during the measurement and compare the results with the measurement by the reference microphone. If 24-hour measurements are taken, it is not necessary to check the correlation at each hour, but only during a few pre-selected hours, including the worst noise hour. Traffic volumes and mixes should be monitored during these hours.

The remaining microphones should be placed outside the residence as shown in Figure 8-6a or 8-6b. Additional microphones may be used to better represent the outside levels immediately outside the residence. Care must be taken that a minimum unobstructed angle of 70° is maintained between a line normal to the highway and a line to the building, and that each microphone is at least 10 feet from the residence façades.

The setup shown in Figure 8-6a is preferred. Microphones 1 and 2 are placed at (outside) locations that are at distances equal to those of the center of the targeted inside rooms (marked by "X") relative to the highway. If the minimum angular requirements cannot be met, the alternate setup in Figure 8-6b may be used. In this setup, the distance to Microphone 1 and the interior centers of the rooms relative to the highway are not equal. In situations where the residence is far from the highway, these differences may be ignored. However, if the residence is close to the highway, a distance adjustment may need to be made, as described in Section 2.1.4.2, to adjust the outside levels measured at Microphone 1 in Setup "b" to those at the locations of Microphones 1 and 2 in setup "a" without building shielding. If the difference is 0.5 dBA or more, the adjustment should be made. This setup can be combined with the inside noise measurements with simultaneous inside and outside measurements. See Section 8.4.2.2 for further details.

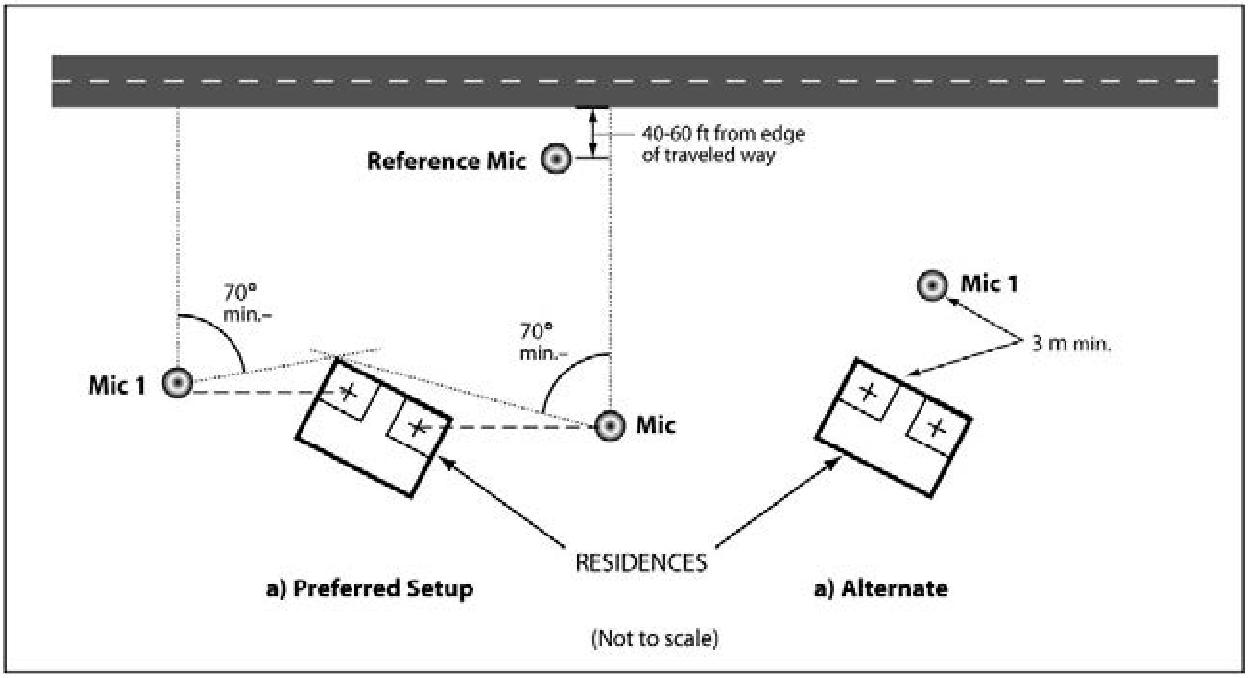


**Figure 8-6.** Outside Residence Noise Measurements (Existing Highway)

In all cases, the microphones should be at least 10 feet from the residence to avoid reflections off the building façade.

### 8.4.1.2 Residences along a Future New Highway (New Alignment)

When the proposed highway will be constructed on a new alignment, existing measurements will not be possible. In this case, the future worst-hour noise levels will have to be determined solely by modeling. The receiver locations should be selected at the locations of Microphones 1 and 2 in Figure 8-6a.

## 8.4.2 Determining Outside to Inside Noise Level Reductions or Building Façade Insertion Loss

Caltrans recommends using the methods described in ASTM E966-02 (later revisions when available) "Standard Guide for Field Measurements of Airborne Sound Insulation of Building Façades and Façade Elements." The measurements are performed with windows open and closed. ASTM E966-02 recommends the following six methods for determining the

OILR, depending on the situation. The noise source is indicated in parentheses.

1. Calibrated Source Method (Loudspeaker)
2. Nearby Average Method (Loudspeaker)
3. Flush Method (Loudspeaker)
4. Equivalent Distance Method (Traffic)
5. 2 Meters (6.6 Feet) Position Method (Traffic)
6. Line Source Flush Method (Traffic)

The first three methods require a loudspeaker for a source and should be employed when no existing traffic source is available, such as when the project involves a proposed highway on an entirely new alignment. The last three methods are preferred when an existing traffic source is available on an existing alignment, such as when the project involves a proposed reconstruction of an existing highway, such as widening or addition of high-occupancy vehicle (HOV) vehicle lanes. However, if the reconstruction involves a major shift in highway alignment or profile in a manner that alters the orientation of the highway significantly relative to the affected residences, loudspeaker sources in locations representing the new orientation may still be preferred.

The six methods are described briefly in this section. Full details are described in ASTM 966-02 or later revisions when available. Anyone who will undertake a noise study for the purpose of potential home insulation under the provisions of the EAG and this section should be familiar with and follow the procedures in this standard.

## 8.4.2.1 Methods 1 to 3

These three methods require loudspeakers for noise source and are employed when no existing traffic is available at the time of the study, such as when the proposed highway will be on a new alignment. The outdoor noise level produced by the loudspeakers is either determined by a previously calibrated level at a specific distance, measured at random distances near the façade, or measured “flush” (within 17 millimeters) near the building façade facing future traffic sources.

### Orientation of Loudspeakers

ASTM E 966-02 gives broad guidelines for the orientation of the loudspeaker source. For the purposes of emulating the future traffic line source, the following statement in Section 8.2.3.1 is the most pertinent: "When the test objective is to evaluate the performance of a façade element for a particular source location, the test should duplicate the condition of concern as closely as possible." Ideally, the axis of loudspeakers in all three methods should be oriented toward the midpoint of the façades shielding the inside rooms of interest along the lines that best represent all directions from the roadway segment exposed to the façade. Such orientations approximate the averages of all angles from the future line source of traffic and can be thought of as the line bisecting the roadway segment angle as observed from the midpoint of the façade of interest. However, this may not be an adequate representation in many cases. For a façade exposure to an infinite roadway (segment angle 180º), the bisected angle would be 90º to the highway. A line normal to the highway would certainly not be an adequate representation of all directions.

A reasonable solution would be to define roadway segments by angles counterclockwise and clockwise from a line normal to the highway, as done in the FHWA-RD-77-108 highway noise prediction method. The ends of each roadway segment were defined relative to a line from the receiver perpendicular to the highway, by angles counterclockwise (by convention negative) or clockwise (by convention positive), as viewed from the receiver. Three basic cases can be identified in this manner, as shown in Figures 8-7a to 8-7c. Please note that by convention the first angle mentioned is always the largest negative ($-\Phi_1$) or the smallest positive ($\Phi_1$). Note that the limits for any segments are -90º and +90º for an infinite roadway. Figure 8-7a depicts a highway segment in both the negative and positive quadrants. Case "b" shows a highway segment in the negative quadrant only, and case "c" shows the same in the positive quadrant only.

Defining roadway segments in the manner shown in Figure 8-7 makes it easier to construct lines that are most representative of all directions from the exposed roadway segments, using a rule that the angle of each exposed roadway in each quadrant should be bisected. For an infinite roadway, a special case of Figure 8-7a, the representative directions of two loudspeakers will be -45º and 45º, as shown in Figure 8-8. For the OILR measurements, both speakers simultaneously or one speaker at a time may be used.

The angle of the exposed roadway segment is often defined not only by the endpoints of the segment, but also by the orientation of the façade relative to the highway. In the example of an infinite roadway shown in Figure 8-8, the façade of interest runs parallel to the future infinite highway, providing an unobstructed view from the façade. This is a special case.

Other orientations of the façade with respect to an infinite highway will reduce the exposed highway segment, as shown in Figure 8-9, which shows five representative orientations of a façade of interest (cases "a" to "e"). For convenience, the special case in Figure 8-8 is included and represented by case "a." Each case shows the future infinite highway, the perpendicular drawn from the midpoint of façade to the highway, and a line along the extension of the façade that, except in case "a," intersects the highway. The latter is the limit of exposed roadway segment. The arrowed lines represent the direction of loudspeaker orientations, constructed by either bisecting the angles formed by the perpendicular to the end of the exposed highway (finite or infinite) or the entire angle if the latter is less than 45º (e.g., case "c").

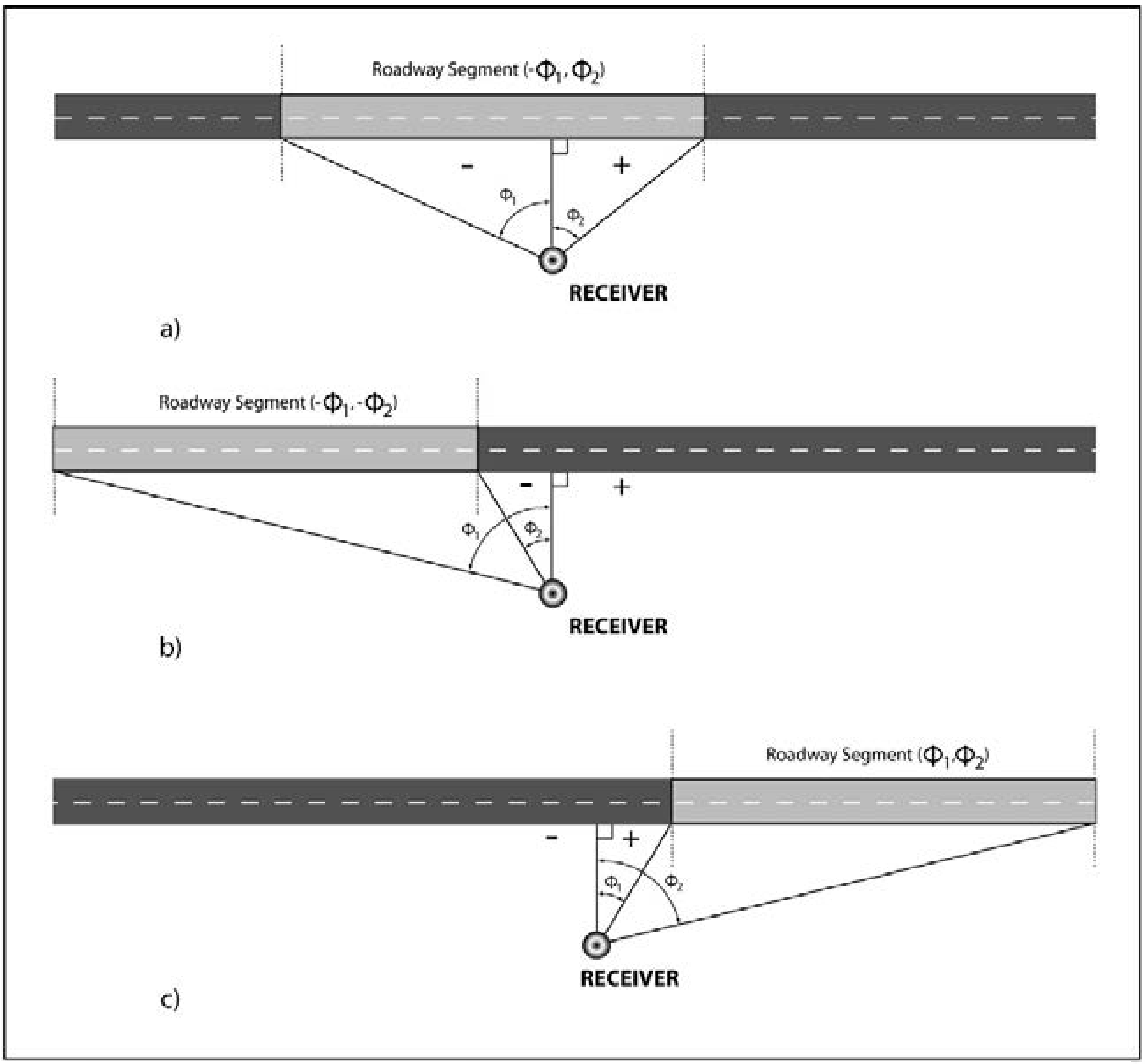


**Figure 8-7.** Defining Roadway Segments by Angles

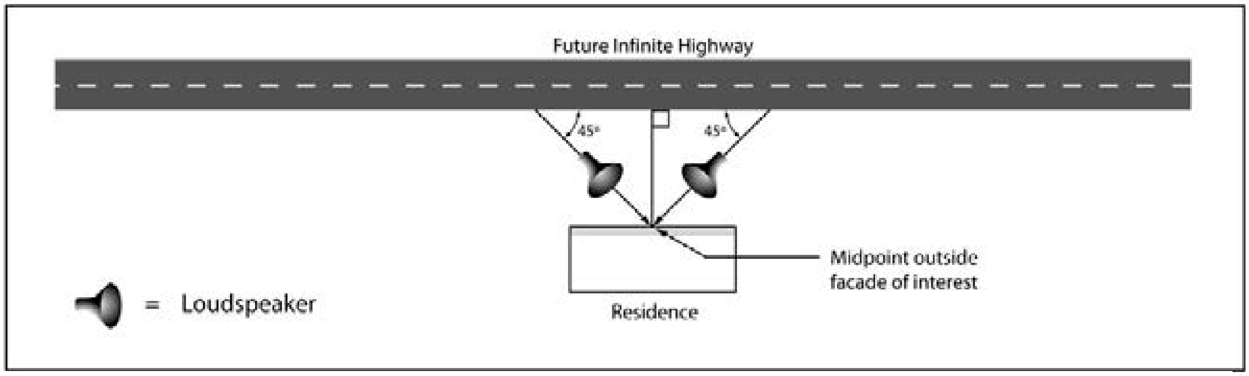


**Figure 8-8.** Orientation of Loudspeakers for an Infinite Highway

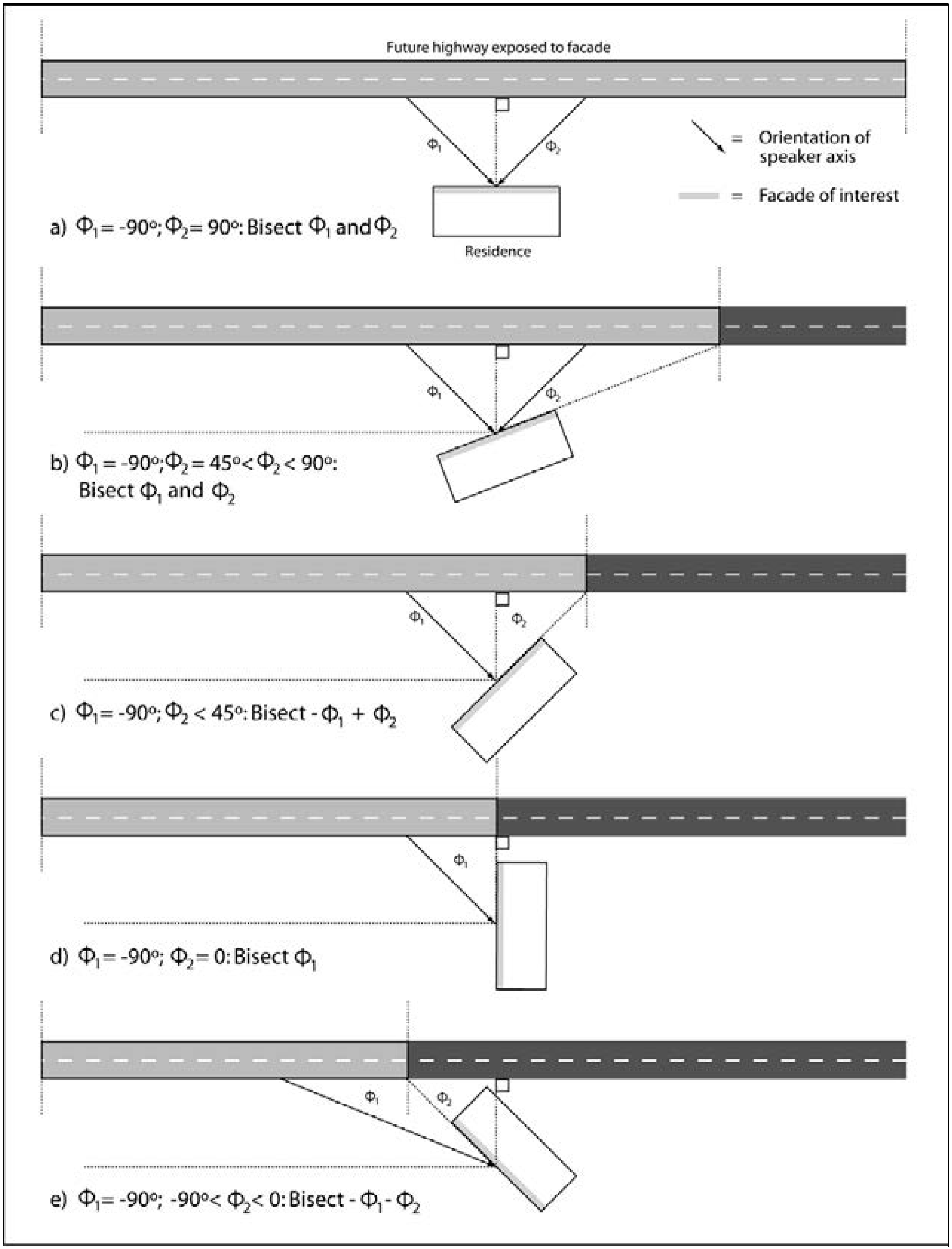


**Figure 8-9.** Loudspeaker Orientation as a Function of Facade Orientation Relative to an Infinite Highway

Figure 8-9 shows the minimum recommended number of speaker orientations for the OILR tests. Please note that two directions are recommended in cases “a” and “b.” More directions may be used if they represent the future exposed highway.

This section has so far covered speaker orientations for an infinitely long highway, where the only segment limitation was caused by the orientation of the façade. For a finite highway, similar procedures may be followed. There is no need to discuss the procedures for a finite highway except for the following case. If the total angle subtended by the exposed roadway angle is less than 90º, one direction may be used, derived by bisecting the total angle. This situation is shown in Figure 8-10 for three different finite segment configurations. For an angle more than 90º, the recommendations discussed for the infinite highway (Figure 8-9) may be used.

Determining the orientation of the speaker may seem difficult to accomplish without the physical evidence of the highway at the time of the study. However, with the use of design plans and aerial photographs, the orientation with respect to the highway may be plotted. Once this is completed, planning the placement of the speakers should not be difficult. Another consideration should be the number of exposed façades. The examples shown in Figures 8-9 and 8-10 deal with one façade only, whereas in reality other façades will probably be exposed as well to the future highway. Through careful planning, the placement and orientation of speakers can be combined for several façades at a time for efficiency.

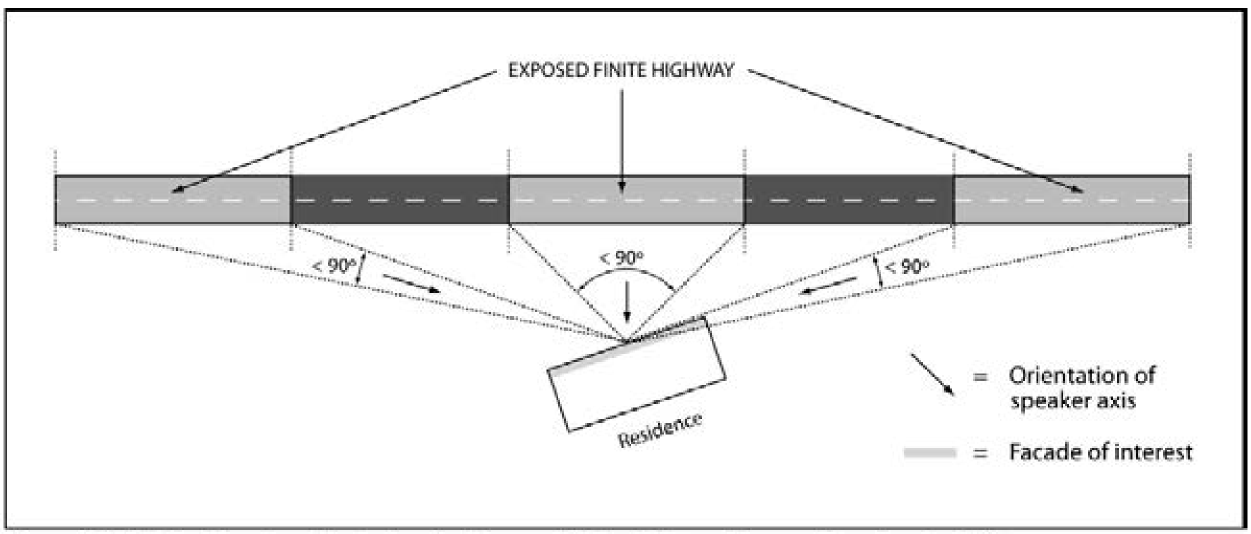


**Figure 8-10.** Speaker Orientation for Exposed Finite Highway Segment Angles of Less Than 90º

## Distance from Loudspeaker to Façade

The loudspeaker must be far enough from the façade so that the ratio of the distances from the speaker to the farthest and nearest parts of the façade of interest are not more than two (Figure 8-11).

## Loudspeaker Characteristics and Test Signal

The directional characteristic of the speaker should be such that at 2,000 Hz the free-field SPL up to an angle of 45º is not more than 6 dB different from the SPL along the axis, and the output must be sufficient in all measured bands from 80 to 5,000 Hz. The electrical signal should consist of random noise filtered in one-third– or one-octave bands. Measurements should be of sufficient duration to account for source level fluctuations.

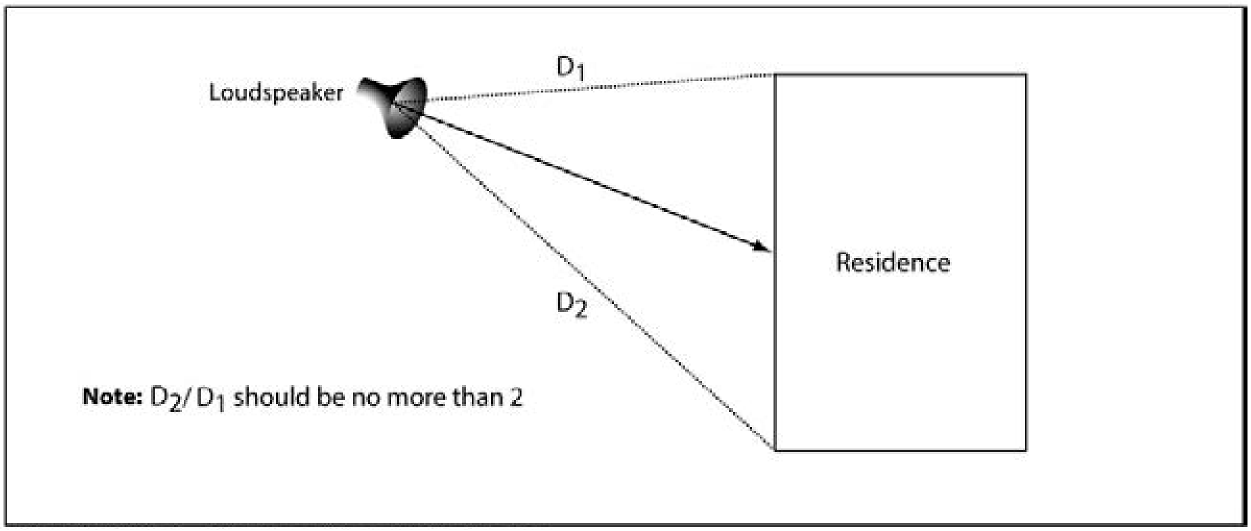


**Figure 8-11.** Distance of Speaker to Facade

## Determination of Method 1

In this method, the loudspeaker is calibrated in a free-field environment (away from the residence, reflective surfaces, or obstructions) by measuring the output at the same distance that it will be from the façade during the OILR test. Once the output is determined at that distance, the speaker is set up at the same distance from the façade and oriented as previously discussed. The outside SPL at the façade is then inferred from the calibration. Inside the rooms of interest, either a single moving microphone may be used or fixed-position microphones. The single moving microphone may be moved along a predetermined traverse or circular path. For the fixed microphones, one or more positions may be used. The minimum separation of microphone positions should be 1 meter. The microphone positions should be located 4 to 5 feet above the floor. No microphone position should be closer than 1 meter to the inside surface of the exterior wall or to any other surface. The OILR for this method is calculated using the following equation:

$$OILR = L_{cal} - L_{in} \qquad \textbf{(8-6)}$$

Where:

$L_{cal}$ = calibrated noise level

$L_{in}$ = average SPL in the room enclosed by the test façade caused by the loudspeaker oriented as previously described

## Determination of Method 2

This method may be used when Methods 1 and 3 cannot be used. The loudspeaker is placed and oriented as previously discussed. SPL is measured outside and inside the facade either simultaneously or separately without changing the output level of the speaker. To minimize wave interference effects, a minimum of five microphone positions should be used for the outside measurements at varying heights and random locations within 1.2 to 2.5 meters of the façade of interest. The positions should represent the left, right, upper, and lower limits of the façade. The inside microphone positions are the same as for Method 1. The OILR for this method is calculated using the following equation:

$$OILR = L_{near} - L_{in} - 3\ dB \qquad \textbf{(8-7)}$$

Where:

$L_{near}$ = arithmetic average of outside near façade SPLs

$L_{in}$ = average SPL in the room enclosed by the test façade caused by the loudspeaker oriented as previously described

3 dB = correction for reflected noise from façade

## Determination of Method 3

If Methods 1 and 2 are not possible or practical, and the façade of interest is hard and smooth, Method 3 may be used. In this method, the outside SPL is measured with a small condenser microphone, 13 millimeters (0.5 inch) in diameter mounted entirely within 17 millimeters of the midpoint of the façade. The microphone itself should not touch the façade, and the airflow through the microphone grille must not be impeded. Such placement allows the reflected pressure waves to be in phase with the incident sound pressure waves for most frequencies of interest. This causes a phenomenon called pressure doubling, where the incident and reflected pressure waves combine constructively over a range of frequencies, causing the sound pressure waves to double. A doubling of the sound pressure waves causes a known increase of 6 dB. Once again, five measurements are suggested. The inside microphone positions are again the same as in Methods 1 and 2. The OILR for this method is calculated using the following equation:

$$OILR = L_{flush} – L_{in} – 6\ dB \qquad \textbf{(8-8)}$$

Where:

$L_{near}$ = arithmetic average of outside near façade SPLs

$L_{in}$ = average SPL in the room enclosed by the test façade caused by the loudspeaker oriented as previously described

6 dB = correction for pressure doubling by façade

## 8.4.2.2 Methods 4 to 6

Methods 4 to 6 should be used when the proposed project consists of reconstruction of an existing highway without significant alteration of alignment and profile. Typical projects in this classification are highway widening and adding HOV lanes. The existing traffic should be used for determining the OILR except in cases where the alignment or profile will change significantly. In those cases, the previously described Methods 1 to 3 should be employed.

Where possible, the OILR measurements may be done simultaneously with the measurements for the worst hour or done separately. As with the worst-hour noise measurements, the use of a near–traffic source reference microphone (see Section 8.4.1.1) is recommended.

### Determination of Method 4

In this method, the outside microphones will be set up in the same manner as explained in Section 8.4.1 and shown in Figure 8-6 for the worst-hour noise level determination. The inside microphone positions are the same as discussed in Methods 1 to 3. The OILR is calculated using Equation 8-6. In this case, $L_{in}$ is the average of the inside SPLs from the traffic source.

### Determination of Method 5

This variation of Method 2 uses one microphone outside set 2 meters (6.6 feet) away from the midpoint of the façade of interest. This method should be used only when the façade of interest is fully exposed (i.e., near parallel) to the highway. Again, the inside microphone positions are the same as discussed in Methods 1 to 3. The OILR is calculated using Equation 8-7. In this case, $L_{in}$ is the average of the inside SPLs from the traffic source.

### Determination of Method 6

This final method is a variation of Method 3; the only difference is the traffic source. Again, the inside microphone positions are identical to Methods 1 to 3. The OILR is calculated using Equation 8-8. In this case, $L_{in}$ is the average of the inside SPLs from the traffic source.

### Background Noise

In all six methods, the background noise outside the façade should be at least 10 dBA less than the loudspeaker or traffic source to ensure that the noise level from the source is not contaminated. For Methods 1 to 3, the background noise is easily measured without the test signal. For Methods 4 to 6, the background noise is more difficult to determine because the traffic cannot be shut off. However, in most cases the traffic source will be very close (otherwise the residences would not qualify for consideration of home insulation), and contamination will not be an issue.

## 8.4.3 Determining Worst-Hour Inside Noise Levels, and Comparison with Guidelines

Once the worst-hour outside noise level (Section 8.4.1) and OILR (Section 8.4.2) have been determined, the worst hourly noise level inside the residence can be calculated simply using the following equation:

$$L_{in}(\text{worst hour}) = L_{out}(\text{worst hour}) - \text{OILR} \qquad \textbf{(8-9)}$$

Where:

$L_{in}$(worst hour) = worst-hour inside noise level in $L_{eq}$(h) dBA

$L_{out}$(worst hour) = worst-hour outside noise level in $L_{eq}$(h) dBA

The calculated $L_{in}$(worst hour) is then compared with criteria set forth in the EAG. Based on the results of the comparison, the various insulation options under the EAG are recommended.

## 8.5 Construction Noise Analysis, Monitoring, and Abatement

Construction noise is usually a concern only in exceptional cases, such as when pile driving and crack-and-seat pavement rehabilitation operations are planned. Caltrans Standard Specifications Sections 7 and 42 and the Caltrans Standard Special Provisions Section 5-1 discuss construction noise levels. Caltrans Standard Specifications are applied to all construction projects. The Standard Special Provisions provide a menu of special provisions that can be selectively applied to a project based on the specific needs of the project.

Section 7 1.01I, “Sound Control Requirements,” of the Standard Specifications states:

> The Contractor shall comply with all local sound control and noise level rules, regulations and ordinances which apply to any work performed pursuant to the contract.
>
> Each internal combustion engine, used for any purpose on the job or related to the job, shall be equipped with a muffler of a type recommended by the manufacturer. No internal combustion engine shall be operated on the project without the muffler.

Section 42-1.02, “Construction,” relates to pavement grooving operations and states:

> The noise level created by the combined grooving operation shall not exceed 86 dBA at a distance of 50 feet at right angles to the direction of travel.

Section 5-1, “Sound Control Requirements,” of the Standard Special Provisions states:

> The noise level from the Contractor's operations, between the hours of 9:00 p.m. and 6:00 a.m., shall not exceed 86 dBA at a distance of 50 feet. This requirement shall not relieve the Contractor from responsibility for complying with local ordinances regulating noise level. The noise level requirement shall apply to the equipment on the job or related to the job, including but not limited to trucks, transit mixers or transient equipment that may or may not be owned

> by the Contractor. The use of loud sound signals shall be avoided in favor of light warnings except those required by safety laws for the protection of personnel.

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

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

If construction noise on any highway project is anticipated to be a substantial problem, further analysis is recommended. Items to be examined are:

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

Caltrans does not routinely analyze construction noise during the project development phase. However, as is discussed in Section 7.3.8, construction noise impacts and likely abatement measures (if necessary) should be discussed briefly in the noise study report for all projects. Generally, Caltrans will only consider construction noise and its abatement in greater detail during the project impact analysis if the project is large, is controversial, or has a prolonged construction phase with extensive pile driving or other loud operations. Construction noise impacts on wildlife may also need to considered in some special situations. An example would be where pile driving will occur near nesting birds that are on the endangered species list.

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

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

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

In addition to noise, construction activities can potentially generate earthborne vibrations that may disturb, damage, or interfer with activities at vibration-sensitive receivers. Section 8.6 briefly discusses earthborne vibrations.

### 8.5.1 Consideration of Construction Noise during Project Development Phase

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

- residences or land use activities to be impacted most by construction noise;
- principal types of equipment to be used;
- noise characteristics (impact noise, continuous noise, etc.) and range of noise levels of equipment used at reference distances;
- duration of construction and the loudest operations;
- appropriate specifications, special provisions, and regulations by which the contractor must abide;
- noise monitoring for compliance during construction; and
- abatement strategies that can potentially be provided, such as:
  - temporary walls, earth berms, or noise curtains;
  - alternative, less noisy construction methods;
  - restricted hours of operation;
  - keeping haul roads away from residences; and
  - building soundwalls slated for the project first.

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

- calculating expected noise levels at the impacted receivers or at a standard distance (usually 50 feet) as dictated by criteria; and
- comparisons of calculated noise levels to specifications, special provisions, and other pertinent criteria.

Caltrans construction noise criteria are typically expressed using the $L_{max}$ descriptor at a reference distance. As stated above, an $L_{max}$ of 86 dBA at 50 feet is commonly used by Caltrans as a maximum construction noise limit. Equipment and operations are usually at or less than that level, except for blasting, pile drivers (impact or vibratory), hoe rams, pavement breakers for crack-and-seat operations, and other impact equipment. Table 8-1 summarizes typical construction noise levels identified in the FHWA Roadway Construction Noise Model User's Guide. These noise levels come directly from data developed during the construction of the Central Artery Tunnel Project in Boston.

**Table 8-1.** Typical Construction Equipment Noise

| Equipment Description | $L_{max}$ Noise Limit at 50 feet, dB, Slow | Usage Factor | Impact Device? |
|---|---|---|---|
| All other equipment more than 5 horsepower | 85 | 50 | No |
| Auger drill rig | 85 | 20 | No |
| Backhoe | 80 | 40 | No |
| Bar bender | 80 | 20 | No |
| Blasting | 94 | N/A | Yes |
| Boring jack power unit | 80 | 50 | No |
| Chain saw | 85 | 20 | No |
| Clam shovel | 93 | 20 | Yes |
| Compactor (ground) | 80 | 20 | No |
| Compressor (air) | 80 | 40 | No |
| Concrete batch plant | 83 | 15 | No |
| Concrete mixer truck | 85 | 40 | No |
| Concrete pump truck | 82 | 20 | No |
| Concrete saw | 90 | 20 | No |
| Crane (mobile or stationary) | 85 | 16 | No |
| Dozer | 85 | 40 | No |
| Dump truck | 84 | 40 | No |

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

Source: Federal Highway Administration 2006.

Table 8-1 also provides a typical usage factor for each equipment type. The usage factor is an estimate of the fraction of time each piece of equipment operates at full power. The usage factor can be used to estimate $L_{eq}$ from the $L_{max}$ values listed in Table 8-1 in those cases where the impact criteria is expressed in terms of $L_{eq}$. Equation 8-10 can used to estimate $L_{eq}$ from $L_{max}$. It also includes a term for estimating noise at distances other than 50 feet.

$$L_{eq}(h), dBA = L_{max} \text{ at 50 feet} - 20\log(D / 50) + 10\log(UF) \qquad \textbf{(8-10)}$$

Where:

$L_{max}$ at 50 feet can be looked up in Table 8-1 or similar table

D = distance of interest

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

If more than one piece of equipment is in operation in the same location, Equation 8-10 can be used for each piece of equipment and the results can be summed to give a combined noise level at the location of interest. Typically, only noise levels from the two or three loudest pieces of equipment are summed. The FHWA Roadway Construction Noise Model automates most of this process.

The Caltrans Standard Special Provisions are currently undergoing revisions that will incorporate equipment noise limits indicated in Table 8-1 and other criteria than can be used on Caltrans projects.

## 8.5.2 Noise Monitoring during Construction

Construction noise monitoring may be part of a program called for in the environmental document, in regulatory permits, or in response to noise complaints. Noise monitoring requirements may be in response to effects on both humans and wildlife. Refer to Section 8.8 for more discussion on the effects of construction noise on wildlife. In most cases, the noise measurements are used to ensure compliance with the appropriate criteria specified in construction contract specifications or other applicable regulations. In the case of complaints, measurements may be conducted to identify the source of the complaints and to develop solutions for reducing the noise. As discussed above, Caltrans is not required to comply with local noise ordinances. However, as a matter of practice, it is Caltrans intent to comply with all applicable environmental requirements per 23 CFR 771.105.

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

The manner in which construction noise measurements are taken depends on the applicable criteria. If the criterion calls for a certain $L_{max}$ at a reference distance, the sound level meter must be placed at the requested distance from stationary equipment and the noise measured in the $L_{max}$ mode during full operation of the equipment. Ideally, the noise level should be measured from four different directions, approximately 90° from each other (Figure 8-12). This may not be possible, however, and perhaps only two or three directions can be measured. A sufficient time period in each of the microphone positions should be allowed to permit the $L_{max}$ to occur. Sound level meters usually have an $L_{max}$-hold button. In this mode, the recorded $L_{max}$ only changes when a higher noise level than the previous maximum is recorded. If the noise is relatively constant and the $L_{max}$-hold does not change for 30 seconds, the measurement is completed. If the noise is not constant, such as with pile driving, a longer time period of at least 2 minutes is recommended.

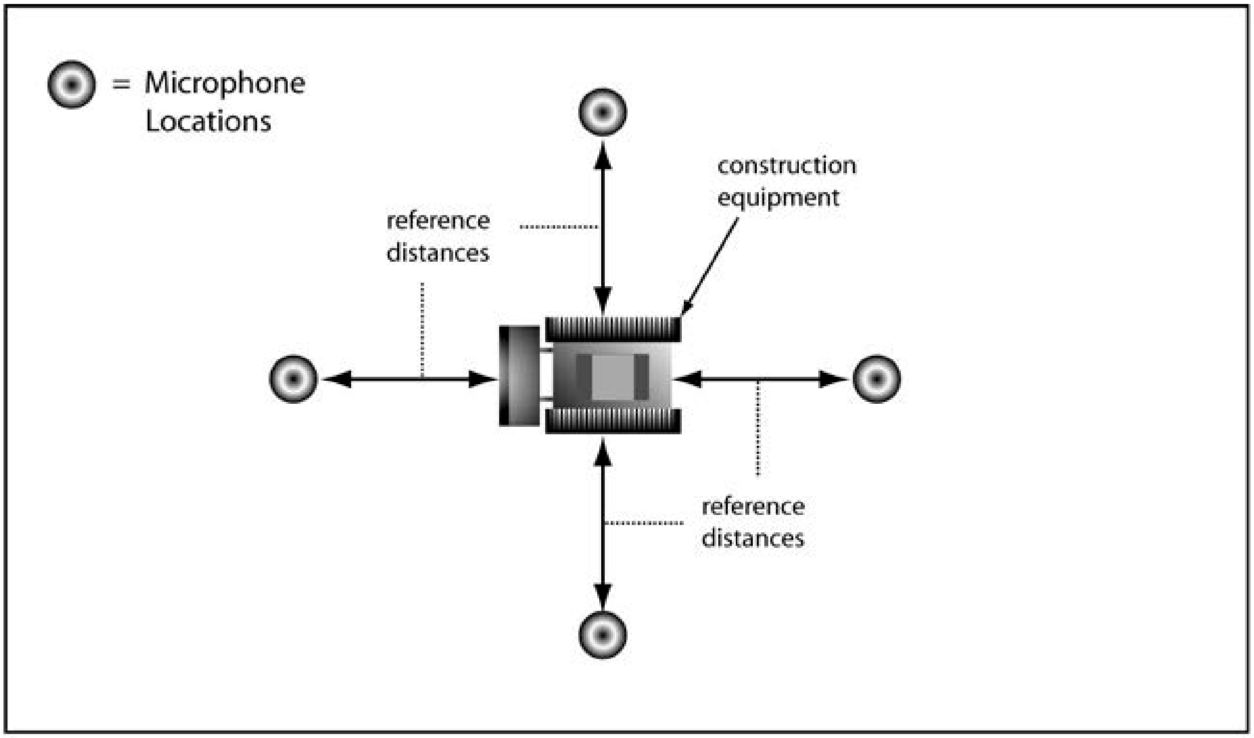


**Figure 8-12.** Measuring One Piece of Equipment

If more than one piece of stationary construction equipment is involved in the same operation, the reference distance should be measured from the nearest piece of equipment, preferably from various directions (Figure 8-13).

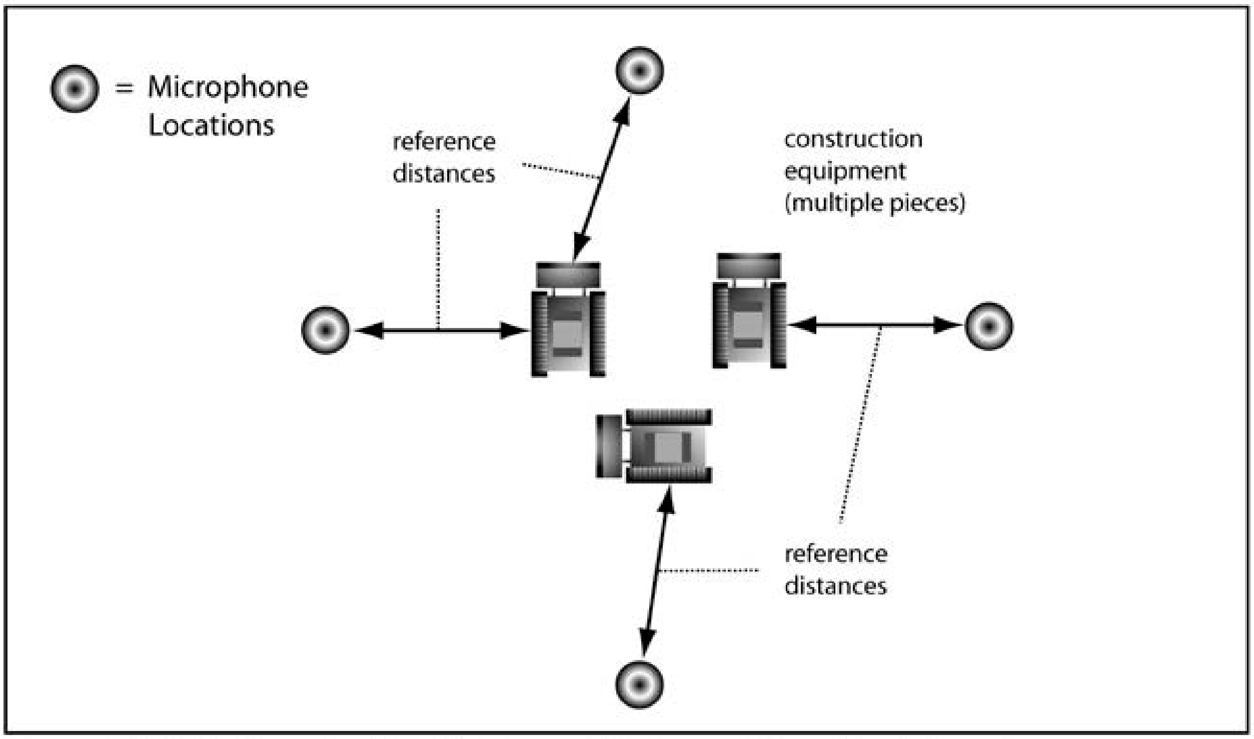


**Figure 8-13.** Measuring Multiple Pieces of Equipment Operating in Same Area

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

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

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

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

## 8.5.3 Construction Noise Abatement

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

### 8.5.3.1 Abatement at Source

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

- reroute haul routes away from residences,
- require modern equipment,
- plan noisiest operations for times of least intrusion,
- plan operations for least use of backup warning devices,
- set backup warning devices to lowest level without jeopardizing safety,
- operate equipment at minimum power, and
- use quieter alternate methods or equipment.

### 8.5.3.2 Abatement in Path

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

### 8.5.3.3 Abatement at Receiver

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

### 8.5.3.4 Community Awareness

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

If construction noise is anticipated to be a major problem, the community should have an opportunity to provide considerable input early in the project development stage. It is essential that communication channels between the Caltrans resident engineer and the community stay open during the construction phase as well.

## 8.6 Earthborne Vibration

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

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

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

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

Heavy trucks are not the only culprits. Trains can produce some of the highest vibrations on a transportation facility. Caltrans has needed to consider cases involving train vibrations where a new highway or light-rail facility necessitated realignment of railroad tracks closer to residences or sensitive operations.

Potential vibration problems should be recognized as early as possible, and strategies to address the problems should be coordinated with the Caltrans Division of Environmental Analysis. The potential impacted vibration-sensitive receptors should be involved early in the awareness and solutions to the vibration problems.

## 8.7 Occupational Hearing Loss and OSHA Noise Standards

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

### 8.7.1 Noise-Induced Hearing Loss

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

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

### 8.7.2 OSHA Noise Standards

29 CFR 1910.95(a) requires the employer to protect the employee against the effects of noise exposure when the permissible noise exposures in Table 8-2 are exceeded. The noise levels must be measured on the A-scale with the sound level meter at slow response.

29 CFR 1910.95(b)(1) requires that when the permissible noise exposure levels are exceeded, “feasible administrative or engineering controls shall be utilized. If such controls fail to reduce sound levels within the levels of Table [8-2], personal protective equipment shall be provided and used to reduce sound levels within the levels of the table.”

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

**Table 8-2.** Table G-16 Permissible Noise Exposure

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

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

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

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

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

  The maximum allowable exposure has been exceeded.

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

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

  The maximum allowable exposure has not been exceeded.

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

29 CFR 1910.95(c)(1–2) requires the employer to “administer a continuing, effective hearing conservation program…whenever employee noise exposures equal or exceed an 8-hour time-weighted average sound

level…of 85 decibels, measured on the A-scale (slow response). Or equivalently, a dose of fifty percent." The 85-dBA noise level or dose of 50% is also referred to as the action level. The hearing conservation program is fully described in 29 CFR 1910.95(c–o).

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

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

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

Addressing the effects of noise on marine and terrestrial animal species provides an exceptionally difficult challenge and requires specialized expertise. With marine life, the acoustical environment is vastly different than on land. In both marine and terrestrial environments, there is a great variety of animal species, each with different tolerances to noise. The nature of the adverse effects on the different species can also differ. Some marine animals may be killed directly by pressure from underwater noise; others may be temporarily stunned, making them easy prey to other animals such as seabirds. On land, some birds may be scared away from their nesting areas, which may interfere with reproduction. Songbirds, which depend on their songs to find a mate, may be unable to communicate with each other in a noisy environment, therefore missing the opportunity to reproduce. Other animals may be temporarily or permanently driven from their habitat. The hearing frequency response to noise is also different in each species. Accordingly, the use of the human response A-scale when evaluating noise impacts on other species may not be appropriate in some cases. The following sections discuss the differences between underwater and atmospheric acoustics, effects on marine life and terrestrial animals, and some abatement strategies.

### 8.8.1 Underwater Noise

The main differences between underwater and airborne noise are the speed of sound, decibel reference level, sound pressures, and propagation. The speed of sound underwater is about 4.4 times faster than that in air. This means that for a given frequency the wavelength is about 4.4 times longer. The underwater speed of sound also increases in a complex manner with temperature, salinity, and depth. The following is a brief discussion of some fundamentals of underwater noise concepts. Refer to Caltrans' "Technical Guidance Manual on the Effects on the Assessment and Mitigation of Hydroacoustic Effects of Pile Driving Sound on Fish" (Guidance Manual), which is available on the Caltrans website at: <http://www.dot.ca.gov/hq/env/bio/fisheries_bioacoustics.htm>. This document also provides a detailed discussion on how underwater noise can affect fish.

The decibel level used in underwater noise is referenced to a pressure of 1 μPa, instead of 20 μPa for airborne noise. A 20-μPa reference is used for decibels in the atmosphere because it corresponds the approximate threshold of normal human hearing (0 dB). In water, this reason is no longer valid. The difference between using 1 and 20 μPa expressed in decibels is 10log(20/1) or 10log(400) = 26 dB. Expressed differently, 1dB(RE 20 μPa) = 26 dB(RE 1 μPa).

Another major difference to consider is that for a given source intensity (energy per unit area—see Section 8.2.2), sound pressures underwater are roughly 60 times greater than in air. Therefore, for the same noise source, the decibel level underwater is $10\log(60^2) = 35.6$, about 36 dB higher.

To understand why sound pressures are about 60 times more in water, new terms must be introduced: characteristic impedance*,* acoustic impedance*,* or sound impedance (Z) of a medium. These terms all have the same meaning. The definition of acoustical impedance of a medium is the ratio of sound pressure (P) in that medium to the particle velocity (v) in that medium:

$$Z = P / v \quad \textbf{(8-11)}$$

Particle velocity is explained in Section 8.2.2. Acoustic impedance of a medium can also be defined as the product of the density of the medium ($\rho$) and speed of sound in the medium (c):

$$Z = \rho * c \qquad \textbf{(8-12)}$$

Acoustic impedance of a medium can be thought of as a resistance of the medium. It is sometimes called the acoustical ohm. Its units are N * s / $m^3$ or Pa * s / m, also called Rayles.

Equation 8-5 formulates sound intensity as I = P * v. Substituting v for P / Z (derived from Equation 8-11), the sound intensity equation can be rewritten as:

$$I = P / Z * P, \text{ or } I = P^2 / Z. \qquad \textbf{(8-13)}$$

Where:

I = sound intensity in the specified medium

P = sound pressure in the specified medium

Z = acoustic impedance of the specified medium

For an identical sound source intensity in air and water, the following equation can be set up:

$$I(\text{water}) = P^2(\text{water}) / Z(\text{water}) = I(\text{air}) = P^2(\text{air}) / Z(\text{air}).$$

From Equation 8-12, Z can be calculated from the densities of water and air, and the speed of sound through these mediums. Both depend on temperature. In water, they also depend on salinity and depth. At a temperature of 20º C, Z(air) = 410 Rayles, Z(water, fresh) = 1,480,000 Rayles, and Z(water, sea) = 1,540,000 Rayles.

The Z values in the above equation can be substituted for the same sound source intensity in air and water:

$$P^2(\text{water, fresh}) / 1{,}480{,}000 = P^2(\text{air}) / 413, \text{ or}$$
$$P^2 (\text{water, fresh}) = P^2(\text{air}) (3{,}584).$$

Similarly, for seawater:

$$P^2(\text{water, sea}) = P^2(\text{air}) (3{,}728).$$

In both cases, the sound pressures squared translate into an increase in SPLs of 10log(3,584) and 10log(3,728), or about 36 dB in water (fresh water or seawater).

The combined increase for an SPL underwater because of a different reference pressure (26 dB) and different acoustic impedance (36 dBA) is about 62 dB for the same sound source. For instance, if pile driving generates an airborne SPL of 100 dB (RE: 20 μPa) on land, the SPL at the same distance will be 162 dB (RE: 1 μPa) for the same pile driving underwater. To avoid any possibility for confusion, the reference pressure used should always be mentioned when displaying SPLs. Some typical underwater sound levels and their origin or effect are listed below (expressed in dB [RE: 1 μPa]).

- Two-kilogram high explosive: 240 dB
- Beluga whale echolocation call at 1 meter: 220 dB
- Air gun array at 100 meters: 200 dB
- Range of underwater pile driving: 200 to 160 dB
- Large ship at 100 meters: 160 dB
- Fin whale call at 100 meters: 140 dB
- Beluga whale threshold of hearing at 1 kHz: 110 dB
- Ambient noise moderate waves: 90 dB
- Seal threshold of hearing at 1 kHz: 80 dB
- Ambient, glassy, and calm water: 60 dB
- Beluga whale threshold of hearing at 30 kHz: 40 dB

## 8.8.2 Propagation of Sound Underwater

Underwater sound propagation is a highly complex function of water depth and the surface and substrate boundary conditions. Because Caltrans is primarily concerned about noise impacts from pile driving, this discussion focuses on the propagation of underwater sound generated by pile driving. Refer to the Guidance Manual for a detailed discussion of this issue.

Pile driving is usually conducted in shallow water where depths are 15 meters or less. Much of the pile driving measured in California has been conducted in very shallow water where depths are less than 10 meters. Measured transmission loss rates in shallow water typical at pile driving sites have been found to vary considerably from site to site. The rates also vary somewhat between the different measurement metrics, Peak, RMS, and SEL. In general, a logarithmic rate has provided the best fit to the data because sound pressure waves spread out in a spherical pattern. As mentioned above, the rate that sound attenuates with distance underwater is complicated by the boundaries and bottom substrates. Over long distances (more than 500 meters), linear correction factors accounting for excess attenuation have improved the prediction. Because hearing is frequency-dependent, and transmission loss is also frequency-dependent, predicting audibility (or detectability) with any certainty at distances beyond 500 to 1,000 meters is not possible.

Empirical data provide examples of sound attenuation with distance. Projects involving pile driving that were most studied indicate that a base 10 logarithmic rate of attenuation is most appropriate. Examples of these projects are described below.

At the San Francisco–Oakland Bay Bridge (SFOBB) project, the transmission loss rates for unattenuated piles varied as a function of pile location and the direction of the measurement from the pile. Attenuation rates were in the range of 4.5 to almost 9 dB per doubling of distance. The equation for the change in sound (ΔdB) is written as follows:

$$\Delta dB = F \log (D1/D2). \qquad \textbf{(}8\text{-}14\textbf{)}$$

Where:

D1 = distance at which the source level is measured

D2 = distance at which the predicted sound is desired

F = attenuation factor that varies as function of water depth, boundary conditions, and other factors

For an attenuation rate of 4.5 dB per doubling of distance, *F* equals 15. For 9 dB per doubling of distance, *F* equals 30.

When the air bubble curtain was in operation, the transmission loss rate was somewhat higher. Measurements between 100 and 1,000 meters indicated *F* values of 19 and 18, respectively, for Peak and RMS sound levels. For distances between 10 and 100 meters from the source, *F* was found to be 20. When pile driving was conducted within a dewatered cofferdam, *F* was found to be 15.

In each of these conditions, measured sound pressures at a certain distance varied by at least 5 dB, even at positions close to the pile. As the measurement position was moved farther away from the pile, the variation increased to 10 dB. For dewatered cofferdams, sound levels either did not drop off or actually increased within 100 to 150 meters of the pile. Sound pressures then decreased, but at different rates for different directions. In some special cases, the measured peak pressure at 500 meters in one direction was similar to the measured peak close to the pile (within 100 meters).

At the Benicia-Martinez Bridge, numerous measurements were made to document the variation in sound level as a function of distance from an unattenuated pile. *F* for distances between 100 and 500 meters from unattenuated piles were found to be 15, 16, and 17, respectively, for Peak, RMS, and SEL sound levels.

Greeneridge Sciences measured transmission loss at Port MacKenzie during the driving of 36-inch-diameter pipe piles. At distances between 60 and 1,000 meters from an unattenuated pile, *F* values were found to be in the following ranges:

- $F_{Peak}$ = 18 to 21
- $F_{RMS}$ = 18 to 23
- $F_{SEL}$ = 16 to 22

The range in *F* values was dependent on the depth of the water column, with lowest values at the deepest depths.

Pile driving at the Russian River near Geyserville showed how the transmission loss varies with the depth of the pile. This project was in shallow water, so transmission through the saturated ground substrate was substantial. When the pile was not driven very far, sound pressures were greatest near the pile. As the pile driving continued, sound pressures near the pile (10 to 20 meters) decreased, but levels increased slightly at positions 50 meters farther away. However, levels at 70 meters were much lower than 50 meters and did not show much change through the entire driving period.

For pile driving sounds that are predominately high frequency (e.g., small-diameter steel pipe or steel H-type piles), the transmission loss can be higher than losses associated with piles that predominantly produce lower frequencies (e.g. larger-diameter piles). Small-diameter steel H-type piles have been found to have high *F* values, in the range of 20 to 30, near the pile (i.e., between 10 and 20 meters). Unattenuated steel pipe piles show *F* values in the range of 15 to 25. Most measurements for concrete piles have been made only close to the pile, at distances of about 10 meters. Some projects included limited measurements at 10- and 20-meter positions, and one project included measurements at 100 meters. The *F* value for concrete piles, based on these data, is about 15.

The use of attenuation systems complicates the dropoff rate. These systems can be very effective at reducing underwater sounds where the primary source of sound is the pile in the water column. As one moves farther away from the pile, groundborne sound generated from vibration at the tip of the pile may become the primary source of sound. Therefore, the attenuation rate may flatten out, or in some cases become positive (i.e., the sound level increases with increasing distance) for a short distance.

### 8.8.3 Effects of Airborne Noise on Terrestrial Wildlife

On land, the effects of transportation-related noise range from scaring away species from their habitats and nesting areas to the inability to communicate with members of their own species, missed mating opportunities, and failure to hear warning signals of approaching predators. These factors play an important role in determining the survival of endangered species. Each missed opportunity to mate affects the procreation of that species, and each missed warning call may be lethal to one or more of its members.

Much of the research on how noise affects wildlife has been done by the military in connection with aircraft noise and sonic booms on various animals. However, not much research has been done on effects from highway and construction noise.

Generally, the effects can be placed into four overlapping categories: startlement, communication, behavior, and hearing. However, there is evidence that some species can adapt to moderate increases of background noise. The variations in noise effects and degrees of adaptation between species make it difficult to set tolerance levels. Sections 8.8.3.1 to 8.8.3.4 briefly discuss the negative effects. Section 8.8.3.5 discusses possible ways that some species adapt. Section 8.8.3.6 discusses the difficulty in setting tolerance criteria and standards.

#### 8.8.3.1 Startlement

As with humans, the first reaction of animals to a sudden noise is generally startlement. Startlement may range from a sudden movement to fleeing the area. If the sound is a single blast, the animal will probably return to the area. If the sound is recurring, however, some species living in the area may abandon their habitat, and others may avoid the habitat. After the sound source has been removed, some species will return, but others may not. If the noise persists, such as when a new transportation facility opens in the region, some species may adapt to the noise, but others may permanently move away from the noise source. The potential loss of nesting areas may have a permanent negative effect on the survival of endangered species. Biologists should inventory the areas surrounding a proposed project to determine the presence of endangered species.

#### 8.8.3.2 Communication

Noise from constructing and operating a transportation facility may interfere with communications within a community of animals through a phenomenon called "masking." Masking is defined as the action of reducing or eliminating a sound's audibility by the introduction of another sound. Frequency spectra and SPL of both sounds determine the degree of masking. Generally, when the introduced sound increases in level, the original sound is more difficult to perceive. Also, as frequencies of the introduced sound approach those of the original sound, the latter becomes less distinguishable. Another factor is the bandwidth of the frequencies. A low-level pure tone may still be distinguishable in the presence of much higher levels of broadband noise, especially when it is near the fringes or outside the effective frequency range of the background noise.

Communication by songbirds is potentially susceptible to masking. The birds use a complex system of calls to attract mates, warn others of predators, announce locations of food sources, or convey other messages. Depending on the frequencies and amplitudes of the noise generated by construction and operation of a transportation facility, the noise may mask the birdcalls, interfering with normal communication of the birds. The range of normal communication could be reduced, which could lead to missed opportunities to find a mate and eventually diminish the population of the species. Missed warning calls could further reduce the numbers by giving predators an increased advantage.

However, songbirds generally communicate in narrow band frequencies of 3 to 5 kHz. Construction and transportation noise tends to occur in a broad frequency range, with most acoustic energy in frequencies lower than those of the birdcalls. Depending on its purpose, a birdcall contains a specific sequence of tones that is easily recognized by other members of its species that are tuned into this sequence. More research is needed to determine the combined effect of all factors involved on communication.

Caltrans has been involved in limited studies concerning birds and noise, specifically the least Bell's vireo and least tern, which resulted in providing abatement measures of highway and construction noise for these endangered bird species in Districts 11 and 12.

#### 8.8.3.3 Behavior

Excessive noise may induce stress in certain species, which may lead to reduced feeding and a reduced energy budget of the members of a species, affecting their long-term survival. When startled, panic responses of some animals could lead to accidents, collisions, or other abnormal behavior that could injure or weaken the animals.

#### 8.8.3.4 Hearing

Land animals have an advantage over fish in that they use more senses that are not sensitive to excessive noise. Nevertheless, as already discussed with songbirds, hearing remains an important sense for many land animals and could be temporarily or permanently damaged by excessive noise.

#### 8.8.3.5 Adaptation

As discussed earlier, excessive background noise in a species habitat may interfere with audible communication between members of the species through masking. There is evidence that some species of songbirds adapt to the presence of background noise by vocalizing louder and changing their pitch to a higher frequency.

Similarly, other animals have adapted to increases in relatively constant noise from highways and even periodic transitory noises, such as those near airports. However, certain species may not be able to adapt. There is a great need for further research to determine the effects of noise on wildlife species and their ability to adapt.

#### 8.8.3.6 Tolerances and Standards

Because of the apparent species-dependency and variety of noise effects, there is a great challenge in determining noise tolerance levels and standards for all species and effects. Noise analysts normally use the A-weighted scale, which is based on human frequency responses. However, animals have hearing ranges in frequencies and threshold levels that are different from that of humans. A-weighting is not appropriate for animals. Another problem is determining the appropriate noise descriptor. These likely depend on the noise effect addressed. For instance, the startle effect may be best addressed by $L_{max}$, while the effect on communication is more adequately described by $L_{eq}$. In each case, a range of frequencies should also be specified in any standard. Finally, the tolerance levels need to be determined for each specific effect on each of the species of interest.

In the recent years, the California Department of Fish and Game has advocated 60 dBA as a limit for songbirds in general and the least Bell's vireo, in particular in District 11 (San Diego). A new freeway constructed through nesting areas of the endangered songbirds incorporated a noise barrier for the birds on the basis of the 60 dBA standard. Although the noise descriptor was never specified, it was generally assumed to be $L_{eq}$. The 60-dBA standard was selected from insufficient data but was nevertheless used in absence of any other standards. Hopefully, standards based on better scientific findings can be agreed on in the future.

A major challenge in determining the effects of noise alone is separating it from the effects of associated actions affecting other senses, such as seeing moving vehicles, equipment, or people and feeling earthborne vibrations.

### 8.8.4 Abatement Strategies

On land, noise abatement measures for wildlife are similar to those for humans. Sensitive areas can be protected from construction noise by placing temporary barriers made of plywood or vinyl "curtains" next to the construction equipment. Such curtains have been used successfully in District 4 and showed noise reductions of up to 15 dB. Another option is to schedule noisy construction operations at certain times of the year to avoid conflicts with mating seasons or nesting activities. District 12 has done this for pile-driving operations near a least tern nesting site in Huntington Beach.

For the operation of transportation facilities, earth berms or permanent soundwalls could be considered. As discussed, District 11 has applied this measure to protect endangered-bird nesting areas. Another strategy is replacing "lost" habitat at locations away from a transportation facilities. This has been done in District 11 with wetlands for migratory birds, but not for reasons of excessive noise.

Underwater noise emitted by pile driving can be reduced by "bubble curtains" created by a placing a movable structure of perforated pipes around a pile to be driven. The pipes are connected to a compressor on land that when turned on compresses the air in the pipes to create a curtain of bubbles around the pile. The bubbles break up the direct contact of the pile with the surrounding water medium. The bubble curtain has been shown to reduce underwater noise levels from pile driving by 10 to 20 dB.

Another version of the bubble curtain device is placing a large-diameter steel pipe (shell) around the pile and bubble curtain to contain the bubbles and create another shell barrier between the source and receiver. Depending on the shell's contact with the bottom, the combination bubble curtain and shell has shown reduction of up to 30 dB.

Finally, abatement measures for underwater pile driving could include scheduling the pile-driving operations for non-critical times of the year, when no spawning takes place or when certain species have migrated to other areas.

Section 9
# Glossary

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

**Audiometer:** An instrument for measuring hearing sensitivity or loss.

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

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

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

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

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

**Band:** See “Frequency Band.”

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

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

**Barrier Attenuation:** The noise reduction from barrier diffraction only.

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

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

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

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

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

**Cycles per Second:** See "Hertz."

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

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

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

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

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

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

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

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

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

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

**Energy Ratio:** See “Relative Energy.”

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

**Equivalent Level:** See “$L_{eq}$.”

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

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

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

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

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

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

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

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

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

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

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

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

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

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

**Ground Effects:** The effects of sound grazing absorptive ground. See also "Absorptive Grounds."

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

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

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

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

**Hourly Equivalent Sound Level:** See "$L_{eq}$(h)."

**Incident Sound:** Direct sound striking a surface. See also "Angle of Incidence."

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

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

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

$$SPL_1 - SPL_2 = 10\log(D_1 / D_2)$$

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

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

**kHz:** Abbreviation for kilohertz, or 1,000 Hz. See also "Hertz."

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

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

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

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

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

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

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

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

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

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

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

$$L = 10\log_2 n_s$$

Where:
L = the loudness level in phons
$n_s$ = loudness in sones

A twofold change in loudness corresponds to a n interval of 10 phons. See also "Phon" and "Sone."

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

**Receiver:** Most basically defined as any natural or artificial sensor that can perceive, register, or be affected by sound (e.g., human ear, microphone). The definition is usually extended to a three-dimensional location where such a receiver is likely to be present. In noise analysis, a receiver is any location of interest to the analyst. In noise measurement, a receiver is the location of the measurement (i.e., microphone). Frequently, one receiver is selected to represent a group of receivers in the same vicinity and with the same acoustical site characteristics.

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

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

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

Where:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\text{Peak} = \sqrt{2} * \text{RMS} \approx 1.414 * \text{RMS}$$
$$\text{RMS} = (1 / \sqrt{2}) * \text{Peak} \approx 0.707 * \text{Peak}$$

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

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

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

**Soft Site:** See “Absorptive Ground.”

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

**Sound Energy:** See “Relative Energy.”

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

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

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

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

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

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

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

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

Where:

$P_0$ = reference pressure of 20 μPa.

$P_1$ = sound pressure.

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

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

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

**Spectrum:** See "Frequency Spectrum."

**Speed of Sound:** The speed of sound for standard temperature of dry air at 0ºC and standard air pressure of 760 millimeters Hg standard is 331.4 meters per second (1,087.3 feet per second). From these base values, the variation of speed of sound with temperature is described by the following equations:

$$\text{Metric Units:} \quad c = 331.4\sqrt{1+\frac{Tc}{273}}$$

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

Where:

c = speed of sound

Tc = temperature in ºC

Tf = temperature in ºF

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

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

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

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

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

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

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

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

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

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

Where:

$E_1$ = sound energy leaving the back of the wall

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

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

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

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

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

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

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

Appendix A

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