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

Table 6-1 assumes no openings or gaps in the barrier material. However, some materials such as wood are prone to develop openings or gaps because of shrinkage, warping, splitting, or weathering. These openings decrease the TL values. The TL of a barrier material with openings can be calculated if the ratio of area of openings to total barrier area and TL of the material are known. The following formula can be used to calculate the transmission loss with the openings (TL_o):

$$TL_o = TL - 10\log_{10}(A_o * 10^{TL/10} + A_c) \quad \textbf{(6-1)}$$

Where:

TL_o = transmission loss of material with openings

TL = transmission loss of material without openings

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

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

This method of calculation assumes that the openings or gaps are distributed equally over the surface of a barrier. For example, a barrier made of 2-inch-thick fir planks has openings that make up about 5% of the total area and are about equally distributed. The transmission loss of the material with these gaps can then be determined. From Table 6-1, the TL for 2-inch fir is 24 dBA. A_o is 5%, or 0.05; A_c is 1-0.05 = 0.95. Therefore:

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

The reduced TL could affect the barrier's performance. For example, it is assumed that before the barrier the noise level was 75 dBA and the intention was to reduce noise levels by 10 dBA (i.e., the diffracted noise was to be 65 dBA, and the transmitted noise was to be 75 – 24 = 51 dBA). The total noise level would have been 65 + 51 = 65 dBA. With the gaps, however, the transmitted noise is now 75 – 13 = 62 dBA, and the total noise level is 65 + 62 = 66.8 dBA. The effectiveness of the barrier is reduced by almost 2 dBA. Instead of a designed noise reduction of 10 dBA, an actual noise reduction of only 8 dBA will be realized in this case.

Properly treated materials will reduce or eliminate noise leakage. For example, lumber should be treated with preservatives that provide proper penetration and do not interfere with any protective coatings (e.g., paint) to be applied later. The wood also should have a low moisture content, requiring kiln drying after waterborne preservatives have been used. Wood planks should have tongue-and-groove deep enough to allow for shrinkage without gaps to maintain a high TL. Such tongue-and-groove is usually non-standard.

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

STC is universally accepted by architects and engineers. The rating uses a standard contour against which the TL values in one-third-octave bands are compared in the frequency range between 125 and 4,000 Hz. The standard contour is moved up or down relative to the test curve until the sum of the differences between them is 32 dB or less, and the maximum difference at each one-third-octave center frequency is no more than 8 dB. The STC is the TL value of the standard contour at the 500-Hz center frequency.

The disadvantage of this rating scheme is that it is designed to rate noise reductions in frequencies of normal office and speech noises, not for the lower frequencies of highway traffic noise. The STC can still be used as a rough guide, but it should be pointed out that for frequencies of average traffic conditions, the STC is 5 to 10 dBA more than the TL. For example, material with an STC rating of 35 has a TL of about 25 to 30 dBA for traffic noise.

The EWNR rating scheme is different from the STC in that it uses a standard contour developed from transportation noise frequencies. Therefore, it agrees closely with the A-weighted TL for traffic noise. The FHWA's *Insulation of Buildings Against Highway Noise* (1977) provides further useful information for calculating outdoor to indoor traffic noise reductions.

6.1.2 Barrier Location

The previous section indicated that by selecting materials with sufficient TL, noise transmitted through a barrier may be ignored because its contribution to the total noise level is negligible. The only remaining noise of concern is diffracted noise. Sections 2.1.4.4 and 5.5.1.5 discuss the basics of diffraction and barrier attenuation. The principal factor determining barrier attenuation is the Fresnel number, which is related to the path length difference (PLD) between the original straight line path between the source and receiver (source–receiver) and the diffracted path, described by the source, to top of the barrier, to the receiver (source–top of barrier–receiver). The greater this difference, the greater the barrier attenuation, to a limit of 20 dB for walls and 23 dB for berms. Figure 6-3 shows the PLD concept.

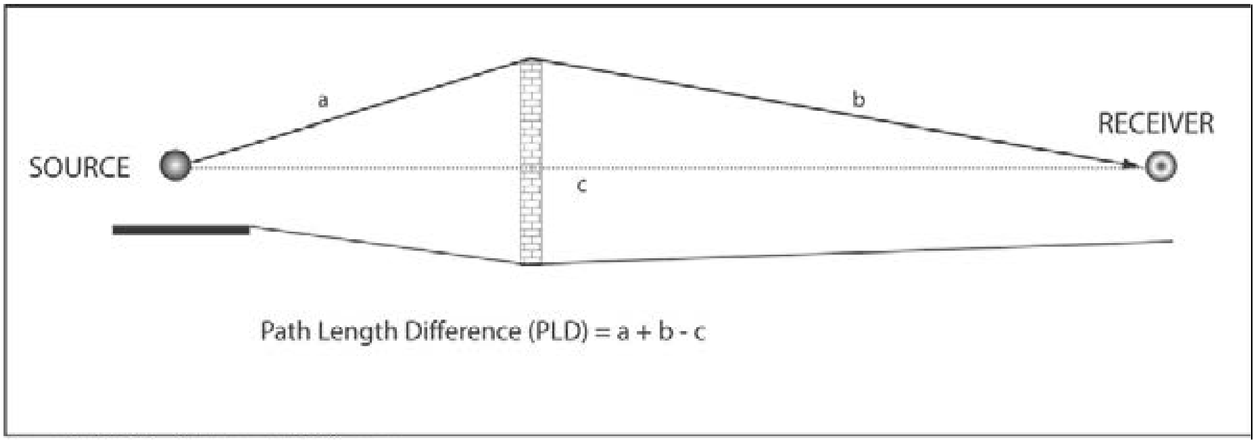

Figure 6-3. Path Length Difference

In level, at-grade roadway-receiver cross sections, a noise barrier of a given height provides greater barrier attenuation when it is placed either close to the source or close to the receiver. The least effective location would be about halfway between the source and receiver. Figures 6-4a to 6-4c show these situations for two source heights (autos and heavy trucks). Location “b” gives the lowest barrier attenuations for a given barrier height.

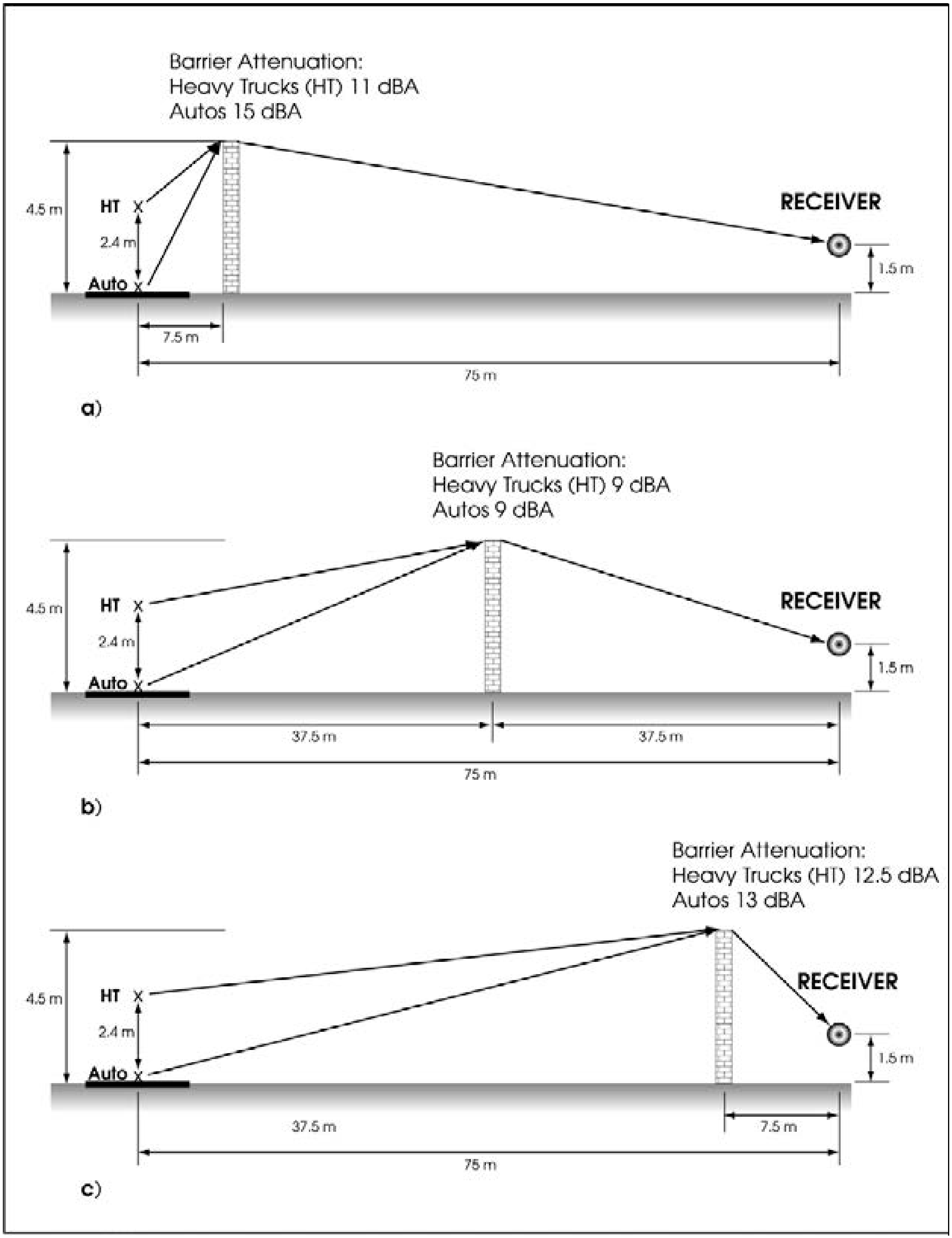

Figure 6-4. Barrier Attenuation as a Function of Location (At-Grade Highway)—Barrier Attenuation Is Least When Barrier Is Located Halfway Between the Source and Receiver “b”; The Best Locations Are Near the Source “a” or Receiver “c.”

In depressed highway sections, the barrier is most effective near the receiver on top of the cut (Figure 6-5). Please note that the without-barrier path is generally not a straight path between the source and receiver. The top of cut is already a fairly effective noise barrier. The PLD in this case is the difference between the paths described by source–top of barrier–receiver line, and source–top of cut–receiver line. The barrier attenuation is then calculated from the difference in barrier attenuation provided by the top of cut and top of the noise barrier.

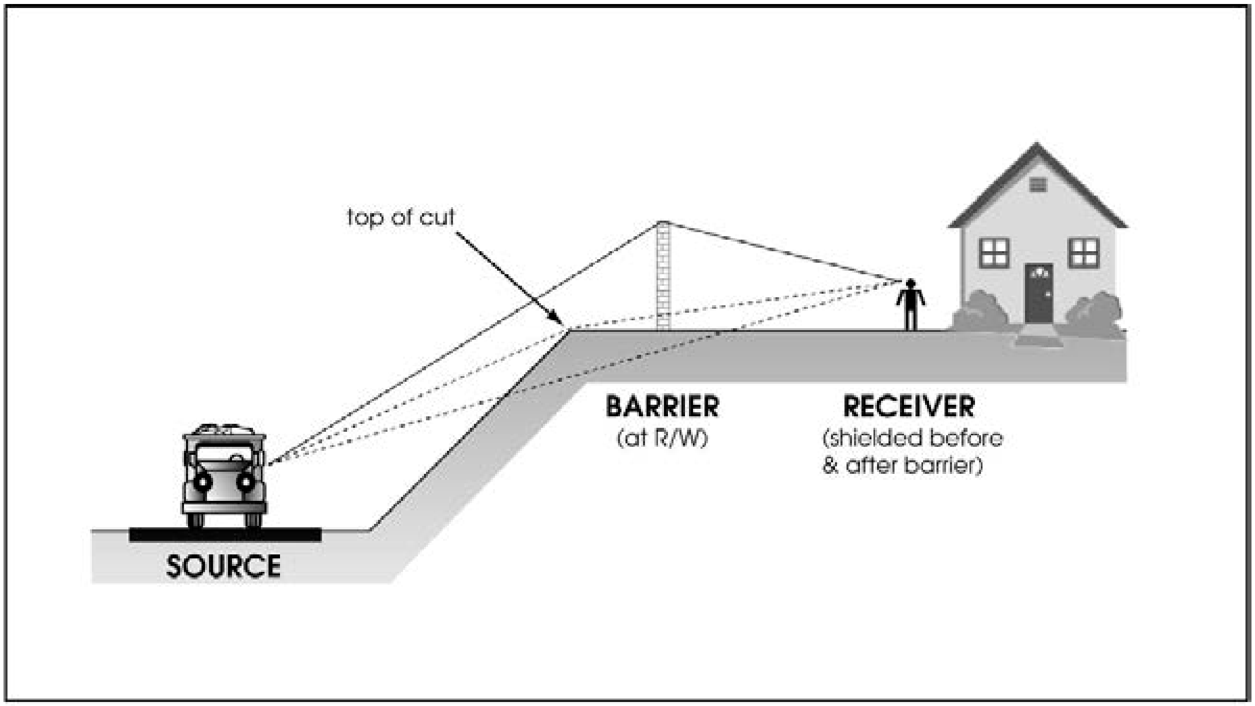

Figure 6-5. Typical Barrier Location for Depressed Highways

Because the attenuation per incremental increase in barrier height diminishes with the effective height of a barrier (see Section 6.1.3), this difference may be small. Noise barriers in depressed highway sections are generally not very effective in reducing noise because the cut section by itself may already be an effective barrier (earth berm).

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

The preceding discussions point out that the most acoustically effective location for a noise barrier depends on the source-to-receiver geometry. In most cases, the choices are fairly obvious. To recap the simplest situations:

- **Highway at Grade:** barrier location near the edge of shoulder or at the right-of-way.
- **Highway in Depressed Section:** barrier at the right-of-way.
- **Elevated Highway on Embankment or Structure:** barrier near edge of shoulder.

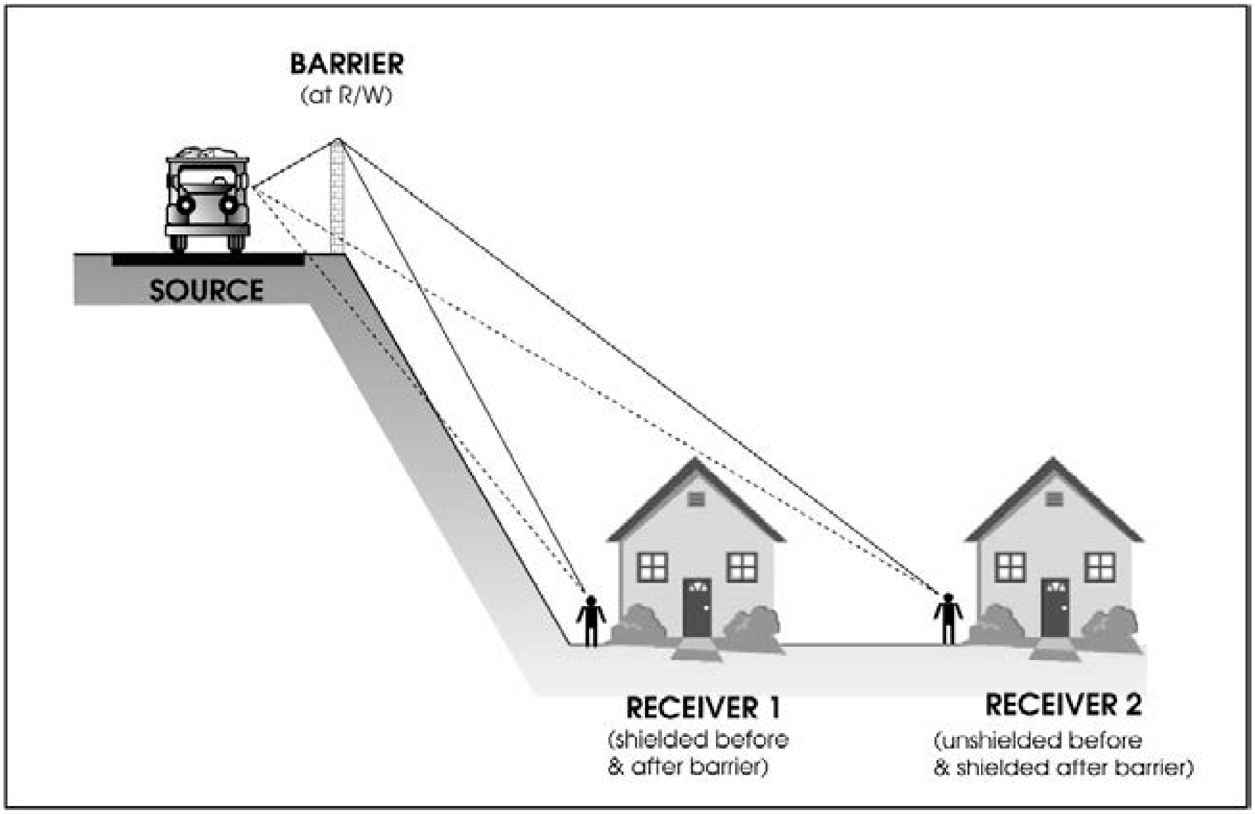

Figure 6-6. Typical Barrier Location for Elevated Highways

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

Transitions between cuts and fills, ramps, and interchanges are some examples of cases that need careful consideration. Figures 6-7 to 6-9 show typical noise barrier locations in some of these transitional areas. Barrier overlaps are often necessary in these cases (Figures 6-7 and 6-8).

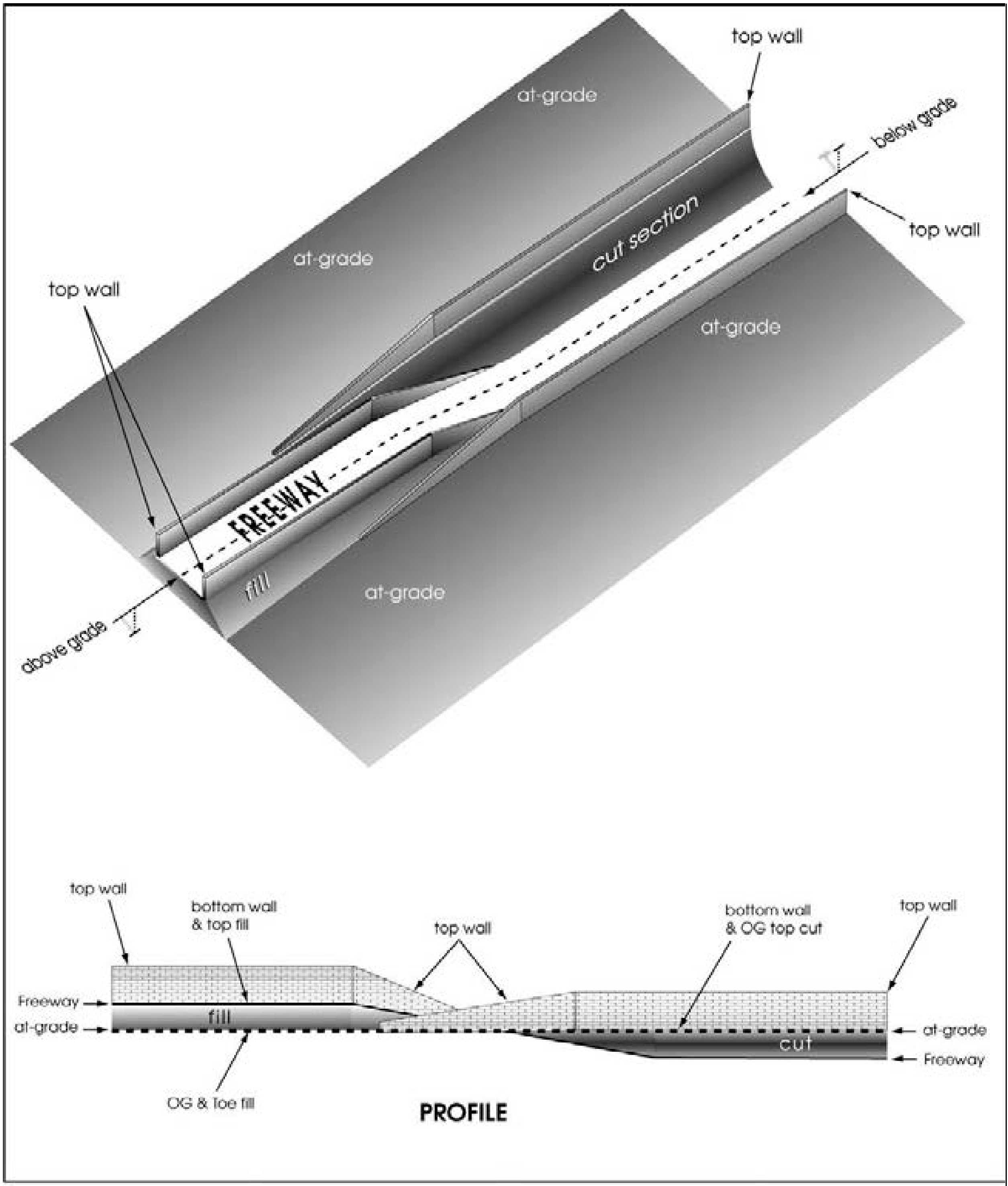

Figure 6-7. Barriers for Cut and Fill Transitions

One of the more common reasons for barrier overlaps is to provide maintenance access to the areas within the right-of-way that are on the receiver side of noise barriers (Figure 6-7). This will be discussed in more detail in the maintenance consideration portion of this section.

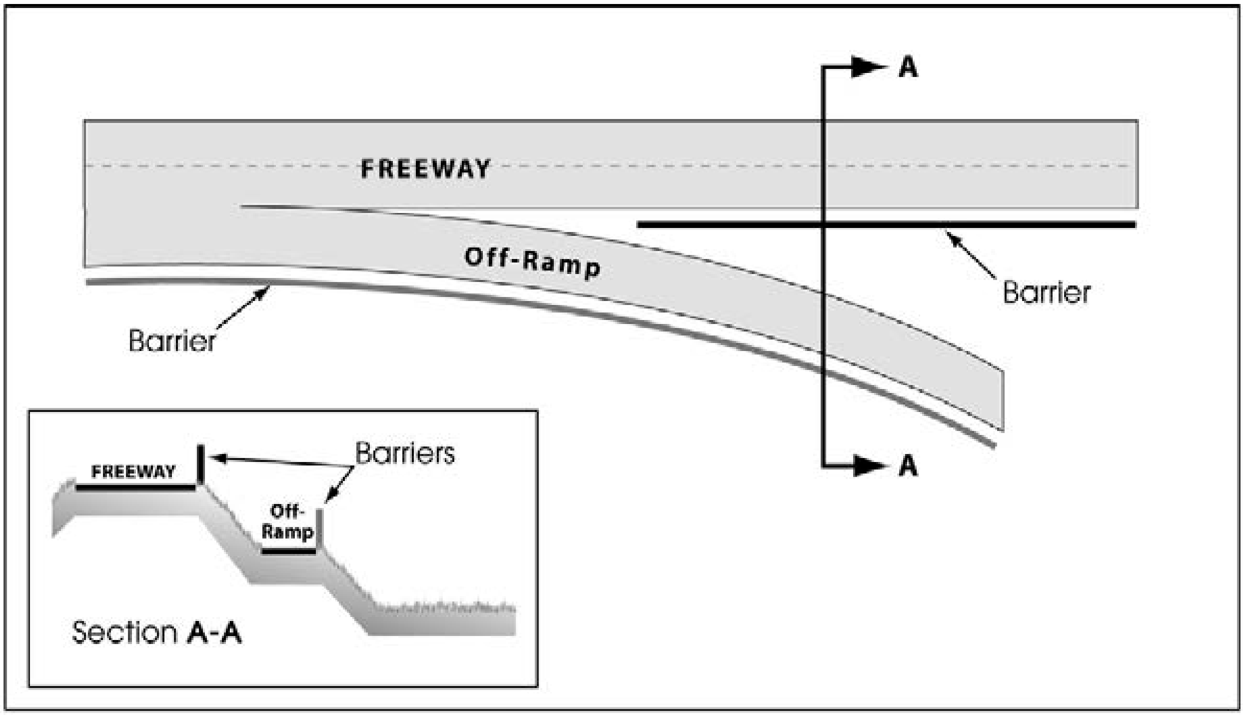

Figure 6-8. Barriers for Highway on Fill with Off-Ramp

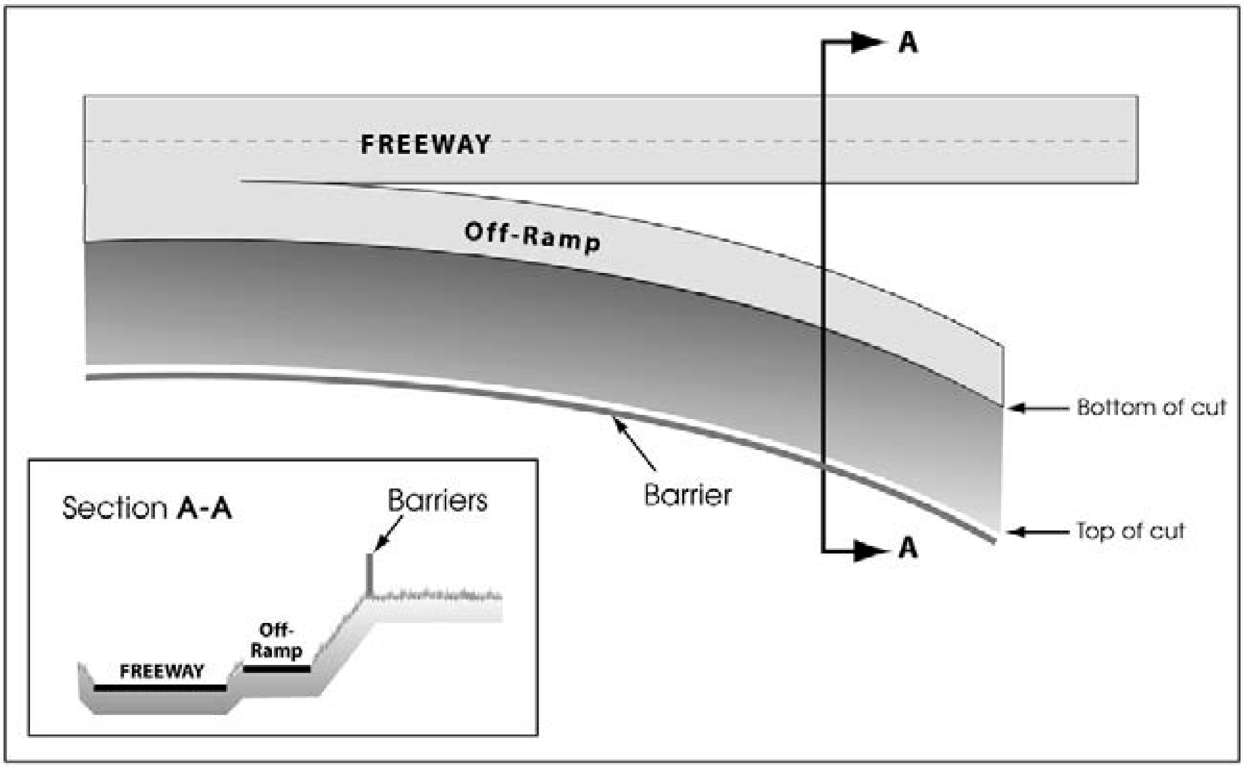

Figure 6-9. Barriers for Highway in Cut with Off-Ramp

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

6.1.3 Barrier Dimensions

Noise barrier dimensions depend largely on the freeway geometry, topography of the surrounding terrain, location of the noise barrier, and size of the area to be shielded by the barrier. According to Sections 2.1.4.4 and 5.5.1.5, barrier attenuation depends on the path length difference between the direct (before-barrier) and diffracted (after-barrier) noise paths. Figure 6-3 reviews the concept. Regardless of its orientation, the triangle formed by the source, top of noise barrier, and receiver will always yield the same barrier attenuation. Because the location of the bottom of the barrier is not part of the triangle, the highway geometry and terrain topography determine how high the barrier should be for a given barrier attenuation. Figure 6-10 illustrates this concept.

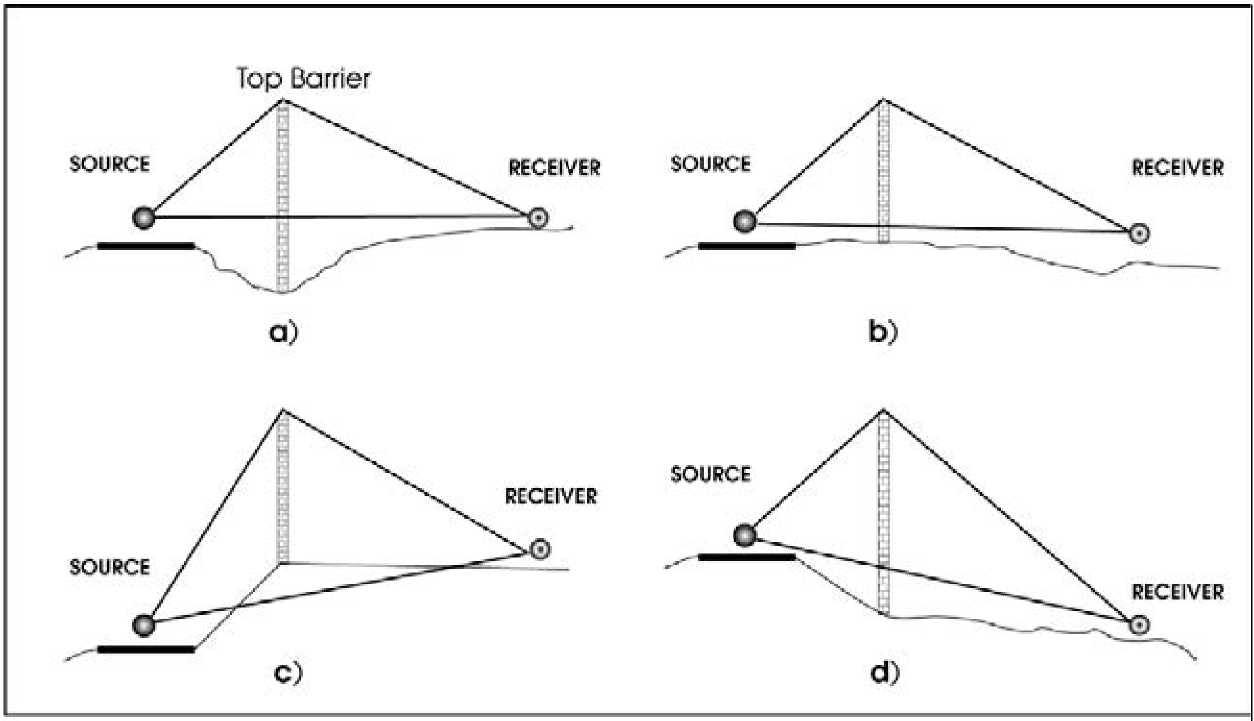

Figure 6-10. Actual Noise Barrier Height Depends on Site Geometry and Terrain Topography (Same Barrier Attenuation for “a,” “b,” “c,” and “d”)

Similarly, the length of the barrier is governed by the extent of the area to be shielded and the site geometry and topography (Figure 6-11).

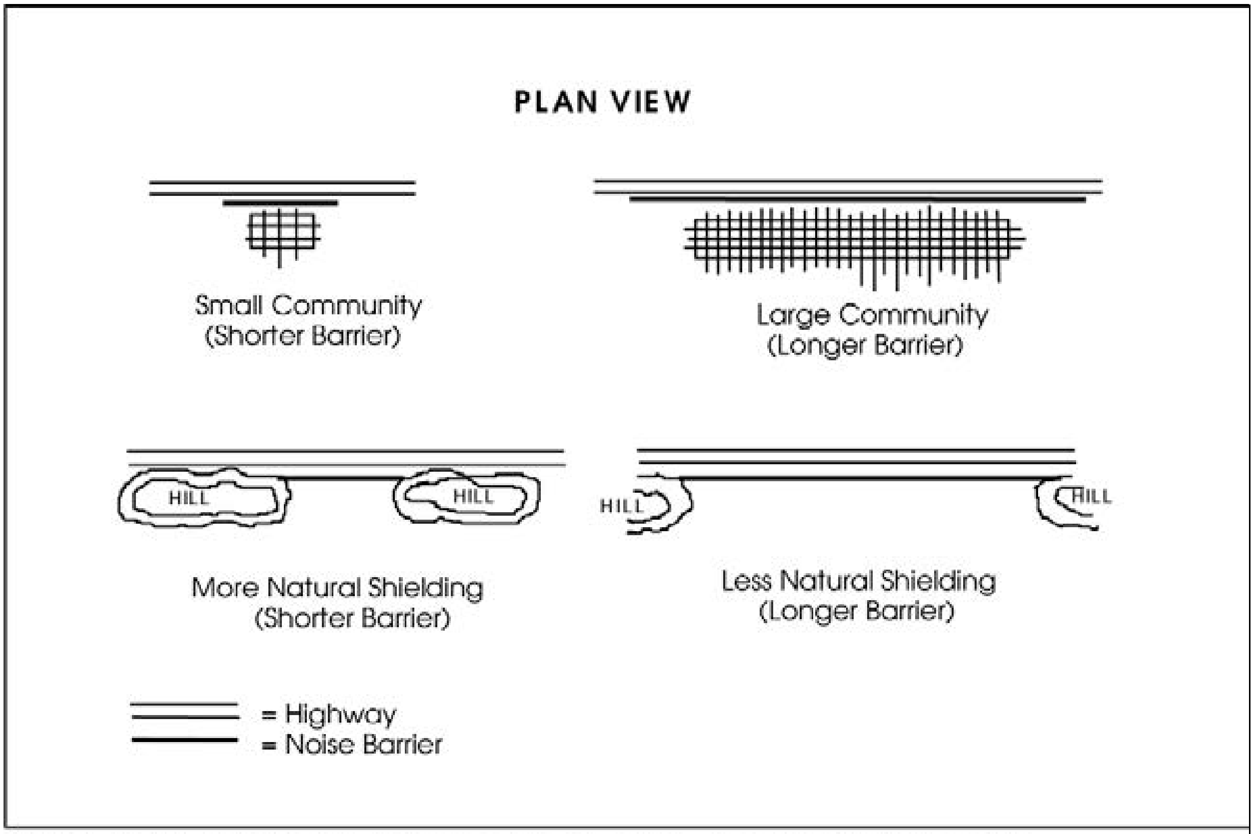

Figure 6-11. Noise Barrier Length Depends on Size of the Area to Be Shielded and Site Geometry and Topography

6.1.3.1 Height

Barrier height generally has the most direct influence on the effectiveness of a noise barrier. Figure 6-3 reviews the PLD concept. An increase in height of a noise barrier will result in a greater PLD and therefore greater noise attenuation. This increase in height is not linear, however.

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

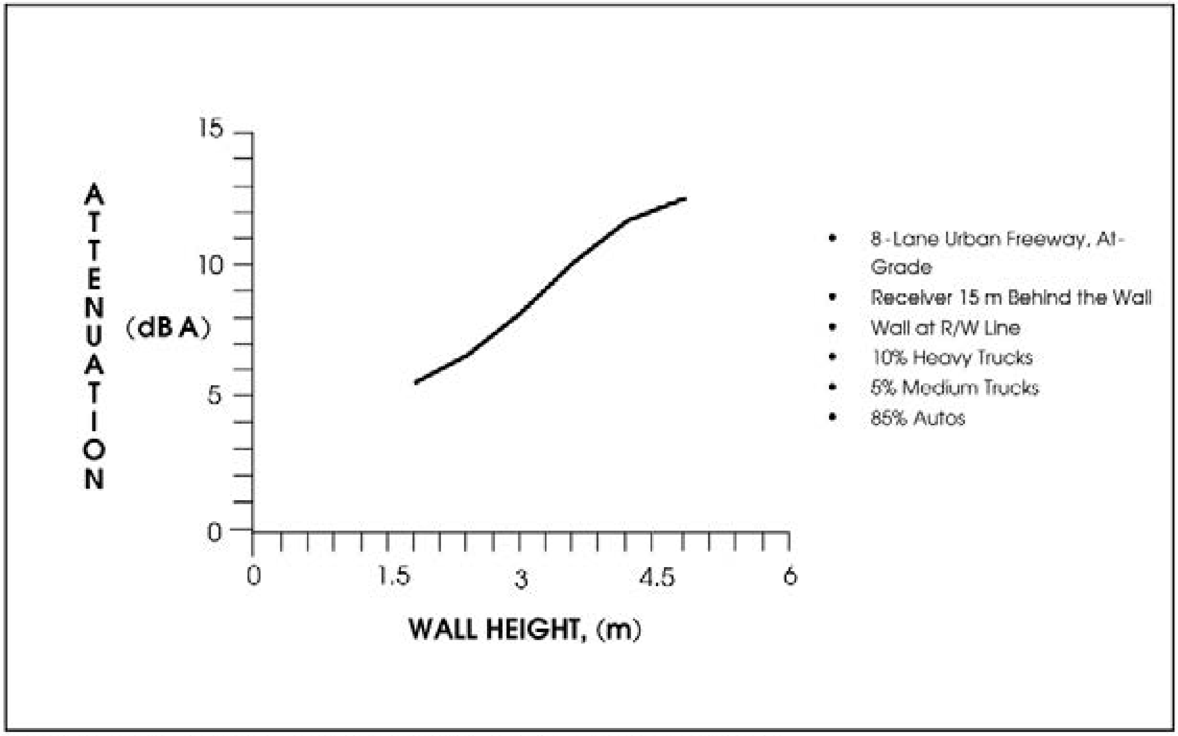

Figure 6-12. Soundwall Attenuation vs. Height for At-Grade Freeway

Please note that in this case the change in attenuation per incremental change in wall height is highest between wall heights of 9 and 11 feet, at 0.9 dBA per 1 foot. Above and below this range, the values are lower. Once the optimum height has been reached, any further increases in noise barrier height result in diminishing returns in effectiveness. However, higher barriers are often necessary to meet design goals.

Noise barriers along depressed freeways are less effective than those along at-grade freeways. In deep cuts, the receiver often is already effectively shielded by the tops of cuts. In some cases, this shielding may not reduce noise levels enough to satisfy noise abatement criteria, and an additional barrier behind the top of cut may be necessary to achieve further noise reductions.

When designing such a barrier, the designer should recognize that the without-barrier or before-barrier condition includes the shielding of the existing top of cut. Because of the diminishing-returns effect, a barrier of a given height along a depressed freeway will generally be less effective than a barrier of the same height at grade. The diminishing-returns effect, however, is not the only factor to consider.

It has been indicated that a berm is more effective than a wall. Computer noise-prediction models generally give berms 3 dBA more attenuation than a wall of the same height. A wall built at or near the top of cut essentially eliminates the extra attenuation afforded by the original top of cut, thereby further reducing the effectiveness of the wall.

Figure 6-13 shows the barrier attenuation vs. height plots for a receiver 50 feet behind a barrier located on the right-of-way of a typical urban eight-lane freeway in a 25-foot-deep depressed section. The traffic mix is the same as that for Figure 6-12, described above. Two attenuation curves are shown.

The upper curve represents attenuation differences between a wall (after-construction condition) and the top of cut (before-construction condition) in which the latter is treated as an existing wall. Such a condition would exist if a soundwall were built on top of an existing retaining wall (i.e., the top of cut would be the top of retaining wall).

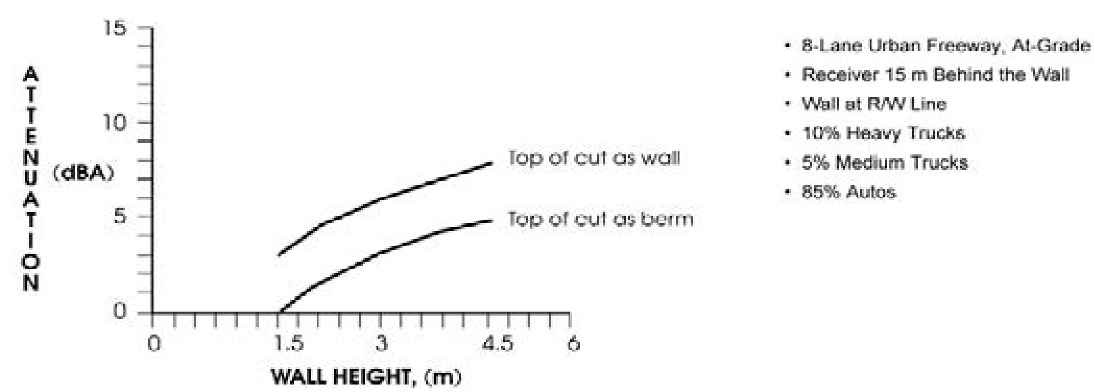

Figure 6-13. Soundwall Attenuation vs. Height for 25-Foot Depressed Freeway

Both the before and after conditions would then involve a wall. Likewise, if the before and after conditions consist of berms (built at or near the top of cut), the upper curve also would be a correct representation. The lower curve consists of attenuation differences between a soundwall and the existing top of cut, with the latter treated as a berm. The additional 3-dBA attenuation provided by the before condition is eliminated by the wall, making it less effective.

A similar phenomenon may also be encountered when freeways are built on embankments. Receivers located near the top of fill may be fully or partially shielded from traffic by the top of fill or hinge point. For these receivers, a wall built on top of the embankment may be less effective than for receivers located farther from the freeway.

The above discussions illustrate the importance of noise source, barrier, and receiver relationships in designing effective noise barriers. These geometries not only affect the barrier attenuation, but also noise propagation in many cases.

Sections 2.1.4 and 5.5.1.3 discuss hard- and soft-site characteristics. The excess noise attenuation provided by a soft site is caused by the noise path's proximity to a noise-absorbing ground surface. If a noise barrier is constructed between a source and receiver, the diffracted noise path is lifted higher off the ground, causing less noise absorption by the ground and a lower rate of noise attenuation with distance. Figure 6-14 illustrates this concept.

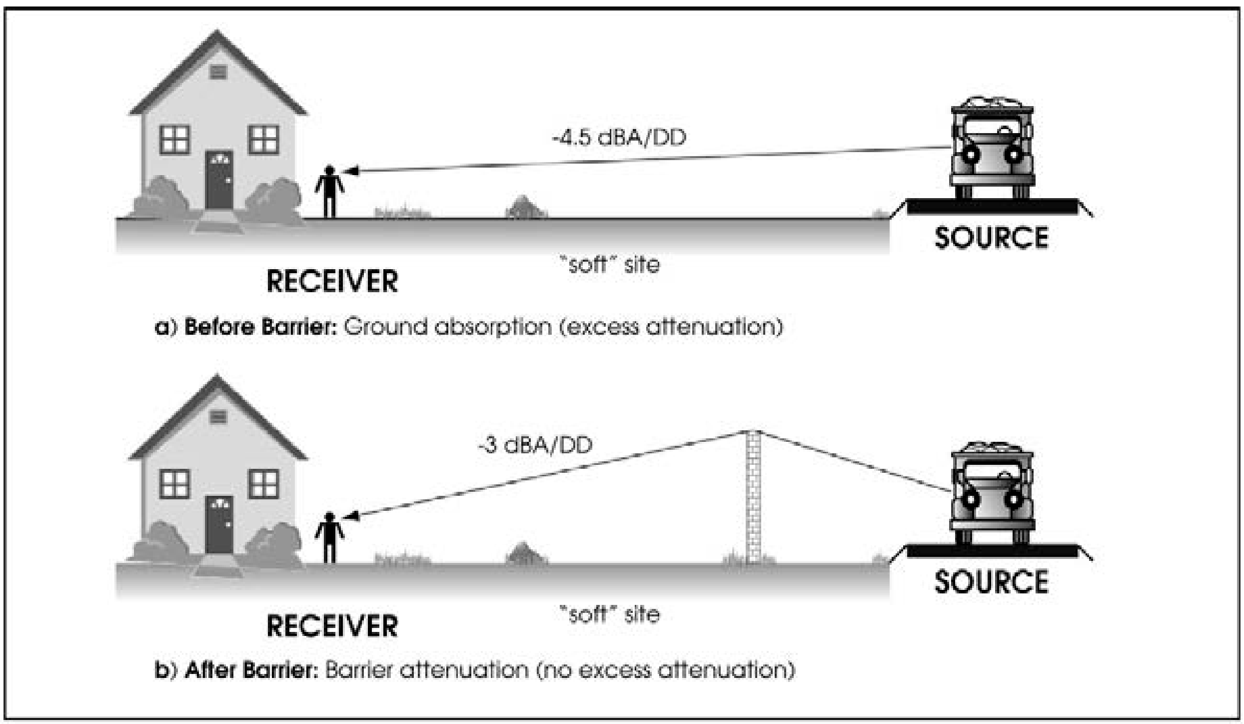

Figure 6-14. Loss of Soft-Site Characteristics from Constructing a Noise Barrier

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

The potential of a barrier to be less effective than indicated by barrier attenuation alone gave rise to the term insertion loss. Section 6.1.5 discusses the difference between barrier attenuation and insertion loss in detail. The insertion loss of a barrier is the net noise reduction provided by a barrier at a receiver. It includes barrier attenuation and before- and after-barrier differences in noise propagation characteristics (i.e., it is the actual noise reduction caused by inserting a noise barrier between source and receiver). A measured insertion loss is usually referred to as field insertion loss.

Finally, another height consideration in the acoustical design of noise barriers is Caltrans guidance to break the line of sight between an 11.5-foot-high truck exhaust stack and 5-foot-high receiver in the first tier of houses. This guideline, detailed in *Highway Design Manual* Chapter 1100, was intended to reduce the visual and noise intrusiveness of truck exhaust stacks at the first-line receivers. The line-of-sight break guidance is still in effect at the time of this writing. However, this guideline may be changed or eliminated in the near future. The online version of the *Highway Design Manual* should be consulted for the latest status of Chapter 1100 and any changes.

Barrier heights determined by the noise prediction model often satisfy the acoustical requirements without shielding high truck exhaust stacks. Although such barriers may reduce noise levels sufficiently in terms of NAC, they have generated complaints from the public in the past. The line of sight break criterion occasionally governs the height of a noise barrier.

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

The 11.5-foot dimension is not related to the noise centroid heights used for heavy trucks in the traffic noise prediction model and therefore should not be used for noise predictions. The heavy truck noise centroid indicated in FHWA-RD-77-108 model are the resultant location of the noise sources coming from a truck, not only the noise from the exhaust outlet. The TNM distributes vehicle sources over two heights for each vehicle group.

Determining the line-of-sight break is a separate process from predicting noise. Generally, it is desirable to calculate and plot the break profile along the barrier alignment before the acoustical design of the noise barrier. A Caltrans computer program named “LOS” is available for this purpose. If more than one barrier alignment is under consideration, the line-of-sight break must be calculated for each alignment alternative.

The line-of-sight break height depends on the three-dimensional locations of the 11.5-foot truck stack, receiver, and bottom of the barrier (interface between barrier and ground). To calculate the height for a certain source, barrier, and receiver combination, the designer needs to determine the critical truck stack lane, which is the lane in which the 11.5-foot truck stack creates the highest line-of-sight break. Figure 6-15 shows a quick method of determining which lane is critical. If the receiver is located above a baseline drawn through far- and near-lane truck stacks, the far lane is critical. If the receiver is located below this line, the near lane is critical. When the receiver is on the line, either lane is critical. Please note that the line does not need to be horizontal or level.

Highway Design Manual Chapter 1100 does not give guidance on whether the entire barrier or only a portion of the barrier should break the line of sight for a certain receiver. On one extreme, a series of line-of-sight intercepts can be calculated from one receiver, covering the entire barrier. On the other extreme, only one intercept can be calculated using a perpendicular line from the receiver to the barrier or highway. In the absence of an official policy, it is recommended that a distance of 2D left and right along the centerline of the critical lane, measured from a perpendicular line from the receiver to the lane, be used (where D = the distance from receiver to the lane). Also, it is recommended that the portion of the barrier evaluated be further constrained by a maximum distance from receiver to truck stack (D_t) of 500 feet. Figure 6-16 shows the recommended constraints.

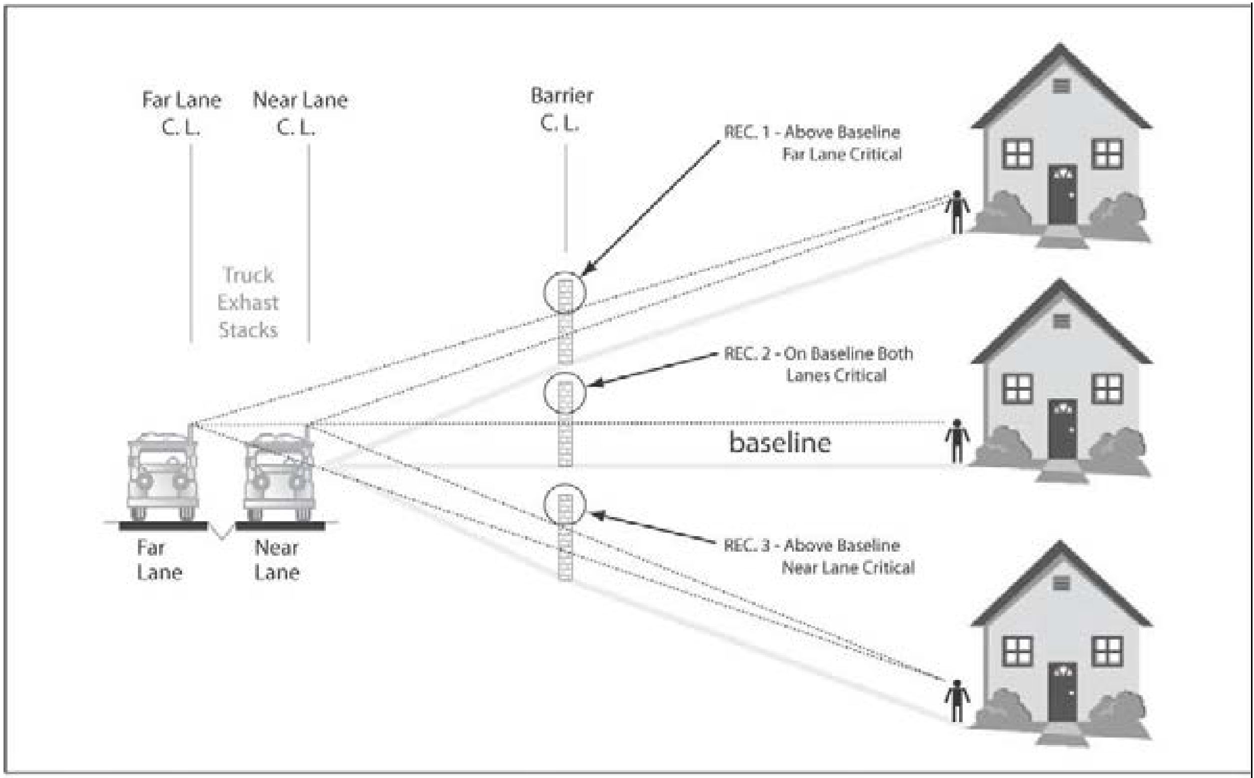

Figure 6-15. Determination of Critical Lane for Line-of-Sight Height (Consult Online Version of *Highway Design Manual* Chapter 1100 for Latest Status or Changes in Line-of-Sight Guidance)

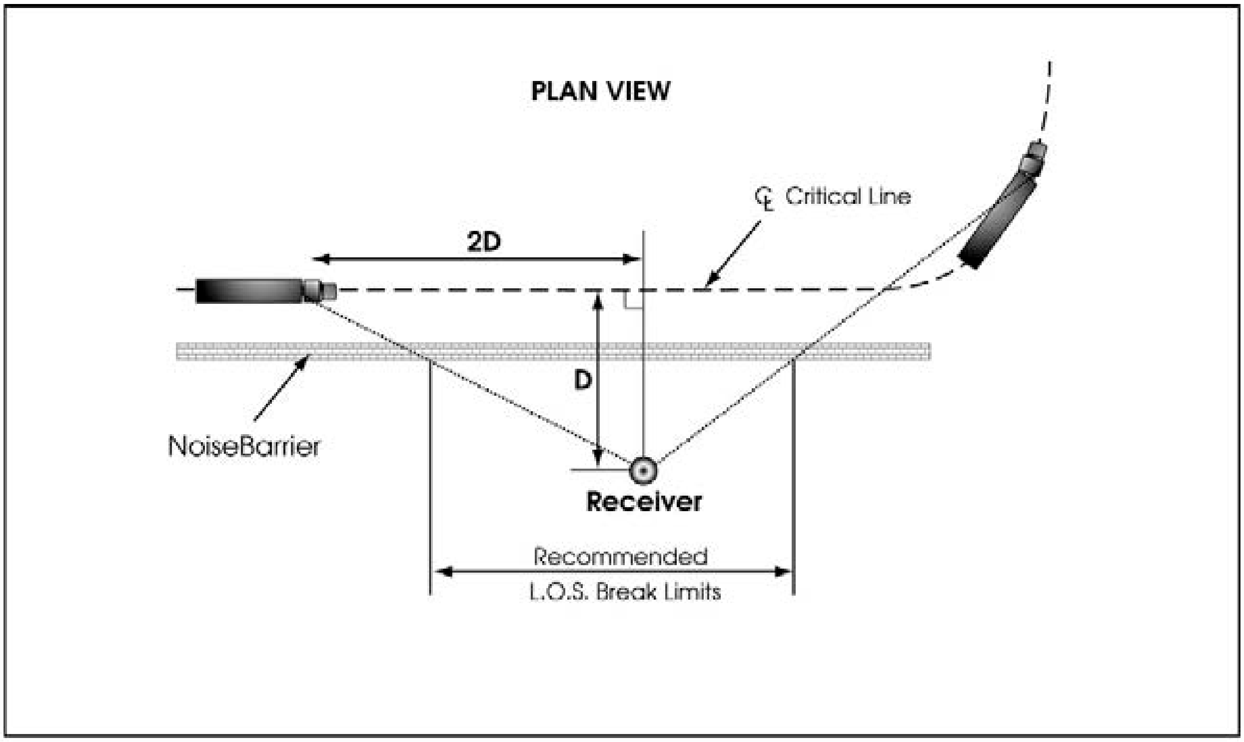

Figure 6-16. Recommended Line-of-Sight Break Limits (Consult Online Version of *Highway Design Manual* Chapter 1100 for Latest Status or Changes in Line-of-Sight Guidance)

6.1.3.2 Length

A noise barrier should be sufficiently long to protect the end receivers (see Figure 6-17). If the barrier is not long enough, the exposed roadway segment will contribute a significant portion of noise energy and sharply reduce the effectiveness of the barrier. For example, if a barrier ends at the receiver, half of the roadway is exposed, and the noise reduction by the barrier is 3 dBA or less.

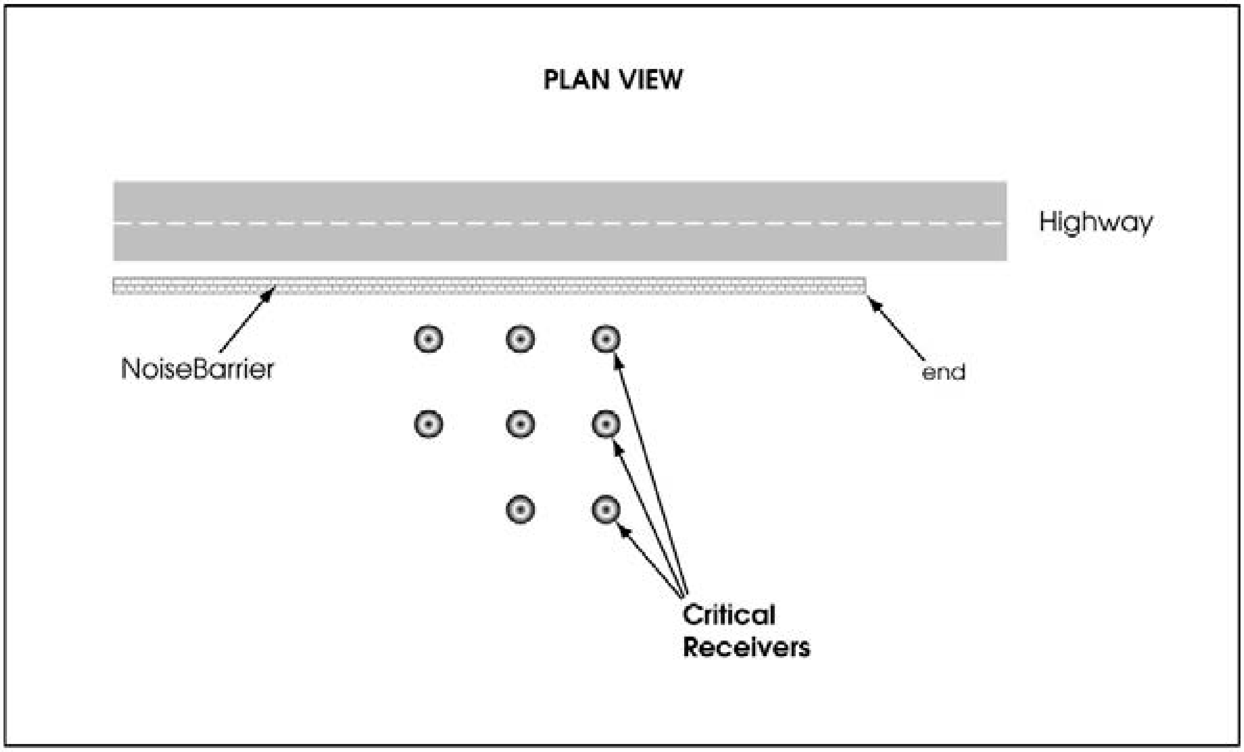

Figure 6-17. Barrier Extended Far Enough to Protect End Receivers

As a general rule, a noise barrier should extend at least 4D beyond the last receiver (where D = the perpendicular distance from barrier to receiver) (see Figure 6-18). The "4D rule," however, should be considered a starting point, and the FHWA model should be used to precisely locate the end of the barrier. Often, the critical end receivers are not in the first row of homes, but several rows farther from the highway (see Figure 6-17). As the barrier-to-receiver distance increases, highway noise becomes lower, but the barrier segment angle is also reduced, making a potential noise barrier less effective. The FHWA model is needed to resolve these opposing factors.

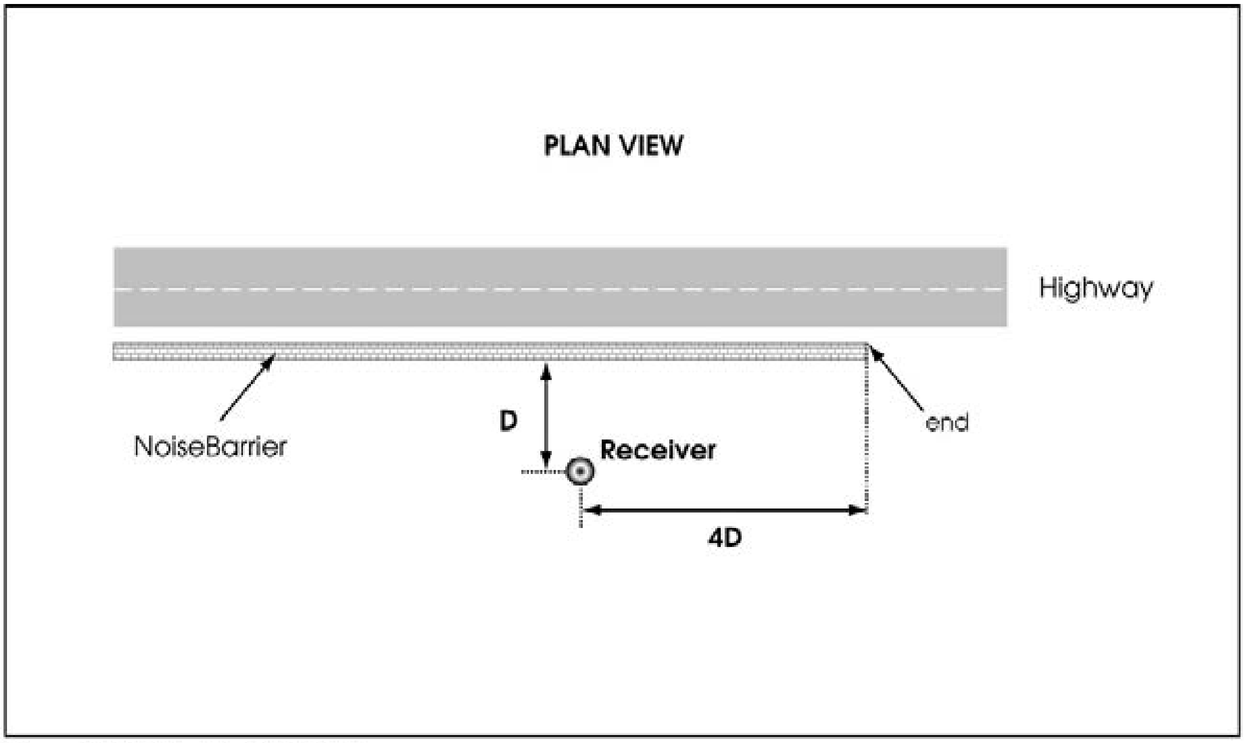

Figure 6-18. 4D Rule

Another way of dealing with end receivers is shown in Figure 6-19. The barrier is "hooked" around the critical receivers. The obvious advantage of this design is the shorter barrier length compared to the normal barrier extension. The disadvantage is legal agreements between Caltrans and the private property owners concerning construction easements, barrier maintenance, and responsibilities.

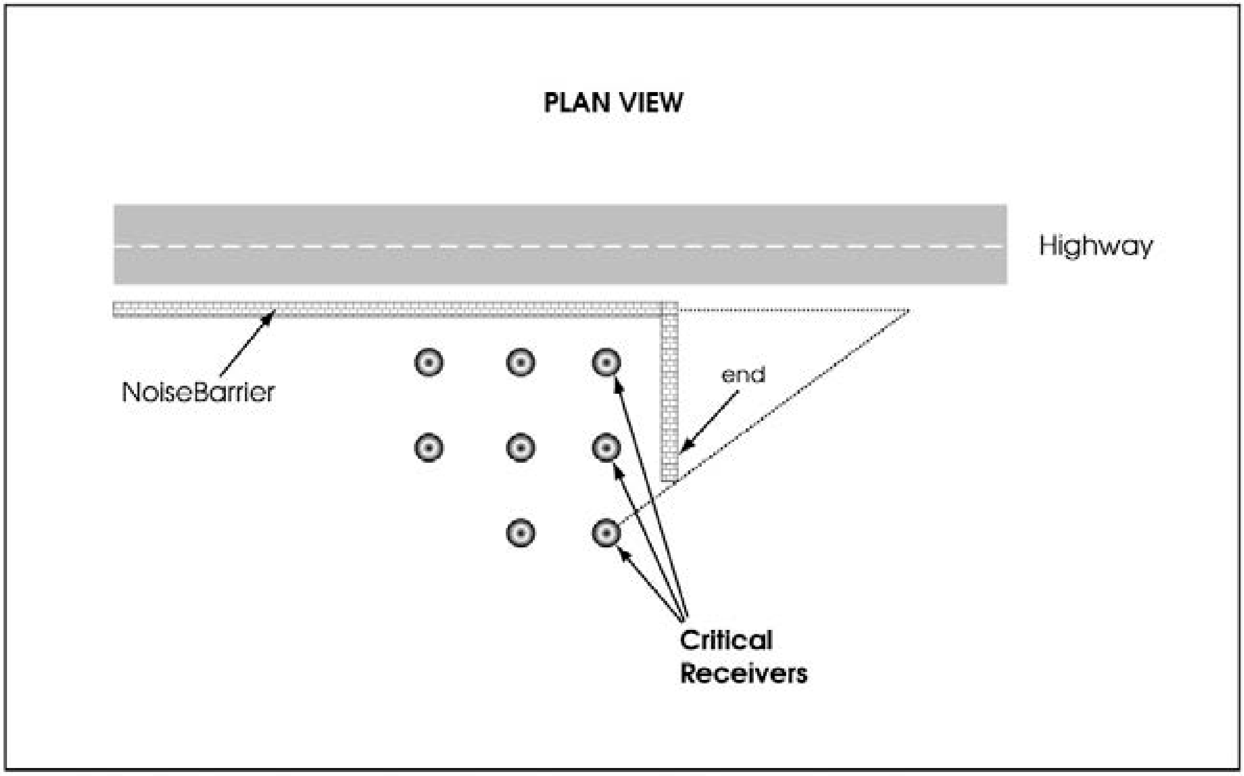

Figure 6-19. Barrier Wrapped around End Receivers, an Effective Alternative

6.1.4 Barrier Shape

Section 5.5.1 indicates that the FHWA model distinguishes between two noise barrier shapes: thin screen (wedge) and earth berm. Figure 6-20 shows representations of the two barrier shapes.

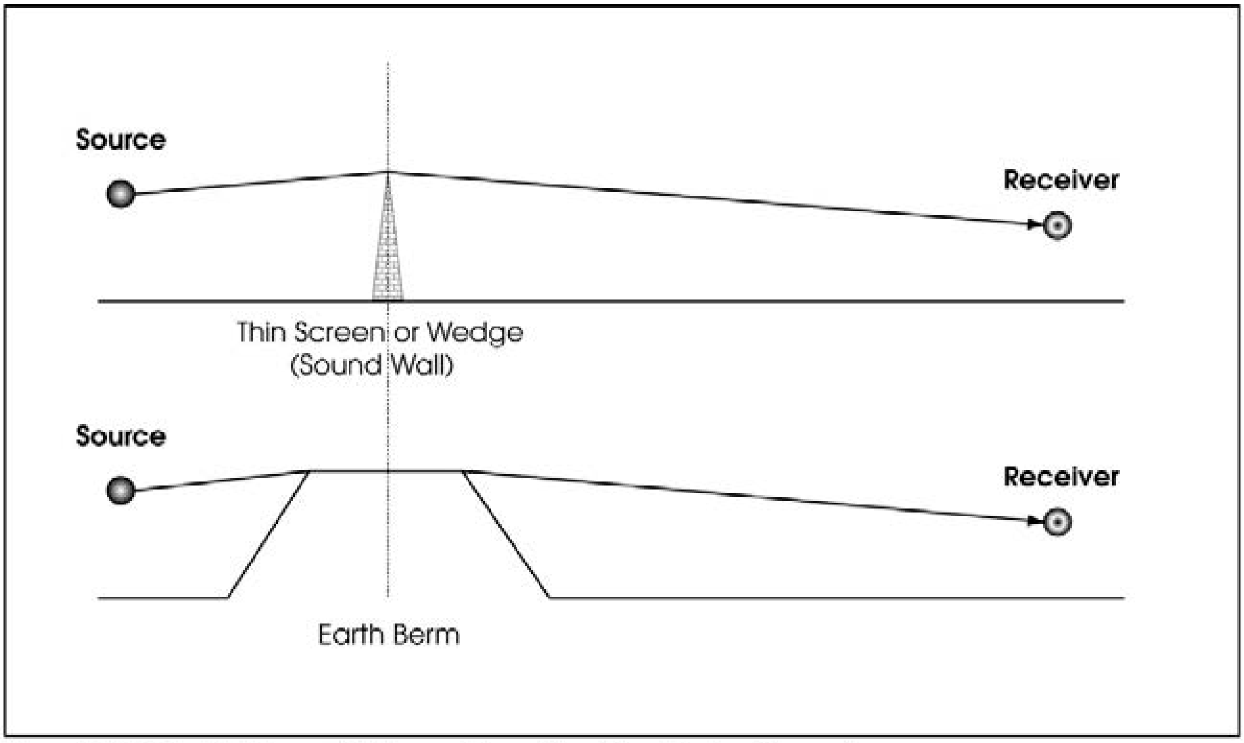

Figure 6-20. Thin Screen vs. Berm (Berm Gives More Barrier Attenuation)

Given the same site cross section, distance between source and receiver, and barrier height, a berm allows a greater barrier attenuation than the thin screen (wedge), such as a soundwall. Although FHWA assumes 3 dBA of attenuation more for the berm than the thin screen, the actual extra attenuation may be somewhere between 1 and 3 dBA.

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

Other barrier shapes have been researched, including “T-tops,” “Y-tops,” pear-shaped tops, and curved walls. Given the same total wall height, these do little to improve barrier attenuation, usually only about 1 or 2 dBA at most. Figure 6-21 shows some different shapes. The extra cost of constructing these shapes usually does not warrant this small benefit.

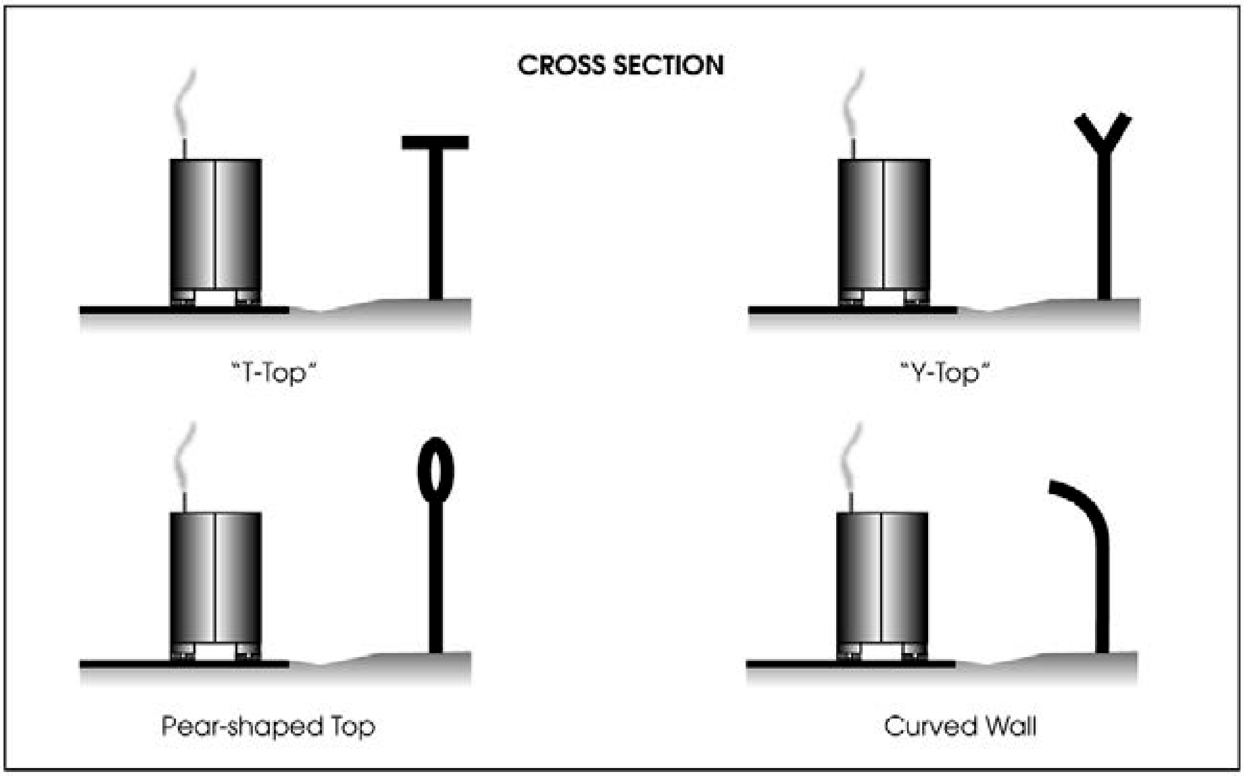

Figure 6-21. Various Wall Shapes (Minimal Benefit for Extra Cost)

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

6.1.5 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 6-22 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.

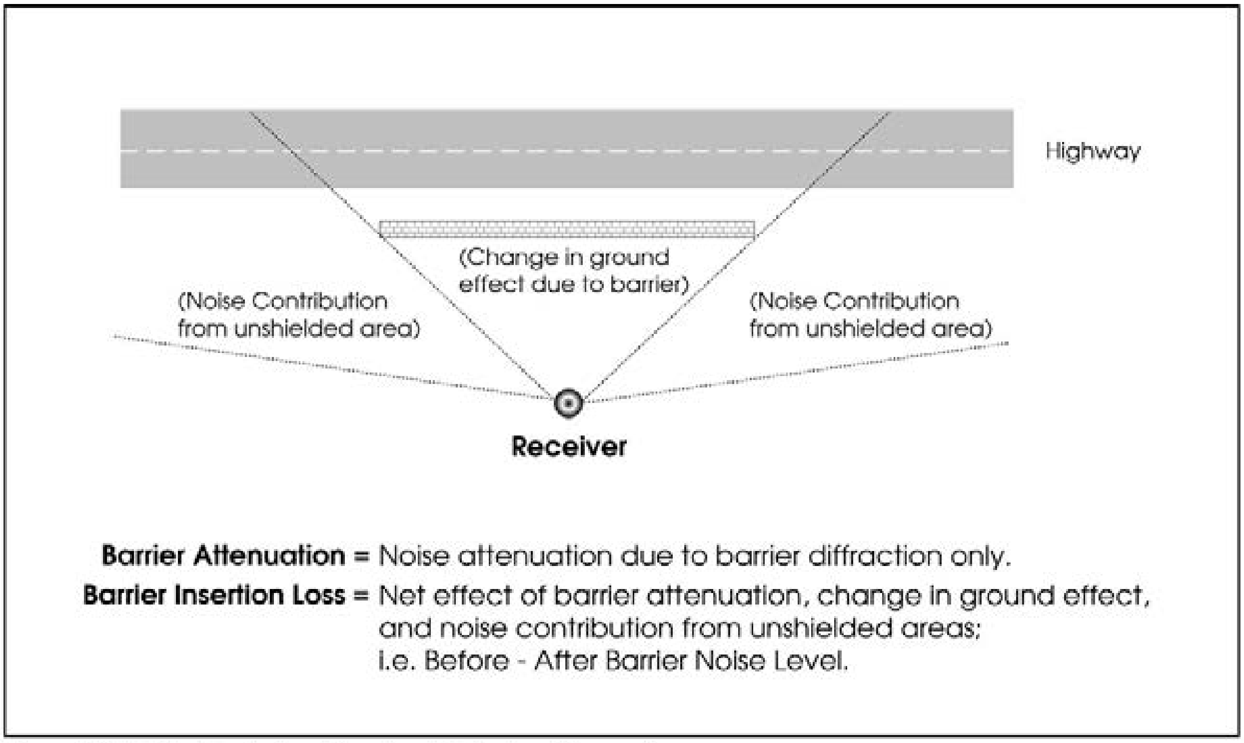

Figure 6-22. Barrier Insertion Loss vs. Attenuation

6.1.6 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 two examples illustrate a method of including existing background noise levels. The first involves a new facility in a residential area. The second involves a project along an existing facility.

Example 1: New Facility

Given

Background noise level: 60 dBA at receivers

New facility (without background): 68 dBA at receivers

Total predicted: 69 dBA at receivers

From this data, it is decided to design a noise barrier that will reduce the total noise level by 5 dBA. The model predicts noise levels without the background noise level. However, the latter 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.

Calculation

Predicted noise level (dBA) = 64 – 60 = $10\log_{10}(10^{6.4} - 10^{6.0}) = 61.8 \approx$ **62 dBA**.

Calculated insertion loss should then be 69 – 62 = **7 dBA** to reduce the total noise level by 5 dBA.

The next example, involving an existing facility, is more complicated, because the background noise levels at the receivers located near the existing highway are contaminated by noise originating from the highway, and therefore not known. Background noise levels can, however, be estimated from measurements taken throughout the community at sites far enough from the highway to not be influenced by it. (see Section 3.2.2.1). Once this is accomplished, the problem is essentially the same as example 1.

Example 2: Existing Facility

Background noise level: 60 dBA at receiver (estimated)

Existing noise level (measured): 65 dBA at receiver

Existing noise level (calculated using model): 64 dBA at receiver

With-project noise level: 68 dBA at receiver (predicted without background)

The existing noise level is contaminated by the background noise level; the difference between the two is less than 10 dBA. Therefore, model calibration is not allowed, and the predicted with-project noise level is used without adjustment, as explained in Section 5.4.1.5. The problem is then solved as shown in Example 1.

6.1.7 Reflected Noise and Noise Barriers

6.1.7.1 Noise Reflection Issues

The subject of noise reflections is one of the issues raised in recent years concerning negative effects of noise barriers. As often occurs, the solution of one problem can create other problems. In the case of noise barriers, reducing noise at receivers on one side of the highway could potentially increase the noise at receivers on the other side. The complex nature of noise barrier reflections, 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 8.

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

- 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.

6.1.7.2 Single Barriers

Simple Terrain

Figure 6-23 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 6-23). 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.

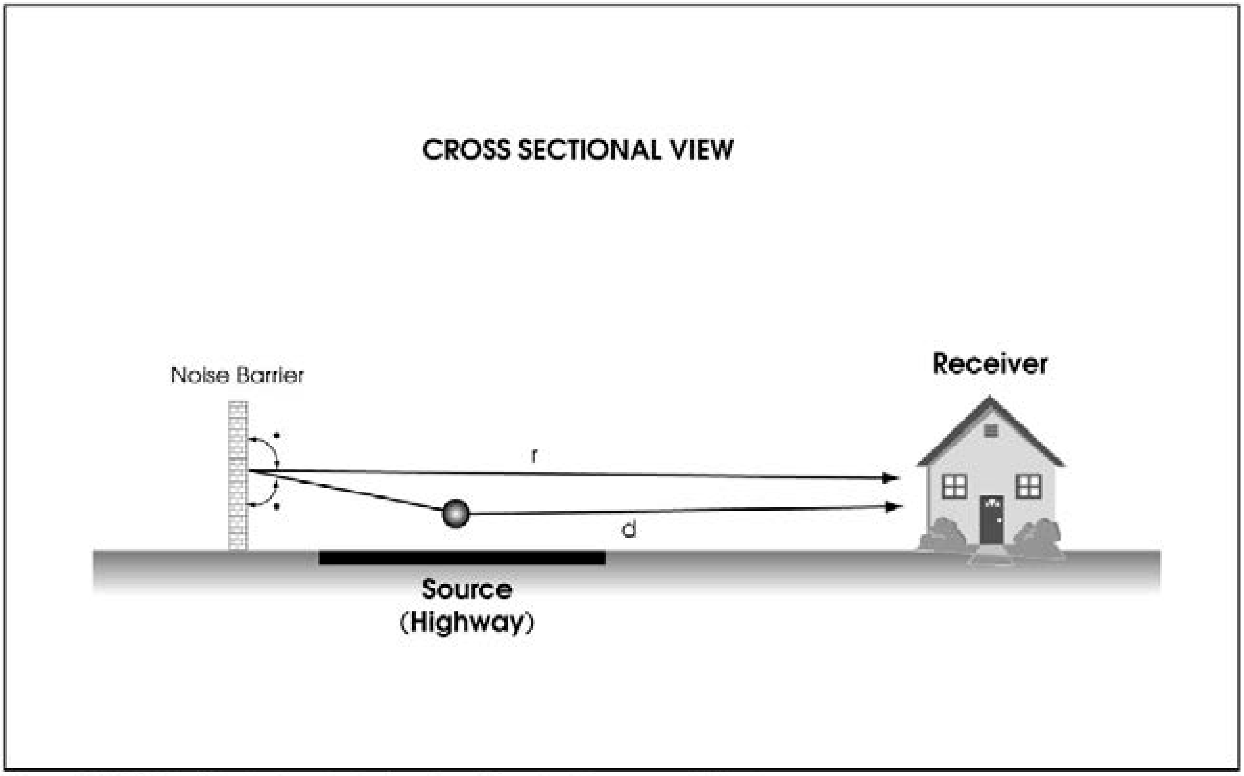

Figure 6-23. Single-Barrier Reflection (Simplest Representation)

Figure 6-24 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.

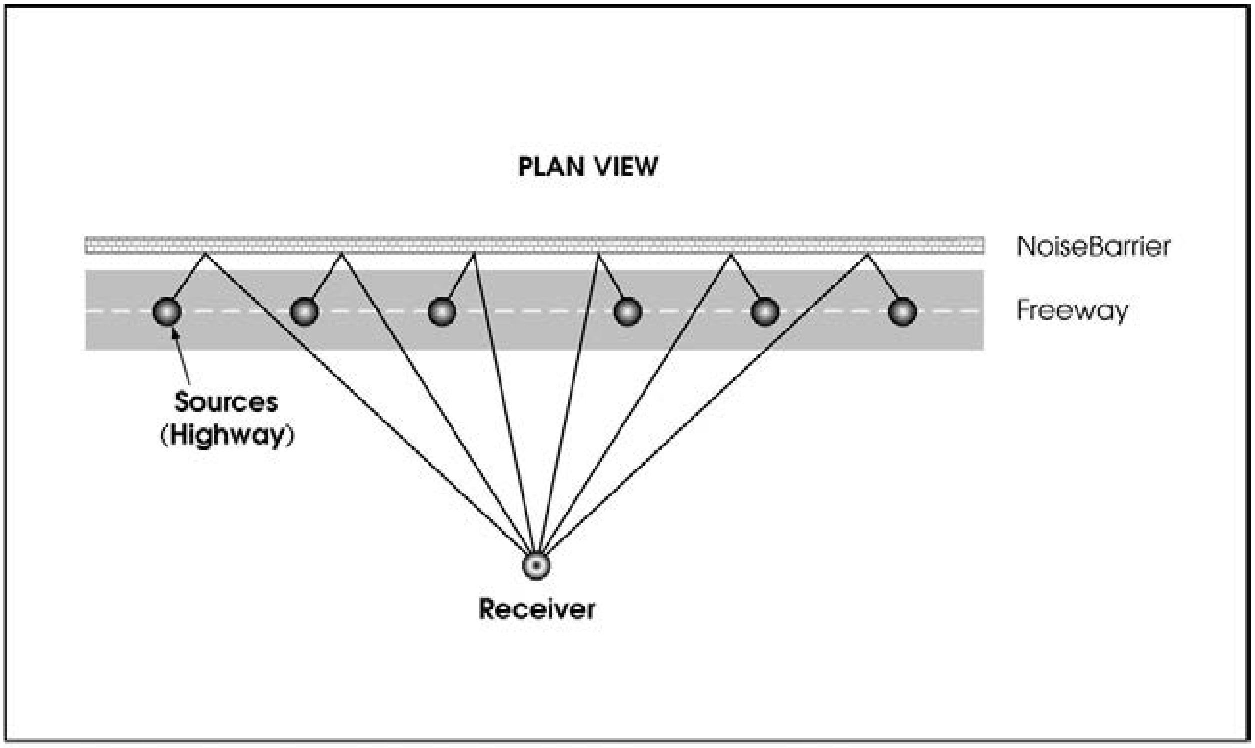

Figure 6-24. Single-Barrier Reflections (Infinite Line Source and Noise Barrier)

Figure 6-25 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 6-23 and 6-24. In plan view, the pavement reflections would also shown to be a line source. The reflection point R_1 shown on the pavement (Figure 6-25) actually may fall off the pavement on absorptive ground, reducing the before-barrier noise levels at the receiver. The pavement reflection point R_2, however, significant only after building the barrier, usually will be on the pavement. Therefore, the difference between before- and after-barrier noise levels could 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.

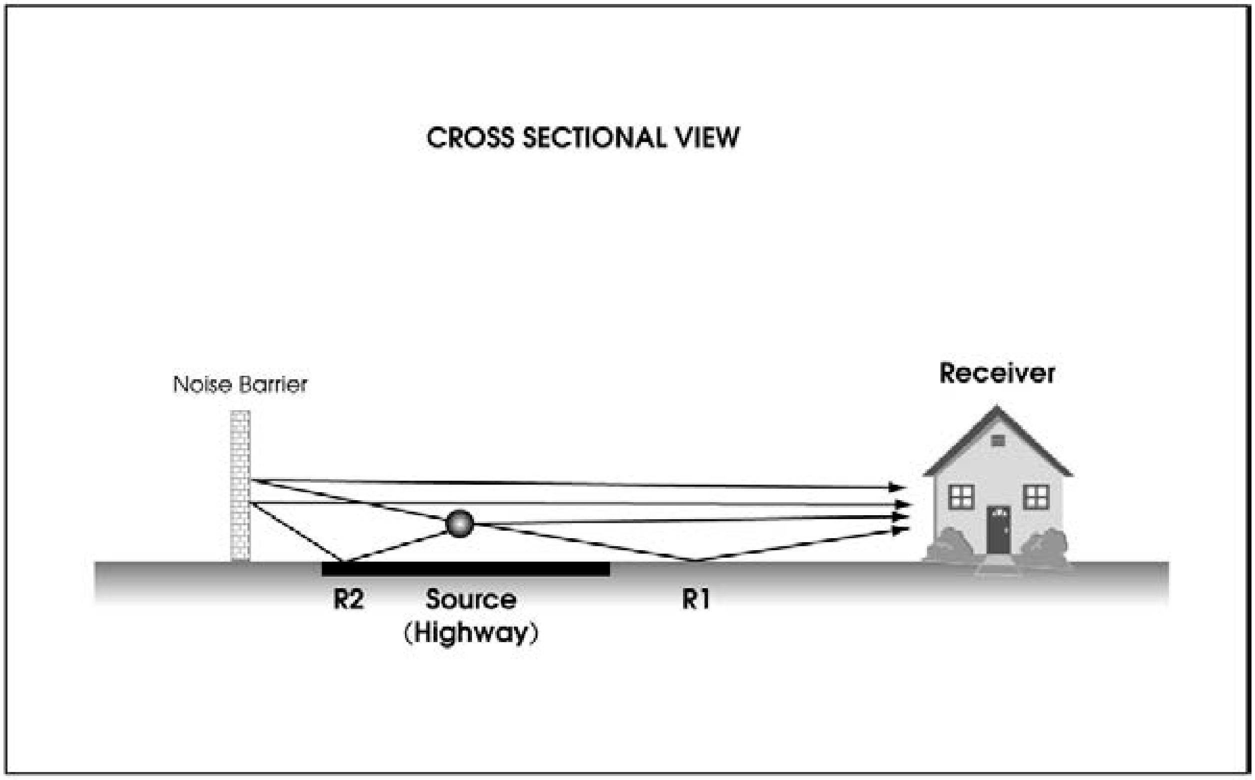

Figure 6-25. Single-Barrier Reflection (More Accurate Representation)

Figure 6-26 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.

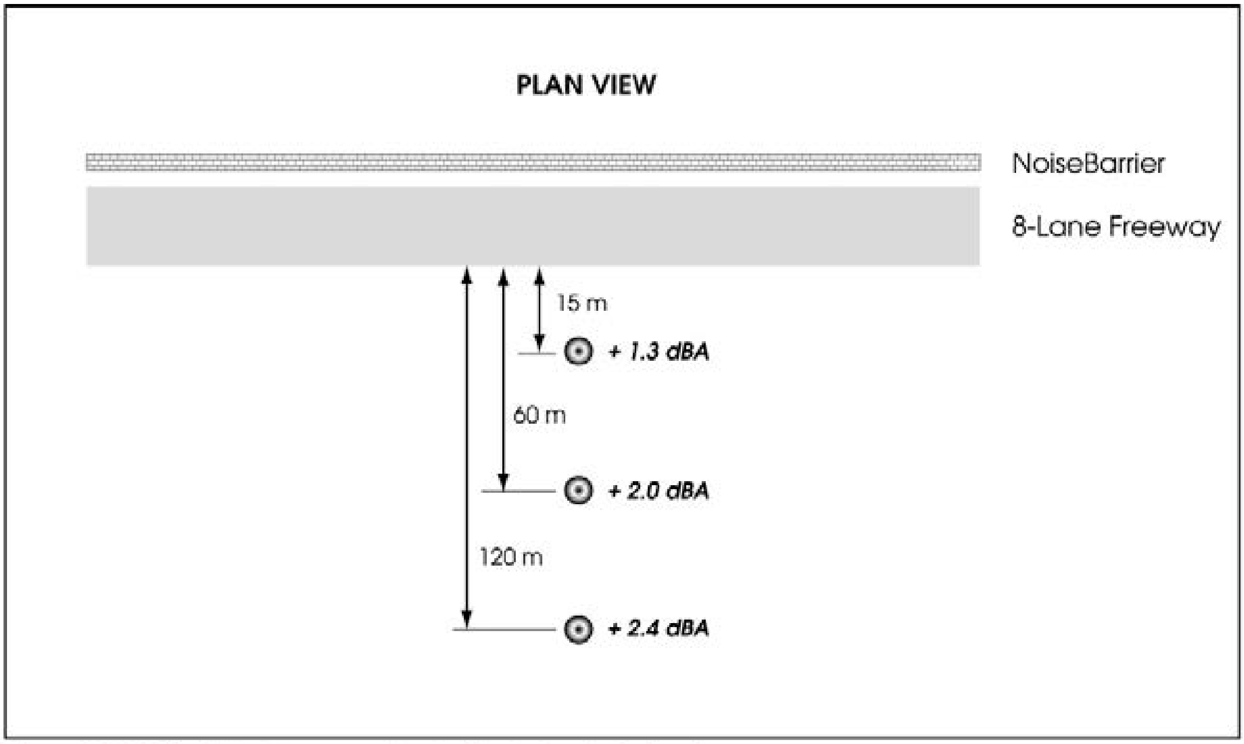

Figure 6-26. Noise Increases from Single-Barrier Reflections

Real-world situations are far more complicated than shown in Figures 6-23 to 6-26. 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. The human ear cannot perceive such small increases.

Complex Terrain

In more complex terrain there are instances when single-barrier reflected noise could increase noise levels perceptibly (3 dBA or more) at a receiver. One such case is shown in Figure 6-27, 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.

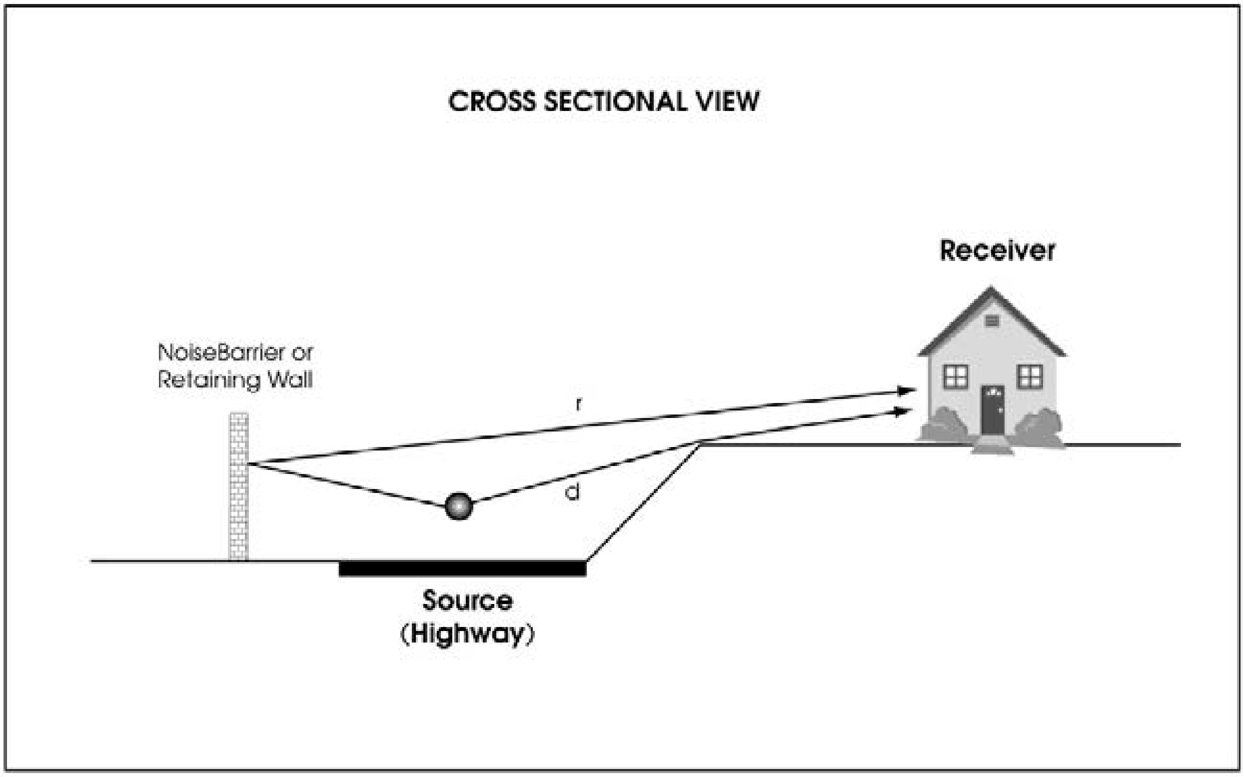

Figure 6-27. Single-Barrier Reflection (Direct Noise Shielded, Reflected Noise Not Shielded)

Reflections off single barriers located at the top of cut (Figure 6-28) generally are directed over a 5-foot-high receiver on the opposite side and therefore are usually not a problem for low receivers. However, higher receivers, such as the second floor of a residence or receivers located on a higher hill behind the front receivers, still may be affected by the reflections if the direct noise is shielded.

Situations depicted in Figures 6-27 and 6-28 (high receivers only) usually increase noise levels by a maximum of 3 to 5 dBA, depending on the angle of reflections and the height and length of reflective barrier. Because noise barrier heights are normally restricted to 16 feet by Caltrans policy, the maximum noise increases from reflections are usually caused by retaining walls, which are not constrained in height.

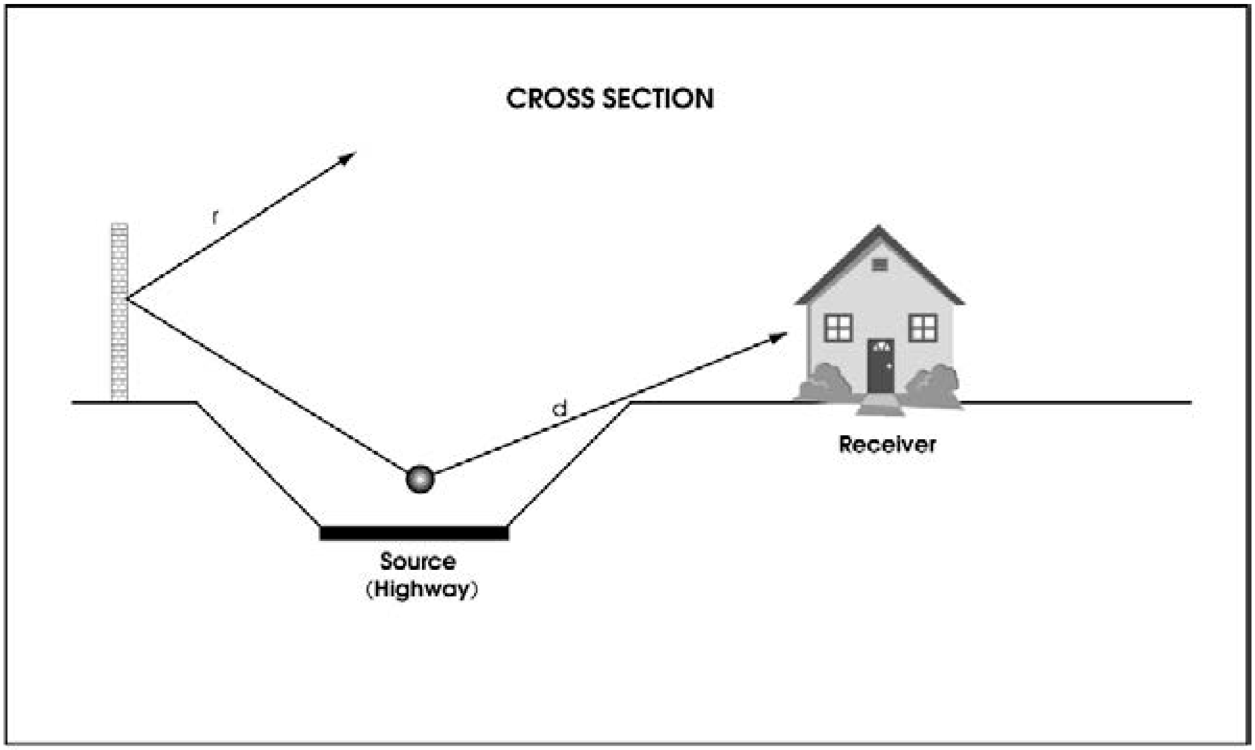

Figure 6-28. Single-Barrier Reflection (Noise Barrier on Top of Opposite Cut)

Single barriers on the top of fills (Figure 6-29) generally do not present any reflection problems. The reflected noise ray is usually well above the receiver.

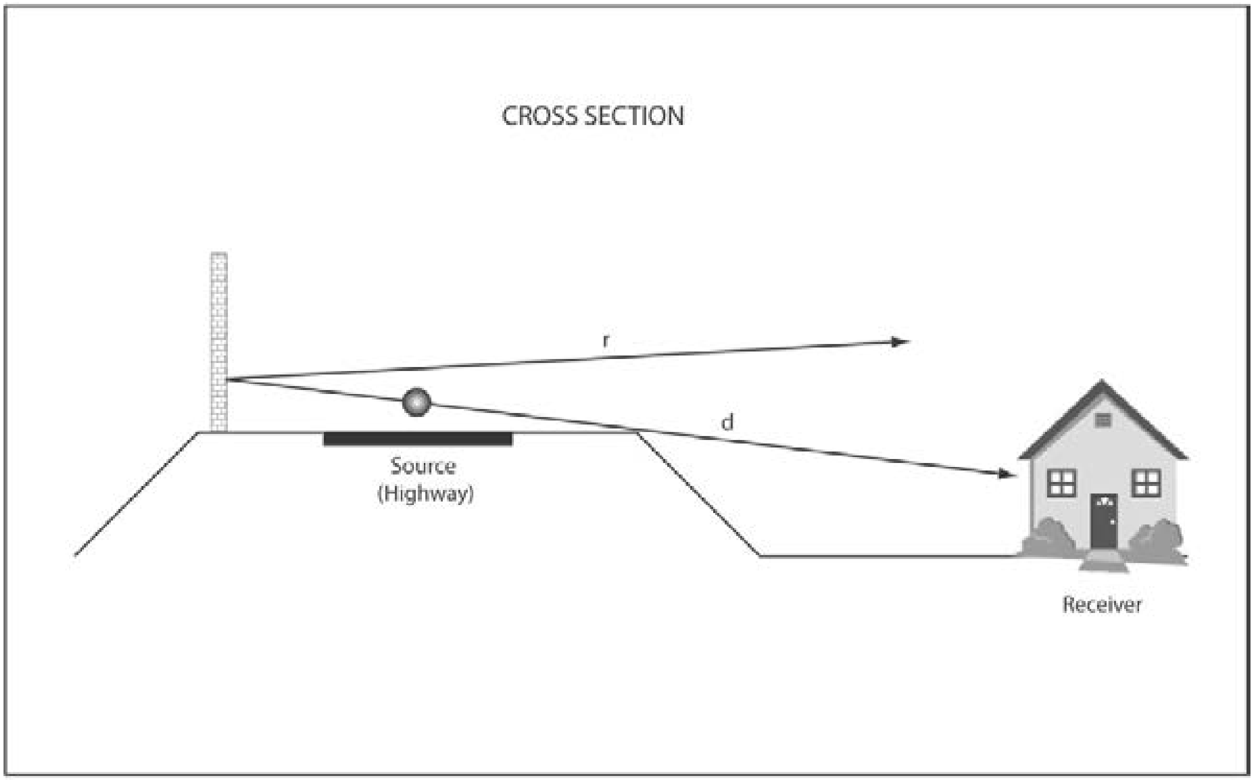

Figure 6-29. Highway and Noise Barrier on Fill

6.1.7.3 Modeling Single Barrier Reflections

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

Caltrans versions of FHWA HTNPM computer programs (L_{eq}V2, Sound32, and Sound2000) also have no provisions for calculating single barrier noise reflections directly. For simple situations, the effects of reflections can be evaluated in LeqV2, Sound32, Sound2000, and TNM using additional elements or coordinates of image sources. Figures 6-30 and 6-31 illustrate these in cross section and plan views.

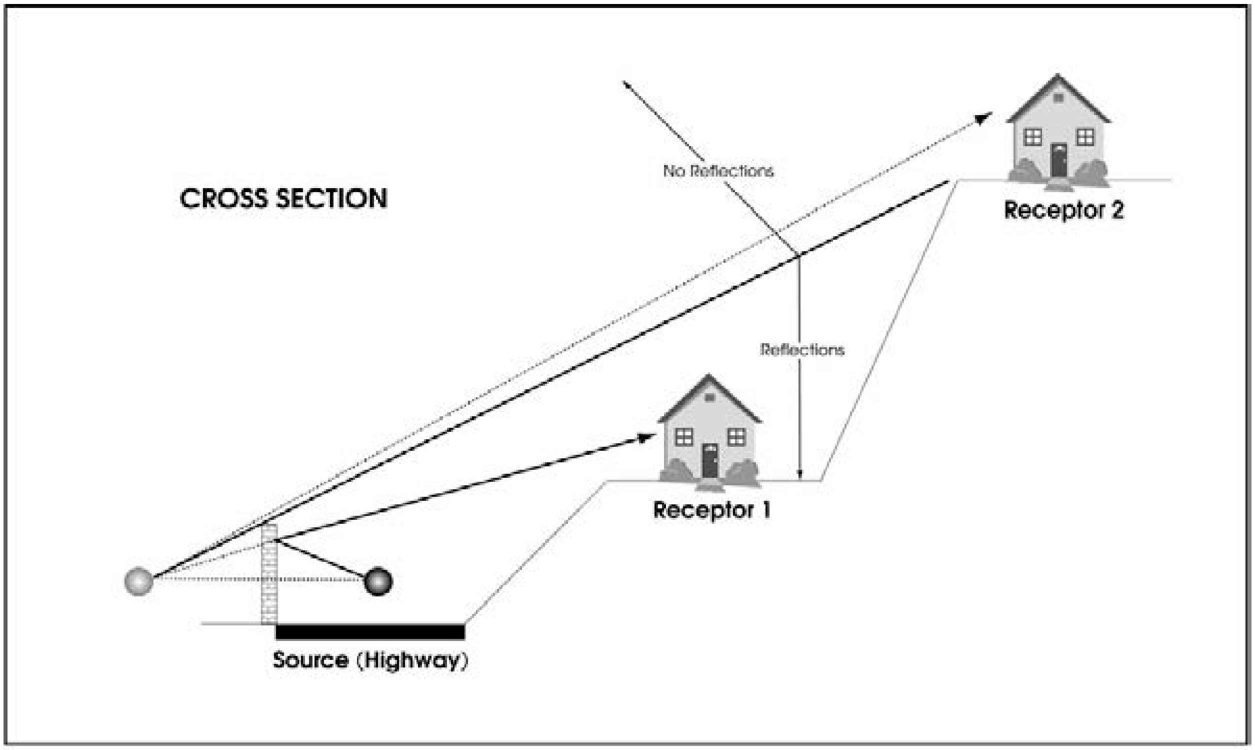

Figure 6-30. Placement of Image Sources (Cross Sectional View)

Figure 6-30 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 6-31 shows plotting of image sources in a plan view. A general case is shown with a finite wall that is not parallel to the roadway. This case was selected to illustrate how image sources are generated in plan view. Examination of Figure 6-31 reveals that a finite wall creates a unique finite image line source for a particular receiver on the opposite side of a highway.

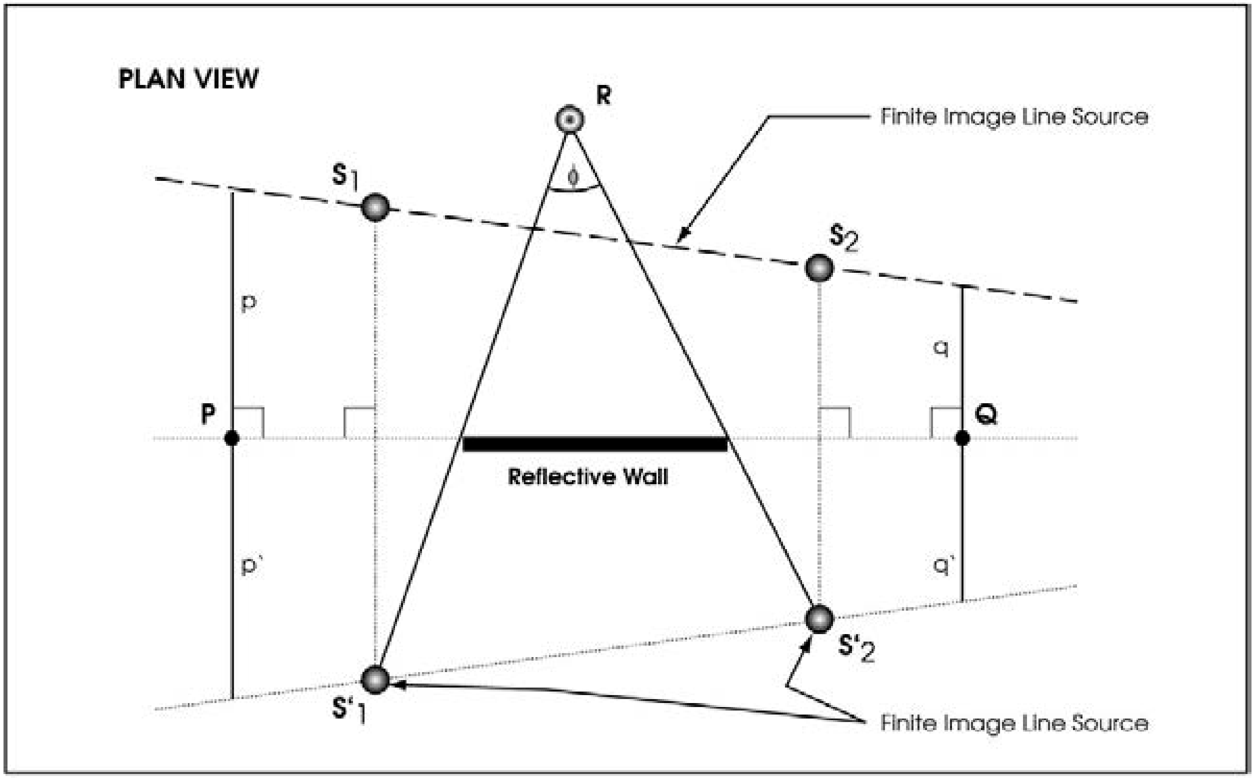

Figure 6-31. Placement of Image Sources (Plan View)

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.

When using LeqV2, the wall must be parallel to the roadway. The above process can be used for this case. The finite image line source will run parallel to the roadway and can be defined as an additional element with a segment angle ϕ. A cross sectional drawing is needed to reveal whether all image traffic and image roadways should be included. For example, if heavy trucks do not produce reflections, the heavy truck volume for the image source can be coded as 0.

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 the parallel barrier analysis mentioned in the next section. However, it is anticipated that in the near future, single barrier reflections will be included in routine calculations in the TNM, eliminating the need for manipulating the input source data.

6.1.7.4 Parallel Barriers

Multiple reflections between reflective parallel noise barriers can potentially reduce the acoustical performance of each individual barrier. Figure 6-32 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 6-32 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 6-32 shows that the path length difference between the first reflective path and the direct path is 2*S*. The difference between the second and first reflective paths is 2(*W* – S). The pattern repeats itself for subsequent reflections. These increases in path length distances for each subsequent reflection soon make their contribution to the total diffracted noise insignificant (i.e., only the first few reflections are important).

For example, for the special case where *W* = 2*S* (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 6-2. 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 6-32).

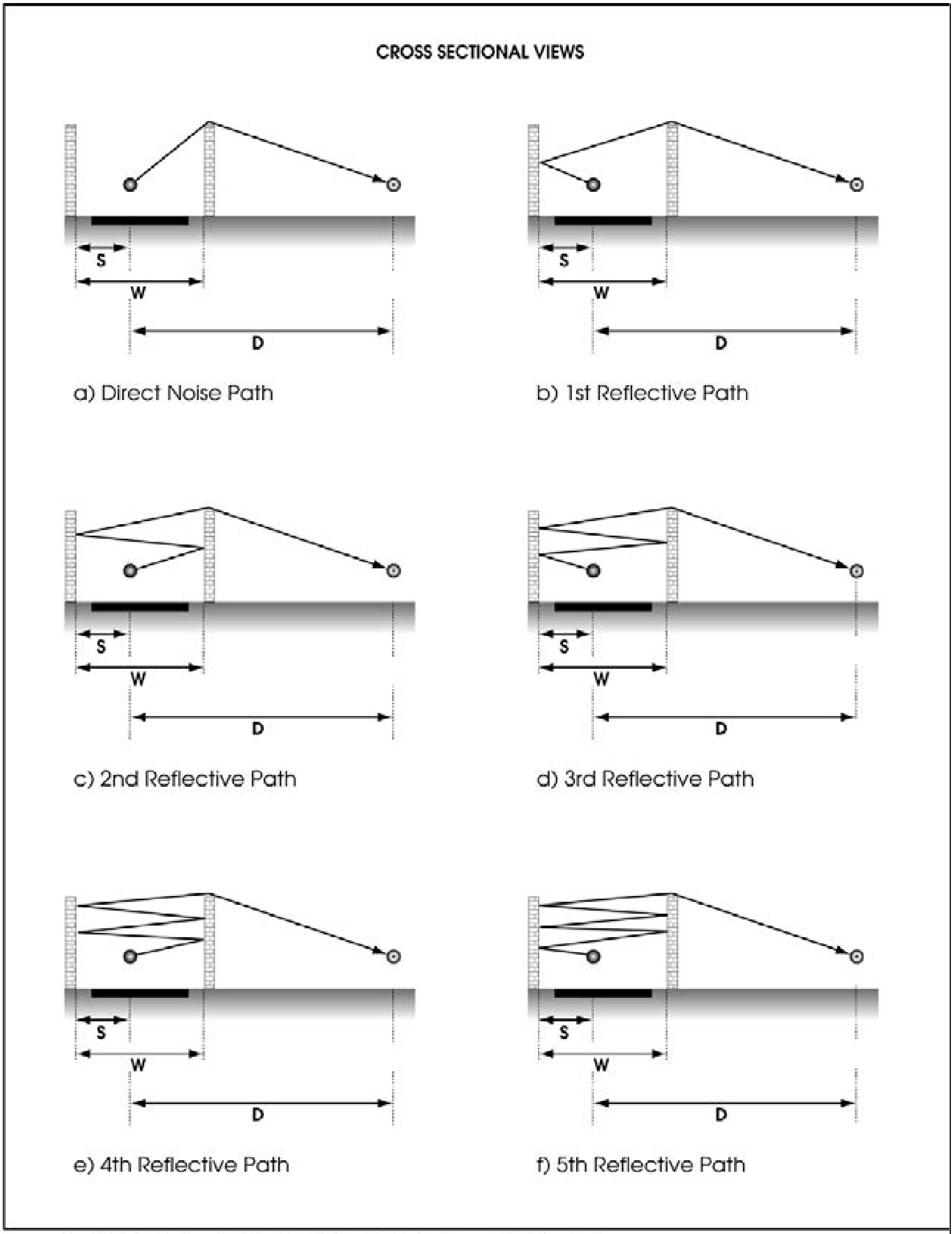

Figure 6-32. Various Reflective Noise Paths for Parallel Noise Barriers

Table 6-2. 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 6-32 and Table 6-2, 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 and is not noticeable to the human ear. This has been supported by research done by Caltrans and others. Because of noise barrier height restrictions of 16 feet, parallel noise barriers in California 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 6-33 illustrates these concepts.

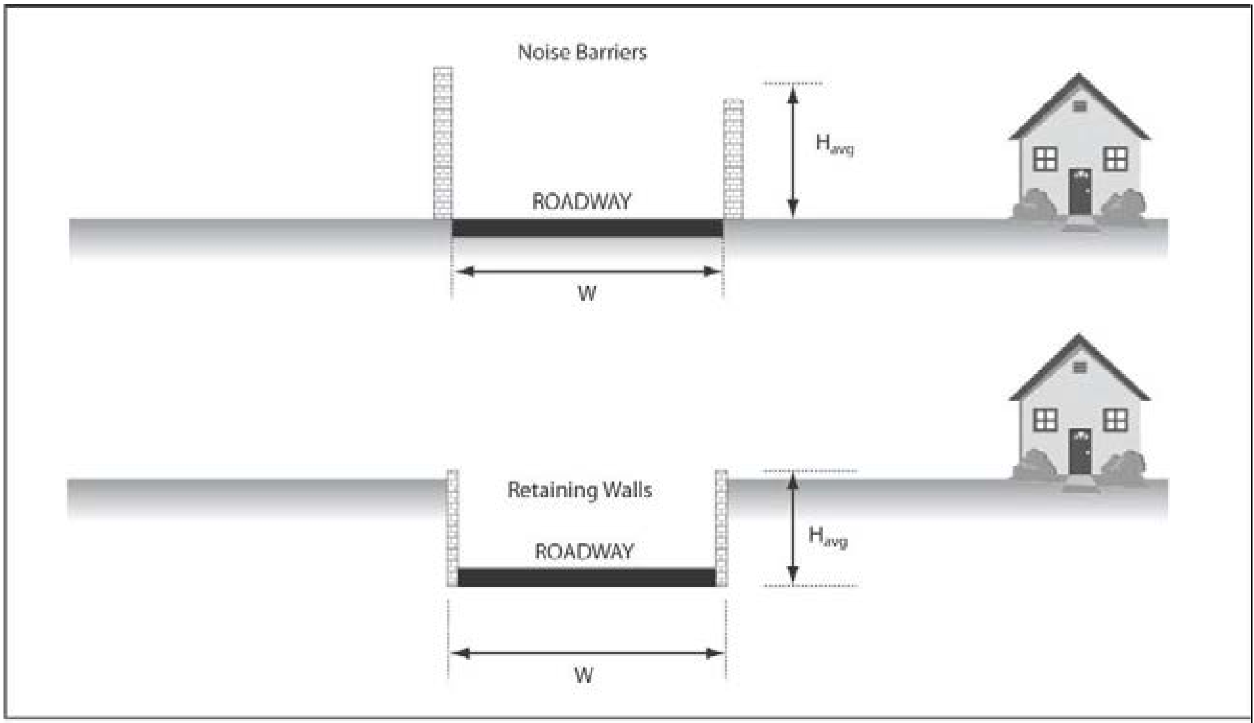

Figure 6-33. W/H_{AVG} Ratio Should be 10:1 or Greater

6.1.7.5 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 challenging problems in noise abatement design. The widespread spatial distributions of traffic noise sources and receivers make it difficult to design noise barriers that interrupt all direct noise paths between the many source-to-receiver combinations. Additionally, reflective surfaces of concrete structural components create many opportunities for noise reflections to circumvent noise barriers. Figure 6-34 shows one example of a potential problem created by the interaction of structures and noise barriers.

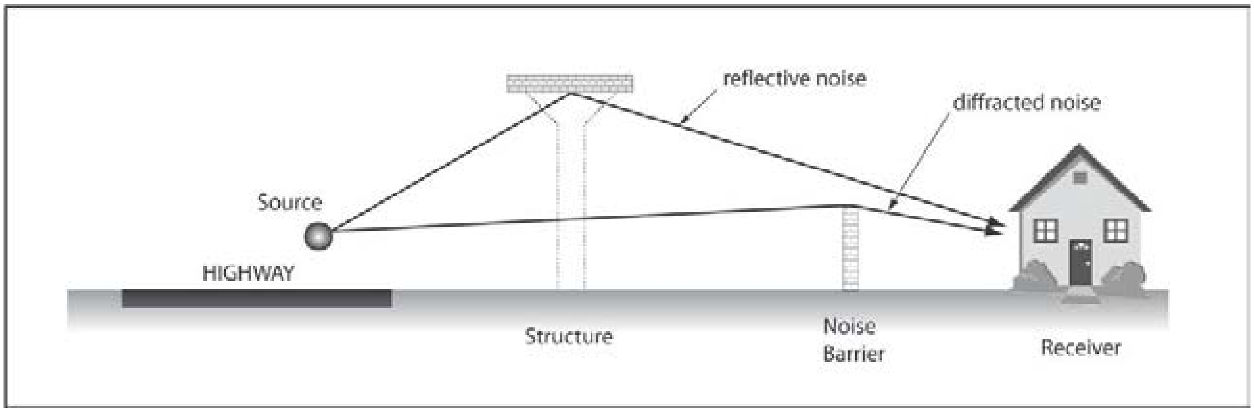

Figure 6-34. Noise Reflection off Structure (Potential Problem)

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 not considered a problem. Because of the barriers' limited height, reflections most likely are scattered and interrupted by the traffic stream. The effects of reflections near tunnel portals also have a very limited range. A Minnesota study showed that although noise levels are elevated immediately in front of the portal, they drop to ambient levels about 65 to 80 feet from the portal.

To date, Caltrans measurements have yet to conclusively uncover problems of interaction with 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.

6.1.7.6 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 6-35, 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 6-35, the direct paths from S_1 and S_2 are diffracted by the barrier at the edge of the lower deck.

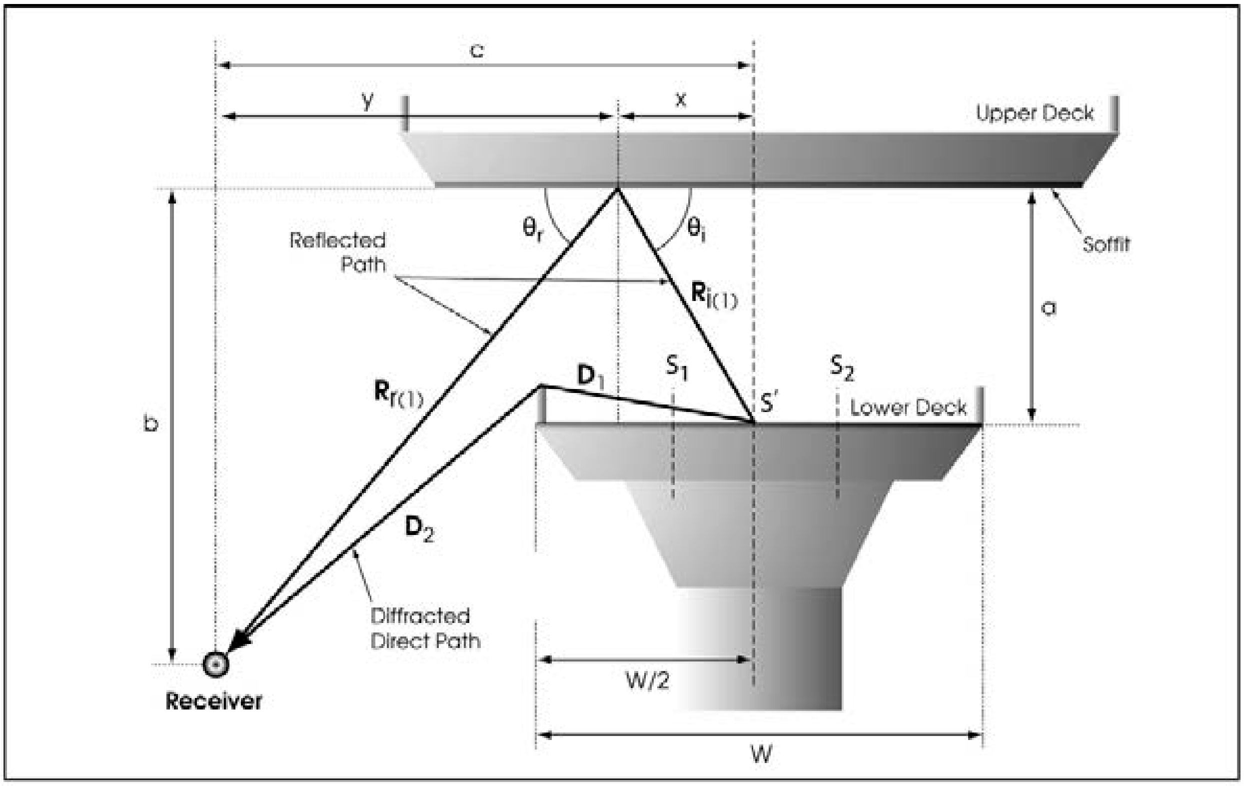

Figure 6-35. Double-Deck Structure Reflections, First Reflective Path

Contribution of Primary Reflection

Begin by analyzing only the primary (first) reflective path, $R_{(1),}$ as shown in Figure 6-35. 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 6-35 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:

$$10\log(D/R_{(1)}) \quad \textbf{(6-2)}$$

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 6-35, 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 6-2. Using Figure 6-35, calculate the lengths of D and $R_{(1)}$. D can be calculated as described below:

$$D = D_1 + D_2$$

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

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

From Equation 6-2, the contribution of the primary reflective path is $10\log(D / R_{(1)})$, 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 6-35, 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 6-35. 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 6-35, the two decks are assumed to be parallel. If they are not, additional 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 (i.e., α or NRC discussed in Section 6.1.7.7) of the soffit are known, Equation 6-2 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:

$$10\log[(D / R_{(1)})(1 - \alpha), \text{ or } (1 - NRC)] \quad \textbf{(6-3)}$$

Where:

α or NRC = fraction of noise energy absorbed by soffit material

(1 – α) or (1 – 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 6.1.7.7.

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 6-36 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.

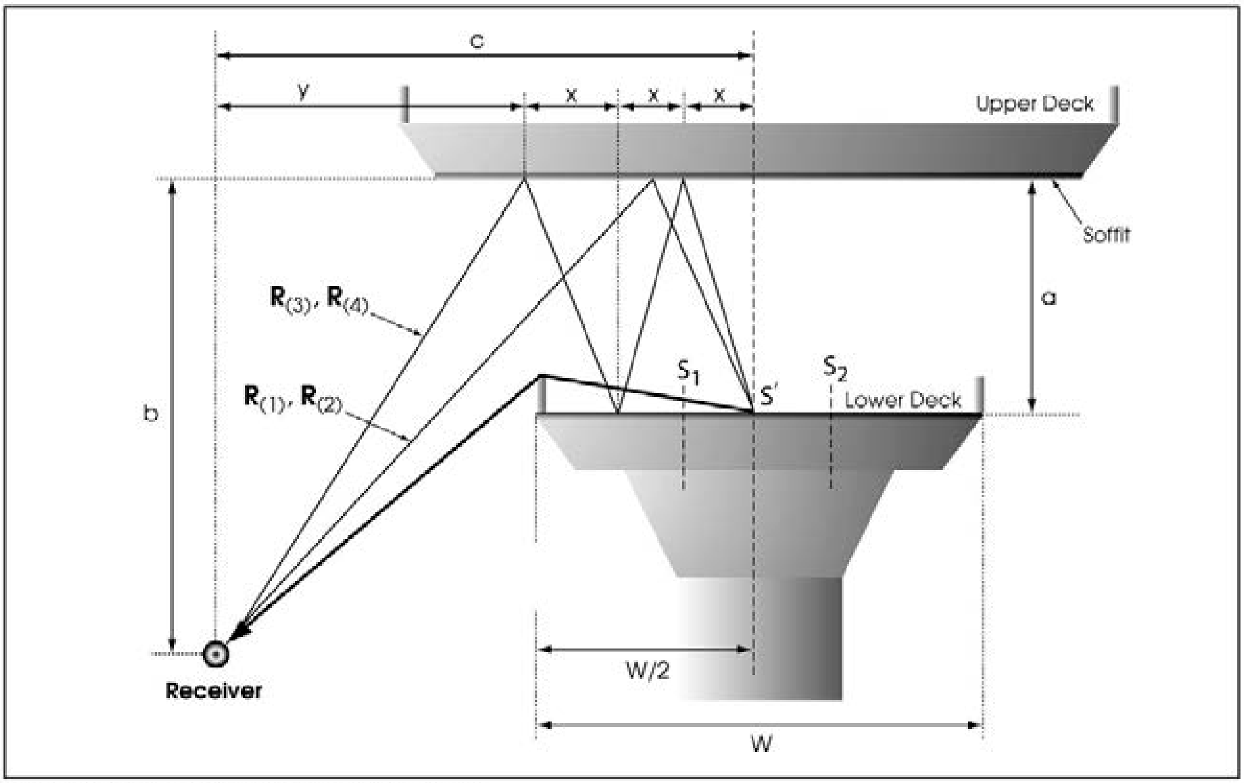

Figure 6-36. Multiple Reflective Paths

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 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 6-36) 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 = 10log(D / $R_{(3)}$) = 10log(66.6 / 152.4) = -3.6 dBA

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

Close examination of Figure 6-36 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 6-3. 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 6-3] 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 6-3. 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:

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

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

6.1.7.7 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 where actual problems would be identified. 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 reasons of structural integrity, safety, cost, and other factors, no absorptive material has been approved yet. 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). In either case, the cost of the barrier will likely increase substantially.

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:

$$NRC = (\alpha_{250} + \alpha_{500} + \alpha_{1,000} + \alpha_{2,000})/4$$

If approved absorptive materials are considered, a minimum NRC of 0.85 should be used as a criterion. This value means that 85% of the incident noise energy is absorbed and 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).

6.1.8 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. With the uncertainty of the future status of Chapter 1100, please consult the Caltrans website for the latest changes and referrals.

6.1.8.1 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 problems and the need of a chain link fence. However, this location may not be preferable for acoustical reasons, as discussed in Section 6.1.2. 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 6-37). The acoustical integrity of the noise barrier can be maintained by either providing a solid gate of appropriate material and transmission loss (see Section 6.1.1) 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 6-38).

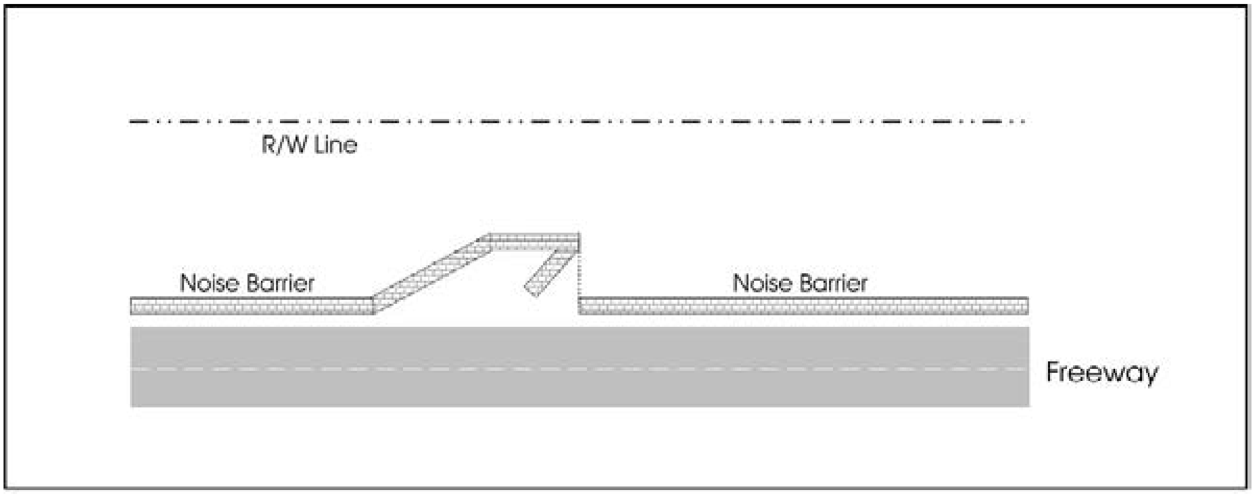

Figure 6-37. Barrier Offset with Solid Gate

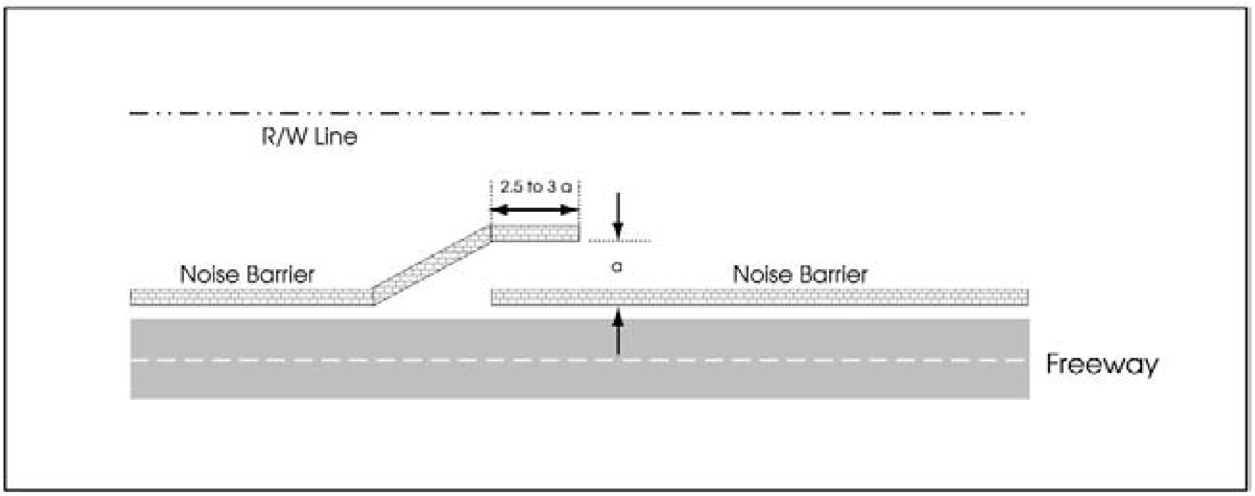

Figure 6-38. Barrier Overlap Offset 2.5 to 3 Times the Width of the Access Opening

6.1.8.2 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 it is possible to coincide them, the maintenance openings should be used for emergency access. 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 do normally not compromise the acoustical performance of a noise barrier. Design details of these openings are available from the Division of Structures Design.

6.1.8.3 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, and
- 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 problems 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.

6.1.8.4 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), according to Caltrans field research. 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 will be covered in the next section.

6.2 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.

6.2.1 Safety

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

The Division of Structure Design has developed standard sheets for noise barriers (soundwalls). These have been distributed to the districts. The standard designs include:

- masonry block,
- precast concrete panel (with post or mounted on safety-shaped barrier),
- wood (post and plank or framed plywood),
- metal (ribbed steel), and
- composite beam (Styrofoam and wire mesh core with stucco exterior).

Other designs, retrofit treatments such as noise-absorptive paneling, and alterations to noise barriers should be approved by the Office of Structure Design. The standard sheets also include designs for gates that provide emergency access to community fire hydrants, emergency access for stranded motorists, and rapid access to accidents, as discussed in Section 6.1.8.

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.

6.2.2 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 have a severe visual effect. A high barrier also can create unwanted 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 6-39). 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.

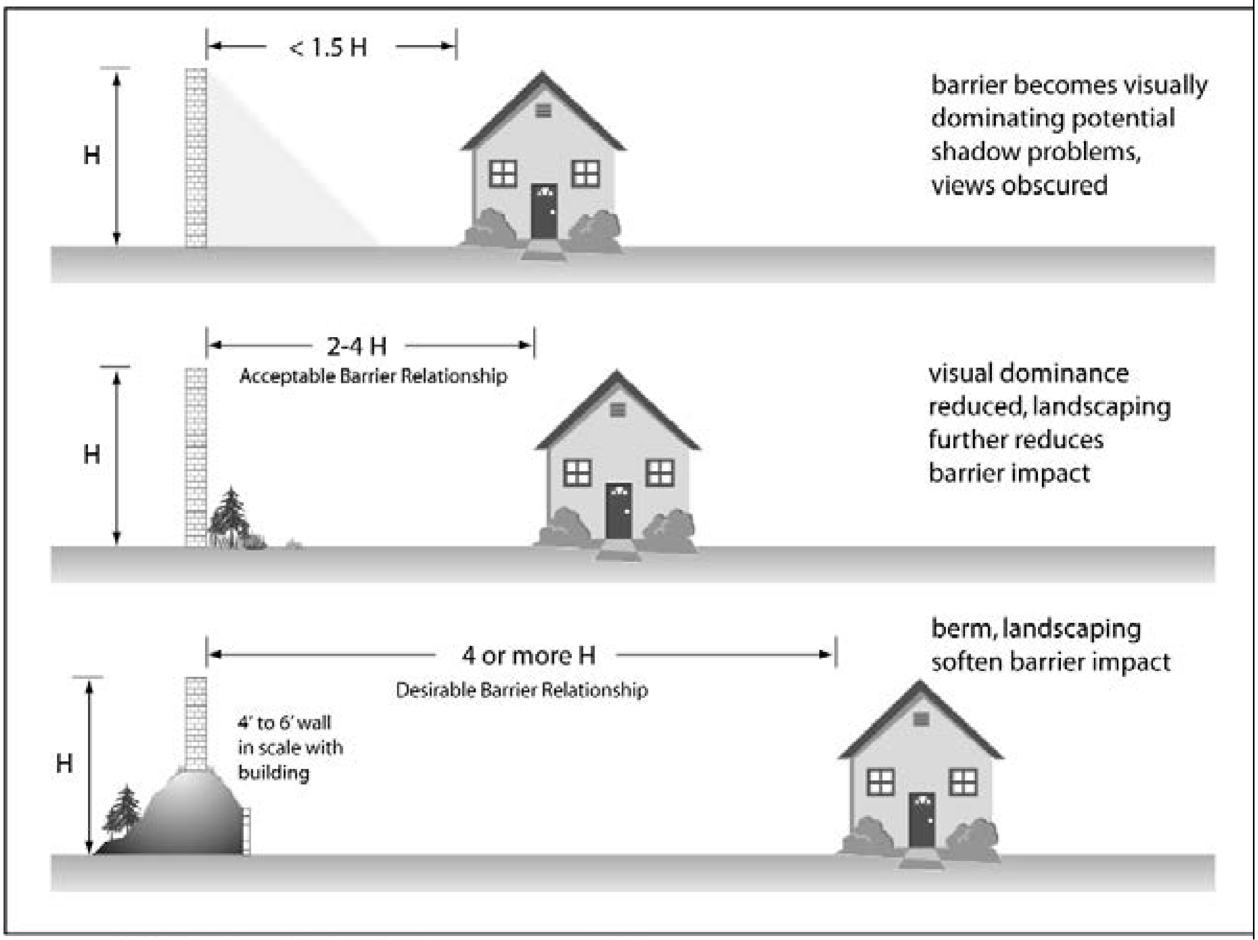

Figure 6-39. Spatial Relationship of Barrier to Adjoining Land Use

Soundwalls should not have abrupt beginnings or endings; they should be tapered or stepped. Only standard aesthetic treatments developed by the Division of Structure Design should be used. 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. 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 Highway Noise Barrier Design Handbook* (Knauer et al. 2000).

Section 7
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 noise analysts or laypersons who desire more detail than 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 the noise study report, other relevant environmental studies, and design considerations into a single, comprehensive document 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.

7.1 Outline

Table 7-1 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 on the Caltrans website at: <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 7-1. 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:
   a. LEQV2 or SOUND32 Based on FHWA RD-77-108 Report and Calveno (FHWA/CA/TL-87/03) Report, or
   b. TNM, Based on FHWA-PD-96-009 and FHWA-PD-96-010

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 Summarizing Data Necessary for "Reasonableness" Determination
6. 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

7.2 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 7-1 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.

Severe noise impacts, as defined in the Protocol, should be highlighted because they may trigger extraordinary abatement. However, the assessment process for severe impacts is separate from the noise study and can be found in the Extraordinary Abatement Guidelines (currently in preparation).

7.3 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.

Depending on the size, location, and type of project, it may be beneficial to combine the noise study with some of the other technical reports, such as air quality to avoid repetition. Suggested sections of the noise study, with brief descriptions of their contents, are provided below.

7.3.1 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.

7.3.2 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.

7.3.3 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. Changes in noise levels 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 selected texts of Section 6.1.7 or 8.1. Likewise, Section 8.1 text may also be useful in addressing concerns about the effects of noise barriers on distant receivers.

7.3.4 Federal and State Standards and Policies

This section covers the applicable federal and state standards and policies. Caltrans noise analysis policies are in the Protocol and *Highway Design Manual* (2001). Federal requirements include 23 CFR 772. State requirements are contained in Streets and Highways Code Section 216. Although information developed in the analysis of impacts and abatement under the previous requirements is also used in assessing noise impacts under the National Environmental Policy Act (NEPA) and California Environmental Quality Act (CEQA), the processes for evaluating these impacts are separate and distinct; no attempt should be made to include them in the noise study report.

Terms used in the policies and standards should be mentioned in this section, as well as the NAC and their significance, definitions of appropriate noise descriptors, and traffic noise impact criteria.

If the project involves local noise ordinances written in terms of a noise descriptor other than L_{eq}(h), an attempt should be made to equate the noise descriptors rather than duplicating most of the noise report using another descriptor (see Section 2.2.3 for a discussion of equating worst-hour L_{eq} to L_{dn}, etc.).

7.3.5 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 5).

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 5.3.1). 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 8.2).

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 5.4) 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 1 m horizontally, and 0.3 m 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.

7.3.6 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 receivers 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. The presence of any other stationary or mobile noise sources (e.g. arterials, airports) should also be noted.

The general topography surrounding the project and any problems in noise measurements or modeling should be pointed out in this section, especially complicated or unusual situations. A discussion on background noise levels (i.e., noise levels unaffected by the existing highway) is also appropriate. The importance of selecting measurement sites to document background noise levels is mentioned in Section 7.3.5.

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 (raw data should be in the appendices); and
- whether existing noise level was measured or modeled (predicted), and:
  - if measured, whether measurement was adjusted to worst hour noise (see Section 3.3.1.2), or
  - if predicted, whether prediction included model calibration (see Section 5.4) (details of the calibration, such as the calibration constant and explanations of why they were excessively large, should be in the appendices).

Table 7-2 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. Raw data of noise measurements, traffic counts, speeds, meteorological conditions, site locations, and topography should be included in the appendices.

7.3.1 Future Noise Environment, Impacts, and Considered Abatement

This section of the noise study report deals with the future noise environment. A discussion of the assumptions and inputs used for the predicted noise levels is appropriate. 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. As shown in Section 7.3.6, the summary information is most often best displayed in tables. Examples of presenting predicted noise levels and impacts are shown in Tables 7-3 and 7-4. 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 covers information for discrete receivers. The information must be expanded to include the entire study area. Table 7-2 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., length, height, insertion loss). 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. The latter is necessary to determine whether abatement measures are reasonable. Although noise barriers are normally considered for abatement/mitigation, other measures may also be considered (see 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. An example is shown in Table 7-4.

The procedures for determining the preliminary reasonableness of noise abatement (see the Protocol) require various inputs, most of which have been discussed. Table 7-5 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 have their own negative impacts. Barriers may interfere with the passage of air, interrupt scenic views, or create objectionable shadows. They can also create maintenance access problems, make it difficult to maintain landscaping, create drainage or snow removal problems, and provide pockets for trash 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.

Discussions and justifications for any locations where noise impacts have been identified but where no reasonable or feasible ordinary abatement measures are available should be included. If any of these areas suffer from severe impacts defined in the Protocol, they should be identified as potential candidates for extraordinary abatement, a process separate from the noise study report.

7.3.2 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 there are unusually sensitive receptors involved or the project is controversial. Procedures for analysis, monitoring, and abatement of construction noise can be found in Section 8.5.

7.3.3 References

Typical references may include 23 CFR 772, the Protocol, *Highway Design Manual* Chapter 1100, FHWA-RD-77-108 or (when TNM is mandated) FHWA-PD-96-009 and -010, DOT-VNTSC-FHWA-98-1 and -2, and other appropriate documents.

Table 7-2. 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	B (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, 5.3.3, and 5.4).

Table 7-3. Predicted Traffic Noise Impacts (Example)

Receiver	Type, Location, or Address	Development Predates 1978 or Is New Highway Construction?	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)	Yes	74	75	+1	B (67)	A/E
2	4321 Main Street, 5 feet from façade (first-row residence)	Yes	75	76	+1	B (67)	A/E
3	2336 Elm Street, center of backyard (first-row residence)	Yes	73	74	+1	B (67)	A/E
4	3538 Elm Street, center of backyard (first-row residence)	Yes	74	75	+1	B (67)	A/E
5	1212 Church Street, 10 feet north of bottom front step	Yes	68	69	+1	B (67)	A/E
6	1723 Oak Street, center of front lawn (0.25 mile from freeway, background noise level)	Yes	56	56	0	B (67)	None
7	1052 Sycamore Drive, middle of cul-de-sac (0.25 mile from freeway, background noise level)	Yes	55	55	0	B (67)	None

[a] A/E = approaches or exceeds NAC.

Table 7-4. 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		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 in the first row of residences.

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

Table 7-5. 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 = 1.8 meters	Height = 2.4 meters	Height = 3.0 meters	Height = 3.7 meters	Height = 4.3 meters	Height = 4.9 meters
SW-1						
Insertion Loss (dBA)	5	6	7	9	10	11
Benefited Residences	24	24	24	48	72	96
New Highway or More Than 50% of Residences Predate 1978?	No	No	No	No	Yes	Yes
Reasonable Allowance Per Benefited Residence	$21,000	$23,000	$23,000	$25,000	$35,000	$35,000
SW-2						
Insertion Loss (dBA)	4	5	6	8	9	11
Benefited Residences	0	24	24	48	48	96
New Highway or More Than 50% of Residences Predate 1978?	No	No	No	No	No	Yes
Reasonable Allowance Per Benefited Residence	Not Feasible	$19,000	$21,000	$21,000	$23,000	$33,000

[a] At critical receivers.

7.4 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 5.4), they should be shown in simple table form (see Table 7-6 for an example). Ideally, 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 7-6. 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 5.4.1.1)

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 problems 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 8
Non-Routine Considerations and Issues

Sections 2 to 7 covered the routine phases of Caltrans highway noise analyses and fieldwork. Some phases, such as the normalization of noise measurements to zero-wind conditions (Section 5.4.2.3), require highly experienced personnel and restricted environmental and site conditions; therefore, they are considered optional. Nevertheless, they can be performed routinely when warranted.

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 any other interested party. The subjects vary and they are summarized for convenience:

- 8.1: Noise Barrier Issues
- 8.2: Sound Intensity and Power
- 8.3: Pavement Noise
- 8.4: Insulating Homes from Highway Noise
- 8.5: Construction Noise Analysis, Monitoring, and Abatement
- 8.6: Earthborne Vibrations
- 8.7: OSHA Noise Standards
- 8.8: Effects of Transportation and Construction Noise on Marine Life and Wildlife (Bioacoustics)

8.1 Noise Barrier Issues

This section discusses some controversial issues and non-routine considerations of noise barriers. Noise barriers are generally considered beneficial for residents near a freeway. However, there have at times 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 covered in Section 6.

A standardized method is also shown to measure the performance of noise barriers at receivers for which they were designed. Although Caltrans has no policy requiring or recommending routine post-construction noise monitoring, measuring before– and after–noise barrier noise has been desirable at times to validate design methods and to investigate claims of disappointing noise reduction.

A third issue discusses the effectiveness of vegetation typically used in highway landscaping in reducing noise. This issue comes about occasionally when trimming of shrubs by Caltrans maintenance personnel triggers complaints of perceived noise increases because of greater visibility of traffic in the community.

8.1.1 Effects of Noise Barriers on Distant Receivers

The public and media in California have at various occasions 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 problems. This section discusses what Caltrans and others have found.

8.1.1.1 Background

Normally, noise barriers are designed for residences and noise-sensitive receptors located adjacent to a highway, and their effects (beneficial or otherwise) are generally limited to receivers within 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 6.1.6. Noise prediction models have not been adequately validated for distances up to 500 feet. Caltrans' *Distance Limits for Traffic Noise Prediction Models* (2002) discusses the reasons for the distance limits.

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 ever been advanced that noise barriers increase noise levels at any distance or under any conditions other than under the limited conditions described in Section 6.1.7. As indicated, present noise prediction models are not at all 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, and
- noise barriers between highways and receivers.

The first two issues involve reflective noise of single and parallel barriers, discussed in Section 6.1.7. 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 and lack of adequate prediction models for these conditions. Caltrans' experience has been that atmospheric conditions can fluctuate measured noise levels at those distances 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.

8.1.1.2 Results of Completed Studies

Caltrans and its consultants and others have performed elaborate research-quality studies concerning noise from highways at adjacent and distant receivers, with and without noise barriers for the three barrier configurations mentioned in Section 8.1. 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 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 6.1.7.2, agreed remarkably with the theoretical calculations shown in the same section, particularly in Figure 6-26. 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 6.1.7.2.

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 6.1.7.4, 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 6.1.7.4 and depicted in Figure 6-33. 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, there is no question that noise barriers are effective in the vicinity of highways, for instance within 330 feet. 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.

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, 5, and 6.

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. However, a soundwall will elevate the noise source over tiers of homes no more than the intervening homes do. Soundwalls in California are generally restricted in height to 16 feet, approximately equal to the average height of residential development.

There is a loss of "ground effect" behind a noise barrier, however. 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 6.1.5). 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 cause a "bulge" 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 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. Such an increase in noise levels from noise barriers has never been measured.

8.1.1.3 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. Such studies are not at this time considered 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).

8.1.2 Measuring Performance of Noise Barriers

Noise barrier proposals by Caltrans often trigger expectations of high noise reductions by the affected public. In environmental documents and at public hearings, project engineers and noise experts should make every effort to educate the public about the noise reductions they can expect realistically. It is even more important and difficult to convey what noise reduction numbers mean to a lay audience. After construction of the noise barrier, the affected residents are often disappointed because the noise, although reduced, is still there. Depending on the neighborhood, quality of life enjoyed, and nature of the highway project, the affected residents may complain vigorously about what they perceive as a poorly designed noise barrier. Controversies over the effectiveness of noise barriers begin in this manner and can erupt if the news media takes up the cause. Although Caltrans does not routinely measure the performance of a noise barrier, there have been cases in which it was desirable. Measuring the performance of a noise barrier requires a non-routine measurement approach and is discussed in this section.

8.1.2.1 Measuring Single Barrier Insertion Loss

Detailed methodologies for determining noise barrier insertion loss are described in ANSI S12.8 (1998) "Methods for Determination of Insertion Loss of Outdoor Noise Barriers." The methods include before- and after-barrier measurements, and various combinations of modeling and measurement techniques. This document is available from the ANSI. It is not the intent of this section to cover all the methods covered in ANSI S12.8, but instead to focus on measuring the performance of a noise barrier only. Two methods are discussed. The first, preferred method is before- and after-barrier measurements. If before-barrier measurements cannot be taken or the decision to measure the barrier insertion loss was made after the barrier was constructed, the second method can be employed.

Before and After Measurements

Figure 8-1 shows a schematic of a preferred setup for before- and after-barrier performance measurements. Figure 8-2 shows an alternate setup for the reference microphone if the preferred setup is not possible because of terrain or other restrictions. In both cases, the reference microphone is not affected by the noise barrier once it is constructed. The purpose of the reference microphone is to normalize the noise measurement for changes in traffic from measurement to measurement. The measurement setups shown conform to the ANSI 12.8 (1998) standard and have been followed by Caltrans and others at various times.

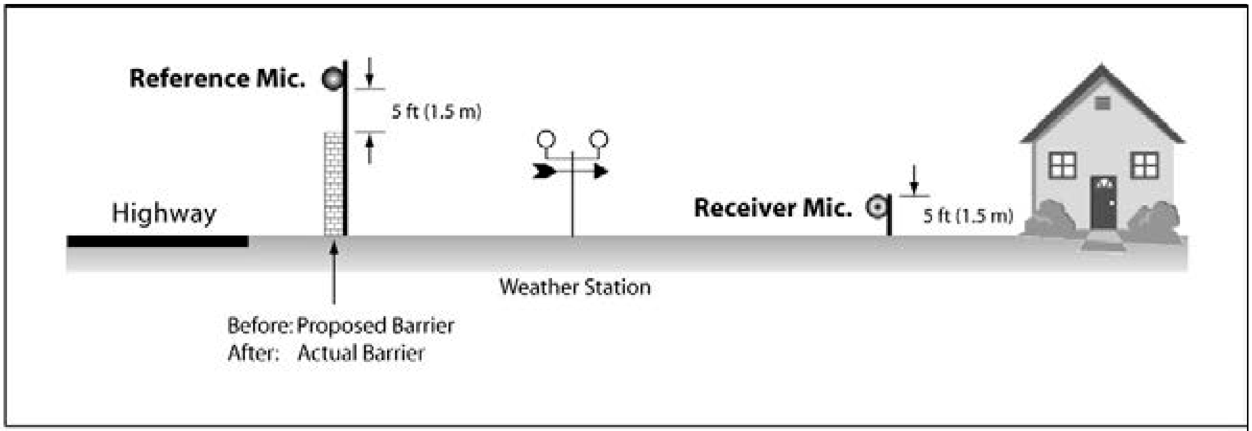

Figure 8-1. Preferred Setup for Measuring Noise Barrier Performance (Insertion Loss)

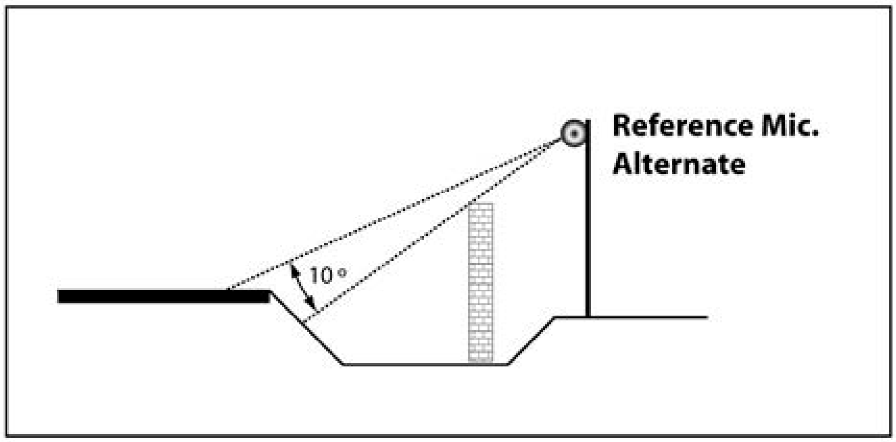

Figure 8-2. Alternate Position of Reference Microphone

In either case, the three-dimensional reference and receiver microphone positions must be identical for the before- and after-barrier measurements.

During the before-barrier measurements, the reference microphone must be placed 5 feet above the top of the proposed barrier (Figure 8-2). This is usually done by attaching the microphone to a pole at the correct height above the ground (height of the proposed barrier plus 5 feet). Adjustable guy wires or ropes attached to stakes in the ground are typically used to secure the pole and microphone. If the surface is paved or hard, heavy weights may be used instead of stakes.

During the after-barrier measurements, the same methods of securing the reference microphone position may be employed, or the microphone may be positioned on a 5-foot pole attached to a bracket that fits over the top of the barrier.

Regardless of the method used to position the reference microphone, it is imperative that its position relative to the pavement (distance and height) is the same before and after barrier construction. The same is true for the receiver microphone, which normally is 5 feet above the ground at the location of interest, but could be at a different height if it better represents the location of interest (e.g., on a deck). Care should be taken that both the reference and receiver microphones are not affected by noise reflections and local shielding that are not representative of the area of interest. Noise measurements are taken simultaneously at the reference and receiver microphones.

Meteorological measurements must be taken simultaneously with the noise measurements, and before- and after-barrier measurement results must be grouped by equivalent meteorological conditions, as explained in Section 3.6 and ANSI S-12.8 (1998). It should be stressed that the measured insertion loss is only correct for the specific meteorological conditions present during before and after measurements.

Traffic counts should be taken during the measurements, and modeled results should be compared with the measured results to ascertain that the observed noise levels at the reference and receiver locations are explained by the traffic and do not include extraneous or unknown sources. Once satisfied that this is true, the noise analyst should calculate the barrier's performance from the measurements.

Once the before- and after-barrier measurements have been grouped by equivalent meteorological conditions, they may be compared. The actual noise levels at the reference and receiver microphones are not of interest, but rather the difference between them. These differences are calculated from the measurements for the before- and after-barrier conditions and for each meteorological condition. The average differences before and after the barrier are compared to calculate the insertion loss, which can be calculated as follows for each before- and after-barrier set of equivalent meteorological conditions.

$$\text{Insertion Loss} = \Delta_i avg_{bef} - \Delta_i avg_{aft} \quad \textbf{(8-1)}$$

When:

$\Delta_i avg_{bef}$ = average difference between reference and receiver microphones during meteorological condition *i* during before-barrier measurements.

$\Delta_i avg_{aft}$ = average difference between reference and receiver microphones during meteorological condition *i* during after-barrier measurements.

Because the insertion loss is calculated from the differences between the reference and receiver microphones, there is no reason to normalize the measurements for differences in traffic.

Simulated Before- and After-Barrier Measurements

This method may be employed if no before-barrier measurements are available for a barrier already constructed. It relies on finding two sites along the same highway: one with the barrier of interest, and one without barriers to simulate the before-barrier condition. Good judgment must be used to ascertain whether the cross section, groundcover, and other important aspects are the same at both sites, with the barrier the only difference. This method is preferably executed by taking noise measurements simultaneously at both sites, employing two reference and two receiver microphones, because meteorological conditions will be easier to match up between the sites. However, if simultaneous measurements are not possible because of limitations on available equipment and personnel, measurements may be taken at different times, as in the case of the before- and after-barrier measurements. The data analysis and insertion loss calculations are the same, as explained in the before- and after-barrier measurements.

Using Two or More Receiver Microphones

If two or more locations of interest are desired, more receiver microphones can be deployed. If more equipment is available, before- and after-barrier measurements may be taken at all locations simultaneously. If only two sound level meters are available, the measurements must always be conducted in pairs (e.g., reference and receiver microphones 1, reference and receiver microphones 2). However, using only two microphones at one time can be time-consuming given the required coverage of equivalent meteorological conditions.

8.1.2.2 Measuring Insertion Loss and Parallel Barrier Degradation

The same methods already discussed may also be applied to measuring the insertion loss and insertion loss degradation of parallel barriers constructed simultaneously or at different times. Three common cases are described below.

First, if both barriers are constructed simultaneously, the previously discussed before- and after-barrier measurement method may be used. The before-barrier measurements may be taken at both sides of the highway or at one side of interest. The after-barrier measurements will then be performed after both barriers are constructed. The resulting insertion loss will then include the insertion loss degradation, if any, from multiple reflections between the barriers.

Second, if one barrier is constructed first and the second some time later, the before-barrier measurements (Stage 1) may be taken on both sides as well. After the first barrier is built, after-barrier measurements may be taken behind the barrier (Stage 2). The resulting insertion loss (Stages 1 to 2) will be for the single barrier only. When the second barrier is built on the opposite side, after-barrier measurements (Stage 3) can be taken on both sides, measuring the insertion loss of both barriers on either side (Stages 1 to 3). However, on the side of the first barrier, the insertion loss degradation from the second barrier can be calculated by subtracting the Stage 3 loss from the Stage 2 loss.

Third, if one barrier is already constructed and a second is proposed on the opposite side of the highway, the simulated before- and after-barrier measurement method can be used in combination with the first and second parallel barrier applications.

Because there are various possible combinations of parallel barrier configurations, not all are discussed. However, knowing the principles of insertion loss measurements, the noise analyst would be able to design an appropriate measurement plan for each case.

8.1.3 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. 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 eyes 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, although sound level meters did not substantiate such a claim objectively. Therefore, the use of vegetation with noise barriers can be beneficial by improving community acceptance and perceived effectiveness.

8.2 Sound Intensity and Power

This TeNS has consistently described the amplitude of sound at a specific location in terms of SPL or noise level. This is also the case for all noise standards, criteria, and descriptors mentioned in the TeNS. 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 power often provide more useful information about noise sources than SPL. 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 power studies.

8.2.1 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 source and remains independent of the factors influencing sound pressure. Knowing the sound power of a noise source, the sound pressure level can be calculated (perhaps not conveniently) 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 newtons 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:

$$10\log_{10}(P_1 / P_0)^2$$

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 = $1N/m^2$. Sound power may similarly be expressed in decibels. The definition of a sound power level (L_W) is:

$$L_W = 10\log_{10}(W_1 / W_0) \qquad \textbf{(8-2)}$$

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.

8.2.2 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 pico-watt (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.

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

$$L_I = 10\log_{10}(I_1 / I_0) \qquad \textbf{(8-3)}$$

Where:

L_I = sound intensity level in decibels

I_1 = sound intensity of interest in watts per square meter

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

The sound intensity of interest (I_1) in watts per square meter can be calculated as follows:

$$I_1 = I_0 * 10^{(L_I/10)} \qquad \textbf{(8-4)}$$

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

$$I = P * v \qquad \textbf{(8-5)}$$

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 8-3). 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. Therefore, sound intensity is useful in mapping sound fields and 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.

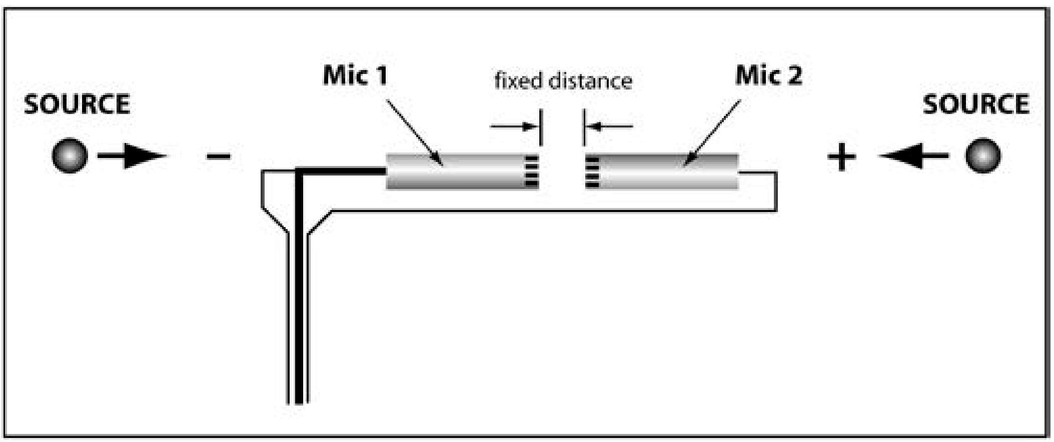

Figure 8-3. Schematic of a Sound Intensity Probe

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 8-4).

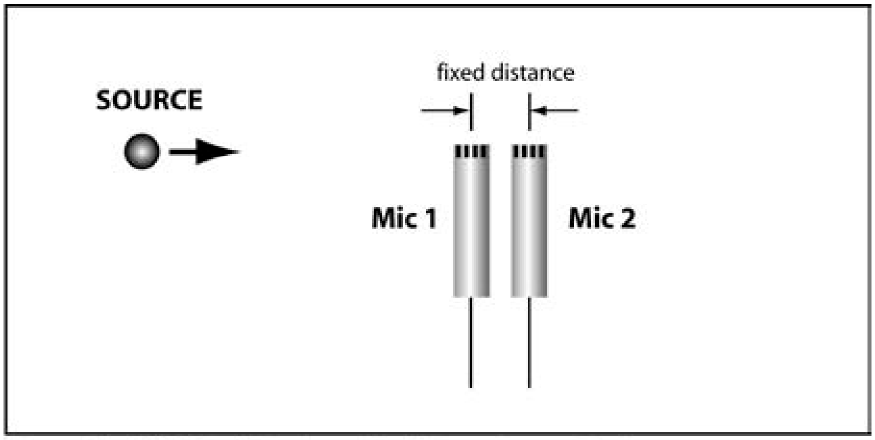

Figure 8-4. Side-by-Side Microphone Probe

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 8-5). 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:

$$W_{total} = \sum_{1}^{K} (A_k \times I_k)$$

The result in units of decibel can be calculated from Equation 8-2, or shown in bels by dividing the decibel result by 10.

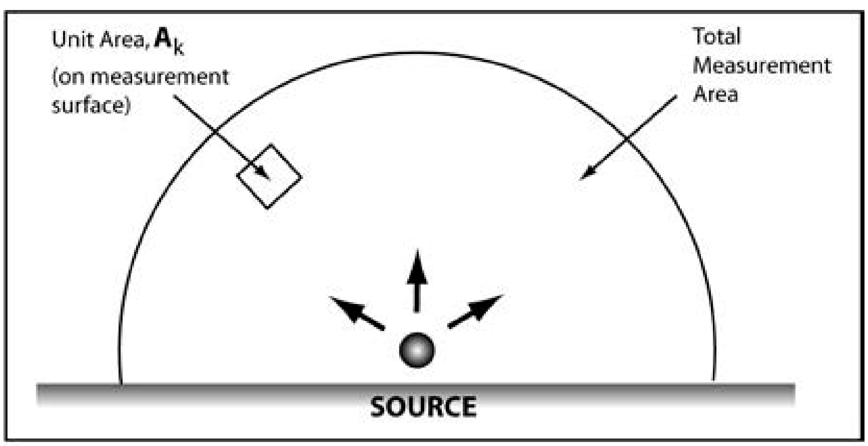

Figure 8-5. Sound Power Measurement Area

8.3 Tire/Pavement Noise

In Section 2, noise is discussed in terms of source, path, and receiver. All three components must be present before a noise problem 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 aspect of highway design that affects noise at the source is the type and texture of pavement used. There are two major types of pavement: black colored asphalt concrete (AC) and white colored Portland cement concrete (PCC). Generally, AC is quieter than PCC, but there can be overlap between the two types of pavement. There are variations in both AC and PCC pavements, and these variations have been engineered to address certain problems. It has been well known for at least a decade that open-graded asphalt concrete (OGAC) produces less noise from tire/pavement interaction than dense-graded asphalt concrete (DGAC). It is also known that DGAC produces less tire/pavement noise than PCC pavement and that longitudinal (parallel to direction of travel) texturing, tining, or grooving in PCC is less noisy than transverse (perpendicular to direction of travel) texturing, tining, or grooving. What is less known and more controversial is the longevity of the lower noise benefits of OGAC and DGAC. The controversy arises from conflicting studies. There appear to be 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 porous OGAC pavement, it is believed that the primary reason for degradation of acoustics (excluding structural failure) is from a closing of the air voids, which may be related to traffic loads or environmental factors.

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 6 years 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 and wayside noise measurements carefully controlled for the effects of meteorology.

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. An increasing amount of evidence suggests that at highway speeds, tire/pavement noise affects total vehicle noise to a greater extent than all the other 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 may be possible to perceptively or significantly 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.

Researchers of tire/pavement noise need to focus on examining the extent to which reducing tire/pavement noise benefits typical receivers. Wayside noise measurements not only need to be taken at standard reference distances, such as 25 or 50 feet from the nearest traveling lane, but also at typical source to receiver distances to examine whether the noise benefits will still be enjoyed at these receivers. Because tire/pavement noise from different pavement types often have different spectral characteristics, propagation over different ground surfaces may reduce the noise benefit received from quieter pavements at greater distances.

At the time of this writing, by policy, pending more studies and research, FHWA does not allow type of pavement to be considered as a noise abatement measure. Caltrans practice of calibrating noise prediction models has recently added optional calibration adjustments for various pavement types (see Section 5.4.2.2). This practice cannot be construed as a consideration of noise abatement. Instead, it helps explain 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.

8.4 Insulating Homes from Highway Noise

This section covers measurement procedures to be used for the interior noise abatement of residential units (home insulation). The measures are not listed in 23 CFR 772.13(c), but they fall under the "unusual and extraordinary" abatement measures in the Protocol that should be considered when "severe" noise impacts are predicted. Although the procedures for home insulation noise measurements have some common elements with classroom noise measurements (see Section 3.3.5) under the provisions of California Streets and Highways Code Section 216, the two procedures should not be interchanged.

Caltrans is currently developing Extraordinary Noise Abatement Guidelines (ENAG) that deal with the process of evaluating extraordinary abatement for severe noise impacts.

The measurement and analysis procedures for home insulation consist of determining whether homes qualify and, if they do, designing noise abatement. For both stages, measurements can be placed into two categories: determining outside noise levels and determining building insertion loss (outside to inside noise level reduction [OILR]). Caltrans recommends following the procedures described in ASTM E966-02, "Standard Guide for Field Measurements of Airborne Sound Insulation of Building Facades and Façade Elements." In addition to these procedures, compliance with applicable Caltrans measurement procedures described in Section 3 should be ensured.

Once the residences meet the criteria in the ENAG, the worst-hour interior noise levels will be determined with windows open and closed, and compared to the criteria. The preferred procedure to follow is to determine the worst hourly traffic noise level outside the home (Section 8.4.1); determine the outside to inside insertion loss provided by the structure of the residence (Section 8.4.2); and determine the worst-hour inside noise level, compare to criteria in the ENAG, and determine insulation options.

8.4.1 Determining Worst-Hour Outside Noise Levels

The purpose of determining the predicted future worst-hour outside noise levels is twofold: to determine whether residences will be exposed to severe noise impact as defined in the ENAG and, if so, to provide a baseline to determine the inside noise levels. The procedures should comply with the appropriate measurement procedures in Section 3, prediction methods described in Section 5, and procedures outlined in this section. Two situations will be discussed: residences along an existing highway to be reconstructed, and residences along a future highway on new alignment.

8.4.1.1 Residences along Existing Highway to Be Reconstructed

General Approach

If the residences are located adjacent to an existing highway to be reconstructed, the future worst-hour noise levels outside the residence can be obtained by measurements of existing traffic noise outside the residence. Sections 3.3.1, 3.3.1.1, and 3.3.1.2 describe the procedures for determining the existing daily worst hour noise level by measurements and modeling.

Once existing worst-hour noise levels are known, they can be adjusted to future noise levels by using the most current model and version used by Caltrans. The adjustment procedure consists of four steps: modeling the existing worst-hour noise level, modeling the future noise level, calculating the difference, and adding the difference to the existing worst-hour noise level obtained from the measurements.

Instrument Setup

Figure 8-6 shows a plan view of the instrument setup for the worst-hour noise measurements. The setup should consist of two or more sound level meters, one used as a reference, preferably within 40 to 60 feet of the edge of the traveled way of the highway. The purpose of the reference microphone is to check the correlation between the source noise levels and receiver noise levels to ensure that the noise received at the residences can be explained by the highway alone. It is good practice is to model the reference location with the traffic and other pertinent conditions present