period. For example, L_{10} is the level exceeded 10% of the time, and L_{50} is the level exceeded 50% of the time.

Masking: The action of bringing one sound, audible when heard by itself, to inaudibility or unintelligibility by the introduction of another sound.

Medium: A substance carrying a sound wave, such as air, water, or steel.

Medium Truck: A vehicle classification for the purpose of noise prediction modeling, defined as all vehicles with two axles and six wheels designed for transportation of cargo. Generally, the gross weight is more than 10,000 pounds and less than 26,500 pounds.

Meter Response: Measure of the quickness with which the needle of an analog sound level meter or the display of a digital sound level meter follows changes in the actual sound level.

Microphone: An electroacoustic transducer that transforms sound waves into equivalent electric waves.

Natural Frequency: Frequency of free oscillation of a system (i.e., the frequency at which a system vibrates when given an initial excitation and allowed to vibrate freely without constraints).

Near Field: The part of a sound field, usually within about two wavelengths of the lowest sound frequency from a sound source, in which the dimensions of the sound source have an important effect and where there is no simple relationship between sound level and distance. For traffic noise, the near field usually exists within 25 feet of the nearest traffic. Noise measurements or predictions should be avoided in the near field.

Noise: Sound that is loud, unpleasant, unexpected, or otherwise undesirable.

Noise Barrier: A generic term for any feature that blocks or diminishes sound in its path from the source to receiver. Although the term can technically refer to any feature, manmade or natural, the two most common features included in noise barriers are soundwalls and earth berms. Almost all noise barriers in California are soundwalls; therefore, the terms "noise barrier" and "soundwall" are frequently interchanged, although soundwalls are a subset of noise barriers. See also "Soundwalls" and "Earth Berms."

Noise Contour: An imaginary line shown on a plan along which all sound levels are equal.

Noise Floor: The level of noise, in decibels, that represents the threshold of sensitivity for a sound level meter and below which the inherent (i.e., device's own) noise limits its detectability of low-level signals.

Noise Reduction Coefficient: A value representing the arithmetic average of the absorption coefficients in four octave bands with respective center frequencies of 250, 500, 1,000, and 2,000 Hz.

Octave: The interval between two sounds having a frequency ratio of 1:2; (e.g., 500 to 1,000 Hz; 440 to 880 Hz).

Octave Band: A frequency band in which the interval between the upper and lower cutoff frequency is one octave. As with all frequency bands, the octave band is usually described by its center frequency. Octave bands are centered by preferred frequencies described by ISO R 266. An example is the 500-Hz octave band. See also "Frequency Band."

One-Third Octave: The interval between two sounds having a frequency ratio of the cube root of 2 (approximately 1.26). Three contiguous one-third octaves cover the same frequency range as an octave.

One-Third Octave Band: A frequency band in which the interval between the upper and lower cutoff frequency is one-third of an octave. As with all frequency bands, the one-third octave band is usually described by its center frequency. Three contiguous octave bands make up one octave band. As with octave bands, one-third octave bands are centered by preferred frequencies described by ISO R 266. For example, three one-third octave bands centered at 400, 500, and 630 Hz make up the 500-Hz octave band. See also "Frequency Band."

Overall Level: The SPL that includes all the energy in all frequency bands of interest.

Pascal: A unit of pressure (in acoustics, normally rms sound pressure) equal to 1 Newton per square meter (N/m^2). The pascal is abbreviated Pa. A reference pressure for a sound pressure level of 0 dB is 20 μPa.

Peak Sound Level: See "Peak Sound Pressure Level."

Peak Sound Pressure: The maximum instantaneous (i.e., non-rms) sound pressure for a transient or impulsive sound of short duration or in a specified time interval for a sound of long duration. The unit is pascals.

Peak Sound Pressure Level: Level of peak sound pressure. The unit is decibels with stated frequency weighting, if any. See also "Peak Sound Pressure" and "Sound Pressure Level."

Permanent Threshold Shift: Permanent hearing loss from frequent exposures to noise of high intensities. See also "Temporary Threshold Shift."

Phon: Unit of loudness judged or calculated in definition of loudness level. See also "Loudness Level."

Pink Noise: Broadband noise that yields the same energy for each octave band over its entire range of frequencies. Because, going from low to high frequencies, each subsequent octave band contains twice the frequency range as the previous band, the energy decreases with increasing frequency to maintain equal energy per octave band. Compare with white noise.

Point Source: A noise source essentially concentrated at a single point from which noise propagates outward in all directions. A single vehicle observed from some distance can be approximated as a point source. See also "Spherical Divergence" and "Spreading."

Propagation: The passage of sound energy from a noise source to receiver through a medium (e.g., air).

Pure Tone: A sound wave whose waveform is a sine wave (single frequency).

Random Incidence: Refers to sound waves that strike the receiver randomly from all angles of incidence. Such waves are common in a diffuse sound field.

Random Noise: Noise that has random characteristics in both time and amplitude (i.e., any occurrence of any amplitude is as likely to occur at any one moment as any other).

Rarefaction: The portion of a sound wave in which the air molecules are rarefied or in a slight vacuum with respect to the barometric air pressure. The opposite of compression.

Rate of Decay: The time rate at which SPL decreases at a given receiver after the sound source is turned off. The commonly used unit is decibels per second (dB/s). It is used in measuring reverberation time of a room. See also “Reverberation” and “Reverberation Time.”

Receiver: Most basically defined as any natural or artificial sensor that can perceive, register, or be affected by sound (e.g., human ear, microphone). When modeling noise, a receiver is a point in the model that represents a single receptor or multiple receptors (defined below). For example if three single-family residences are in an area where acoustic conditions are the same, each residence is a receptor. For more modeling purposes the three residences can be represented by a single receiver in the model.

Receptor: Most basically defined as any natural or artificial sensor that can perceive, register, or be affected by sound (e.g., human ear, microphone). In the context of a noise analysis under the requirements of 23 CFR 772 a receptor is a single specific dwelling unit or the equivalent of a single dwelling unit. For example in a park with three baseball fields, each field is considered to be equivalent to a single dwelling unit for the purposes of noise analysis.

Reference Energy Mean Emission Level: The speed-dependent, energy-averaged maximum passby noise level generated by a defined vehicle type, as measured by a sound level meter at 50 feet from the centerline of travel at a height of 5 feet.

Reference Pressure: Any sound pressure to which a test pressure is being compared on a decibel scale, such as in the following expression:

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

Where:

P_0 = reference pressure (usually defined as 20 μPa).

Also, the sound pressure at 1,000 Hz that normal young adults can just detect, taken as 20 μPa.

Reflection: Bouncing back of sound waves away from an object that is larger in exposed section than the wavelengths and of sufficient surface weight, density, and stiffness to present a very large increase in impedance compared to the surrounding air.

Reflective Ground: Grounds that do not absorb sound energy and reflect back most of the energy. Examples are paved surfaces (e.g., asphalt, concrete) and hard-packed soils. The opposite of absorptive ground.

Refraction: The bending of sound waves in arcing curves either downward or upward because of different velocities of sound with respect to height above the ground. The sound velocity differences are caused either by differences in near-ground wind velocity from wind shear, or vertical changes in temperature (sound velocity increases with air temperature). Downward refraction occurs for downwind sound propagation and during near-ground temperature inversions (temperature increases with height), and is responsible for noise increases. Upward refraction occurs for upwind sound propagation and during near-ground temperature lapses (temperature decreases with height), and is responsible for noise decreases.

Relative Energy: The energy ratio between a sound level and reference level. For example, the sound energy of 60 dB is 10^6, or 1,000,000 times larger than that of 0 dB. The sound energy of 67 dB is $10^{6.7}$, or 5,011,872 times larger than that of 0 dB.

To add or subtract sound levels, the relative energies (not the decibel levels) may be added directly. Therefore, for the case above, total relative energy is as follows:

60 dB + 67 dB = 1,000,000 + 5,011,872 = **6,011,872 (RE: 0 dB)**
10log(6,011,872) = **67.8 dB.**

The same result would be obtained if a reference of 50 dB were selected, as shown below.

$50\text{ dB} + 10\log[10^{(6-5)} + 10^{(6.7-5)}] =$
$50\text{ dB} + 10\log(10^{1} + 10^{1.7}) =$
$50\text{ dB} + 10\log(60.12) =$
50 dB + 17.8 = **67.8 dB.**

Resonance: The relatively large amplitude of sound or vibration produced when the frequency of the source of the sound or vibration “matches” (i.e., synchronizes) with the natural frequency of vibration of an object. See also “Natural Frequency.”

Resonator: A device that resounds or vibrates in sympathy with a source of sound and vibration (i.e., the source frequency matches the natural frequency of the resonator).

Reverberant Field: The region in a room where the reflected sound dominates, as opposed to the noise source where the direct sound dominates.

Reverberation: The persistence of sound in an enclosed space, because of multiple reflections, after the sound source has stopped.

Reverberation Room: A room having a long reverberation time, especially designed to make a sound field inside it as diffuse as possible. Also called a live room. The opposite of an anechoic chamber. See also “Anechoic Chamber.”

Reverberation Time: The time taken for the sound energy to decrease to one millionth (10^{-6}), corresponding to a drop of 60 dB in SPL, of its steady-state value when the sound source is suddenly stopped. It is a measure of the persistence of an impulsive sound in a room and of acoustical absorption present inside the room.

Root Mean Square Pressure: The square root of the mean of the squares of a set of instantaneous positive, negative, or zero pressure amplitudes. The rms value is calculated by squaring the pressure values at each instant, adding them, dividing the total by the number of values, and taking the square root of the result. The squaring of both the positive and negative values ensures a positive result. An rms sound pressure is directly correlated with sound energy. For a single-frequency sound or sine wave, there is a simple relationship between the peak sound pressure and rms value:

$$\text{Peak} = \sqrt{2} * \text{rms} \approx 1.414 * \text{rms}$$

$$\text{rms} = (1 / \sqrt{2}) * \text{Peak} \approx 0.707 * \text{Peak}$$

Shadow Zone: The area behind a noise barrier that is blocked from direct view of the source of noise on the roadway.

Shielding: A noise reduction at the receiver because of the placement or existence of natural or artificial barriers (e.g., walls, berms, rows of buildings, or trees, if thick and dense enough).

Sine Wave: A sound wave, audible as a pure tone, in which the sound pressure is a sinusoidal function of time.

Soft Site: See “Absorptive Ground.”

Sound: A vibratory disturbance created by a moving or vibrating source in the pressure and density of a gaseous, liquid medium or in the elastic strain of a solid that is capable of being detected by hearing organs. Sound may be thought of as mechanical energy of a vibrating object transmitted by pressure waves through a medium to the ears. The medium of main concern is air. Unless otherwise specified, sound will be considered airborne, not structureborne, earthborne, etc.

Sound Energy: See “Relative Energy.”

Sound Insulation: The use of structures and materials designed to reduce the transmission of sound from one room or area to another, or from the exterior to interior of a building. Also, the degree by which sound transmission is reduced by means of sound-insulating structures and materials.

Sound Intensity: The average rate of sound energy transmitted in a specified direction through a unit area normal to this direction at a point considered.

Sound Level: Frequency-weighted SPL measured using metering characteristics and frequency weighting, such as A, B, or C, specified in the ANSI Specification for Sound Level Meters.

Sound Level Meter: An instrument used for measuring sound levels in a specified manner. It generally consists of a microphone, amplifier, output display, and frequency weighting networks.

Sound Power: The total amount of energy radiated into the atmosphere per unit time by a source of sound.

Sound Power Level: The level of sound power, averaged over a period of time, the reference being 10^{-12} watts.

Sound Pressure Level: Ten times the logarithm to the base 10 of the ratio of the time mean-square pressure of a sound, in a stated frequency band to the square of the reference sound pressure in gasses, of 20 μPa. SPL represents only unweighted rms levels. The unit is decibels. See also “Root Mean Square.”

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

Where:

P_0 = reference pressure of 20 μPa.

P_1 = sound pressure.

Source: A general term designating the sound energy generator. In transportation, noise sources are classified as point and line sources, which have different propagation characteristics. See also "Point Source" and "Line Source."

Source Heights: The effective acoustic height of vehicle noise sources. These heights have been determined from vehicle noise emission data, and are programmed in the appropriate computerized noise prediction models. The heights represent the energy average of all subsources (e.g., exhaust, tires, and engine noise) and are most important in evaluating noise barrier attenuation.

Sound Transmission Class: A single figure rating system designed to estimate sound insulation properties of a partition or a rank ordering of a series of partitions. It is intended for use primarily when speech and office noise constitutes the principal problem.

Spectrum: See "Frequency Spectrum."

Speed of Sound: The speed of sound for standard temperature of dry air at 32ºF and standard air pressure of 29.29 inches Hg standard is 1,087.3 feet per second. From these base values, the variation of speed of sound with temperature is described by the following equations:

$$\text{English Units: } c = 1051.3\sqrt{1 + \frac{T_f}{459}}$$

Where:

c = speed of sound

T_f = temperature in ºF

Spherical Divergence: Sound waves generated by a point source, such as approximated by a single vehicle, tend to form spherical wavefronts that propagate by radiating outward from their original point source in spherical pressure waves of ever-increasing areas. This process is referred to as "spherical divergence" or "spreading." The same sound energy distributed over an ever-increasing spherical area is responsible for reducing the sound’s energy per unit area (intensity) by one-quarter for each doubling of distance. This corresponds with a noise level decrease of 6 dB per doubling of distance. See also “Cylindrical Divergence.”

Spherical Wave: A sound wave in which the surfaces of constant phase are concentric spheres. A small (point) source radiating into an open space produces a free sound field of spherical waves.

Steady-State Sound: Sounds for which average characteristics remain constant in time (e.g., sound of an air conditioner, fan, or pump).

Structureborne Sound: Sound that reaches the receiver over at least part of its path by vibration of a solid structure.

Temporary Threshold Shift: A temporary hearing loss, evidenced by an increase in the threshold of audibility (see “Threshold of Audibility”) occurring after exposure to noise of high intensity. After a given time, usually up to several hours, the ear recovers to almost normal, but not quite so. After an excessive number of exposures of high intensity a hearing loss, or permanent threshold shift develops gradually.

Threshold of Audibility: The minimum SPL at which a person can hear a specific sound for a specified fraction of trials.

Transducer: A device capable of being actuated by waves from one or more transmission systems or media, and supplying related waves to one or more other transmission systems or media (e.g., microphones, loud speakers, accelerometers, seismometers).

Transient Sound: Transient sounds are those whose average properties do not remain constant over time (e.g., aircraft flyover, passing train, sonic boom, gunshot).

Transmission Loss: The loss in sound energy at a specific frequency, expressed in decibels, as sound passes through a barrier or a wall. It may be expressed mathematically as:

$$10 \times Log\left[\frac{E_1}{E_2}\right]$$

Where:

E_1 = sound energy leaving the back of the wall

E_2 = sound energy as it strikes the front of the wall

Transmission loss is not a reduction in total energy, only a transformation from sound energy into heat. Almost all highway noise barriers provide a loss of at least 25 dBA, which means that less than 1/3 of a percent of the sound energy travels through the wall.

Wave: In acoustics, a propagation wave is a cyclic pressure variation in air. The waves move at a characteristic speed (e.g., the speed of sound) through the medium (e.g., air) as an elastic response to a pressure perturbation at a source.

Wave Front: A portion of any wave, whether in compression or rarefaction state, that can be followed as it propagates throughout the medium, analogous to the crest of a tidal wave as it crosses the ocean. At all points on the wave front, the wave has equal amplitude and phase.

Wavelength: For a non-periodic wave, such as sound in air, the normal distance between analogous points of any two successive waves. The wavelength of sound in air or water is inversely proportional to the frequency of the sound. Therefore, the lower the frequency, the longer the wavelength.

White Noise: Broadband noise, the energy of which is constant over a wide range of frequencies (i.e., energy/Hz = constant). Because each octave band range increases by a factor of two, from low to high frequencies, each subsequent octave band contains twice the acoustical energy as the previous one. This corresponds to an increase of 3 dB in energy for each subsequent octave band. Compare with “Pink Noise.”

Ultrasonic: Pertaining to sound frequencies above the audible sound spectrum (in general, more than 20,000 Hz).

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Appendix A

References Cited

Appendix A
References Cited

American Association of State Highway Transportation Officials. 2011. Draft Standard TP 99-12. *Determining the Influence of Road Surfaces on Traffic Noise Using the Continuous-Flow Traffic Time-Integrated Method (CTIM)*. Washington, DC.

———. 2012. Standard Method of Test for Measurement of Tire/Pavement Noise using the On-Board Sound Intensity (OBSI) Method. Washington, DC.

American National Standards Institute. 1983. *American National Standard Specification for Soundlevel Meters.* New York, NY.

California Department of Transportation. 1995. *Traffic Noise Attenuation as a Function of Ground and Vegetation*. Final Report. Sacramento, CA.

———. 1998. *General Guidelines for Studying the Effects of Noise Barriers on Distant Receivers.* Sacramento, CA.

———. 2002. *Distance Limits for Traffic Noise Prediction Models.* Technical Advisory, Noise TAN-02-02. Prepared by Hendriks, R. for the Division of Environmental Analysis, Sacramento, CA.

———. 2003. *Additional Calibration of Traffic Noise Prediction Models.* Technical Advisory, Noise TAN-03-01 Final. Prepared by Hendriks, R., for the Division of Environmental Analysis.

———. 2004. *Transportation- and Construction-Induced Vibration Guidance Manual.* Prepared by Jones & Stokes for California Department of Transportation Environmental Program – Noise, Vibration, and Hazardous Waste Management Office, Sacramento, CA.

———. 2009. *Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish.* Final. Prepared by ICF

Jones & Stokes and Illingworth and Rodkin, Inc., for California Department of Transportation, Sacramento, CA.

———. 2013. *Traffic Noise Analysis Protocol for New Highway Construction, Reconstruction Projects, and Retrofit Barrier Projects*. September.

Dooling, R. J. and A. N. Popper. 2007. *The Effects of Highway Noise on Birds.* Rockville, MD.

Federal Highway Administration. 1978. *Highway Traffic Noise Prediction Model*. Report FHWA-RD-77-108. Washington, DC.

———. 1996a. *Measurement of Highway-Related Noise*. Report FHWA-PD-96-046. Washington, DC.

———. 1996b. *Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model (FHWA TNM®), Version 1.0.* Report No. FHWA-PD-96-008/DOT-VNTSC-FHWA-96-2. U.S. Department of Transportation, Research and Specialties Program.

———. 2004. *Synthesis of Noise Effects on Wildlife Populations*. Report FHWA-HEP-06-016. Washington, DC.

———. 2006. *FHWA Roadway Construction Noise Model User's Guide*.

———. 2007. *The Little Book of Quieter Pavement*. Washington, DC.

______. 2011. *Highway Traffic Noise: Analysis and Abatement Guidance.* Washington, DC.

Fleming G. G., A. S. Rapoza, and C. S. Y. Lee. 1995. *Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model (FHWA TNM®) Version 1.0.* Report No. FHWA-PD-96-008/DOT-VNTSC-FHWA-96-2. John A. Volpe National Transportation Research Center, Acoustics Facility, Cambridge MA. U.S. Department of Transportation, Research and Special Programs Administration.

Fleming, G. G., H. S. Knauer, C. S. Y. Lee, and S. Pederson. 2011. *FHWA Highway Noise Barrier Design Handbook.* Prepared for U.S. Department of Transportation, Federal Highway Administration.

Harris, Cyril M. 1979. *Handbook of Noise Control*. McGraw-Hill, Inc.

Hoover & Keith. 2000. *Noise Control for Buildings, Manufacturing Plants, Equipment, and Products*. Houston, TX.

Illingworth & Rodkin, Inc. 2006. *Comparative Measurements of Tire/Pavement Noise in Europe and the United States Noise Intensity Testing in Europe (NITE) Study*.

———. 2011a. *I-80 Davis OGAC Pavement Noise Study*. Petaluma, CA.

———. 2011b. *Eight Year Evaluation of the Noise Performance of the Caltrans Asphalt Research Pavements on LA 138*. Petaluma, CA.

———. 2011c. *Initial and Long-Term Evaluation of the Tire-Pavement Noise Produced by Various Portland Cement Concrete Surface Textures Measurements on the State Route KN 58 Mojave Bypass 2003 to 2010*. Petaluma, CA.

National Cooperative Highway Research Program. 2009. NCHRP Report 635 Acoustic Beamforming: Mapping Sources of Truck Noise. Washington, DC.

———. 2011a. NCHRP Project 1-44: Measuring Tire-Pavement Noise at the Source. Washington, DC.

———. 2011b. NCHRP Project 1-44 (1) Measuring Tire-Pavement Noise at the Source: Precision and Bias Statement. Washington, DC.

———. 2011c. *Research Results Digest 363 - Hydroacoustic Impacts on Fish from Pile Installation.* Washington, DC. Renterghem, T. V. and D. Botteldooren. *Optimal Tree Canopy Shape for Improving Noise Barrier Efficiency.* University of Ghent, Belgium.

Rochat, J. L., D. R. Read, G. G. Fleming, and G. Gregg. *Caltrans Thin Lift Study: Effects of Asphalt Pavements on Wayside Noise*. Volpe National Transportation Systems Center. Cambridge, MA.

Rymer, B. and P. Donavan. 2011. *Determining End Limits of Quieter Pavement Projects*. Petaluma, CA. Sandberg, Ulf and Jerzy Ejsmont. 2002. Tyre/Road Noise Reference Book, INFORMEX Ejsmont & Sandberg Handelsbolag, Kisa, Sweden.

Shatnawi, S. 2009. Caltrans Memorandum—Quieter Pavement Bulletin. Available: <http://www.dot.ca.gov/hq/maint/Pavement/Offices/Pavement_Engineering/PDF/QP_Memo_Bulletin_Oct-15-09.pdf>. Accessed September 2013.

Woehner, Helmut. 1992. Sound Propagation at Tunnel Openings. *Noise Control Engineering Journal* 39(2).