DEPARTMENT OF TRANSPORTATION
DIVISION OF ENVIRONMENTAL ANALYSIS – MS 27
1120 N STREET
P. O. BOX 942874
SACRAMENTO, CA 94274-0001
PHONE (916) 653-7507
FAX (916) 653-7757
TTY (916) 653-4086

Flex your power!
Be energy efficient!

August 27, 2003

Mr. Gary Hamby
Division Administrator
Federal Highway Administration
California Division
980 Ninth Street, Suite 400
Sacramento, CA 95814-2724

Dear Mr. Hamby:

RE: Highway Traffic Noise Model Calibration for Various Roadway Surfaces

The June 1995 FHWA Highway Traffic Noise Analysis and Abatement Policy and Guidance states the following: "Unless definite knowledge is available on the pavement type and condition, and the noise generating characteristics, no adjustment should be made for the pavement type in the prediction of highway traffic noise levels." The Department of Transportation (Department) has conducted robust long-term research into the noise generating characteristics of roadway surfaces including use of cutting edge technology to address the durability of the acoustic benefit. In addition, we have reviewed pavement studies from around the world and, although there is much more to learn about this phenomenon, we find there is no longer uncertainty in the fact that differing pavement surfaces yield real, durable and sometimes substantial differences on traffic noise levels.

The effect of pavement surface type on traffic noise levels is "reasonably foreseeable," therefore, this effect needs to be considered when determining project impacts and the significance thereof. Accounting for real-world conditions will allow for more accurate assessment of a project's effects and reduce the uncertainty of traffic noise projections. To this end, the Department has developed a method to account for these changes in traffic noise levels resulting from three general types of roadway surfacing material: Portland cement concrete, dense-graded asphalt, and open-graded asphalt. The enclosed Noise Technical Advisory TAN 03-01 (Enclosure) details our proposed modeling practice using this calibration factor. It is our intent to implement this practice barring no questions or comments from your staff. If you care to discuss this subject, please let me know.

Sincerely,

GARY R. WINTERS
Chief
Division of Environmental Analysis

Enclosure

California Department of Transportation
Division of Environmental Analysis
Hazardous Waste, Noise & Vibration Office
Sacramento, California

Additional Calibration of Traffic Noise Prediction Models

Technical Advisory, Noise
TAN-03-01
Final

August 27, 2003

Prepared by Rudy Hendriks – Caltrans Retired Annuitant

NOTICE:

This technical advisory is for informational purposes only. The contents of this document are not official policy, standard, specification or regulation and should not be used as such. Unless otherwise indicated, the views expressed in this advisory reflect those of the author, who is solely responsible for the accuracy of data and information presented herein.

Table of Contents

Technical Advisory, Noise, TAN 03-01

Additional Calibration of Traffic Noise Prediction Models

	Page No.
Introduction	*1*
Purpose of this Technical Advisory	*1*
Summary of Existing Model Calibration Procedures	*2*
Part A - Adjustments for Non-Typical Vehicle Population	*3*
Part B - Adjustments for Non-Average Pavement Surfaces	*8*
Part C – Normalizing Measurements to Zero Wind Conditions	*11*
References	*26*

Additional Calibration of Traffic Noise Prediction Models

Introduction

Caltrans noise analysts routinely use highway traffic noise prediction models to predict existing and future highway noise levels, with and without noise barriers, for adjacent receivers. Whenever possible, model results are compared to measurements and calibrated if necessary. The process of model calibration, described in the "Technical Noise Supplement to the Traffic Noise Analysis Protocol" (TeNS (1998)) (1), is an important part of routine noise impact analysis and noise barrier design. The purpose of model calibration is to account for certain conditions that cannot be accounted for by the model.

TeNS 1998 defines model calibration as: "[T]he process of adjusting calculated future noise levels by algebraically adding a calibration constant derived from the difference between measured and calculated noise levels at representative sites." Noise measurements can of course only be made for current conditions. The underlying assumptions in model calibration are:

- Future site conditions will not change or they change minimally, and/or
- Future changes in site conditions can be accounted for in the model

These necessary assumptions normally preclude the calibration of models for highway reconstruction projects where site conditions will be significantly altered, or in cases where a highway is proposed on an entirely new alignment.

Throughout the years, Caltrans and its contractors have gathered sufficient data through measurements to establish a categorical relationship between traffic noise and pavement surface types. Additionally, procedures have been developed to adjust the model for vehicle noise emissions that are different from the reference energy mean emission levels used in the model, and to normalize noise measurements for various wind conditions through measurements at a representative site. The information can be used to further calibrate noise prediction models and to refine noise measurements to increase model calibration accuracy. The result of such a refinement would be a reduction of the K-constant and with it, a reduction in unexplained errors in the model results.

Purpose of this Technical Advisory

This Technical Advisory discusses three optional model calibration procedures in addition to the procedures discussed in TeNS (1998). The purpose of this Technical Advisory is to give the noise analyst a further opportunity to provide

a best effort account of these reasonably foreseeable effects as required by environmental law. With all model calibrations, the user should be cautioned to determine and apply the adjustments to the model with care and good judgment.

The information in this Technical Advisory will ultimately be included in the next updated version of TeNS (1998), available in the near future.

Summary of Existing Model Calibration Procedures

TeNS (1998) describes the current model calibration procedures. Although there is no need to repeat the information in this Technical Advisory, it will be useful for clarity to summarize the basic assumptions included in the current calibration procedures and their relationships with the additional calibration procedures covered in this technical advisory. Under current procedures, the model cannot be calibrated if the proposed project to be analyzed will be on a new alignment, because before project measurements cannot be compared to modeled results. There is no existing highway to model. Currently, pertinent site conditions that determine whether the model can be successfully calibrated for a project to reconstruct an existing highway are divided into two groups. These are:

Group 1 – Site conditions that **can** be accounted for by the model. These include, but are not necessarily limited to:

- Traffic mix, speeds, volumes
- Three-dimensional roadway locations
- Noise attenuation rates and distance
- Acoustically opaque noise barriers (i.e. barriers with a transmission loss of at least 10 dBA greater than the desired noise reduction)
- Finite roadway and finite noise barrier adjustments
- Three-dimensional receiver locations
- Grade corrections

Group 2 – Site conditions that **cannot** be accounted for by the model, and are therefore ignored, even though they affect the noise environment. They include, but are not necessarily limited to:

- Atypical (non-typical) vehicle noise populations (individual sites may have vehicles that are not representative of the reference energy-mean vehicle noise emission levels (Remels) used by the model.
- Pavement surface type and condition
- Meteorological conditions.
- Transparent shielding (i.e. noise transmission loss through material is less than 10 dBA greater than the desired noise reduction)

- Reflections off nearby buildings and structures

For the purpose of calibrating the model, Group 1 site conditions are allowed to change somewhat between now and the future. Group 2 site conditions are currently not allowed to change (TeNS 1998), because they affect noise levels by some unknown extent and are ignored by the model.

The additional calibration procedures presented in Parts A, B, and C of this Technical Advisory allow optional adjustments to be made for the following Group 2 site conditions. The three parts are:

Part A- Adjustments for non-typical vehicles.
Part B- Adjustments for non-average pavement surface type.
Part C- Normalizing measurements to zero wind conditions.

The first two adjustments (Parts A and B) are made to the model. The third (part C), a wind correction, is made to the measured noise levels. The three adjustments can be made in conjunction with each other. The effect of each or all of the three adjustments should be a reduction of the K constant.

Part A- Adjustments for Non-Typical Vehicle Population

These procedures should be only performed when the traffic moves at highway speeds between 55 and 65 mph (or 90 and 105 km/h). The procedures may be used with Part B if future pavement surface type (e.g. Portland Cement Concrete -PCC, Dense Graded Asphalt Concrete-DGAC, Open Graded Asphalt Concrete-OGAC) will be different from the existing pavement surface type. If the pavement surface type does not change this procedure may be used directly.

When we measure highway noise at a site, it is normally assumed that the traffic on the highway is typical of that measured for the Remels in the noise prediction models. The Calveno (2) Remels were measured at various sites throughout California. The data for TNM Remels (3) were gathered at various sites throughout the nation. At highway speeds the differences between the two are no more than 1 dBA for each vehicle group. Both sets of Remels were derived from a variety of geographic areas and represent average values, and although the individual differences in each vehicle group are quite large, the average values are representative of the Remels at most sites.

Some sites, however, may be exposed to traffic noise from a non-typical vehicle fleet. Examples might be an agricultural area, where a disproportionate number of the trucks are farm trucks, or a mining area or quarry where specialized trucks are used, or recreational areas frequented by a large number of recreational vehicles. The non-typical vehicle group(s) may be only for the

existing condition, but not for the future condition, or it may be for both conditions. If the latter is true, the existing non-typical vehicle group must be the same as the future vehicle group. At these sites the Remels used in prediction models are not representative of the actual vehicle noise emission levels. With measurements of the actual vehicle population, however, the models can be adjusted by the procedures outlined in this section. These procedures are divided in three stages. The first stage is the measurements, the second stage is the adjustment calculation, and the third stage is applying it to the model. The vehicle groups most frequently suspected of being non-typical are heavy trucks. However, the procedures described in this section may be applied to any suspect vehicle group.

Measurements – Generally, individual vehicle passby measurements (Lmax, dBA) at 15 m (50 ft) must be performed at sites that conform to the requirements set forth in the Calveno Report (1). For obvious reasons, these sites must be located along the highway of interest. A short summary of the site requirements follows. For complete details, consult the Calveno report:

- Open area, such as a field, without obstacles or reflecting surfaces within 100 feet of either the vehicle path or microphone locations.
- Site free of electromagnetic interference, i.e. no overhead power lines or electrical substation nearby.
- Base of microphone stand shall be no more than 0.6 m (2 ft) above or below the plane of roadway pavement.
- Roadway sideslope shall not vary more than 0.6 m (2 ft) in elevation
- The ground between highway and microphone may be hard or soft (soft preferred).
- Traffic must be at constant speeds between 55 and 65 mph (or 90 – 105 km/h).
- No contamination from other noise sources is allowed.
- The microphone must be placed at a height of 1.5 m (5 ft) above the ground, at 15 m (50 ft) from the centerline of the roadway on which the vehicles of interest travel.
- The vehicle speeds must all be between 55 and 65 mph (or 90 and 105 km/hr). Speeds may be measured by radar gun, or by timing the passby vehicle through a known marked distance.

The individual passby noise measurements must be not be contaminated by noise from other vehicles. For a single heavy truck, which on average is about 10 dB louder than automobiles it is relatively easy to measure an Lmax that is at least 10 dB above the ambient noise from other vehicles, when measured during a break in traffic. For a single automobile this would be much more difficult. However, most model calibrations involving non-typical vehicle groups probably target heavy trucks. Experiences with Calveno measurements indicated that as long as there was a short break in traffic and no other heavy trucks within at least 400 feet the Lmax of the truck would not be contaminated. The Calveno report should be consulted on recommended minimum vehicle separation distances and procedures to insure that the measurements are not contaminated.

Examination of Calveno data shows an average population standard deviation of 2.5 dBA for heavy trucks and medium trucks at 15 m (50 ft) within each 3 mph (5 km/h) speed window between 53 to 64 mph (85 – 103 km/h). For automobiles, the average standard deviation was 2.7 under the same conditions. For such standard deviations, a minimum of 25 vehicles for each medium and heavy truck vehicle group, and 30 for automobile vehicle group within a 3 mph (5km/h) speed window must be measured for the average Remels to be accurate within 1 dBA, with a 0.05 significance level (95% confidence level). Normally, highway noise measurements involve a much larger number for each vehicle group. Therefore the Remels can usually be relied on with great confidence in the model calibration process.

To allow for extending a 3 mph (5 km/h) speed window to 10 mph (about 15 km/h), which results in a higher standard deviation, the minimum amount of measurements for the target vehicle group is extended to 50, for the sample mean to be accurate within 1 dB of the population mean.

Adjustment Calculation – After a minimum of 50 uncontaminated passby measurements of the vehicle group of interest, the Lmax data should be energy-averaged. The average speed of all the measured vehicles should also be calculated. The resulting measured Remel can now be compared with either Calveno (for use with Sound2000, Sound32, or LeqV2) or TNM Remel calculated for the average measured speed.

The Calveno Remel can be calculated from the following equations:

Heavy Truck Remel = 50.4 + 19.2 Log (Average Measured Speed, mph)
Medium Truck Remel = 35.3 + 25.6 Log (Average Measured Speed, mph)
Automobile Remel = 5.2 + 38.8 Log (Average Measured Speed, mph)

The TNM Remel can be calculated from the following TNM Baseline Remel equation:

$\mathbf{L_{(s_i)} = 10Log_{10}[s_i^{A/10} * 10^{B/10} + 10^{C/10})}$, where:

$\mathbf{L_{(s_i)}}$ = Remel for vehicle type i at average measured speed s

$\mathbf{S_i}$ = Average measured speed

A, B, and C are constants for the following vehicle types:

Vehicle Type	A	B	C
Autos	41.740807	1.148546	50.128316
Medium Trucks	33.918713	20.591046	68.002978
Heavy Trucks	35.879850	21.019665	74.298135

The above-calculated Remel should then be compared with the measured energy-averaged Lmax. If the difference is 1 dB or less, no adjustment will be necessary. If the difference is 2 or more dB, the model may be adjusted according to the procedure explained in the following section.

Applying Adjustment to the Model – The Remel equations shown in the previous section are incorporated in the Sound32 model. They are not easily accessible. However, since Remels are energy-averaged noise levels, they can be easily related to the source strength, in this case to the vehicle volumes input into the model. By adjusting the volume of the measured vehicle group we can "trick" the model into yielding the same result as if we had input the difference between the measured Remel and the model Remel, by using the following procedure to arrive at an adjusted volume.

Let the Measured Remel minus the Model Remel = ΔdBA. Note that when the sign is properly accounted for, ΔdBA becomes the adjustment to the model Remel. We can relate this adjustment to the vehicle volume input to the model. If the measured Remel is higher than the model Remel, we can adjust for this difference by increasing the vehicle volume. And, if the measured Remel turns out to be less than the model Remel, the vehicle volume needs to be decreased. The following equation shows the relationship between ΔdBA and the volume change.

$$\mathbf{(\pm)\Delta dBA = 10\ Log\ (V_A/V)} \qquad \textbf{(eq. 1)}$$

where: ΔdBA = Measured Remel – Model Remel
V_A = Adjusted Volume
V = Actual Volume

Let $V_A/V = N$ = the ratio of the adjusted volume to the actual volume, or the multiplier to adjust the actual volume with. Then:

$(\pm)\Delta dBA = 10 \text{ Log } (N)$

To solve for N:

$$\mathbf{N = 10^{(\pm)\Delta dBA/10}} \qquad \textbf{(eq. 2)}$$

Note that if ΔdBA is negative that N will be a fraction between 0 and 1.

To adjust the model, simply multiply the volume by N and input into model.

An example of the calibration process follows in the next section.

Example of Calibrating for Non-Typical Vehicle Population. A noise analysis for a proposed highway widening from two to four lanes includes a location labeled Receiver A. Existing noise measurement at Receiver A was 75 Leq(h), dBA. The traffic volumes corresponding with the measurement, expanded to one hour were: 2500 autos, 90 medium trucks, and 210 heavy trucks. The average observed speed was 60 mph. Based on these data, the model calculated result was 71 Leq(h), dBA. The heavy truck population was suspected to be non-typical of the heavy truck population represented in the model. To verify this, a site was selected along the highway to measure 50 individual Lmax noise measurements of heavy trucks in accordance with the procedures described in the previous section. The energy-average of the individual passby measurements was 86.2 dBA. The average observed speed for those passbys was 58 mph.

The heavy truck Calveno Remel, calculated for 58 mph = 50.4 + 19.2 * Log (58) = 84.2 dBA, according to the previous section. The difference between the measured Remel and the Calveno Remel, ΔdBA = 86.2 - 84.3 = +1.9 dBA.

Therefore, the suspicion that the heavy truck population was non-typical, was justified. To adjust the model for this difference, we use equation (3) in the previous section:

$$N = 10^{(\pm)\Delta dBA/10} = 10^{+1.9/10} = 1.55$$

The heavy truck volume counted during the existing measurement at Receiver A is then adjusted by multiplying by 1.55, and becomes 1.55 x 210 = 326. The new calculated (modeled) noise level based on the adjusted heavy truck volume is 72 Leq(h), dBA. The new K constant is 75 dBA (measured) – 72 dBA (modeled) = +3 dBA.

This K-constant, in conjunction with the multiplier N=1.55 for heavy trucks, can now be used for predicting existing worst traffic noise, and future traffic noise conditions. If the future conditions would include the same heavy truck

population as the existing conditions, both the multiplier N and the calibration constant K should be used. If, however, the future population will be judged typical, then only K should be applied to the future noise predictions.

Part B- Adjustments for Non-Average Pavement surface types

Over the years Caltrans' and other studies (4, 5) have shown distinct differences in noise levels emanating from traffic on DGAC, OGAC, and PCC pavements. Examination of the California Vehicle Noise (Calveno) data (2), indicated that of the eleven sites where traffic moved predominantly at highway speeds, five were PCC and six were DGAC. The Remels for speeds between 55 and 65 mph were therefore obtained from vehicles traveling on PCC and DGAC in close to a 45/55 proportion. The "average" pavement surface type on which Calveno Remels used in the SOUND32 traffic noise prediction model are based, lies therefore about half way between PCC and DGAC. The same representation exists in the Remels used in the TNM traffic noise prediction model (3).

Adjustments for Pavement surface type. Data from the above-mentioned studies, suggest that using DGAC as a reference, PCC pavement surface type, as used in California (longitudinal tining or grooving) is at least 2 dBA louder at highway speeds than DGAC for all vehicle groups, and OGAC is at least 3 dBA quieter than DGAC. These values are conservative, in that they tend to understate the differences. In a landmark study (4) along I-80, the OGAC was about 5 dBA quieter than original DGAC), and has maintained this level of attenuation for 5 years. Although more studies are recommended, Caltrans HQ Environmental feels confident on the basis of completed and ongoing studies indicate that the preliminary figures of +2 dBA for PCC and –3 dBA for OGAC are conservatively valid with reference to DGAC. These values may be used in absence of other site-specific evidence. If such evidence is available and properly documented, other values based on the evidence may be used. An example of this may be an existing highway paved with DGAC, and subsequently re-paved with OGAC. If the difference between the original and subsequent pavement surface type has been measured and sufficiently documented, this value may be used for calibration for a noise studies for a proposed reconstruction project along the existing alignment, at least for the existing condition. If the reconstruction specifically calls for the same type of OGAC pavement surface type, the measured calibration value may be used for the after-construction condition.

Applying Adjustments. Using the above relationships with a conservative assumption that the "average pavement" in SOUND32 and TNM models is DGAC instead of the mix of DGAC and PCC, we can further adjust the models for PCC and OGAC pavement surface types. **These adjustments should only be made for highway speeds of 55 mph or greater**. The following scenarios outline how the adjustments may be made to the model:

1) For Noise Predictions for Construction on a New Alignment.
Notice that this is the only case the model can be calibrated for a highway along a new alignment. These adjustments are to be made to the future predicted noise levels at each receiver.

   a) If pavement surface type will be DGAC, no adjustment
   b) If pavement surface type will be PCC, add 2 dBA
   c) If pavement surface type OGAC, subtract 3 dBA
   d) If pavement surface type unknown, no adjustment.

2) For Reconstruction on an Existing Alignment:

   a) For comparison with measurement at model calibration sites, first adjust the model results for each receiver as follows:
      (1) If existing pavement surface type is PCC, add 2 dBA, or
      (2) If existing pavement surface type is DGAC, no adjustment, or
      (3) If existing pavement surface type is OGAC, subtract 3 dBA, or
      (4) Substitute (1) or (3) with measured data if available

   b) Compare measured noise levels with model results including adjustments in a). Then $K= M-C_{adj}$, where K = calibration constant, M = measured noise level, and C_{adj} = adjusted calculated noise, or pavement surface type adjusted model result

   c) Apply K constant derived in b) for predicted future noise level. Add the following future pavement surface type adjustments to the calibrated noise results:

      (1) If future pavement surface type is PCC, add 2 dBA, or
      (2) If future pavement surface type is DGAC, no adjustment, or
      (3) If future pavement surface type is OGAC, subtract 3 dBA, or
      (4) Substitute (1) or (3) with a)(4)

Examples of Calibrating for Pavement surface type. The following two examples show the calibration process for a new alignment and reconstruction on an existing alignment.

Example 1, New Alignment:

Given:

- Model calculated = 68 dBA at receiver
- Pavement surface type will be OGAC (adjustment = -3 dBA)

Pavement surface type-adjusted predicted = 68 – 3 = 65 dBA at receiver.

Example 2, Reconstruction on Existing Alignment:

Given:

- Existing measured (M) = 68 dB at receiver
- Existing calculated by model (C) = 69 dBA at receiver
- Existing pavement surface type = PCC (adjustment = +2 dBA)
- Future calculated by model = 70 dBA (w/o K) at receiver
- Future pavement surface type = OGAC (adjustment =-3 dBA)

First adjust model result for existing pavement surface type:
C_{adj} = 69 + 2 dBA = 71 dBA at receiver

Then calculate calibration constant K = M-C_{adj} = 68 – 71 = -3 dBA

Apply K to future calculated by model: 70 –3 dBA =67 dBA at receiver

Apply pavement surface type adjustment for OGAC = 67 – 3 = 64 dBA at receiver.

Check on process:

If K = 0, and the model calculated noise levels for existing and future stay the same, but pavement surface types change, the difference between measured existing and future predicted noise should be the same as the combined pavement surface type adjustments. In the above example, the difference due to PCC and OGAC should be +2 – (-3) = 5 dBA. To check this, let's rewrite the above example 2 so that K will be 0 and the model calculated noise levels do not change:

- Existing measured (M) = 68 dB at receiver
- Existing calculated by model (C) = 66 dBA at receiver
- Existing pavement surface type = PCC (adjustment = +2 dBA)
- Future calculated by model = 66 dBA (w/o K) at receiver
- Future pavement surface type = OGAC (adjustment =-3 dBA)

*** Sound32 does this automatically when K is specified (in this case K=-3)**

First adjust model result for existing pavement surface type:
C_{adj} = 66 + 2 dBA = 68 dBA at receiver

Then calculate calibration constant K = M-C_{adj} = 68 – 68 = 0 dBA

Apply K to future calculated by model: 66 +0 = 66 dBA at receiver

Apply pavement surface type adjustment for OGAC = 66 – 3 = 63 dBA at receiver.

The difference between existing and predicted (adjusted for pavement surface type) is 68 dBA – 63 dBA = 5 dBA, which is what it should be, even though the model results stayed the same.

Part C- Normalizing Measurements to Zero Wind Conditions

Prediction models calculate noise levels without considering atmospheric conditions, such as wind speeds and directions, and temperature profiles. Federal and State noise policies and standards also do not consider atmospherics, and thus are assumed to be for zero winds and neutral temperature gradients.

Noise measurements on the other hand, are normally made under varying atmospheric conditions. The same traffic volumes, truck mixes and speeds yield varying noise levels at receivers near a highway, depending on these atmospheric conditions. It is therefore highly desirable to normalize noise measurements to the neutral conditions, before the model is compared with and adjusted to the measurements.

The findings from a 1991 Caltrans Route 99 study (6) indicated that for a given site the change in noise levels due to atmospheric conditions can for a significant part be explained by cross wind components (CWC's). Without a noise barrier, an average of half of the fluctuations in noise levels normalized for traffic can be explained by variations in CWC's within 250 feet (75 m) from a freeway. With a noise barrier present, about two-thirds of the fluctuations can be explained by variations in CWC's. Apparently barriers enhance wind effects on noise, although not nearly as much near the ground as higher up. The Route 99 findings (6) have been used to develop a procedure for normalizing noise measurements - taken under various conditions of wind speeds and directions - to a zero wind or calm condition. This procedure should be planned and executed under supervision of personnel experienced in taking noise and meteorological measurements. It can only be used for projects involving reconstruction of an existing highway.

Existing Analysis Procedures. In a typical Caltrans noise analysis for highway reconstruction projects, a number of receivers are selected throughout the project area for traffic noise impact analysis. Receivers are defined as any location of interest in the project area. They are further defined in the Caltrans Traffic Noise Analysis Protocol and in TeNS (1998). A number of noise measurement sites, representing the receivers are also selected. The number of

noise measurement sites depends on the size of the project, complexity of terrain, and also on the amount of controversy surrounding the project. The noise measurement sites may or may not coincide with receivers, however, they must be acoustically representative of the receivers. TeNS (1998) may be used for guidance on acoustical representation. At these noise measurement sites the noise and basic meteorological conditions (i.e. wind speed and direction, relative humidity, and temperature) are measured. The purpose of the noise measurement sites is to document existing noise conditions, and to calibrate the model per procedures described in TeNS (1998).

Need for Normalization Sites. Measurements taken at the routine noise measurement locations should ideally be taken under neutral atmospheric conditions (i.e. zero winds and isothermal temperature profiles). For logistical reasons it may not be possible to take measurements only during these ideal conditions. The procedure described in this technical advisory is designed to carry out a more detailed study at one or several noise measurement sites (from hereon in called *normalization sites*), involving at least two microphones and repeat visits under varying wind conditions. The number of normalization sites depends on the highway alignment and number of acoustically different areas in the project.

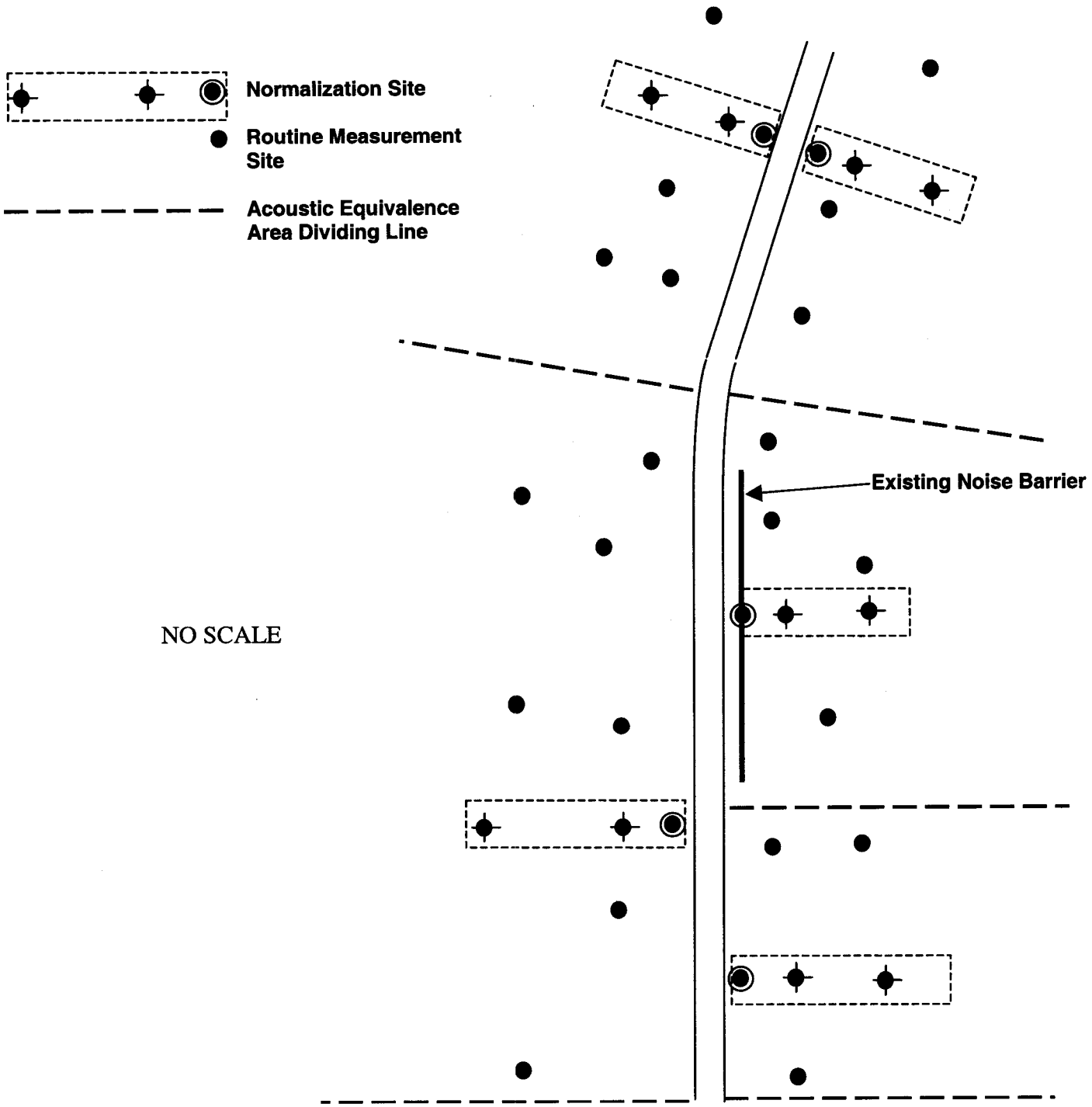
The meteorological and noise data collected at the normalization site(s) are then used to normalize the noise data at the represented routine noise measurement sites. The concept is that an accurate "wind vector" with both speed and direction must be determined. In effect, the noise measurements taken under each specific wind condition are adjusted to a zero wind condition, based on the data collected at the normalization sites.

Normalization Site Selection and Requirements. The normalization procedure should not be attempted in complex topographies, or where local features cause significant variations in wind speeds and directions in the area of interest. Additional selection requirements for a normalization site are:

- Must be acoustically representative of the noise measurement sites.
- Generally flat terrain with the least amount of obstructions is preferred.
- Anemometer(s) should be placed in open areas, away from obstructions, and in the vicinity of the noise instrumentation. A basic understanding of how the wind flows around obstacles and interacts with the ground surface is essential.
- At least one normalization site on each side of the highway.
- One normalization site should be assigned for each tangent section, if the alignment changes more than 22.5 degrees in direction.
- If an existing barrier is present in the study area, a normalization site should be selected behind the barrier. The reference mic should then be placed 1.5 m (5 ft) on the top of barrier.

Figure 1 shows a normalization site selection map using three microphones.

Figure 1. Normalization Site Selection Map for Three-Microphone Setups
This site map shows the placement of normalization sites in five different areas of acoustical equivalence



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 and roughly on a perpendicular line from the highway.

One microphone (*reference mic)* is placed close to the traffic source at a distance of 40 to 60 feet (12 to 18 m) from the centerline of the near lane and at a preferred height of 15 feet (4.5 m). The findings of the 1991 Caltrans study (6) showed that at this close distance from the source, noise levels at this reference position were not affected by wind. Other near-source data collected at a standard 1.5 m measuring height also showed a minimal effect from changing wind conditions, which suggests that a 1.5 m alternate height may be used.

The remaining one or more microphones (*receiver mic's)* are placed at the locations of interest at a height of 1.5 m, farther away from the freeway where they *are* affected by the wind. Thus the noise level differences between the reference and receiver microphones include the effects of geometric spreading, ground absorption, and atmospheric refraction due to wind and temperature gradient. The effects of geometric spreading and ground absorption remain constant. The noise level differences due to variations in traffic volumes, mixes, and speeds also remain constant. However, the effects of atmospheric refraction change as wind velocity and temperature gradient change. These effects are also distance dependent.

Figures 2 and 3 show a typical cross-section and a plan view for a three mic instrument setup for normalization measurements. The anemometer(s) should be placed in the vicinity of the noise instrumentation, but away from local obstructions and features that could affect the wind measurements. It is important to note that the same anemometer(s), setups, and locations should be used throughout the normalization process.

The most basic setup must include two mic's, one reference and one receiver mic. 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 mic 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 (as shown in Figure 1), the three mic setup would be more advantageous. The two receiver mic's would be set up at distances that bracket the closest and farthest noise measurement sites.

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

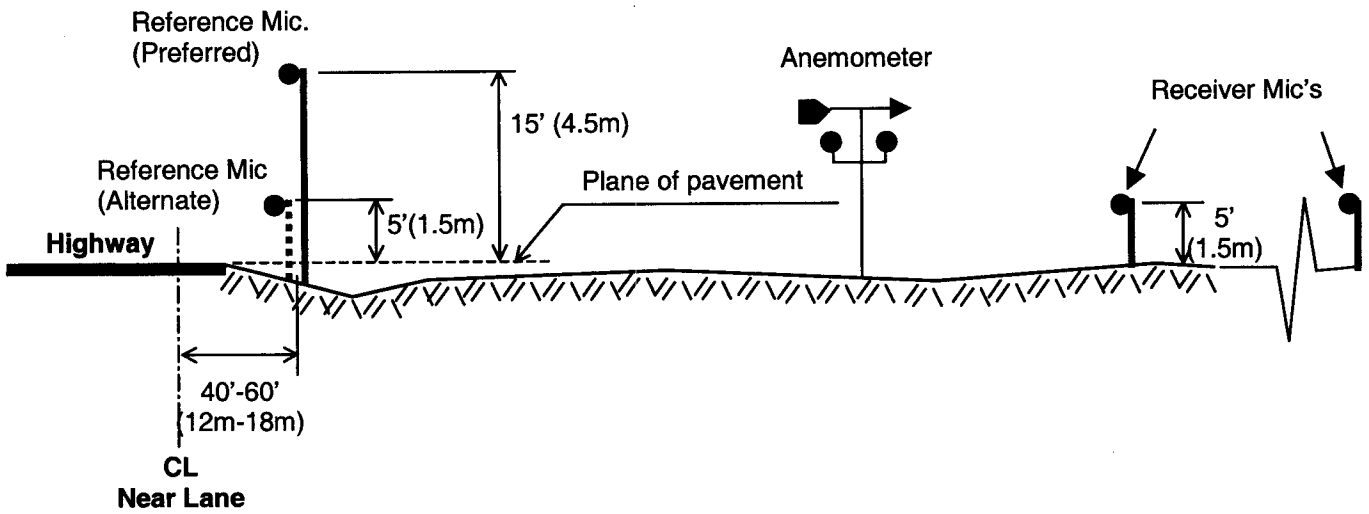
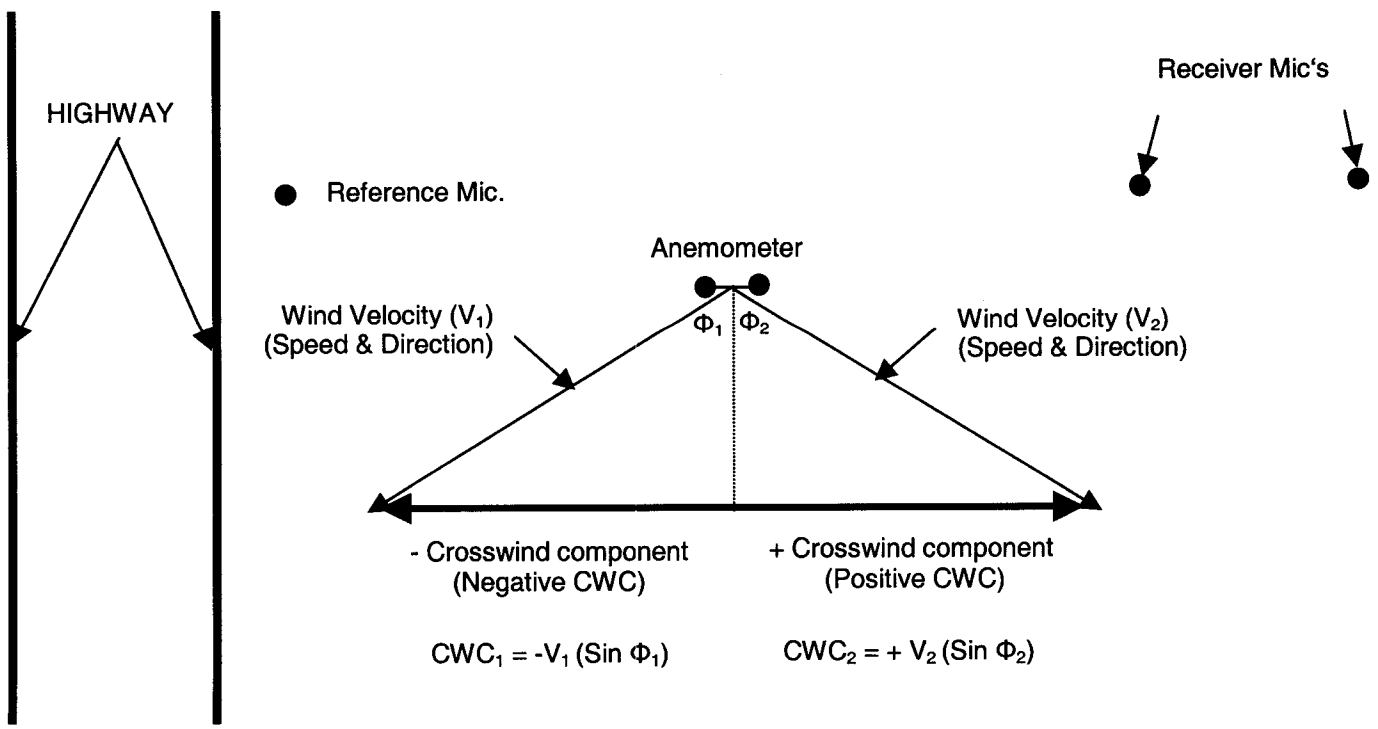


Figure 3. Typical 3-Mic Setup for Normalization Measurements (Plan View)



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 vise versa. More measurements are recommended, preferably under a wide range of crosswind speeds within the limits of +/- 5 m/s. The duration of the measurements should be the same as the standard measurement time used throughout the project, i.e. normally 15 minute-L_{eq}'s. Although traffic does not need to be counted for wind normalization purposes, it is highly recommended to count traffic volumes for heavy trucks, medium trucks, and autos. This information can be input in the model to verify that the noise levels measured at the reference mic. 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 either with respect to true north or another known direction (such as the direction of the highway) can be used for this purpose. During the wind measurement, the following need to be observed:

- wind direction
- wind speed
- duration of wind speed and/or direction

Although both wind speeds and directions often fluctuate fairly rapidly over time, both may be "eyeball-averaged" 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 1:

Table 1. Example of wind observations.

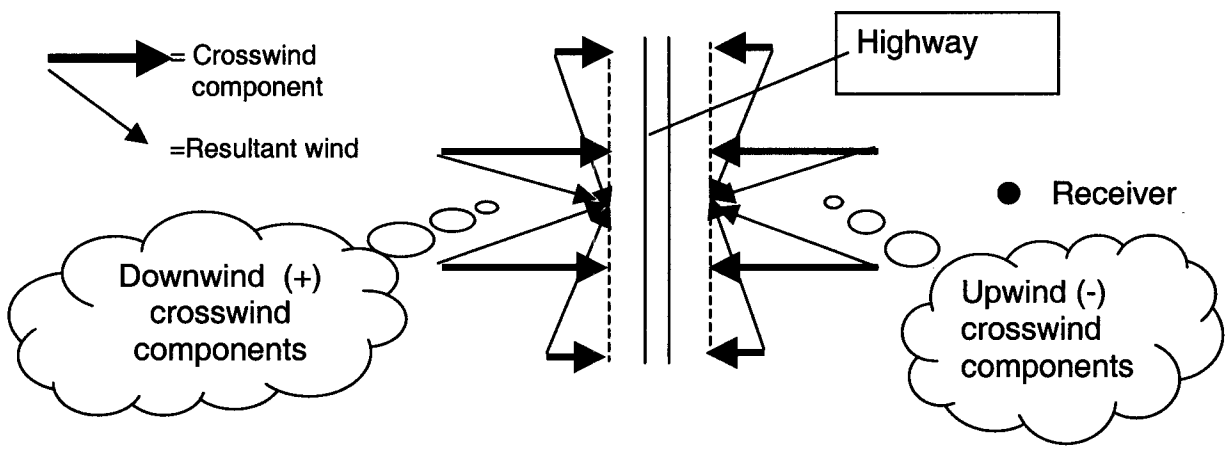
Wind Direction*	Wind Speed (m/s)	Duration (min:sec)
345°	4.5	3:00
305°	2.5	7:00
270°	2.0	5:00

*** Direction FROM which the wind is blowing; degrees clockwise relative to North, or Right Azimuth, North (R.Az.N.)**

During a set of noise and wind measurements the following restriction apply:

- The wind from any direction may not exceed 5 m/s (11 mph)
- The crosswind (component 90° to the highway) direction is not allowed to change from upwind to downwind or downwind to upwind (Figure 4)

Figure 4 – Plan View of Upwind and Downwind Conditions



A "calm wind" is defined as –1 m/s < crosswind speed < +1 m/s. Note that this condition can also occur at higher wind speeds when the wind direction is close to parallel with the highway. Under such conditions wind directions and speeds must be measured. However, if the wind speed from any direction during the entire measurement, or a portion thereof, averages less than 1 m/s, the wind can be recorded as calm (resultant wind and crosswind component = zero) 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 was mentioned before, the noise level differences between the reference mic and the receiver mic vary due to atmospheric refraction, caused significantly by the effects of wind. The noise differences additionally normalize the effects of traffic volume fluctuations. The first step in data analysis is therefore calculating the differences between each pair of reference and receiver mic measured noise levels.

Wind Data Analysis. The second step in the data analyses 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, or R. AZ. N.), and speed in meters per second. Tables 2, 3 and 4 show how to calculate the resultant wind from the observed wind data shown in Table 1.

Table 2. Wind Trajectory Calculation

	WIND					
Noise Meas. Run No.	**Obs. No.**	**Speed (m/s)**	**Duration (seconds)**	**Distance Traveled** (Speed x Duration) **(meters)**	**Direction From: Degrees R.Az.N***	**Direction To**: Degrees R.Az.N***
1	1	4.5	180	810	345°	165°
	2	2.5	420	1050	305°	125°
	3	2.0	300	600	270°	90°

*** R.Az.N = Right Azimuth from North ** Direction "To" = Direction "From" - 180°.**

For convenience in calculating the coordinates of the wind traverse in Table 3, the wind directions TO, shown in the last column of Table 2, may be converted to bearings. These bearings are shown in the fourth column of Table 3.

Table 3. Wind Traverse Calculations

WIND TRAVERSE							
		Wind Trajectory				**Coordinates (Beginning coordinates set at N 000, E 000)**	
Noise Meas. Run No.	**Obs.No.**	**Dist.** (From Table 2) (meters)	**Dir. To:** (From Table 2) (meters)	**Latitude** dist.x cos[dir.] **N(+), S(-)**	**Departure** dist. x sin[dir.] **E(+), W(-)**	**N(+),S(-)**	**E(+),W(-)**
1						**000**	**000**
	1	810	S 25° E	-734	+342	**-734**	**+342**
	2	1050	S 65° E	-444	+952	**-1178**	**+1294**
	3	600	90°E	0	+600	**-1178**	**+1894**

Table 4 - Resultant Wind Calculation

RESULTANT WIND

Noise Meas. Run No.	**Latitude** (From Tabel 3) **N(+), S(-)**	**Departure** (From Table 3) **E(+), W(-)**	**Resultant Bearing of Wind Direction To:** $\tan^{-1}$ [E,W/N,S] **(degrees)**	**Resultant Wind Distance Traveled** [N,S]/cos [dir.] **(meters)**	**Resultant Wind Distance Traveled (Check)** [E,W]/sin [dir.] **(meters)**	**Resultant Wind Speed** Average dist/dur. **(m/s)**
1	-1178	+1894	**S 58° E = 122° R.AZ.N**	2223	2233	**2228/900 = 2.5 m/s**

The resultant wind for the data shown in Table 4 is therefore 2.5 m/s at a bearing of S 58° E direction TO, or 180° – 58° = 122° R. Az. N. direction TO, or 302° R. Az. N. direction FROM.

Frequently, the resultant wind speeds and directions can be "eyeball-averaged" if there is little variation in speeds and direction during a measurement. This would make procedures followed in Tables 2, 3, and 4 unnecessary.

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

$$\mathbf{CWC = S\,[\sin(\phi)]}$$

Where: S = resultant wind speed
ϕ = angle between highway and resultant wind (See Figure 3)
(0° = parallel, 90° = perpendicular to the roadway

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

Noise and wind data correlations. Since only the receiver mic is presumed affected by the wind, the noise level measured at the receiver mic is expected to be higher when the CWC is positive and lower when it is negative (compared to a zero CWC). The difference between the reference and receiver mic's (Delta dBA, or ΔdBA) will be less with a positive CWC and greater with a negative

CWC, i.e. there should be a negative correlation between ΔdBA and CWC. The previously mentioned PB99 study (1) showed this to be true. A linear regression equation can be calculated from the measured data, in the form of:

ΔdBA = a + b (CWC)

in which "a" represents ΔdBA at a zero (calm) wind condition.

The following is an example showing the resultant winds of five 15-minute wind observations and calculated CWC's for a hypothetical roadway bearing of N 43° E (Table 5), ΔdBA's associated with the CWC's (Table 6), and finally, the data plots, regression line and calculated regression equation (Figure 5):

Table 5 - Resultant Winds and CWC's
(Roadway bearing N 43° E)

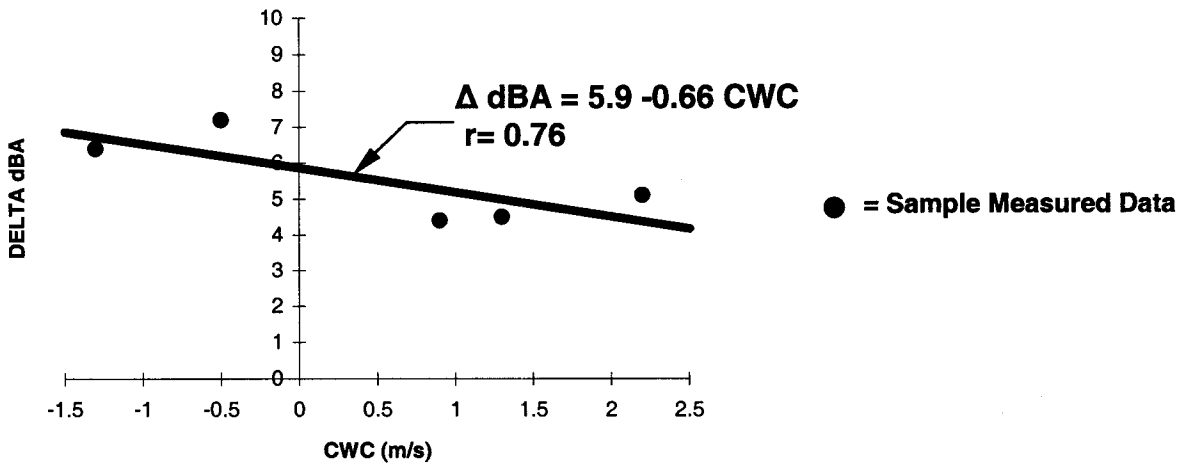
	Resultant Wind		CWC
Meas. No.	Direction* (Rt. Az. N)	Speed (m/s)	(m/s)
1	336°	0.5	-0.5
2	188°	2.2	-1.3
3	260°	1.7	+0.9
4	278°	1.6	+1.3
5	312°	2.2	+2.2

*** Direction FROM which the wind blows, right azimuth from North (Rt.Az. N.)**

Table 6 - CWC Vs. Δ dBA

Meas. No.	CWC	ΔdBA (Ref. – Rec. Mic's)
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 - Δ dBA Vs CWC Linear Regression from Table 6 data



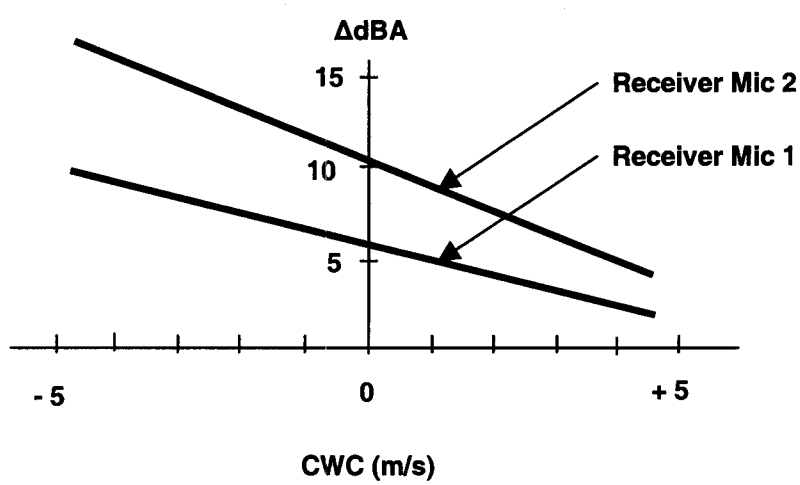
The regression equation in Figure 5 would have been derived from data obtained at a normalization site. This equation represents the difference between noise levels at the reference mic and a receiver mic versus the crosswind component. The equation is site-specific and distance dependent. In the equation, the 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, since the Δ dBA is inversely proportional to the crosswind speed. The slope may be used at any noise measurement site that is represented by the normalization site.

As an example, suppose the measured noise at a certain noise measurement site was 65 dBA. The crosswind component during the measurement was calculated from the measured wind data and found to be + 2m/s (4.4 mph), i.e. the measurement site was downwind from the highway. The wind effect would be the difference between Δ dBA at 0 m/s and Δ dBA at +2 m/s, i.e. the slope of the regression line. Using the slope in the regression equation, the wind effect (Δ dBA), at 2 m/s would be -0.66(2) = -1.3 dBA. Since the result is negative, it would be subtracted from the noise measurement. However, the result should always be rounded off to the nearest whole dBA, i.e. 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, than the noise level would be adjusted. The noise measurement normalized for wind would then be 63 dBA or less.

The normalized noise measurement may now be compared with the modeled result to derive a K-constant and calibrate the model as described in TeNS (1998).

For a 3-mic setup the two receiver mic's are positioned to bracket the variation in distances of the routine noise measurement sites. The wind effects at each noise measurement site may be interpolated from the wind effects at the near and far receiver mic's calculated from a normalization site. An example of how to do this is shown in Figure 6, Table 7 and Figure 7. Figure 6 shows fictitious regression lines for Receiver Mic's 1 and 2 at a normalization site shown in Figure 7.

Figure 6 – Sample Regression Lines for Two Receiver Mic's (3-Mic Setup)



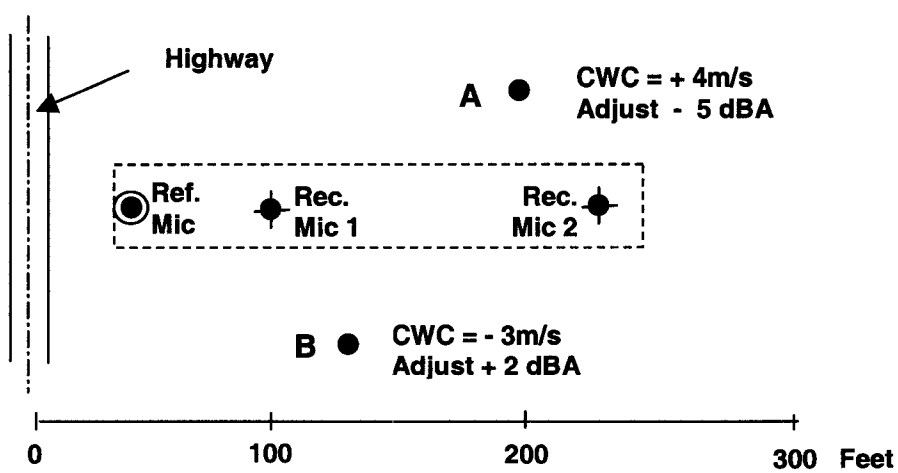
The regression equations are shown in Table 7, along with the calculated adjustments for each crosswind component (CWC) within the range of measured data, in this case the extremes from –5 m/s to + 5 m/s. In reality, these extremes may not occur during the repeat visits to the site.

Table 7 - Regression Data for Figure 6

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

Figure 7 shows two routine noise measurement sites (A and B), which are represented by the normalization site. Also shown are the CWC's observed during the measurement(s) at each site, and the corresponding adjustments for zero winds. These were obtained from Table 7 for both receiver mic's and interpolated for distance.

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



Suppose the equivalent lane distances (TeNS, 1998) for the following mic's are:

Receiver Mic 1 = 100 ft
Receiver Mic 2 = 220 ft
Noise Site Mic A = 190 ft
Noise Site Mic B = 120 ft

From Table 7, the adjustments at the distances for Receiver Mic's 1 and 2 for the CWC observed at Mic A (+4 m/s) are –3 and –5 dBA respectively. The interpolated result for Mic A then is [(190-100)/(220-100) x (-5 – (- 3))] –3 = -4.5 dBA, or –5 dBA. For Mic B (CWC = -3 m/s), the adjustments at Receiver Mic's 1 and 2 are +2 and +4, respectively. The interpolated result would be [(120-100)/(220-100) x (+4 – (+2))] +2 = +2.3 dBA, or +2 dBA. The adjusted noise levels at A would be then be 5 dBA less than the raw measurement. At B, the measured noise level would be increased by 2 dBA. 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.

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 (air temperature and temperature gradients, cloud cover, and humidity) should not vary significantly. It is therefore strongly recommended to perform the measurements at each visit within the same season, and preferably within the atmospheric equivalence constraints of ANSI S12.8 (1998), which are included in Chapter N-3000, Section N-3620 *Equivalent Meteorological Conditions* in TeNS (1998). Other constraints on applying the results of this procedure are:

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

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 the K-constant, or the difference between measured and calculated (modeled) noise levels. The K-constant 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. Since the K-constant 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 come at a price. However, the increased amount of field work, the necessity of experienced staff, and the minimal cost of additional equipment is certainly more than 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 will also 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 is the case with all tools, some are used more than others. However, if a certain tool is needed, it is usually worth the price paid for it.

References

1. "Technical Noise Supplement (TeNS) – A Technical Supplement To The Traffic Noise Analysis Protocol", California Department of Transportation, Environmental Program, Noise Air Quality, and Hazardous Waste Management Office, October 1998.

2. Rudolf W. Hendriks, "California Vehicle Noise Emission Levels", Report No. FHWA/CA/TL-87/03, California Department of Transportation, Office of Transportation Laboratory, Sacramento, CA, January 1987.

3. Gregg G. Fleming, Amanda S. Rapoza, Cynthia S.Y. Lee, "Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model (FHWA TNM), Version 1.0", Report No. FHWA-PD-96-008, DOT-VNTSC-FHWA-96-2 (Final), U.S. Department of Transportation, Research and Special Programs Administration, John A. Volpe National Transportation Systems Center, Cambridge, MA, November 1995.

4. Illingworth & Rodkin, Inc., "I-80 Davis OGAC Pavement Noise Study – Traffic Noise Levels Associated With an Open Grade Asphalt Concrete Overlay", 4th Year Summary Report, Prepared for California Department of Transportation, Environmental Program, Noise and Vibration Studies, December 1, 2002

5. Parsons, I-280 Pavement Surface Noise Study, Final Report, Woodside, San Mateo County, Prepared for California Department of Transportation, District 4, June 26, 2003

6. Rudolf W. Hendriks, "Field Evaluation of Acoustical Performance of Parallel Highway Noise Barriers Along Route 99 in Sacramento", Report No. FHWA/CA/TL-91/01, California Department of Transportation, Division of New Technology and Research, Sacramento, CA, January 1991.