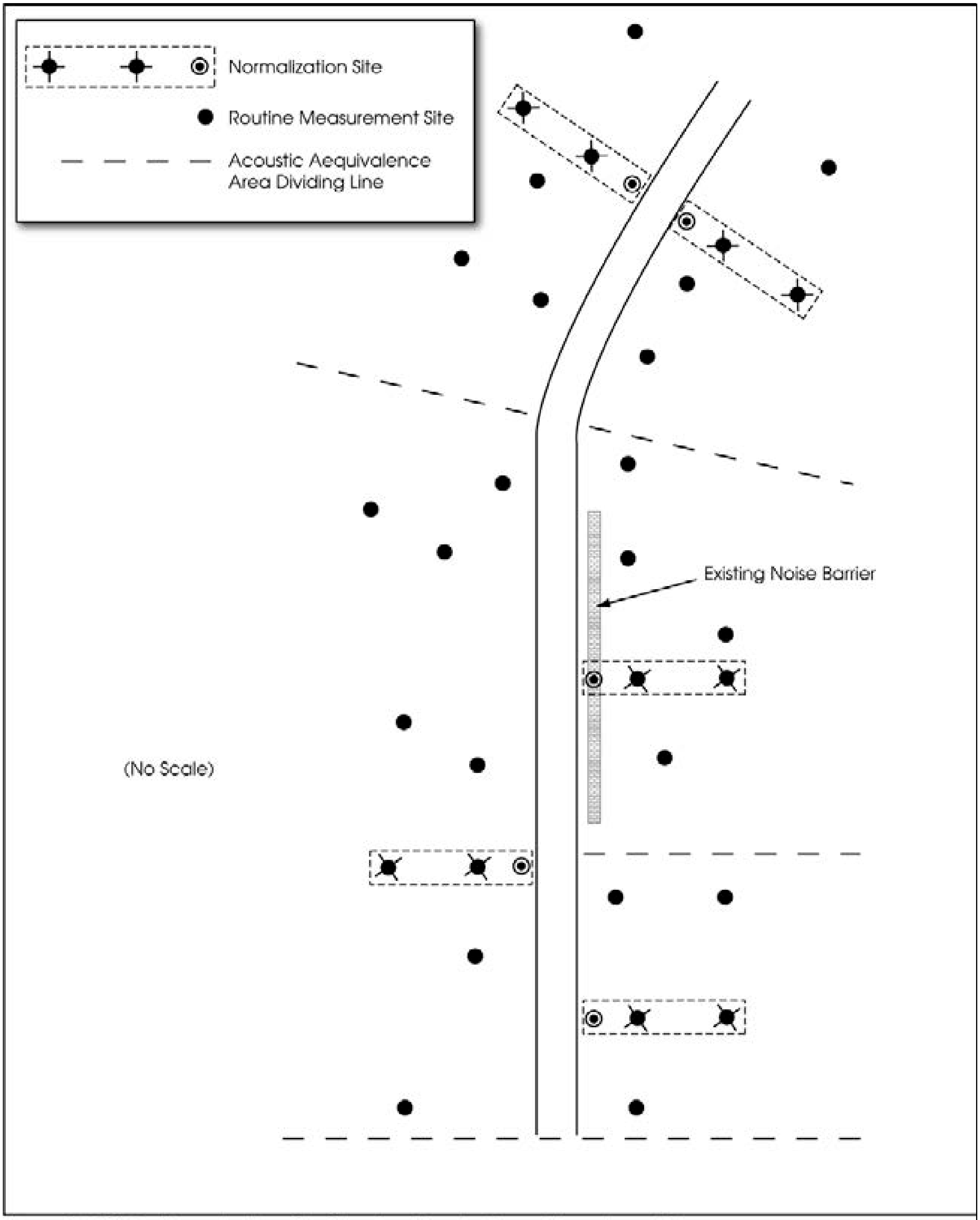

Figure 5-1. Normalization Site Selection Map for Three-Microphone Setups

Instrument Setup

The normalization methodology involves a relatively simple field procedure performed at two or more normalization sites, depending on the size of the project, variations in receiver distances, and other factors influencing acoustical equivalence from site to site. At a typical normalization site, two or more microphones and sound level meters are set up at different distances, roughly on a perpendicular line from the highway.

One microphone (reference microphone) is placed close to the traffic source at a distance of 40 to 60 feet from the centerline of the near lane and at a preferred height of 15 feet. The findings of the Caltrans 1991 SR99 study (Caltrans 1991) showed that noise levels at this reference position were not affected by wind at this close distance from the source. Other near-source data collected at a standard 5-foot measuring height also showed a minimal effect from changing wind conditions, which suggests that alternate heights may be used.

The remaining microphones (receiver microphones) are placed at the locations of interest at a height of 5 feet , farther away from the freeway, where they are affected by the wind. Therefore, the noise level differences between the reference and receiver microphones include the effects of geometric spreading, ground absorption, and atmospheric refraction from wind and temperature gradients. The effects of geometric spreading and ground absorption remain constant. The noise level differences from variations in traffic volumes, mixes, and speeds also remain constant. However, the effects of atmospheric refraction change as wind velocity and temperature gradients change. These effects are also distance-dependent.

Figures 5-2 and 5-3 show a typical cross section and plan view for a three-microphone instrument setup for normalization measurements. The anemometers should be placed in the vicinity of the noise instrumentation, but away from local obstructions and features that could affect the wind measurements. The same anemometers, setups, and locations should be used throughout the normalization process.

The most basic setup must include two microphones—one reference and one receiver. Such a setup may be used if all the routine noise measurement sites are nearly the same distance from the highway. If that is the case, the receiver microphone should be placed at about the same distance as the noise measurement sites. However, where the noise measurement sites are at various distances from the highway (Figure 5-1), three-microphone setups would be more advantageous. The two receiver microphones would be set up at distances that bracket the closest and farthest noise measurement sites.

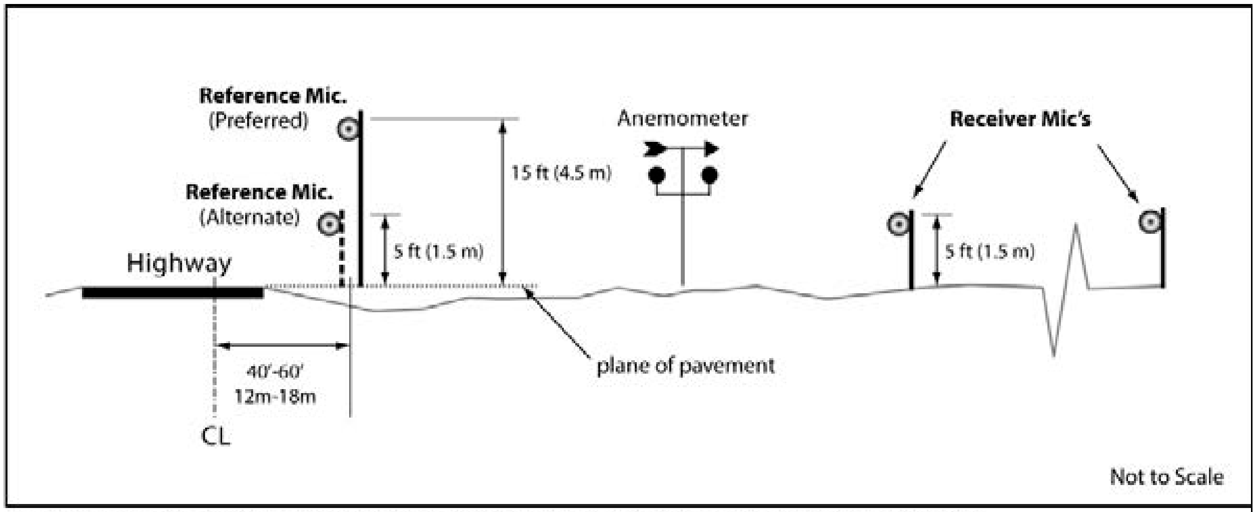

Figure 5-2. Typical 3-Microphone Setup for Normalization Measurements (Cross Section)

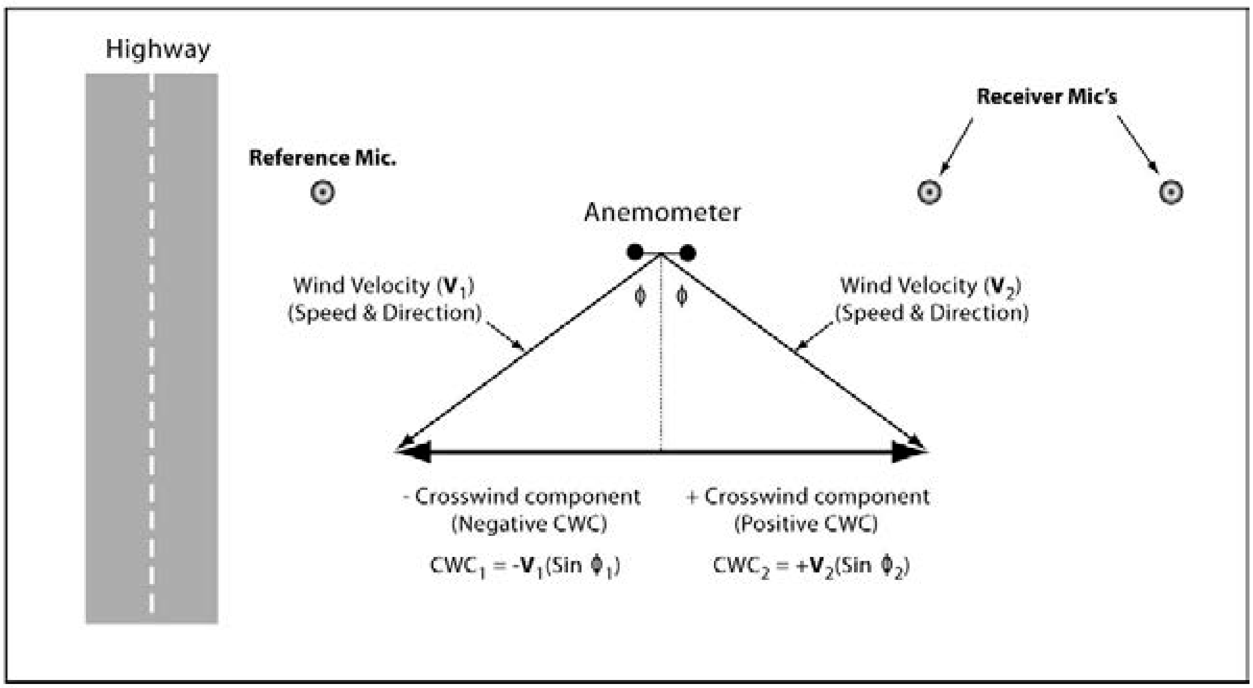

Figure 5-3. Typical 3-Microphone Setup for Normalization Measurements (Plan View)

Noise Measurements

After setting up and calibrating the sound level meters at a normalization site, the various simultaneous noise measurements would be taken under up- and downwind conditions in terms of crosswind components (negative and positive wind vectors, respectively, perpendicular to the highway). This probably would require visiting the site on different days, when wind directions are opposite. No noise measurements should be taken when wind speeds are more than 5 m/s. At least five measurements are suggested: three downwind and two upwind (or vice versa). More measurements are recommended, however, preferably under a wide range of crosswind speeds within the limits of about 5 m/s. The duration of the measurements should be the same as the standard measurement time used throughout the project, normally 15 minutes. Although traffic does not need to be counted for wind normalization purposes, it is highly recommended that traffic volumes be counted during the measurements. The information can be input in the model to verify that the noise levels measured at the reference microphone are explained by the traffic and not by other sources.

Wind Measurements

Wind measurements must be taken simultaneously with the noise measurements. A simple anemometer oriented with respect to true north or another known direction (e.g., the direction of the highway) can be used for this purpose. During the wind measurement, wind direction, wind speed, and duration of wind speed and direction need to be observed.

Although both wind speed and direction often fluctuate fairly rapidly over time, both may be averaged by eye by the observer. Only when there is a well-defined change in direction or speed should the shift be recorded. For example, hypothetical wind data for a 15-minute noise measurement may take on the form shown in Table 5-3.

Table 5-3. Example of Wind Observations

Wind Direction[a]	Wind Speed (m/s)	Duration (minutes:seconds)
345º	4.5	3:00
305º	2.5	7:00
270º	2.0	5:00

[a] Direction from which the wind is blowing. Expressed in terms of degrees clockwise relative to north (Right Azimuth from North [R.Az.N]).

During a set of noise and wind measurements, two restrictions apply. First, the wind from any direction may not exceed 5 meters per second. Also, the crosswind (component 90º to the highway) direction is not allowed to change from upwind to downwind or vice versa (Figure 5-4).

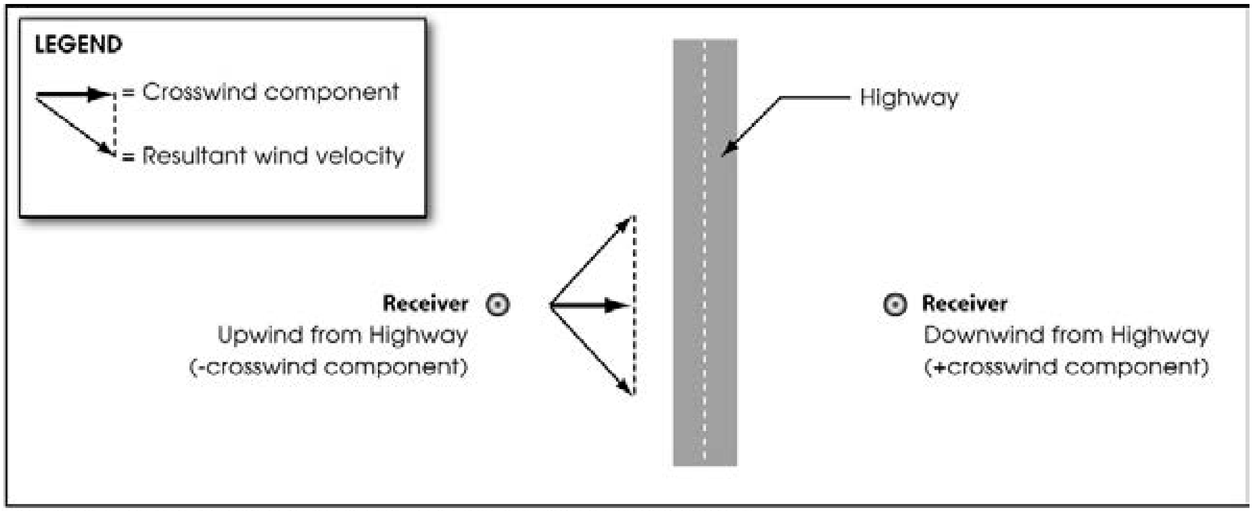

Figure 5-4. Plan View of Upwind and Downwind Conditions

Calm wind conditions are considered to occur when crosswind speeds are between -1 and 1 m/s. Please note that this condition can occur at higher absolute wind speeds when the wind direction is close to parallel to the highway. Under such conditions, wind direction and speed must be measured. However, if the wind speed from any direction during the entire measurement (or a portion of it) averages less than 1 m/s, the wind can be recorded as calm (the resultant wind and crosswind component = 0) for that portion of the measurement. The wind data will need to be correlated with the noise data, as shown in the following sections.

Noise Data Analysis

As mentioned, the noise level differences between the reference and receiver microphones vary because of atmospheric refraction, caused significantly by the effects of wind. The noise differences also normalize the effects of traffic volume fluctuations. The first step in data analysis is calculating the differences between measured noise levels for each pair of reference and receiver microphones.

Wind Data Analysis

The second step in the data analysis is to calculate the crosswind components from the wind data. This process consists of several intermediate steps. First, for each noise measurement the resultant wind velocity needs to be calculated from the wind observations. The resultant wind velocity is defined as the single equivalent wind velocity that would cause a parcel of air to reach the same location at the end of a noise measurement as a parcel of air transported by the observed wind velocities. The resultant wind velocity is expressed by direction from which it was blowing in degrees clockwise from the north (Right Azimuth from North [R.Az.N.]), and speed in meters per second. Tables 5-4, 5-5, and 5-6 show how to calculate the resultant wind from the observed wind data shown in Table 5-4.

Table 5-4. Wind Trajectory Calculation

Noise Measurement Run	Observation	Speed (m/s)	Duration (seconds)	Distance Traveled (meters)	Direction From (Degrees R.Az.N[a])	Direction To (Degrees R.Az.N[a])[b]
1	1	4.5	180	810	345º	165º
	2	2.5	420	1,050	305º	125º
	3	2.0	300	600	270º	90º

[a] R.Az.N = Right Azimuth from North
[b] Direction to = direction from – 180º

For convenience in calculating the coordinates of the wind traverse in Table 5-5, the wind direction *to*, shown in the last column of Table 5-5, may be converted to bearings. For example, the “direction to” of 165° in Observation 1 in Table 5-4 is equal to a bearing of S25°E. These bearings are shown in the fourth column of Table 5-5.

Table 5-5. Wind Traverse Calculations

		Wind Trajectory				Coordinates[b]	
Noise Measurement Run	Observation	Distance (meters)[a]	Direction to (bearing)[a]	Latitude dist.x cos[dir.] N(+), S(-)[c]	Departure dist. x sin[dir.] E(+), W(-)[c]	N(+), S(-)[c]	E(+), W(-)[c]
1						000	000
	1	810	S 25º E	-734	+342	-734	+342
	2	1,050	S 65º E	-444	+952	-1,178	+1,294
	3	600	90º E	0	+600	-1,178	+1,894

[a] From Table 5-5.
[b] Beginning coordinates set at N 000, E 000.
[c] Latitude is the difference in ordinates of the “begin” and “end” points of each trajectory “leg.” If “direction to” is north, the value should be added. If it is south, the value should be subtracted. Departure is the difference in abscissas of the “begin” and “end” point of the above “leg.” If the direction is east, the value should be added. If it is west, the value should be subtracted.

Table 5-6. Resultant Wind Calculation

1	2	3	4	5	6	7
Noise Measurement Run	Latitude N(+), S(-)[a]	Departure E(+), W (-)[a]	Bearing of Resultant Wind Direction To: $\tan^{-1}$ [E,W/N,S] (degrees)[b]	Resultant Wind Distance Traveled (Col. 2)/cos [dir.] (meters)[b]	Resultant Wind Distance Traveled (Check) (Col. 3)/sin [dir.] (meters)[b]	Resultant Wind Speed Average dist/dur. (m/s)[b]
1	-1,178	+1,894	S 58º E = 122º R.Az.N.	2,223	2,233	2,228/900 = 2.5

[a] From Table 5-5.
[b] The calculation in Column 6 serves as a check on Column 5. Columns 5 and 6 should yield reasonably close results. Column 7 uses the average of Columns 5 and 6.

Therefore, the resultant wind for the data shown in Table 5-6 is 2.5 m/s at a bearing of S 58º E direction *to*, or 180º – 58º = 122º R.Az.N. direction *to*, or 302º R.Az.N. direction *from*.

Frequently, the resultant wind speeds and directions can be averaged by eye if there is little variation in speed and direction during a measurement. This would make the procedures followed in Tables 5-4 to 5-6 unnecessary.

After calculating the resultant wind for each noise measurement, the next step is to calculate the CWC, i.e., the wind component perpendicular to the highway. The bearing or R.Az.N. of the roadway must be known. The angle (ϕ) (Figure 5-3) formed by the resultant wind and roadway then can be readily calculated from the differences in azimuths or bearings, and the CWC can be calculated by the following equation:

$$S[\sin(\phi)]$$

Where:

S = resultant wind speed

ϕ = angle between highway and resultant wind (Figure 5-3)

0º = parallel to roadway

90º = perpendicular to roadway

The sign of the CWC is determined by its direction relative to the highway and microphones. If the CWC blows from the highway to microphones, then the sign is positive (+). If it blows from the microphones to highway, the sign is negative (-) (Figures 5-3 and 5-4). This convention means that if the CWC is positive, the microphones are downwind from the highway, and if the CWC is negative, the microphones are upwind.

Noise and Wind Data Correlations

Because only the receiver microphone is assumed to be affected by the wind, the noise level measured at the receiver microphone is expected to be higher when the CWC is positive and lower when it is negative (compared with a zero CWC). The difference between the reference and receiver microphones (ΔdBA) will be less with a positive CWC and more with a negative CWC (i.e., there should be a negative correlation between ΔdBA and CWC). The previously mentioned SR 99 study (Caltrans 1991) showed this to be true. A linear regression equation can be calculated from the measured data, in the form of the following equation:

$$\Delta dBA = a + b\,(CWC)$$

Where

a = ΔdBA at a zero-wind (calm) condition

b = slope of the linear regression (ΔdBA / ΔCWC)

The following tables and figure provide an example that shows the resultant winds of five 15-minute wind observations and calculated CWCs for a hypothetical roadway bearing of N 43º E (Table 5-7); ΔdBAs associated with the CWCs (Table 5-8); and the data plots, regression line, and calculated regression equation (Figure 5-5).

Table 5-7. Resultant Winds and Crosswind Components

	Roadway Bearing N 43º E		
	Resultant Wind		
Measurement	Direction (R.Az.N.)[a]	Speed (m/s)	CWC (m/s)
1	336º	0.5	-0.5
2	188º	2.2	-1.3
3	260º	1.7	+0.9
4	278º	1.6	+1.3
5	312º	2.2	+2.2

[a] Direction *from* which the wind blows.

Table 5-8. Crosswind Component vs. ΔdBA

Measurement	CWC	ΔdBA
1	-0.5	7.2
2	-1.3	6.4
3	+0.9	4.4
4	+1.3	4.5
5	+2.2	5.1

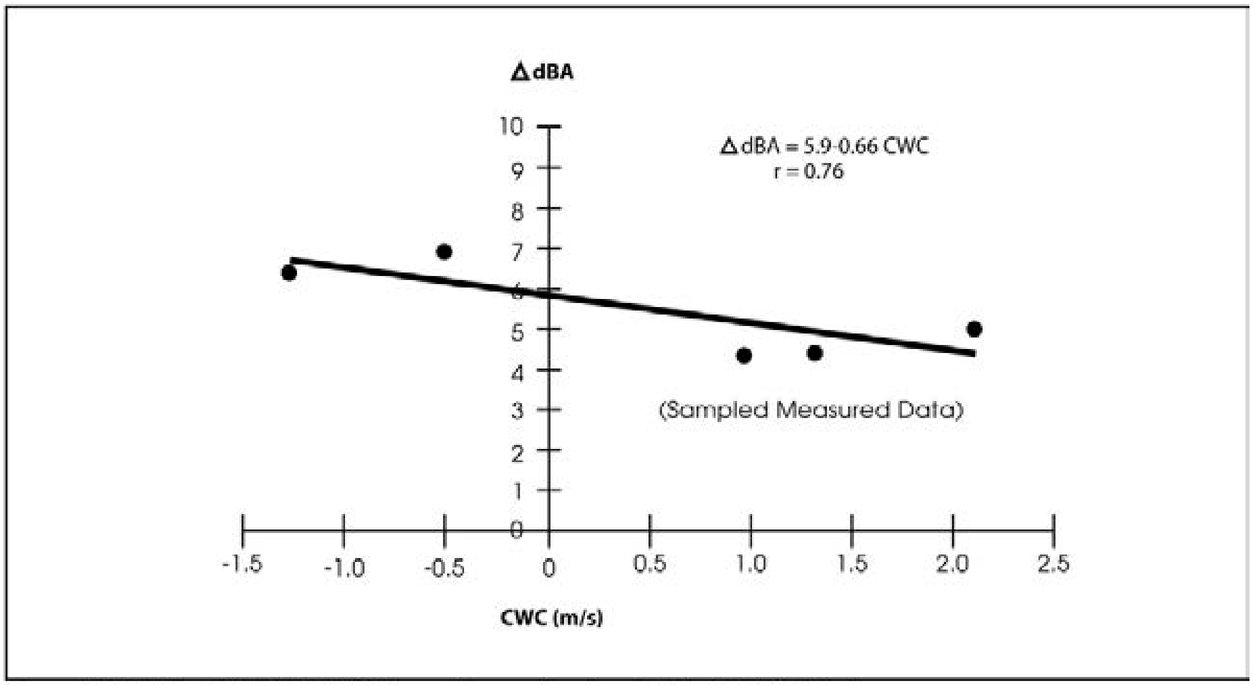

Figure 5-5. ΔdBA vs. Crosswind Component Linear Regression from Table 5-8 Data

The regression equation in Figure 5-5 would have been derived from data obtained at a normalization site (Table 5-8). This equation represents the difference between noise levels at the reference and receiver microphones vs. the crosswind component. The equation is site-specific and distance-dependent. In the equation, 5.9 is the noise difference at 0 m/s crosswind, and 0.66 is the slope of the linear regression line. The slope describes the wind effect and should always be negative because ΔdBA is inversely proportional to crosswind speed. The slope may be used at any noise measurement site that is represented by the normalization site.

For example, the measured noise at a certain noise measurement site was 65 dBA. The CWC during the measurement was calculated from the measured wind data and found to be +2 m/s (4.4 mph) (i.e., the measurement site was downwind from the highway). The wind effect would be the difference between ΔdBA at 0 m/s and at +2 m/s (i.e., the slope of the regression line). Using the slope in the regression equation, the wind effect (ΔdBA) at 2 m/s would be -0.66 *2 = -1.3 dBA. Because the result is negative, it would be subtracted from the noise measurement. However, the result should always be rounded to the nearest whole dBA, (e.g., 1.5 dBA would be rounded off to 2 dBA, 1.4 dBA to 1 dBA). In this case, the result would be -1 dBA, so no correction would be applied under the constraints outlined in the next section. Had the correction been -2 dBA or more negative, the noise level would be adjusted. The noise measurement normalized for wind then would be 63 dBA or less.

The normalized noise measurement now may be compared with the modeled result to derive *K* and calibrate the model as described in Section 5.4.1.

For a three-microphone setup, the two receiver microphones are positioned to bracket the variation in distances of the routine noise measurement sites. The wind effects at each site may be interpolated from the wind effects at the near and far receiver microphones calculated from a normalization site. An example of the procedure is shown in Figure 5-6, Table 5-9, and Figure 5-7. Figure 5-6 shows fictitious regression lines for Receiver Microphones 1 and 2 at a hypothetical normalization site shown in Figure 5-7.

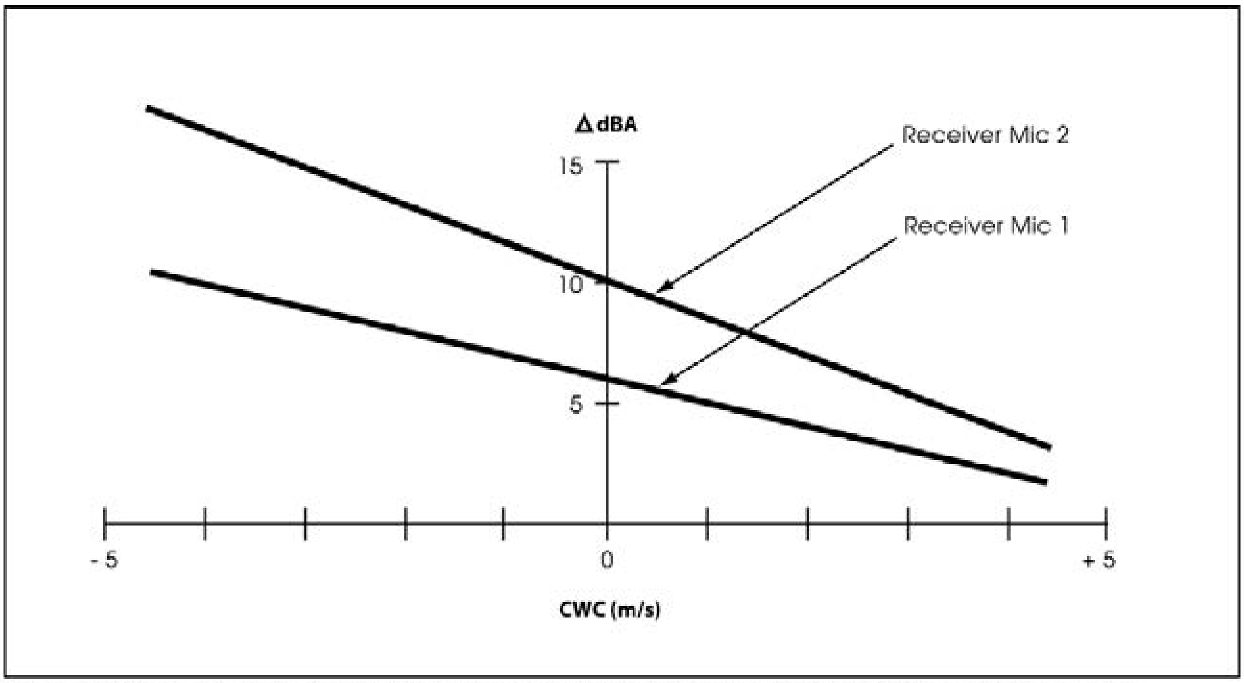

Figure 5-6. Sample Regression Lines for Two Receiver Microphones (Three-Microphone Setup)

The regression equations are shown in Table 5-9, along with the calculated adjustments for each CWC within the range of measured data, in this case the extremes from -5 to + 5 m/s. In reality, these extremes may not occur during the repeat visits to the site.

Table 5-9. Regression Data for Figure 5-6

CWC (m/s)	Regression Equation for Receiver Microphone 1: ΔdBA = 5.8 – (0.77)CWC Slope = -0.77 Adjustment (dBA) = [-0.77(CWC)]	Regression Equation for Receiver Microphone 2: ΔdBA = 10.2 – (1.22)CWC Slope = -1.22 Adjustment (dBA) = [-1.22(CWC)]
-5	+3.8 ≈ +4	+6.1 ≈ +6
-4	+3.1 ≈ +3	+4.9 ≈ +5
-3	+2.3 ≈ +2	+3.7 ≈ +4
-2	+1.5 ≈ +2	+2.4 ≈ +2
-1	No adjustment (calm)	No adjustment (calm)
0	No adjustment (calm)	No adjustment (calm)
+1	No adjustment (calm)	No adjustment (calm)
+2	-1.5 ≈ -2	-2.4 ≈ -2
+3	-2.3 ≈ -2	-3.7 ≈ -4
+4	-3.1 ≈ -3	-4.9 ≈ -5
+5	-3.8 ≈ -4	-6.1 ≈ -6

Figure 5-7 shows two routine noise measurement sites (A and B), which are represented by the normalization site. Also shown are the CWCs observed during the measurements at each site and the corresponding adjustments for zero wind, which were obtained from Table 5-9 for both receiver microphones and interpolated for distance.

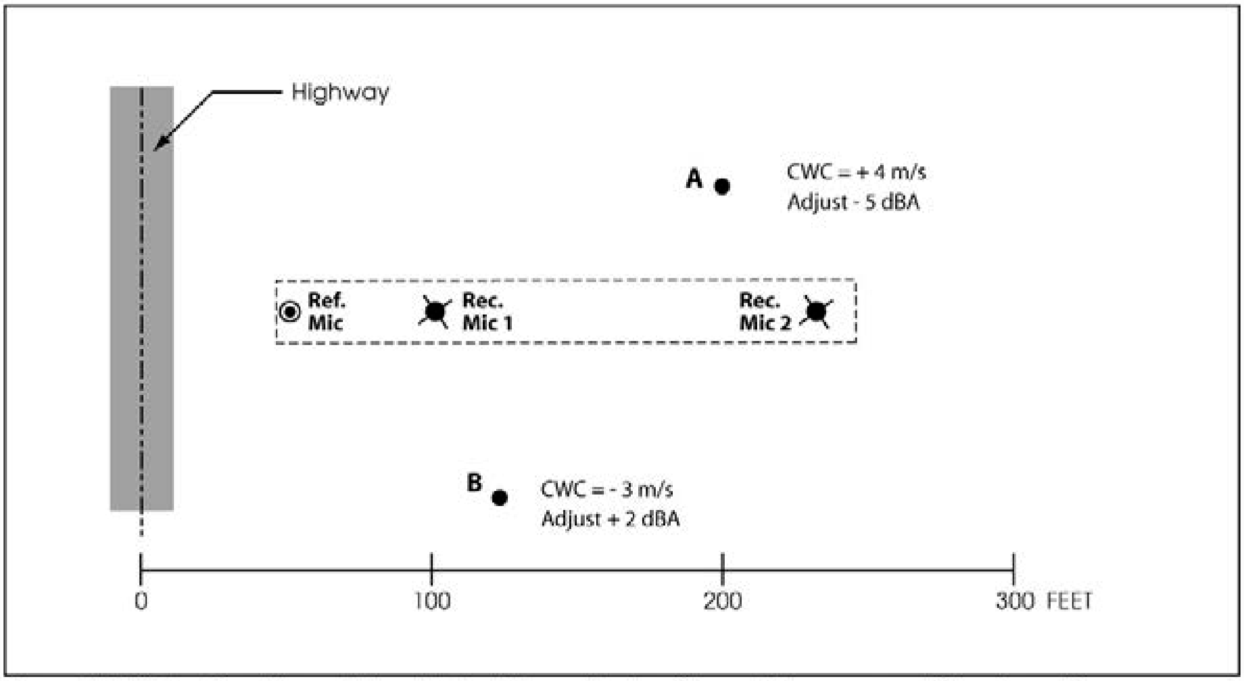

Figure 5-7. Plan View of Normalization Site and Noise Measurement Sites A and B

For this example, the equivalent lane distances for the following microphones are defined as follows.

- Receiver Microphone 1 = 100 feet
- Receiver Microphone 2 = 220 feet
- Noise Site Microphone A = 190 feet
- Noise Site Microphone B = 120 feet

From Table 5-9, the adjustments at the distances for Receiver Microphones 1 and 2 for the CWC observed at Microphone A (+4 m/s) are -3 and -5 dBA, respectively. The interpolated result for Microphone A then is calculated as follows:

$$[(190 - 100) / (220 - 100) * (-5 - (-3))] - 3 = -4.5 \approx -5 \text{ dBA.}$$

For Microphone B (CWC = -3 m/s), the adjustments at Receiver Microphones 1 and 2 are +2 and +4, respectively. The interpolated result is calculated as follows:

$$[(120 - 100) / (220 - 100) * (+4 - (+2))] + 2 = +2.3 \approx +2 \text{ dBA.}$$

The adjusted noise levels at Microphone A would then be 5 dBA less than the raw measurement. At Microphone B, the measured noise level would be increased by 2 dBA. Please note that the data shown for the above example tend to be exaggerated. The slopes of the regression lines may not be as steep as shown for the distances involved. Also please note that the system of units for distance may be the same or different from that used for the CWCs—units of distance and CWC may be English or metric, and they may differ from each other.

Constraints on Normalization Procedure

Because of the many variables involved in the meteorological effects on noise, the following constraints should be placed on the normalization procedure. The repeat visits to the normalization sites should be done when wind directions and speeds vary from visit to visit. However, other important meteorological parameters (e.g., air temperature, temperature gradients, cloud cover, humidity) should not vary significantly. Therefore, it is strongly recommended to perform the measurements at each visit within the same season, preferably within the atmospheric equivalence constraints of ANSI's "Methods for Determination of Insertion Loss of Outdoor Noise Barriers" (2003), which are included in Section 3.6.2. Other constraints on applying the results of this procedure are listed below.

- The index of determination (r^2) of the regression ΔdBA vs. CWC should have a minimum of 0.5. This corresponds to a minimum coefficient of correlation of 0.7. If this statistic is not achieved, more data should be collected, or the data should not be used for normalization.
- Wind normalization noise adjustments should be rounded to the nearest whole decibel.
- Adjustments will be made only for values of +/-2 dBA or more.

Summary

The optional procedure to normalize the effects of wind on noise levels to that of a zero-wind (calm) condition is unique in the model calibration process because it adjusts the noise measurement instead of the model. Therefore, it affects only the existing noise measurements directly. The goal of adjusting these measured noise levels is to reduce *K*, or the difference between measured and calculated (modeled) noise levels. *K* may be thought of as the unexplained difference between measured and modeled noise levels. Without normalization, the model calibration for a certain receiver will only be accurate for the wind condition present during the noise measurement. The normalization procedure removes some of the "unexplained difference" and places them in the "explained difference" category. Because *K* is applied to future predicted noise levels, this procedure should increase the accuracy of Caltrans noise predictions.

The improved accuracy of future noise predictions will require increased field work, experienced staff, and additional equipment. However, this increased cost may be offset by the following.

- More accurate identification of impacted receivers. This will better avoid the consideration of noise abatement in areas that are not impacted. It also will trigger consideration of noise abatement in areas that otherwise would have been missed. Noise abatement funding would be more fairly distributed and better address actual needs.
- Improved acoustical design of noise abatement.
- Increased public trust in Caltrans.

Finally, the normalization procedure is another tool available to the noise analyst. As with all tools, some are used more than others. However, if a certain tool is needed, it is usually worth the cost.

5.5 Predicting Future Noise Levels

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

The traffic noise prediction procedures are specified in 23 CFR 772. FHWA requires that all new project noise studies initiated after January 15, 2005, be evaluated using TNM. The exception to this requirement is for a reevaluation noise study of a project that was originally evaluated using the previous FHWA Highway Traffic Noise Prediction Model (HTNPM). Because the HTNPM may still be used on some reevaluation projects, the following discussion of the model is provided.

5.5.1 Highway Traffic Noise Prediction Model Methodology (FHWA-RD-77-108)

The FHWA Highway Traffic Noise Prediction Model (HTNPM) is described in FHWA report FHWA-RD-77-108.

Caltrans' computer implementations of the HTNPM FHWA model (approved by FHWA) are LeqV2, Sound32, and Sound2000. LeqV2 is a simple model that follows the FHWA-RD-77-108 report procedures. It can handle only one receiver at a time and address only simple site geometries. Noise barriers are assumed to be parallel (horizontally and vertically) to the roadways. LeqV2 can be run with Calveno or National REMELs. Three-dimensional roadway and barrier segments and receiver geometries are expressed as distances and angles from the observer (receiver), and elevations relative to the roadway.

Sound32 is the Caltrans version of the two federal programs STAMINA2.0 (also based on FHWA-RD-77-108 report model and OPTIMA). The two FHWA programs were modified and combined in the Caltrans version. Modifications and improvements incorporated into Sound32 include:

- the ability to use either Calveno or old National REMELs (not to be confused with the new TNM REMELs discussed in Section 5.5.2);
- the addition of berm calculations (according to the HTNPM, berms are considered more effective than walls in attenuating noise);
- the correction of inaccuracies that may occur in STAMINA/OPTIMA when more than one barrier is located between a receiver and roadway;
- the correction of a problem that occurs in STAMINA with low barriers, which causes the program to skip the calculation of medium truck barrier attenuation when there is no heavy truck barrier attenuation;
- the addition of emission levels for heavy trucks on positive grades from California-specific data (Calgrade); and
- the ability to easily modify the Calgrade levels by editing a data file rather than changing the program code.

Sound2000 is the latest version of Sound32. Inputs and results are identical. The only difference between them is the operating system. Sound32 (as with LeqV2) is a DOS program, whereas Sound2000 operates in a Microsoft Windows environment.

As with STAMINA2.0, Sound32 uses an x-y-z coordinate system for the roadway and barrier segments and receivers, instead of the distances, angles, and elevations used in LeqV2.

For simple highway/barrier/receiver geometries, LeqV2, Sound32, or Sound2000 may be used. For more complex geometries, Sound32 or Sound2000 should be used for efficiency.

For the same conditions under which LeqV2 can be used, Sound32 and Sound2000 yield approximately the same results. Some negligible differences of generally less than 0.5 dBA could result because of rounding.

The accuracy of LeqV2, Sound32, and Sound2000 is distance-dependent. Typically, less than 30 meters from the source, accuracies are about 1 dBA. Farther away from the source, the results are less accurate. At 100 meters, accuracies are about 3 dBA or more. Therefore, model results should be rounded by conventional method and reported to the nearest dBA.

The following sections provide a brief overview of the FHWA HTNPM. The sections are intended to introduce the procedures and point out some of the shortcomings. The HTNPM report forms the basis for the computer programs, and users are encouraged to read it to understand what is happening inside the computer models. Various technical advisories for noise (TANs) are also available from Caltrans' website. The TANs give further guidance on the use of the models.

The FHWA-RD-77-108 procedures start with the REMELs and apply a series of adjustments to these emission levels to arrive at the predicted noise levels (Figure 5-8). The following sections give a brief overview of each of these adjustments.

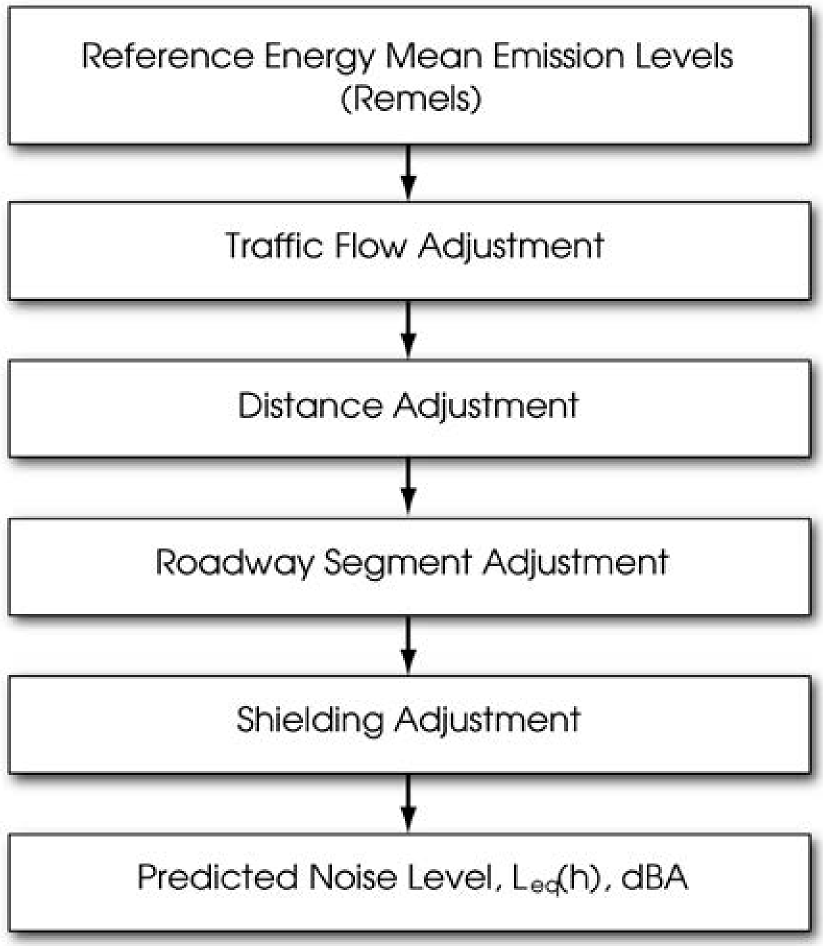

Figure 5-8. Flow Chart of FHWA Highway Traffic Noise Prediction Model

5.5.1.1 Reference Energy Mean Emission Levels

The first step in the prediction procedure is to determine the REMELs. The emission level, L_0, is defined as the speed-dependent energy-averaged A-weighted maximum passby noise level generated by a defined vehicle type, as measured by a microphone at 50 feet from the centerline of travel (traffic lane) at a height of 5 feet. The Calveno REMELs are shown in Figure 5-9. They were developed as part of research performed by the former Caltrans Office of Transportation Laboratory and meet the previously mentioned 23 CFR 772 requirement 2b.

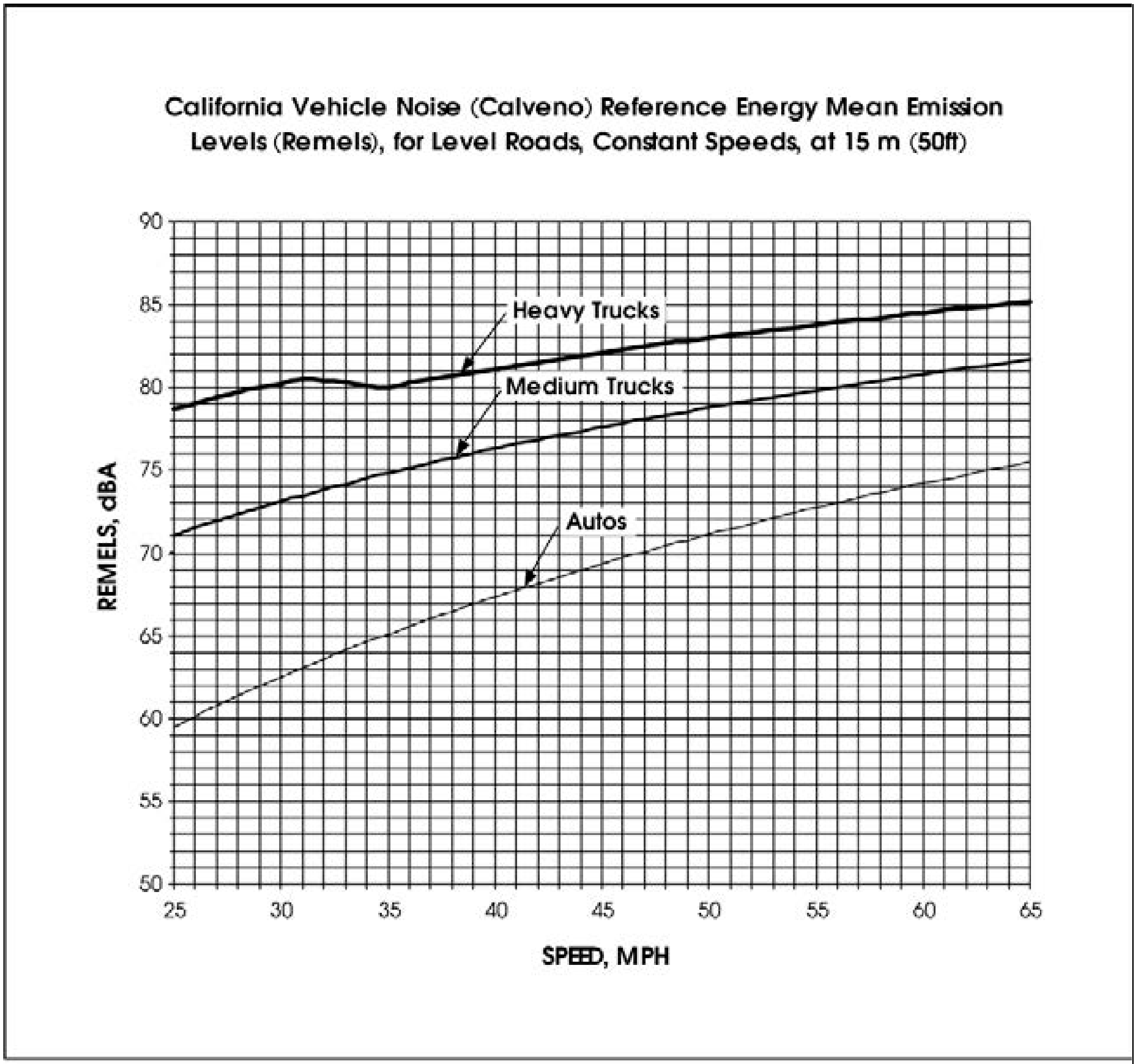

Figure 5-9. California Vehicle Noise Reference Energy Mean Emission Levels

Following are the linear regression equations for the speed-dependent curves in Figure 5-9.

- **Heavy Trucks**
  - 25 to 31 mph: 51.9 + 19.2log10(speed, mph)
  - 35 to 65 mph: 50.4 + 19.2log10(speed, mph)
  - 31 to 35 mph: straight line
- **Medium Trucks**
  - 35.3 + 25.6$\log_{10}$(speed, mph)

- **Autos**
  - $5.2 + 38.8\log_{10}$(speed, mph)

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

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

- **Automobiles:** all vehicles with two axles and four wheels designed primarily for transportation of nine or fewer passengers (automobiles) or transportation of cargo (light trucks). Generally, the gross vehicle weight is less than 10,000 pounds.
- **Medium Trucks:** all vehicles with two axles and six wheels designed for transportation of cargo. Generally, the gross vehicle weight is more than 10,000 pounds and less than 26,500 pounds.
- **Heavy Trucks:** all vehicles with three or more axles designed for the transportation of cargo. Generally, the gross weight is more than 26,500 pounds.

Calveno curves are only valid for vehicles traveling at a constant speed between 25 and 65 mph on level roadways.

5.5.1.2 Traffic Flow Adjustment

The traffic flow adjustment is an expansion of the reference levels to account for the traffic volumes and to adjust for the vehicle speeds. Given the reference level, an observer will hear a car going 60 mph half as long as one going 30 mph. The traffic flow adjustment is calculated using the following equation:

$$\text{Traffic Flow Adjustment} = 10\log_{10}\left(\frac{N_i \pi D_o}{TS_i}\right) \quad \textbf{(5-7)}$$

Where :

N_i = number of vehicles in the *i*th class

D_0 = 15 meters

T = time (normally 1 hour)

S_i = speed in kilometers per hour

The equation can be simplified to:

$$\text{Traffic Flow Adjustment} = 10\log_{10}\left(\frac{N_i D_0}{S_i}\right) - 25 \quad \textbf{(5-8)}$$

Where

Subtraction of 25 is derived from $10\log_{10}\left(\frac{\pi}{1,000}\right) = -25$

1,000 = conversion from meters to kilometers

5.5.1.3 Distance Adjustment

The distance adjustment is generally referred to as either drop-off rate or the alpha soil parameter (see Section 2.1.4 for a discussion of propagation of sound). The distance adjustment is expressed in terms of decibels per doubling of distance of noise reduction:

$$\text{Distance Adjustment} = 10\log_{10}\left(\frac{D_0}{D}\right)^{1+\alpha} \quad \textbf{(5-9)}$$

Where:

D = perpendicular distance from receiver to centerline of lane

D_0 = reference distance of 15 meters

α = excess attenuation from ground effects

When the ground between the roadway and receiver is hard, the site is considered reflective and α becomes 0. The distance adjustment reduces to the following equation, and the dropoff rate becomes 3 dB/DD (see Section 2.1.4.1):

$$\text{Distance Adjustment} = 10\log_{10}\left(\frac{D_0}{D}\right) \quad \textbf{(5-10)}$$

With the FHWA model, the user must decide on the appropriate dropoff rate to use. Table 5-10 may be used for guidance. Distance adjustments to distances less than 50 feet should always be made using 3 dBA/DD ($\alpha = 0$).

Table 5-10. FHWA Highway Traffic Noise Prediction Model Criteria for Selection of Dropoff Rates

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

Distance adjustments to distances less than 50 feet should always be made using 3 dBA/DD ($\alpha = 0$).

Lane by Lane

Ideally, distance adjustments are made from each individual lane (line source) of a multi-lane highway. However, this is often cumbersome and often not possible without making certain assumptions about the distribution of traffic volumes over the various lanes. The next two sections show simplifications of the process that can be made in many instances without compromising too much accuracy.

Equivalent Lane Distances

The distance adjustments previously shown assumed one lane of traffic only and involved the distance from the center of a lane to the receiver. As the number of traffic lanes increases, computation of the noise levels on a lane-by-lane basis becomes very tedious, even for a computer. It has become common practice to group the directional traffic into an imaginary single lane, which will provide approximately the same acoustical results as an analysis done on a lane-by-lane basis. This imaginary single lane is located at a distance from the receiver called the equivalent lane distance (D_E). For a free field, with no barriers present, the equivalent distance is computed as follows:

$$D_E = \sqrt{(D_N)(D_F)} \qquad \textbf{(5-11)}$$

Where:

D_N = perpendicular distance from receiver to center of near lane

D_F = perpendicular distance from receiver to center of far lane

These distances are shown in Figure 5-10a. When a barrier is present, the equivalent distance is computed as follows:

$$D_E = \sqrt{(D_N)(D_F)} + X \qquad \textbf{(5-12)}$$

Where:

D_N = perpendicular distance from receiver to center of near lane

D_F = perpendicular distance from receiver to center of far lane

X = perpendicular distance from receiver to barrier

These distances are shown in of Figure 5-10b. Care should be used when using equivalent lane distances when deep cuts or high fill sections are involved or when the directional traffic varies significantly from 50/50.

Figure 5-10 illustrates the use of one equivalent lane distance for both directions of traffic. A compromise may be made between the accurate but cumbersome lane-by-lane and the simplistic but less accurate single equivalent distance by using directional equivalent lane distances (i.e. using the near and far lane for each direction). This method, yielding two equivalent lane distances, one for each direction, is less cumbersome than using individual lane distances and more accurate than the single equivalent lane distance for all lanes. It also can be used effectively if the directional traffic is unbalanced or the center median is very wide.

LeqV2 automatically calculates the equivalent lane distance for each lane group (element) identified using user input distances to the centerline of the near lane of each lane group and the user input number of lanes in each lane group; it assumes 12-foot lane widths.

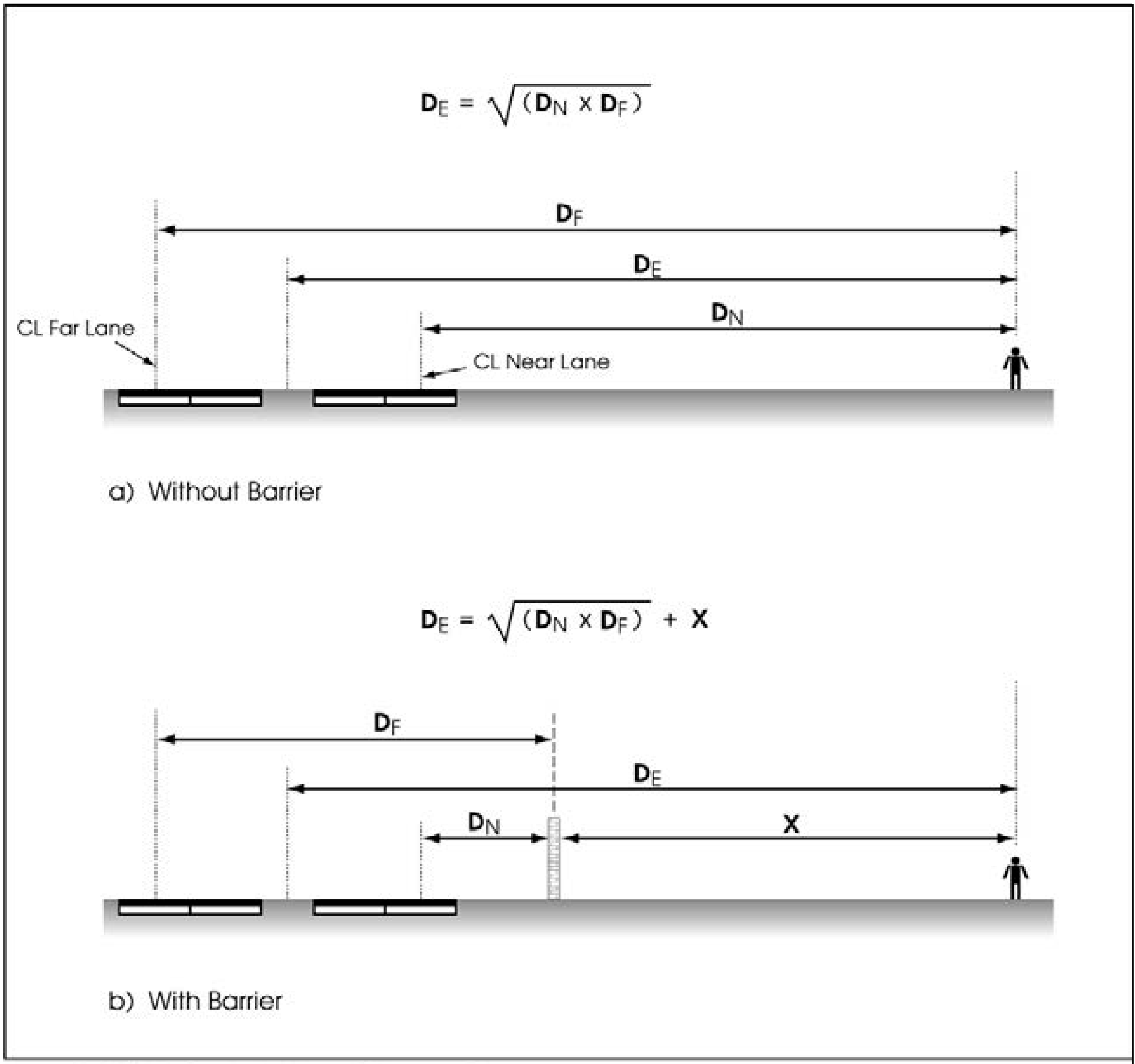

Figure 5-10. Equivalent Lane Distances

Centerlines of Directional Traffic

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

In most cases, using the centerlines of the directional traffic instead of directional equivalent lane distances does not change the final results by more than a few tenths of a decibel. Because of its simplicity, this is the most common method used with Sound32.

5.5.1.4 Finite Roadway Adjustment

When the roadway is not infinitely long in both directions in relationship to the observer, it becomes necessary to adjust the reference levels to account for only the energy coming from a portion of the roadway. It is often necessary to separate a roadway into sections to account for changes in topography, traffic flows, shielding, etc. For hard sites where the dropoff rate is 3 dBA/DD ($\alpha = 0$), the adjustment is calculated as follows:

$$\text{Finite Roadway Adjustment for Hard Site} = 10\log_{10}\left(\frac{\Delta\phi}{180}\right) \qquad \textbf{(5-13)}$$

Where:

ϕ_1, ϕ_2 = angles in degrees as shown in Figure 5-11

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

Please note that in all cases $\Delta\phi$ will be positive and numerically equal to the included angle subtended by the roadway relative to the receiver. For soft sites, where the dropoff rate is 4.5 dBA/DD ($\alpha = 0.5$), the adjustment is more complex because it also must account for the excess distance attenuation:

$$\text{Finite Roadway Adjustment for Soft Site} = 10\log_{10}\frac{1}{\pi}\int_{\phi 1}^{\phi 2}\sqrt{\cos\phi}\; d\phi \qquad \textbf{(5-14)}$$

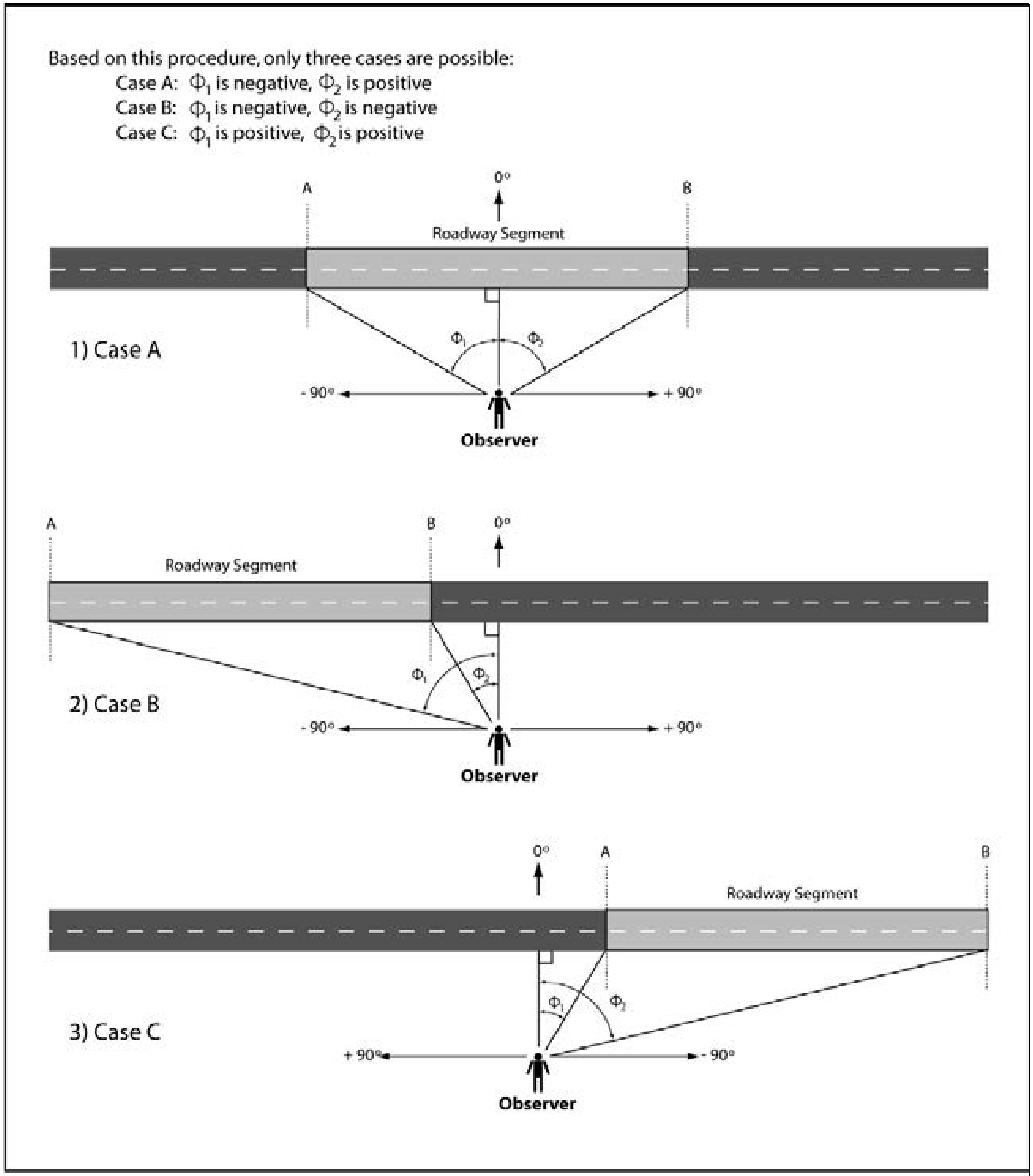

Figure 5-11. Identification of Angles

5.5.1.5 Shielding Adjustments

Shielding is one of the most effective ways to reduce traffic noise. Shielding occurs when the observer's view of the highway is obstructed or partially obstructed by natural or manmade features interfering with the propagation of the sound waves. Figure 5-12 illustrates the general rules for various shielding adjustments.

Figure 5-12 shows the attenuation credit given by the FHWA model to plantings, woods, and vegetation: 5 dBA for the first 100 feet and an additional 5 dBA for the second 100 feet. The height of the trees should extend at least 16 feet above the line of sight, and the woods must be dense enough to completely block the view of the traffic from the receiver. To be effective throughout the year, the trees must be mostly evergreens. Ordinary landscaping along the highway is not effective in actually reducing traffic noise, but it may provide a psychological effect ("out of sight, out of mind") that tends to reduce the awareness of traffic noise.

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

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

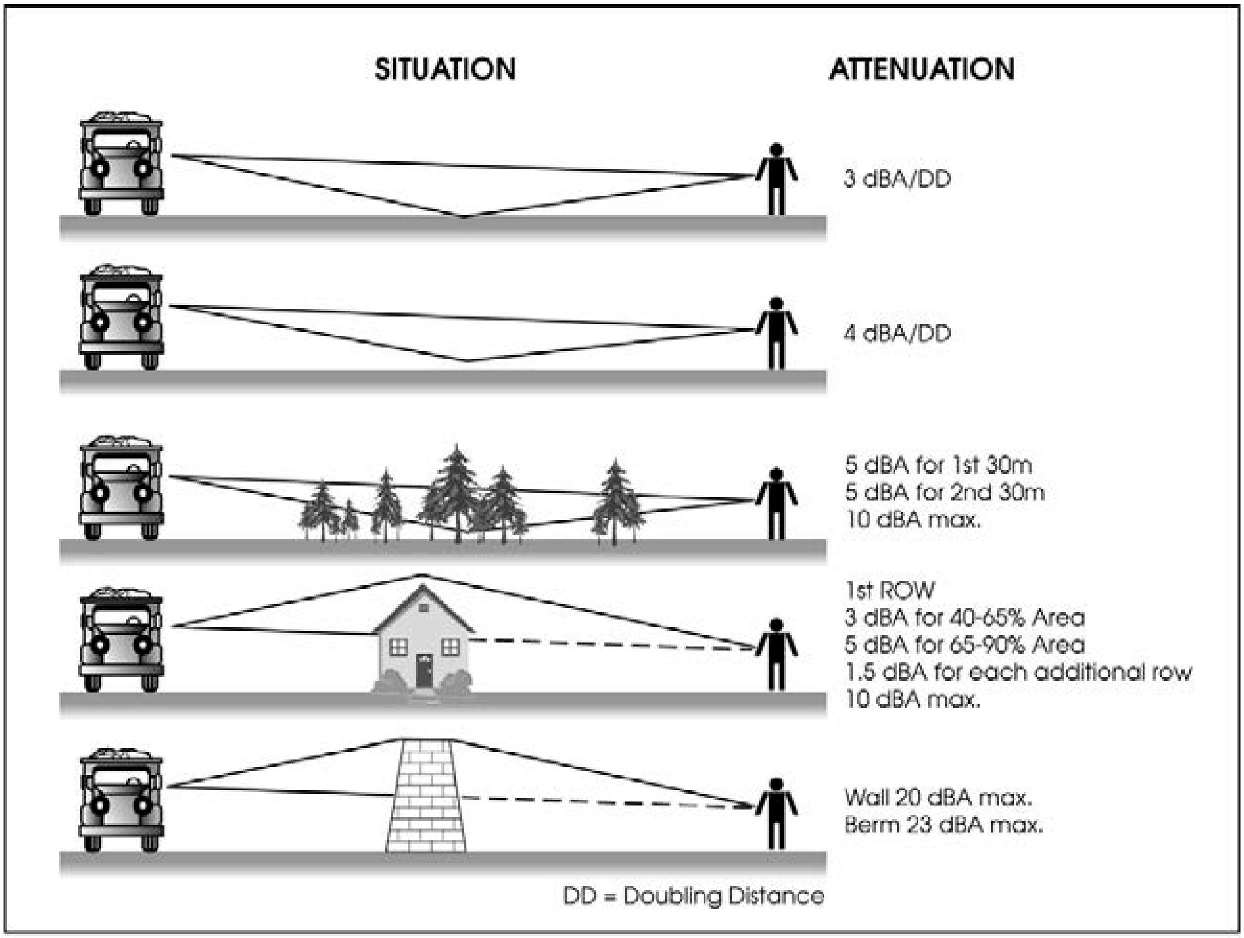

Figure 5-12. Shielding Adjustments

Noise Barriers

Section 2.1.4.4 discusses the general characteristics of noise barriers and principles of diffraction, transmission loss, and barrier attenuation. Noise barriers can be constructed from any number of materials. The FHWA model works under the following assumptions.

- The noise transmitted through the barrier will not contribute to the diffracted noise (i.e., it is at least 10 dBA less than the noise diffracted over the top of the barrier). For this to be true, the barrier's transmission loss must be at least 10 dBA more than the noise attenuation from diffraction. For example, if the desired barrier attenuation is 10 dBA, the transmission loss of the barrier material must be at least 20 dBA. See Figure 5-13 for the effects of insufficient transmission loss.
- The barrier cannot have cracks that would allow noise leakage. The FHWA model does not consider any noise that passes through a

barrier or that may be diffracted around the ends of a barrier. See Section 6.2.3 for a discussion of the effects of barrier openings for maintenance purposes on barrier performance.

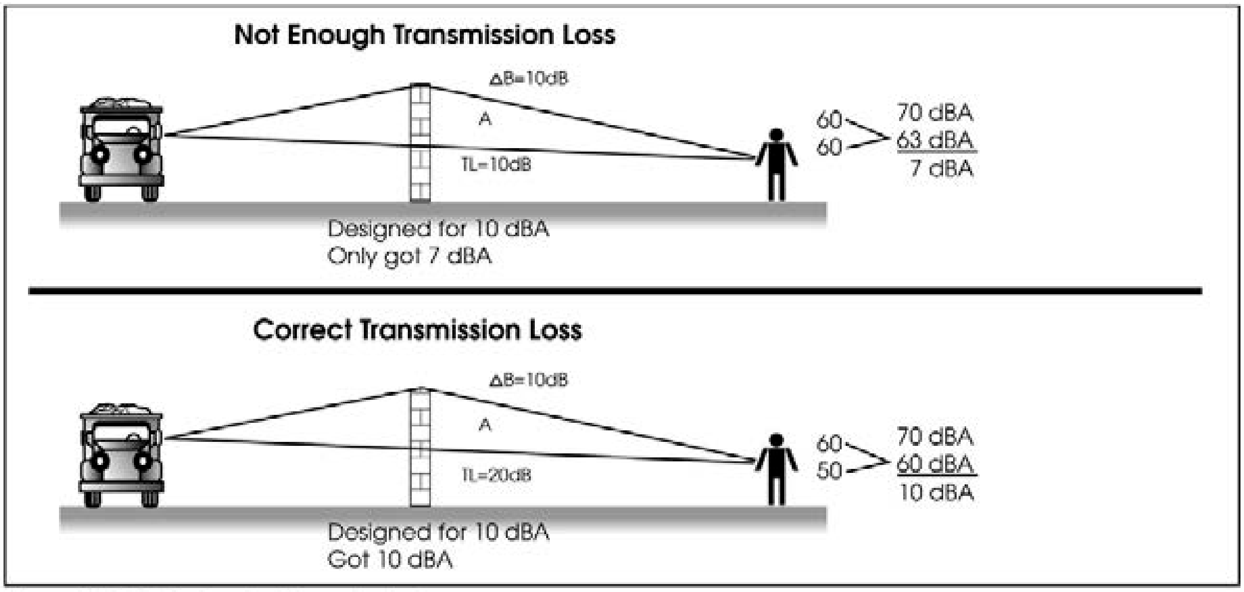

Figure 5-13. Barrier Transmission Loss

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

$$N_o = 2\left(\frac{\delta_o}{\lambda}\right) = 2\left(\frac{f\,\delta_o}{c}\right) \quad \textbf{(5-15)}$$

Where:

δ_o = pathlength difference

λ = wavelength of sound

f = frequency of sound

c = speed of sound = 343 m/s (1,125 feet/second)

Highway traffic noise is broadband (i.e., contains energy in the frequency bands throughout the audible range), and the Fresnel number will vary according to the frequency chosen. However, it has been found that the attenuation of the A-weighted sound pressure level of a typical traffic is almost identical to the sound attenuation of the 550-Hz band. For this frequency, Equation 5-15 reduces to:

$$N_o \approx 3.21\delta_o \quad \textbf{(5-16)}$$

When

δ_o is in meters (2f / c = 1,100 / 343 = 3.21)

$$N_o = 0.98\delta_o, \text{ or } N_o \approx \delta_o \quad \textbf{(5-17)}$$

When

δ_o is in feet (2f / c = 1,100 / 1,125 = 0.98)

Note: The path length difference, δ_o, is the difference between a perpendicular ray traveling directly to the observer and a ray diffracted over the top of the barrier.

$$\delta_o = a_o + b_o - c_o \quad \textbf{(5-18)}$$

Where

a_o, b_o, c_o = distances normal to the barrier, as shown in Figure 5-14

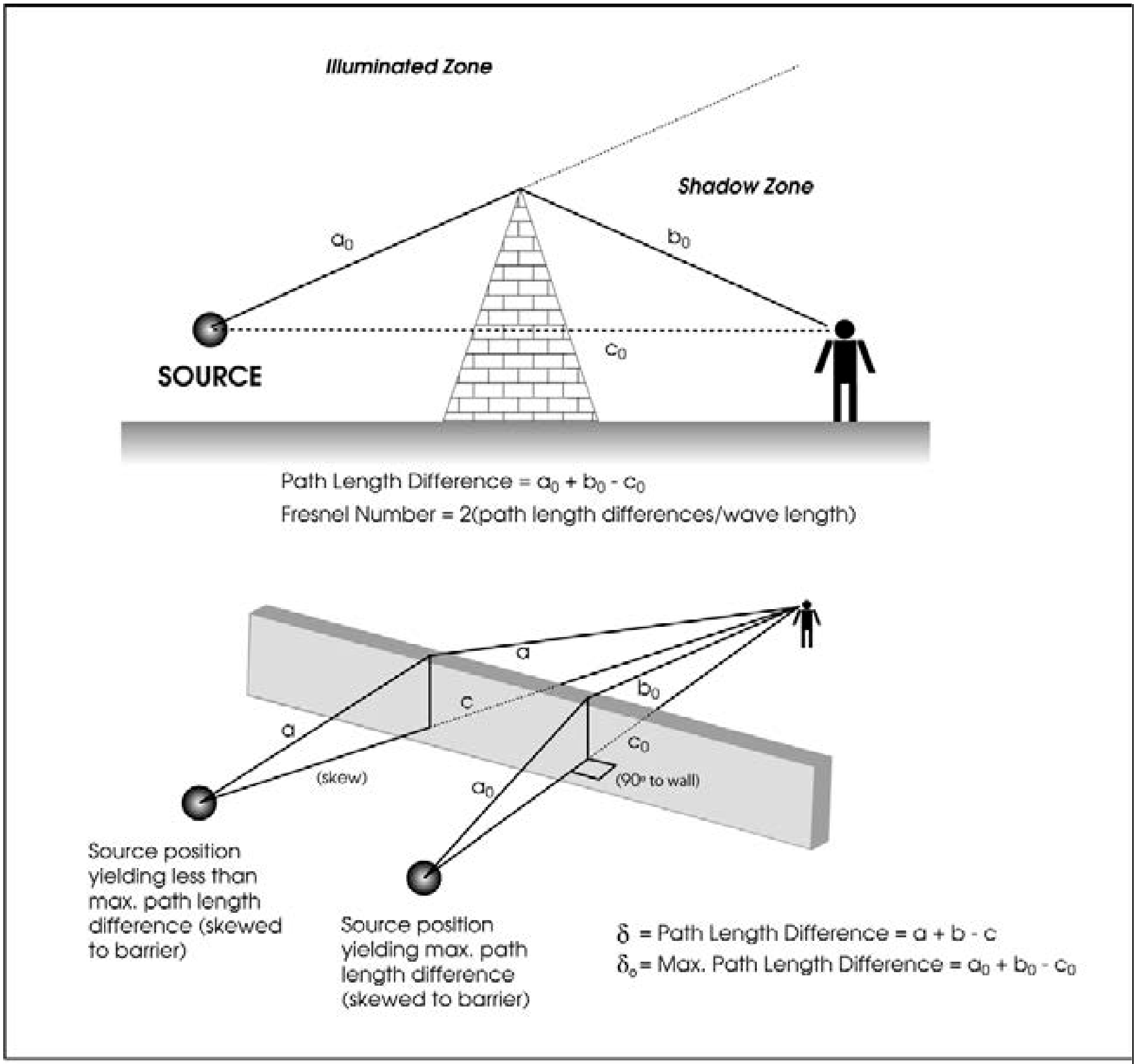

Figure 5-14. Path Length Difference and Fresnel Number

For barrier calculation purposes, the vehicle noise sources are also simplified to those shown in Figure 5-15. These heights attempt to account for and centralize the locations of the many individual sources of noise radiated from the vehicle types.

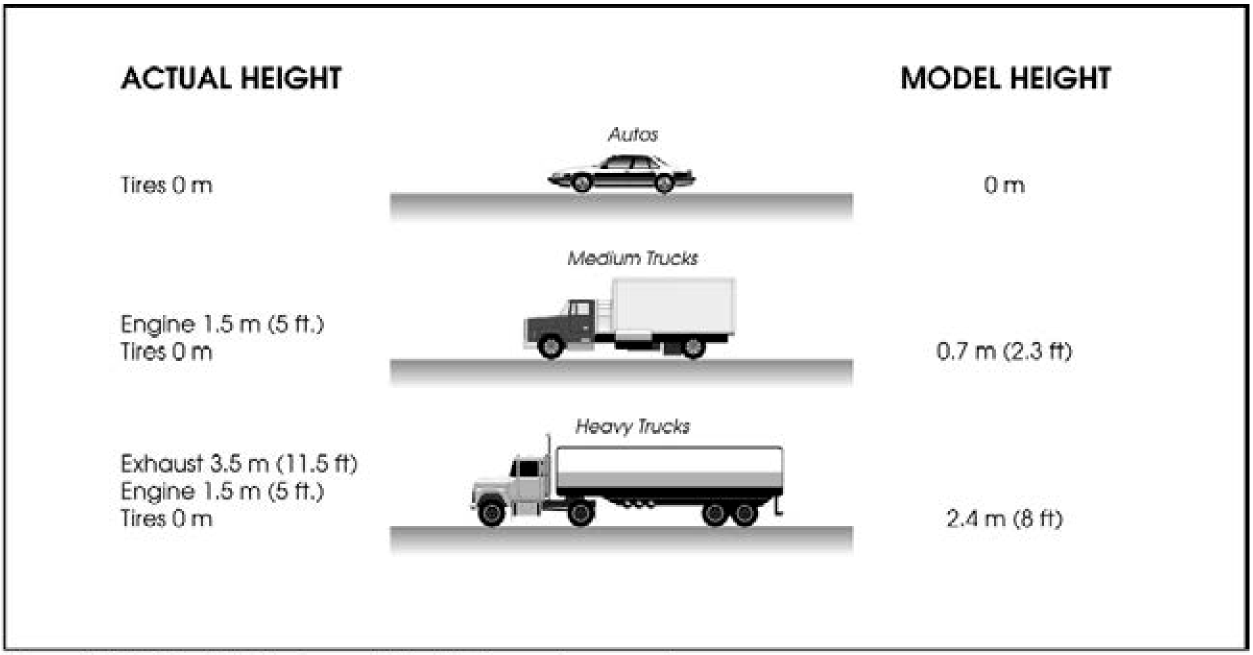

Figure 5-15. Vehicle Source Heights above Pavement

For barriers of finite length, the attenuation provided by a barrier depends on the amount of the roadway shielded from the observer. As with the finite roadway adjustment for soft sites, the finite barrier attenuation (ΔB_i) calculations involve the solution of an integral in Equation 5-19.

Please note ε in the Equations 5-21, 5-22 and 5-23:

$\varepsilon = 0$ for a wall, and

$\varepsilon = 3$ for a berm.

The FHWA model assumes that earth berms perform about 3 dB better than free-standing walls because of the shape of the top of the barrier; ε accounts for this difference.

Ground Effects

The situation where the ground between the roadway and observer is reflective (i.e., the dropoff rate is 3 dB per doubling of distance = 0) is illustrated in Figure 5-16a. As indicated in Table 5-10, under these circumstances the dropoff rate is 3 dBA/DD. When a barrier is constructed between the roadway and observer, the top of the barrier appears to be the noise source to the observer; again, the dropoff rate should be 3 dBA/DD, as shown in Figure 5-16b.

$$\Delta B_i = 10\log_{10} \frac{1}{\phi_R - \phi_L} \int_{\phi_L}^{\phi_R} (x) d\phi \qquad \textbf{(5-19)}$$

Where

$$x = 1 \text{ for } N_i \leq -0.1916 - 0.0635 \qquad \textbf{(5-20)}$$

$$x = \frac{10^{-0.3\varepsilon} \tan^2 \sqrt{2\pi} |N_0|_i \cos\phi}{\sqrt{10} \cdot 2\pi |N_0| \cos\phi} \text{ for } (-0.916 - 0.0635\varepsilon) \leq N_i \leq 0 \qquad \textbf{(5-21)}$$

$$x = \frac{10^{-0.3\varepsilon} \tanh^2 \sqrt{2\pi (N_0)_i \cos\phi}}{\sqrt{10} \cdot 2\pi (N_0)_i \cos\phi} \text{ for } 0 \leq N_i \leq 5.03 \qquad \textbf{(5-22)}$$

Note:
$\tanh(x) = (e^x - e^{-x}) / (e^x + e^{-x})$

$$x = \frac{10^{-0.3\varepsilon}}{10^0} \text{ for } N_i \geq 5.03 \qquad \textbf{(5-23)}$$

When the ground between the roadway and observer is soft (4.5 dBA/DD, $\alpha = 0.5$), the ground effects can provide an additional 1.5 dBA/DD when both the source and receiver are close to the ground (Figure 5-16c). In this case, when a barrier is constructed between the observer and roadway, the top of the barrier again appears to be the noise source to the observer and the appropriate dropoff rate is 3 dBA/DD (Figure 5-16d). Therefore, the 1.5 dBA/DD excess attenuation from the ground effects has been lost. Constructing a barrier effectively raises the source height, and the ground effect is lost. Therefore, if the barrier attenuation was 9 dBA, an observer at 200 feet would experience a net noise reduction of only 6 dBA (9 dBA barrier attenuation minus the 3 dBA lost excess ground effects). This net noise reduction at the receiver is referred to as noise barrier insertion loss. The difference between barrier attenuation and insertion loss is further explained in Section 6.1.5.

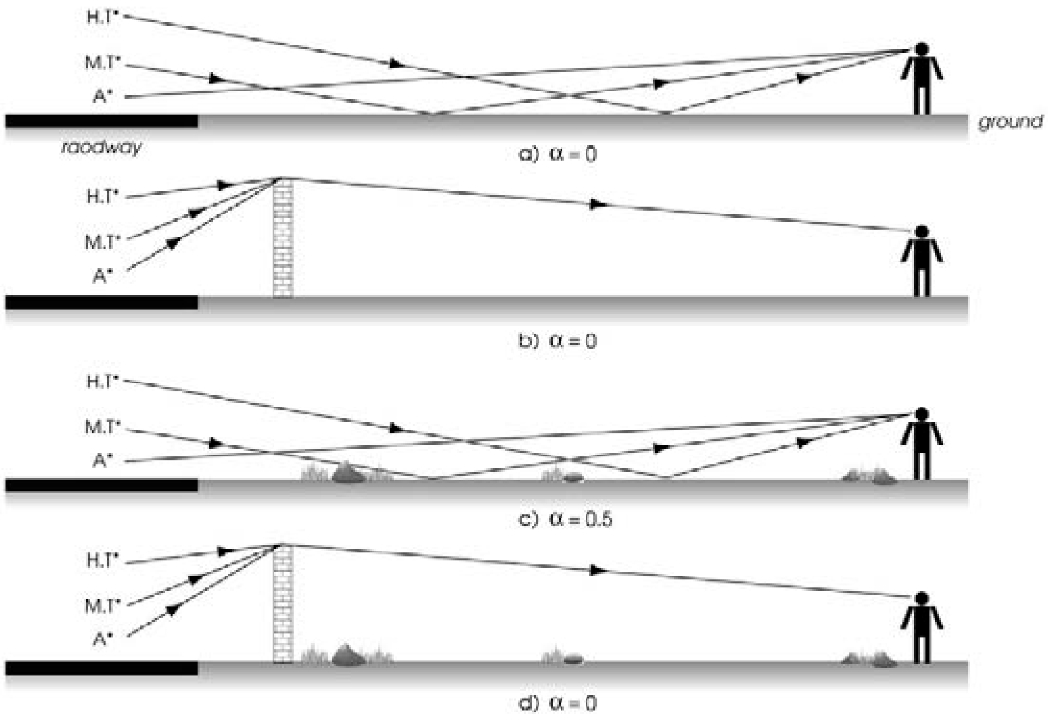

Figure 5-16. Ground Effects

5.5.1.6 Stop-and-Go Traffic

Sound32 and LeqV2 predict the hourly L_{eq} for constant-speed traffic. They are not equipped to deal with stop-and-go driving conditions typical of ramps, arterials, and city streets.

A model suitable for use with STAMINA2.0 (federal computerized version of the FHWA Model) was developed and reported in the following source:

> Bowlby, W., R. L. Wayson, and R. E. Stammer, Jr. 1989. *Predicting Stop-and-Go Traffic Noise Levels*. November. (NCHRP Report 311.) Washington, DC: Transportation Research Board, National Research Council.

The report, excerpts, and recommendations for use with Sound32 are available from Caltrans Division of Environmental Analysis in Sacramento. However, with implementation of TNM, the method specified has become obsolete. The TNM has superior provisions for dealing with interrupted-flow traffic.

5.5.2 FHWA Traffic Noise Model Overview

The FHWA TNM was released on March 30, 1998. FHWA has mandated that all new federal-aid highway projects that begin after January 15, 2006, be evaluated using TNM. TNM, therefore, replaced the FHWA-RD-77-108 methodology, LeqV2, Sound32, and Sound2000. The model is described in *FHWA Traffic Noise Model, Version 1.0, Technical Manual* (Menge et al. 1998). The instructions for using the TNM version 1.0 software are contained in *FHWA Traffic Noise Model, Version 1.0, User's Guide* (Anderson et al. 1998). TNM Version 2.5 is the current version as of the publishing of this document.

"Federal Highway Administration Traffic Noise Model" and "FHWA TNM" are a registered copyright and trademark. This provides FHWA with the exclusive right to use these names. The copyright and trademark encompass the user's guide, technical manual, software source, and executable codes.

The following sections provide a brief overview of TNM. For detailed information, the technical manual and user's guide should be consulted.

5.5.2.1 TNM Reference Energy Mean Emission Levels

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

- **Automobiles:** same definition as in FHWA-RD-77-108;
- **Medium Trucks:** same definition as in FHWA-RD-77-108;
- **Heavy Trucks:** same definition as in FHWA-RD-77-108;
- **Buses:** all vehicles designed for more than nine passengers; and
- **Motorcycles:** all vehicles with two or three tires and an open-air driver/passenger compartment.

In addition, the database includes data for:

- vehicles on grades;
- three different pavements (DGAC, OGAC, and PCC);

- accelerating vehicles;
- acoustic energy apportioned to two subsource heights above the pavement (0 meters and 5 feet for all vehicles, except for heavy trucks, where the subsource heights are 0 meters and 12 feet); and
- data stored in one-third-octave bands.

Figure 5-17 compares the new TNM Baseline REMELs with the Calveno REMELs. The latter were used in Sound32 and LeqV2 (see Section 5.5.1) and must not be used with the TNM. The TNM Baseline REMEL curves in Figure 5-17 were plotted from the following TNM Baseline equations:

$$\text{Speed} = 0 \text{ (idle)}: \; L(s_i) = 10\log_{10}(10^{C/10}) \quad \textbf{(5-24)}$$

$$L(s_i) = C \quad \textbf{(5-25)}$$

$$\text{Speed} > 0: \; L(s_i) = 10\log_{10}[(0.6214 s_i)^{A/10} + 10^{B/10} + 10^{C/10}] \quad \textbf{(5-26)}$$

Where:

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

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

A, B, C are constants for each vehicle type, shown below (Table 5-11)

Note: For speeds in mph omit 0.6214 in above Equation 2.

Table 5-11. TNM Constants for Vehicle Types

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

Note: Baseline REMELs = REMELs for the following conditions:

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

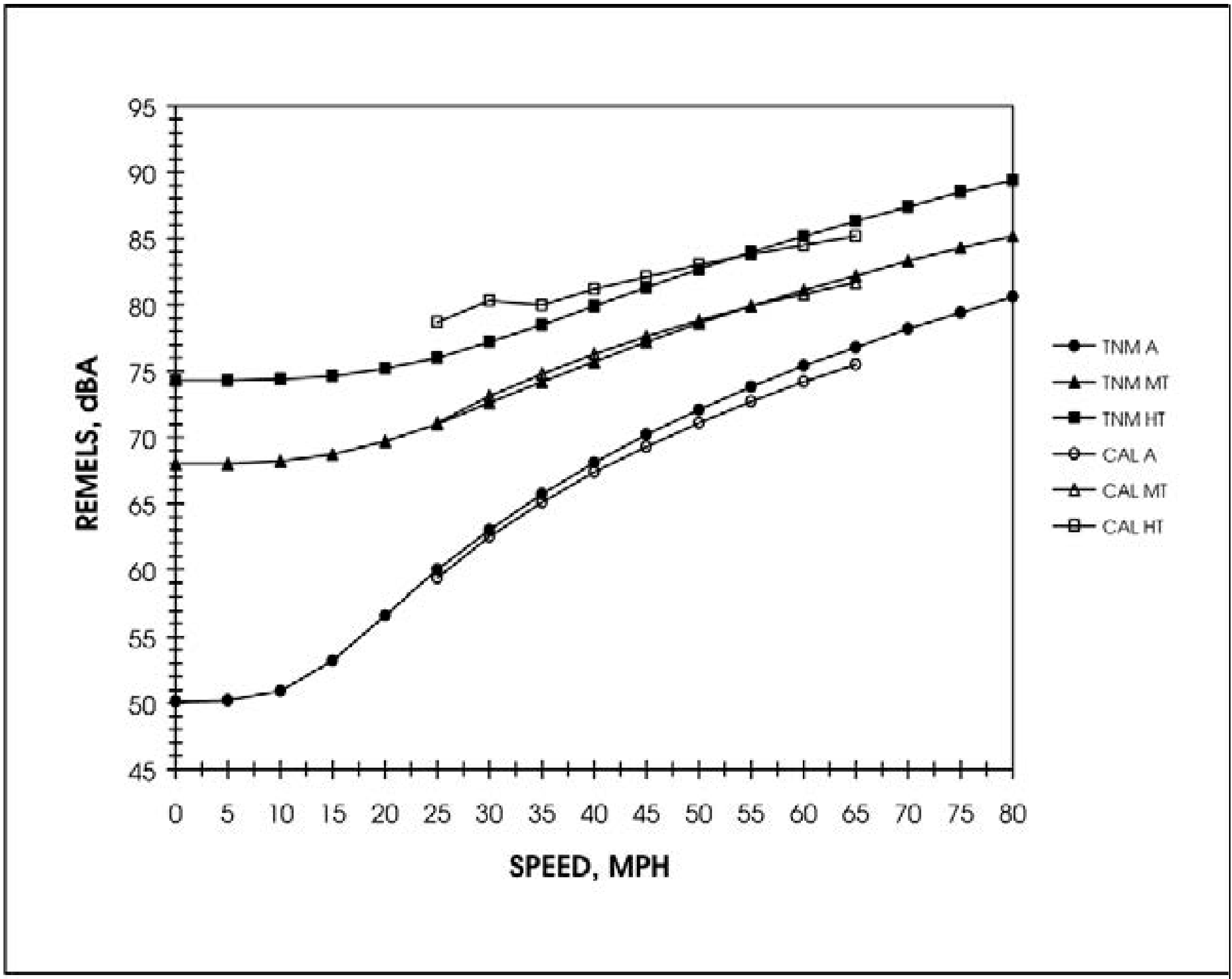

Figure 5-17. Comparison of A-Weighted Baseline FHWA TNM vs. Calveno REMELs

The exact TNM and Calveno REMEL values at 55 mph are shown in Table 5-12:

Table 5-12. Comparison of A-Weighted TNM and Calveno REMELs at 55 mph

REMEL	Auto (dBA)	Medium Truck (dBA)	Heavy Truck (dBA)
Calveno	72.8	79.9	83.8
TNM	73.8	79.9	84.0

5.5.2.2 Noise Level Computations

TNM calculations of noise levels include:

- three noise descriptors (L_{eq}[h], L_{dn}, and CNEL—see Section 2.2.2.2);
- capability of inserting traffic control devices, including traffic signals, stop signs, tollbooths, and on-ramp start points (the TNM calculates vehicle speeds and emission levels, and noise levels accordingly);
- computations performed in one-third-octave bands for greater accuracy (not visible to users); and
- noise contours if specified.

Roadways and roadway segments define noise source locations (x-y-z coordinates). Hourly traffic volumes determine the noise characteristics of the source.

5.5.2.3 Propagation, Shielding, and Ground Effects

The TNM incorporates state-of-the art sound propagation and shielding (e.g., noise barriers) algorithms, which are based on recent research of sound propagation over different ground types, atmospheric absorption, and shielding effects of noise barriers (including earth berms), ground, buildings, and trees. However, the TNM does not include the effects of atmospheric refraction, such as varying wind speed and direction or temperature gradients. TNM propagation algorithms assume neutral atmospheric conditions (zero wind speed, isothermal atmosphere). The propagation algorithms can use the following user input information.

- Terrain lines (x-y-z coordinates) define ground location. Height above the ground is important in noise propagation.
- Ground zones (x-y-z coordinates) define perimeters of selected ground types. The latter may be selected from either a ground-type menu (e.g., lawn, field grass, pavement), specified default, or user input flow resistivity (if known).
- Berms may be defined with user-selectable heights, top widths, and side slopes. They are computed as if they are terrain lines.
- Rows of buildings (x-y-z coordinates) with percentage of area shielded relative to the roadways may be input to calculate additional attenuation.
- Tree zones (x-y-z coordinates) may be included for additional attenuation calculations if appropriate.

The propagation algorithms also include double diffraction. The net effect from the most effective pair of barriers, berms, or ground points that intercept the source-to-receiver line of sight is computed.

5.5.2.4 Parallel Barrier Analysis

The TNM includes a multiple-reflection module that computes a degradation of the performance of one reflective barrier in the presence of another reflective barrier on the opposite side of the roadway. Unlike other TNM acoustics, which are computed in three dimensions, this module computes the results from a two-dimensional cross section. The results of this module are used to modify the TNM noise levels.

5.6 Comparing Results with Appropriate Criteria

After the predicted noise levels (including model calibration, if appropriate) have been determined, they should be compared with the appropriate impact criteria in the Protocol. Examination of traffic noise impacts includes comparing the following for each project alternative when appropriate:

- predicted noise levels with existing noise levels (for “substantial increase” impacts),
- predicted noise levels with the appropriate NAC (for “approach or exceed” impacts), and
- predicted noise level of classroom interior with 52 dBA-L_{eq}(h).

5.7 Evaluating Noise Abatement Options

If traffic noise impacts have been identified, noise abatement must be considered. Noise abatement measures may include those listed in the Protocol. These potential measures are based on avoiding impacts, interrupting noise paths, or protecting selected receivers. If the project alternative locations are flexible, alignments and profiles can be selected to avoid sensitive receivers or reduce the noise impacts. Most often, highway alignments and profiles are selected based on other overriding factors. The construction of noise barriers is usually the most common noise abatement option available. The consideration of noise abatement described in the Protocol requires at a minimum a preliminary design of the abatement. Section 6 provides guidance on the design considerations of noise barriers.

Section 6
Noise Barrier Design Considerations

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

Many factors need to be considered in the proper design of noise barriers. First, barriers must be acoustically adequate. They must reduce the noise as described by policies or standards. Acoustical design considerations include barrier material, locations, dimensions, shapes, and background noise levels. Acoustical considerations, however, are not the only factors leading to proper design of noise barriers.

A second set of design considerations, collectively labeled non-acoustical design considerations, is equally important. As often occurs, the solution of one problem (e.g., noise) may cause other problems such as unsafe conditions, visual blight, and lack of maintenance access because of improper barrier design. With proper attention to structural integrity, safety, aesthetics, and other non-acoustical factors, these potential negative effects of noise barriers can be reduced, avoided, or even reversed.

Highway Design Manual Chapter 1100 (California Department of Transportation 2001) should be consulted for specific noise barrier design criteria. Because these may change in the future, the discussion in this section will focus on general applications and consequences of the design criteria, not on the criteria themselves. There is also a possibility in that Chapter 1100 may be incorporated with the Protocol in the future. The Caltrans Headquarters Division of Environmental Analysis should be consulted for the latest status.

The acoustical and non-acoustical design considerations in this section conform to the *FHWA Highway Noise Barrier Design Handbook* (Knauer et al. 2000).

6.1 Acoustical Design Considerations

The FHWA models described in Section 5 are used for determining proper heights and lengths of noise barriers. The models assume that the noise barriers do not transmit any sound through the barrier. Only the noise diffracted by the barrier and any unshielded segments are considered. Therefore, the material of the barrier must be sufficiently dense or thick to ensure that the sound transmission through the barrier will not contribute to the total noise level calculated by the model at the receiver.

The material, location, dimensions, and shape of a noise barrier all affect its acoustical performance. To better understand the interaction of these acoustical factors, it is essential to review the concepts of shielding of noise barriers in Sections 2.1.4.4 and 5.5.1.5 and to introduce some new concepts.

Figure 6-1 is a simplified sketch showing what happens to vehicle noise when a noise barrier is placed between the source and receiver. The original straight path from the source to receiver is now interrupted by the barrier. Depending on the barrier material and surface treatment, a portion of the original noise energy is reflected or scattered back toward the source. Another portion is absorbed by the material of the barrier, and another is transmitted through the barrier. Please note that the reflected (scattered) and absorbed noise paths never reach the receiver.

However, the transmitted noise continues on to the receiver with a loss of acoustical energy (redirected and some converted into heat). The common logarithm of energy ratios of the noise in front of the barrier and behind the barrier, expressed in decibels, is called the transmission loss (TL). The TL of a barrier depends on the barrier material, primarily its weight, and the frequency spectrum of the noise source.

The transmitted noise is not the only noise from the source reaching the receiver. The straight line noise path from the source to the top of the barrier, originally destined in the direction of "A" without the barrier, now is diffracted downward toward the receiver (Figure 6-2). This process also results in a loss of acoustical energy.

Therefore, the receiver is exposed to the transmitted and diffracted noise. Whereas the transmitted noise only depends on barrier material properties, the diffracted noise depends on the location, shape, and dimensions of the barrier. These factors will be discussed in the following sections.

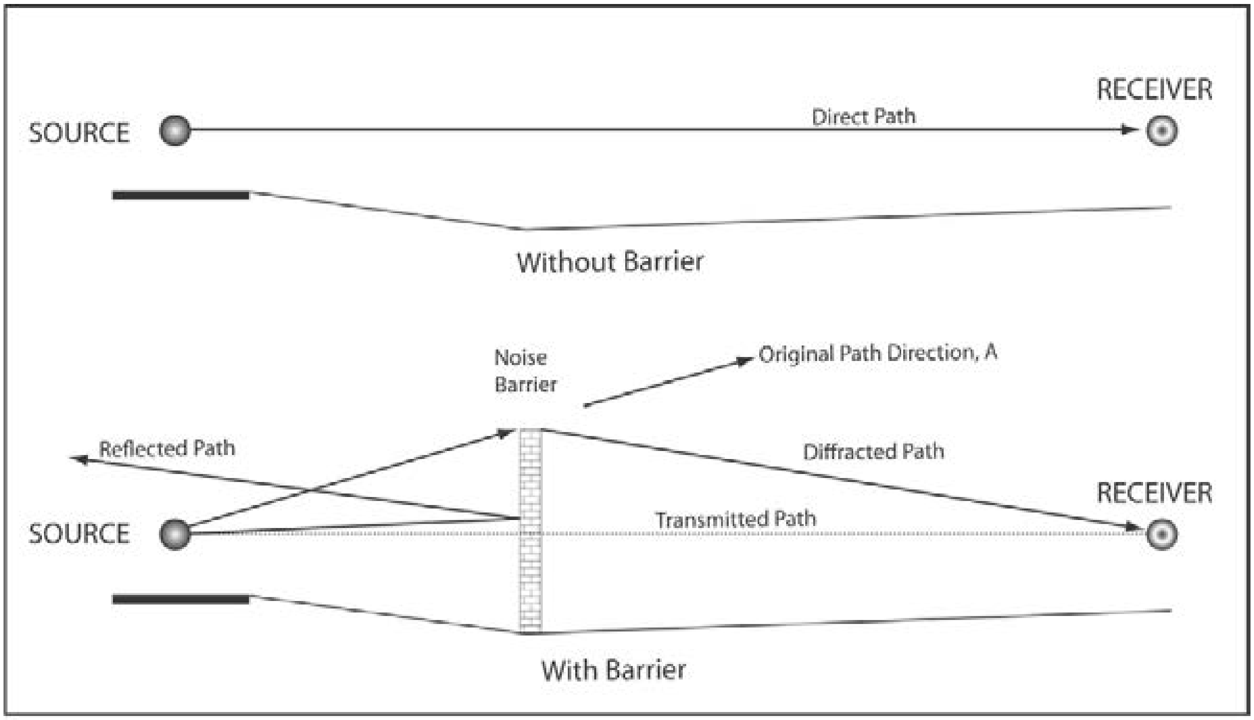

Figure 6-1. Alteration of Noise Paths by a Noise Barrier

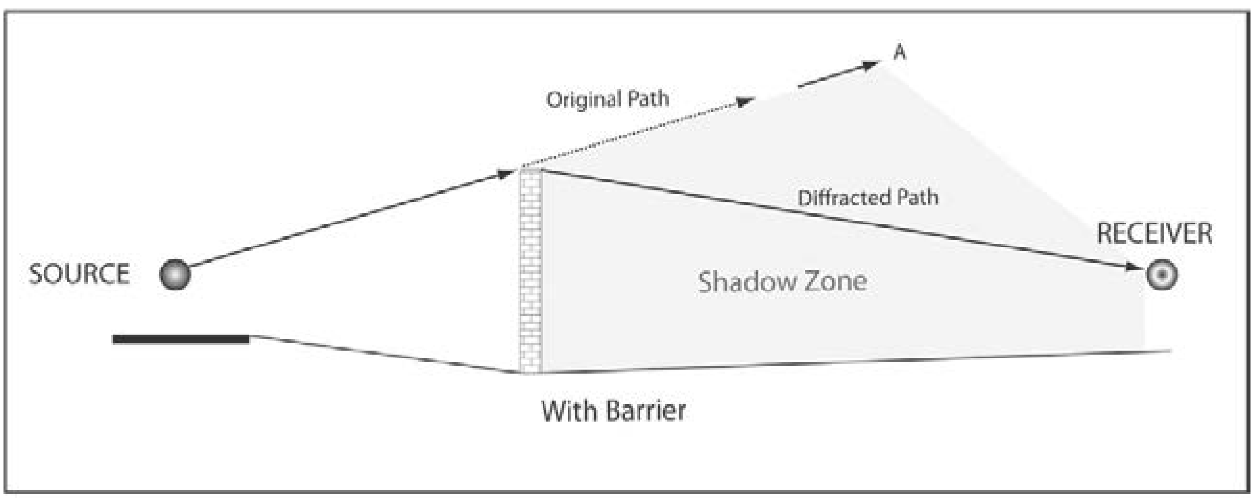

Figure 6-2. Barrier Diffraction

6.1.1 Barrier Material and Transmission Loss

For acoustical purposes, any material may be used for a barrier between a noise source and a noise receiver as long as it has a TL of at least 10 dBA more than the desired noise reduction. This ensures that the only noise path to be considered in the acoustical design of a noise barrier is the diffracted noise path. For example, if a noise barrier is designed to reduce the noise level at a receiver by 8 dBA, the TL of the barrier must be at least 18 dBA. The transmitted noise may then be ignored because the diffracted noise is at least 10 dBA more.

As a general rule, any material weighing 4 pounds per square foot or more has a transmission loss of at least 20 dBA. Such material would be adequate for a noise reduction of at least 10 dBA due to diffraction; this is the average noise reduction of Caltrans noise barriers. Please note that this weight can be attained by lighter/thicker or heavier/thinner materials. The more dense the material, the thinner it may be. TL also depends on the stiffness of the barrier material and frequency of the source.

Barrier theory used in the FHWA model states that the maximum noise reduction that can be achieved is 20 dBA for thin screens (walls) and 23 dBA for berms. Therefore, a material that has a TL of 33 dBA or more would always be adequate for a noise barrier in any situation.

Table 6-1 gives approximate TL values for some common materials, tested for typical A-weighted traffic frequency spectra. They may be used as a rough guide in acoustical design of noise barriers. For accurate values, material test reports by accredited laboratories should be consulted. These usually accompany literature provided by the manufacturer.

Table 6-1. Approximate Transmission Loss Values for Common Materials

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