PART 5

Noise

Field Evaluation of Acoustical Performance of Parallel Highway Noise Barriers in California

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The effect of multiple reflections between two parallel highway noise barriers on the acoustical performance of each of the barriers has been a subject of considerable controversy. Mathematical and scale modeling predict possible large reductions (degradations) in the effectiveness of noise barriers with smooth, hard surfaces (such as masonry or concrete) due to parallel configurations. However, noise measurements under conditions of actual highway traffic, typical barrier heights, and separations have yet to confirm the large degradations. The methods and results of a parallel noise barrier research project performed by the California Department of Transportation are presented. Field measurements of noise, traffic, and meteorology were made in three stages: before barrier construction, after construction of the near barrier, and after construction of the barrier on the opposite side of a highway. The selected site was typical of many parallel barrier configurations in California. More than 100 simultaneous, A-weighted, 15-min energy-averaged noise levels were measured at 11 microphones from 5 to 23 ft high and 15 to 200 ft behind the near barrier. The noise data were matched by crosswind vector wind velocities and normalized for differences in traffic. Analysis results showed degradations of 0 to 1.9 dBA, independent of wind. Vector wind velocities of −3 to +11 mph caused variations in noise levels of up to 9 dBA at 200 ft behind the near barrier.

This paper presents the results of a FHWA-funded research project entitled *Field Evaluation of Acoustical Performance of Parallel Highway Noise Barriers Along Route 99 in Sacramento, California*. The project investigated the effects of multiple noise reflections between two parallel masonry sound walls on the acoustical performance of one of the sound walls. The study was performed by the California Department of Transportation (Caltrans), Division of New Technology, Materials and Research (NT, M&R).

BACKGROUND

By far the most common method of mitigating traffic noise in California is to construct noise barriers between highways and critical receivers. About 330 mi of noise barriers have been built so far in California. These barriers intercept the direct noise path between noise sources and receivers and provide adequate noise attenuation when properly designed.

One of the consequences of interrupting the noise path with a barrier is the possibility of reflecting noise to the opposite side of a highway. The amount of reflected noise depends on the surface of the barrier. A hard, smooth surface such as a concrete wall will reflect almost all of the noise that strikes it. Although other materials may be used for noise barriers, the vast majority of Caltrans barriers are made of noise-reflective masonry blocks. Reflections off such barriers may be classified as single or multiple reflections depending on whether a single barrier is present on one side of the highway or parallel barriers are present on both sides.

Single-barrier reflections can theoretically increase noise levels by 3 dBA on the unprotected opposite side of a highway. This maximum value is associated with a 100 percent increase in acoustical energy at the receiver, due to a perfect specular reflection of the noise source. In rare cases in which direct noise is shielded and reflected noise is not, noise increases may be more than 3 dBA.

In practice, however, single reflections off barrier surfaces rarely increase noise levels more than 1 to 2 dBA on the opposite side of the highway; often the increases are not even measurable (*1*).

Of greater interest are multiple reflections between parallel sound walls and their potential negative effects on the performance of each individual sound wall. Mathematical calculations and measurements in laboratories indicate substantial degradations in parallel barrier field insertion losses. Degradations measured under real-world conditions, however, are generally considerably less (*2*).

The reason most often cited for this lack of agreement is the difficulty in finding suitable sites for studying multiple reflections under actual traffic conditions. A parallel barrier study should ideally include extensive measurements before barrier construction, after construction of one barrier, and after construction of both barriers. Such a three-staged approach requires careful scheduling of construction activities, allowing adequate time for noise measurements under free-flowing traffic and a variety of meteorological conditions. All pertinent variables must be meticulously documented during the measurements.

In 1987 and 1988, Caltrans District 7 initiated a demonstration project for retrofitting one of two existing parallel masonry noise barriers with noise-absorptive panels along Route I-405 in Los Angeles. The project was done in response to noise complaints by some residents of the nearby community of Brentwood. The residents specifically addressed reflective noise as the major cause of a perceived noise increase. A thoroughly documented filed study involving before and after noise measurements, meteorological observations, and traffic counts revealed that the absorptive panels reduced the noise

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levels about 1 dBA. Treating the opposite wall with absorptive material in essence simulated a "no wall" condition, so it was inferred that the opposite wall had a negligible effect on the performance of the near wall (*3*).

The study also showed a considerable influence of wind speed and direction on the noise readings within 250 ft of the highway. The data clearly showed that noise level differences of 4 dBA could be attributed to relatively minor wind shifts (*3*). This made it necessary to study before and after measurements for the same wind conditions. Measurements performed during various wind speeds and directions made this possible.

The geometry of the site studied was very complicated and considerably less than ideal for application to other site locations. A site that was representative of many parallel barrier locations needed to be studied.

An excellent site was found in 1988. Two parallel masonry sound walls were to be constructed along State Route 99 in south Sacramento. The site was fairly typical of parallel barrier locations throughout California.

With cooperation of the design engineers, special provisions directed the contractor to build the wall nearest to the site first, cease construction operations for 1 week, construct the opposite (far) wall, and once again cease operations for 1 week. This sequence in construction would enable NT, M&R personnel to measure the acoustical performance (insertion loss) of the near wall without and with the opposite (far) sound wall. The difference between the two would give an indication of insertion loss degradation due to multiple reflections between the parallel walls.

OBJECTIVES

The objectives of this research project were to

1. Measure the reduction in acoustical performance of a noise barrier on one side of a highway due to multiple reflections caused by the presence of another barrier on the opposite side of the highway—and do so at a site that incorporates a barrier configuration and geometry that is representative of most parallel barrier locations in California; and
2. Develop recommendations and guidelines ("do nothing" or mitigate) depending on the findings of this research project and define the parallel barrier projects to which they apply.

LITERATURE SEARCH

A literature search was conducted for previous research on parallel barriers (*4–15*).

Of particular interest was a recent report on measurements behind two experimental parallel noise barriers at Dulles Airport, near Washington, D.C. Using a combination of noise-absorptive material and tilting walls, the researchers reported barrier insertion loss improvements of 2 to 6 dBA over the reflective barrier configuration (*14*). However, the walls were separated by a distance of 87 ft, far less than the typical separation of parallel noise barriers along California highways.

WORK PLAN AND APPROACH

Experimental Design

The measurements, criteria, and analysis methods used in this project were generally consistent with ANSI S12.8 (1987). The Los Angeles I-405 data pointed out the importance of matching noise measurements by crosswind vector component wind speed ranges (*3*). The data also suggested that the wind velocity criteria set forth in ANSIS12.8 (1987) are too lenient. The standard recommends a maximum allowable range of 2.4 m/sec (5.4 mph) in average velocity as an equivalent crosswind criterion. In this study, the range was held to only 2.0 mph for the purposes of establishing atmospheric equivalency for comparing noise measurements.

In this study the measured crosswind components spanned a range of −2.9 to +11.3 mph. A negative crosswind blows from noise receiver to noise source; a positive wind blows from source to receiver. The winds were measured at a reference height of 20 ft, about 300 ft behind the near noise barrier. The purpose of the wind measurements was to establish atmospheric equivalency throughout the three stages and not necessarily to investigate atmospheric effects in detail. Hence, one height was deemed sufficient for comparative measurements during the study periods.

Extensive noise, traffic, and meteorological measurements were designed for the following three stages of the project:

1. Before construction,
2. After construction of the near barrier, and
3. After construction of near and far barriers.

Noise measurements for Stages 1, 2, and 3 were normalized for differences in traffic via a primary control microphone in a location that was not influenced acoustically by the sound walls. This microphone was about 0.8 mi south of the site, at the same distance and height as a secondary control microphone at the site. The secondary control microphone was assumed to be influenced by reflections off the far sound wall on the opposite side of the highway during Stage 3 measurements.

In this study, the term "control microphone" is synonymous with "reference microphone," as defined by ANSI S12.8 (1987).

After the data were normalized, comparisons of Stage 1 and 2 data within the same meteorological regimes gave a measure of near-wall insertion loss (reduction of noise levels due to inserting the wall between the freeway and the receivers) at each microphone.

Comparisons of Stage 2 and 3 measurements yielded a measure of insertion loss degradation, that is, reduction of near-wall performance due to the placement of a reflective wall on the opposite side of the freeway.

Noise Measurement Site and Microphone Locations

The noise measurement site was located along the east side of Route 99 between Florin Road and Mack Road at Trailhead Park, in south Sacramento. The highway consisted of two northbound (NB) and two southbound (SB) lanes during the three measurement stages. The lane profiles were ap-

proximately 4 ft above the average park ground elevation near the site.

Eleven microphones (mics) were used simultaneously: 10 at the Trailhead Park test site and 1 at the primary control location roughly 4,200 ft southerly along Route 99, as shown in Figures 1 and 2. The mics were designated C2 and Numbers 1 through 9 (Figure 1), and C1 (Figure 2). Figure 3 shows a cross section perpendicular to Route 99, along the mic line at Trailhead Park, with barrier locations and mic heights and distances.

Mic C1 was placed in the same three-dimensional position relative to the edge of traveled way (ETW) as Mic C2. Because of its location, noise levels measured at C1 were unaffected by the presence of sound walls during the Stage 2 and 3 measurements. Noise levels measured during Stage 3 at C2, however, were affected by reflections from the far sound wall on the opposite side of the freeway. They were presumed to be unaffected by the presence of the near wall.

Mic C1 and C2 were primary and secondary control mics, respectively. Both measured the Route 99 traffic noise levels at the same height (15 ft) above and same distance (31 ft) from the ETW. This height and distance corresponds with a position of 5 ft over the top of the near noise barrier at its intersection with the mic line at Trailhead Park.

Because of the 4,200-ft separation between Mics C1 and C2, the vehicles passing both locations would be different at any one instant of time. However, because of time-averaging of traffic and noise levels, these differences were expected to be small and mostly random, with perhaps a small systematic difference due to local site and pavement conditions. Mic C1, for instance, was near an on-ramp on which accelerating vehicles, passing closer to Mic C1 than the mainline traffic, could have introduced a small systematic difference between C1 and C2. Although the C1 location was less than ideal, no better locations were available. Average relationships between the noise levels measured at C1 and C2 during each stage could be used in the source normalization process necessary for stage comparisons. Mics 1 through 9 positions were selected to measure within barrier-shielded as well as unshielded zones.

Instrumentation

Noise

All sound-level meters (SLMs) used in this project conformed to ANSI S1.4 1971 (R1976) Type 1 requirements. Mics 1 through 9 were mounted with test-tube clamps to three telescoping aluminum swimming-pool-net poles (maximum length 23.5 ft) secured with adjustable guy lines. After the near barrier was constructed, Mic C2 was mounted on a 5-ft-tall removable bracket that slipped over the top of the 8-in.-thick masonry sound wall.

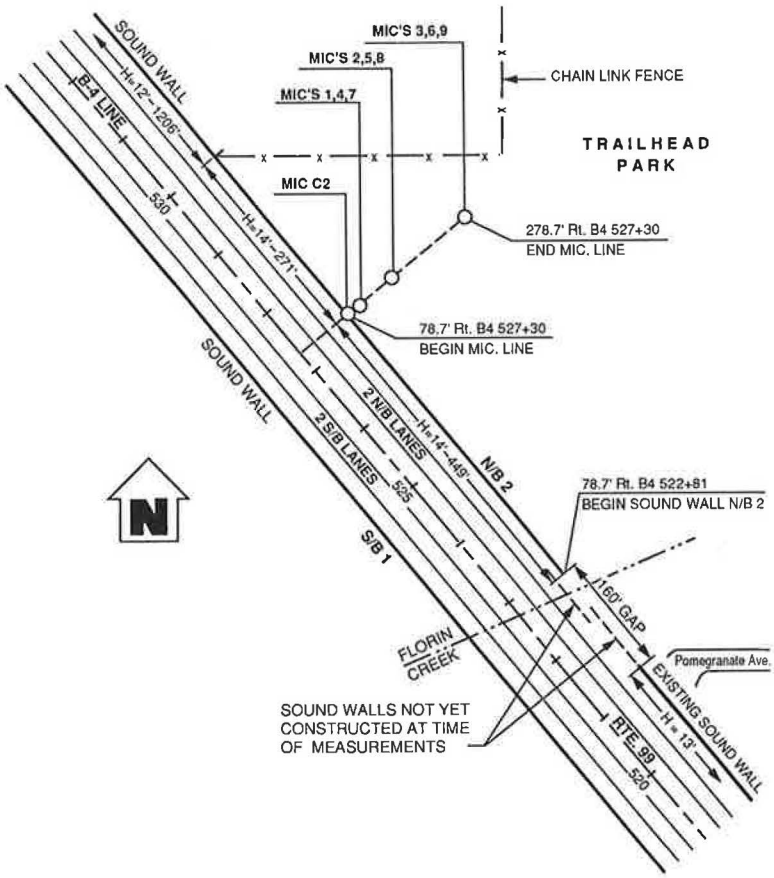

FIGURE 1 Site location, Mics C2 and 1 through 9.

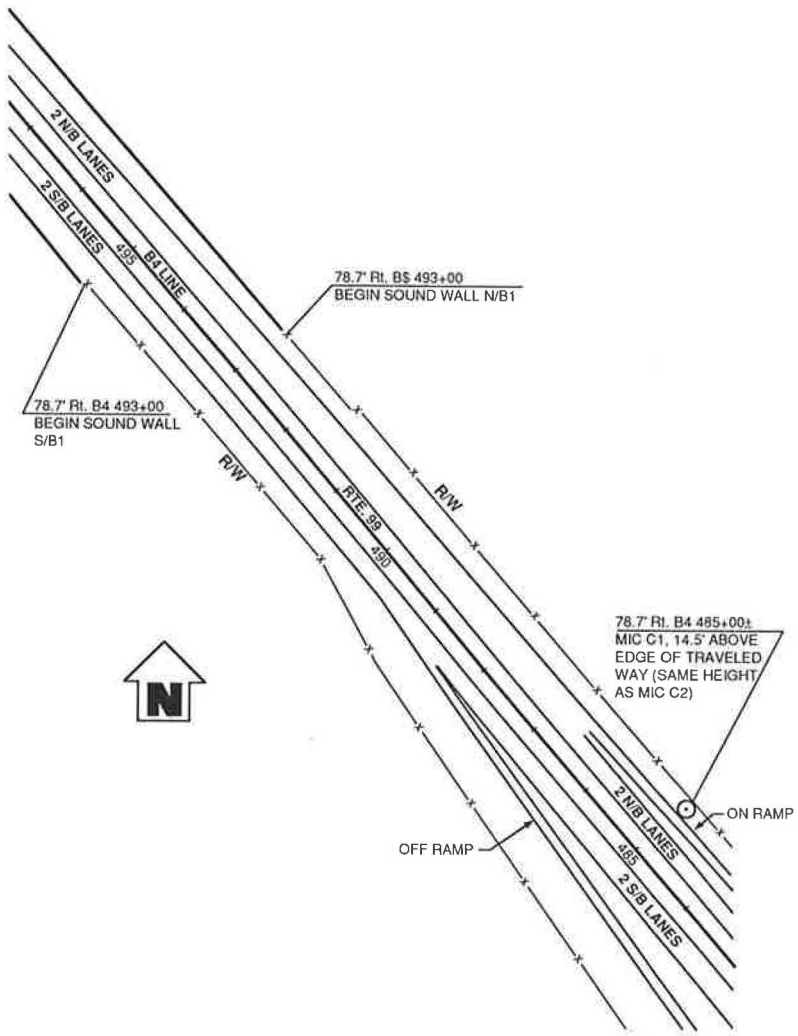

FIGURE 2 Site location, Mic C1.

The mics and preamplifiers were attached to SLMs by way of extension cables. The DC outputs of the SLMs were connected via long cables to specific channels on a 16-channel custom-made data logger inside a van. The data logger processed the signals into various descriptors such as Leq, L10, and L50 for each mic.

Mic C1 was mounted via a test tube clamp to a telescoping warning sign stand, extended to the same height as Mic C2, relative to the pavement. The display of the SLM at Mic C1 was read and recorded by the instrument operator.

Each mic–SLM–data logger system was calibrated before and after each day's measurement series. All systems (including the self-contained measuring system at Mic C1) were calibrated with the same master calibrator throughout all measuring stages.

Meteorology

Meteorological observations were taken at the van approximately 300 ft behind the near barrier. Wind speed and direction were taken at a height of approximately 20 ft. The data were fed into two channels of a data logger with a sampling rate of one per second in the van. The data logger calculated 1-min averages of wind speed and direction. These averages were later converted to 15-min "resultant winds" and crosswind vectors, coinciding with the noise measurement periods.

Air temperature and humidity were read from a combined thermometer and humidity indicator at the beginning and end of each 15-min measuring period. The two readings for each were recorded and later averaged.

The sky condition was observed at the beginning of each 15-min measurement period and classified as clear, partly cloudy, or overcast.

Traffic

Traffic was videotaped during the noise measurements on the Mack Road overcrossing (in northerly direction). Vehicles were later counted from the tapes and classified in three vehicle groups: heavy trucks, medium trucks, and automobiles (*16*). Vehicles were also grouped by direction (NB or SB). Traffic speeds were taken randomly at the same location with a radar gun.

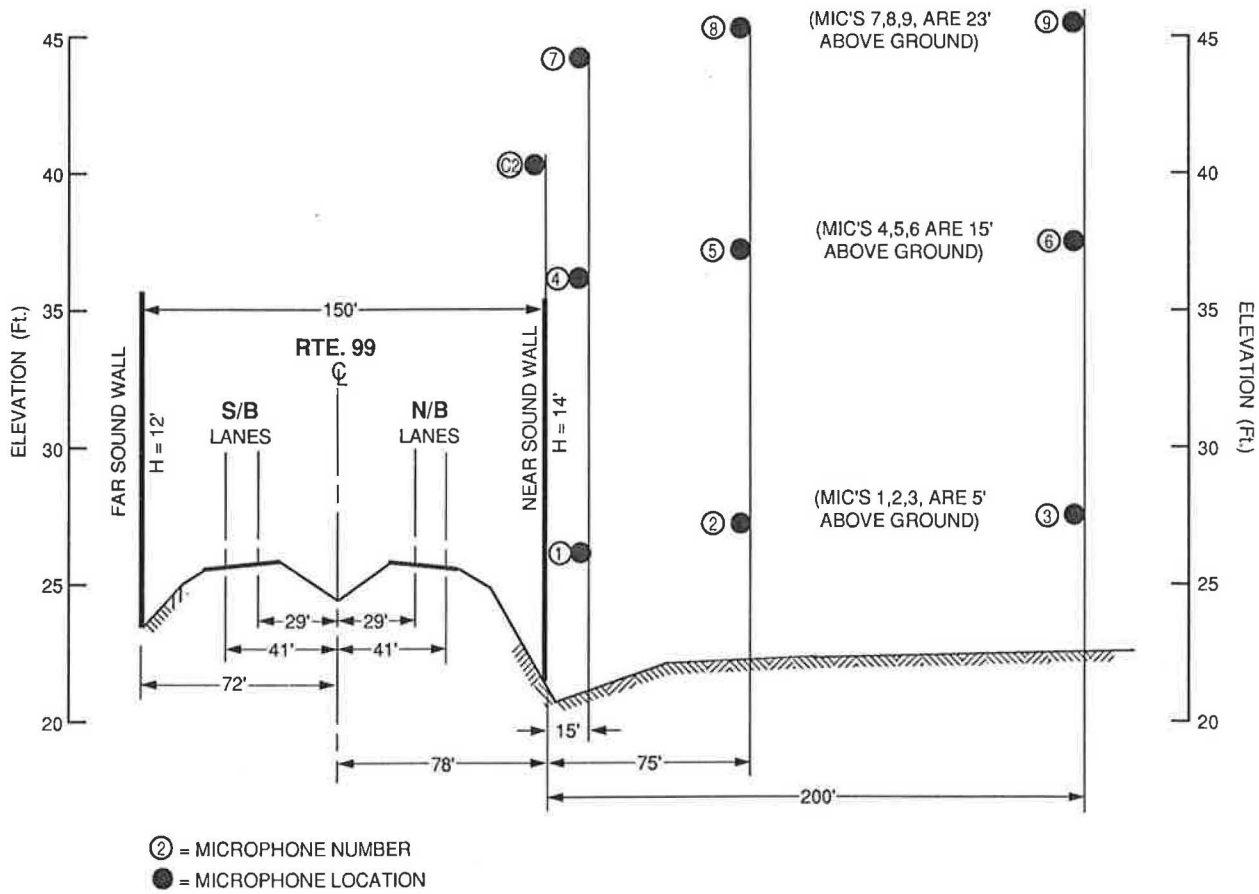

FIGURE 3 Cross section at Mics C2 and 1.

MEASUREMENTS

With few exceptions, all noise measurements were made during weekdays, between 10:00 a.m. and 3:00 p.m., under free-flowing traffic conditions. The noise descriptor used throughout the study was the Leq(15 min), in units of decibels on the A-weighted scale (dBA).

A total of 105 uncontaminated measurement runs were made: 27 during Stage 1, 45 during Stage 2, and 33 during Stage 3. Each run consisted of the 11 simultaneous noise levels recorded by the mics shown in Figures 1 through 3.

Spot checks in the park, away from the freeway and other activities, indicated maximum ambient Leq noise levels of 49 dBA. Since the minimum Leq(15min) measured during any stage was 58.9 dBA, none of the noise measurements was judged to be contaminated by more than 0.5 dBA.

DATA ANALYSIS METHODS

Normalization of Data

The Stage 1, 2, and 3 noise measurement data were normalized to account for variations in traffic. The differences between the primary and secondary control mics (C1 and C2) and the differences between Mic C2 and Mics 1 through 9 were calculated and compared for the three stages. Dealing with the differences had the effect of normalizing the data for traffic variations (*3*).

Relationships Between Control Mics by Stage

The next step of normalization was to determine the mean difference between Mics C1 and C2 for each stage. The field data showed the independence of the C1 minus C2 differences with crosswind velocities in all three stages. The differences could therefore be grouped by stage without concern for wind speed and direction. The differences are shown in Figure 4. Statistical *t*-tests (*17*) revealed that the means were statistically significant at a level of 0.05.

Calculation of Insertion Losses and Degradations

Once the average relationship between the two control mics was established for each stage, the Stage 2 and 3 insertion losses and the Stage 3 insertion loss degradations were calculated for each mic location and for each wind class. The calculation methods are shown in Figure 5.

ANALYSIS RESULTS

Insertion Losses and Degradations

The mean insertion losses for all wind classes are shown in Figure 6, and the mean insertion loss degradation due to the opposite wall are shown in Figure 7. Although the insertion

STAGE 1 (BEFORE BARRIERS)	STAGE 2 (NEAR BARRIER)
Mean Diff. = +0.14 dBA Standard Deviation = 0.29 No. of Measurements = 27	Mean Diff. = +0.35 dBA Standard Deviation = 0.23 No. of Measurements = 38

Difference of Mean Differences = -0.21 dBA

Results of "t" Test, Significance Level = 0.05:

Calculated "t" = -3.25
Critical "t" = -1.67 (one-tailed)

CONCLUSION: The Mic C1 - Mic C2 differences of Stage 1 and Stage 2 are statistically different by 0.2 dBA.

STAGE 2 (NEAR BARRIER)	STAGE 3 (BOTH BARRIERS)
Mean Diff. = +0.35 dBA Standard Deviation = 0.23 No. of Measurements = 38	Mean Diff. = -0.29 dBA Standard Deviation = 0.25 No. of Measurements = 33

Difference of Mean Differences = +0.64 dBA

Results of "t" Test, Significance Level = 0.05:

Calculated "t" = 11.23
Critical "t" = 1.67 (one-tailed)

CONCLUSION: The Mic C1 - Mic C 2 differences of Stage 2 and Stage 3 are statistically different by 0.6 dBA. It appears that this difference was caused by multiple reflections between the near barrier and the opposite (far) barrier, i.e. the Stage 3 noise levels increased by 0.6 dBA at Mic C2, compared to the same levels of Stage 2.

FIGURE 4 Analysis of Mic 1 – Mic 2 differences by stage.

losses showed a wind dependency, the degradations did not. With the exception of all wind classes at Mic 1, two wind classes at Mic 2, and one at Mic 3, the degradations were statistically significant. The Student *t*-test with a significance level of 0.05 was used to perform these analyses (*17*).

The mean degradations range from 0 dBA at Mic 1 to 1.4 dBA at Mics 8 and 9. These results are consistent with the findings in the Los Angeles study (*3*) and indicate that although the degradations were statistically significant at all mic locations except Mic 1, they were not significant in terms of human perception. It is generally recognized that humans cannot perceive noise increases of 1 to 2 dBA.

The standard errors of the Stage 2 and 3 insertion losses (*16*) and degradations averaged 0.8 dBA.

Effects of Wind

To study the effects of crosswind vector wind velocities on noise levels, the differences in noise levels between Mic C2 and each mic (Mics 1 through 9) for each run were paired with their associated crosswind components and grouped by stage. The data were then submitted to a regression analysis. Similar analyses had been done in the I-405 parallel barrier demonstration project in Los Angeles (*3*).

As was so in Los Angeles, the linear regression analyses in this project clearly showed that for the wind ranges tested, the data could be represented by linear regression lines in the general form of

$$y = a + bx$$

I. MIC C1 - MIC C2 ADJUSTMENTS BY STAGE

A. Stage 1 (Before Barriers):
Mean Difference Mic C1 - Mic C2 = +0.14 dBA

B. Stage 2 (Near Barrier):
Mean Difference Mic C1 - Mic C2 = +0.35 dBA
Adjustment 1 at Mic C2, Stage 2 = +0.2 dBA

C. Stage 3 (Both Barriers):
Mean Difference Mic C1 - Mic C2 = -0.29 dBA
(Noise Level at Mic C2 increased 0.64 dBA during Stage 3 compared to Stage 2)
Adjustment 2 at Mic C2, Stage 3 = -0.6 dBA

II. STAGE 2 INSERTION LOSS CALCULATION

$$\text{Mean } IL_{2(i,j)} =$$

$$= \text{Mean } (C2\text{-}i)_{2(j)} - \text{Mean } (C2\text{-}i)_{1(j)} + \text{Adj.1}$$

III. STAGE 3 INSERTION LOSS CALCULATION

$$\text{Mean } IL_{3(i,j)} =$$

$$= \text{Mean } (C2\text{-}i)_{3(j)} - \text{Mean } (C2\text{-}i)_{1(j)} + \text{Adj.1} + \text{Adj.2}$$

IV. INSERTION LOSS DEGRADATION

$$\text{Mean } Deg_{(i,j)} =$$

$$= \text{Mean } IL_{2(i,j)} - \text{Mean } IL_{3(i,j)} =$$

$$= \text{Mean } (C2\text{-}i)_{2(j)} - \text{Mean } (C2\text{-}i)_{3(j)} + \text{Adj. 2}$$

WHERE:	IL	= Insertion Loss
	Deg	= Degradation
	C1 and C2	= Noise Levels at Ref.Mic's C1 and C2
	i	= Noise Levels at Mic 1, 2,.....9
	j	= 2 Mph Wind Class j
	1,2,3	= Measurement Stage No.

FIGURE 5 Insertion loss and degradation calculation method.

where

y = difference between Mic C2 and Mic 1, 2, . . . 9 (dBA);
x = crosswind vector wind velocity (a negative velocity indicates a wind blowing from receiver to source; a positive wind indicates a wind blowing from source to receiver);
a = a constant; in this case the difference between Mic C2 and Mic 1, 2, . . . 9 at a 0-mph crosswind; and
b = slope of the regression line, in this case the change in velocity (dBA/mph).

The slope of the regression line is the most useful parameter for showing the effects of vector wind velocity. A negative slope indicates that downwind from the source the differences between Mic C2 and the mic of interest become smaller as the vector wind velocity increases. The same differences become greater upwind from the source. If a is set at zero, the regression equation is normalized to a zero wind condition at the mic of interest, and the slope directly indicates the wind

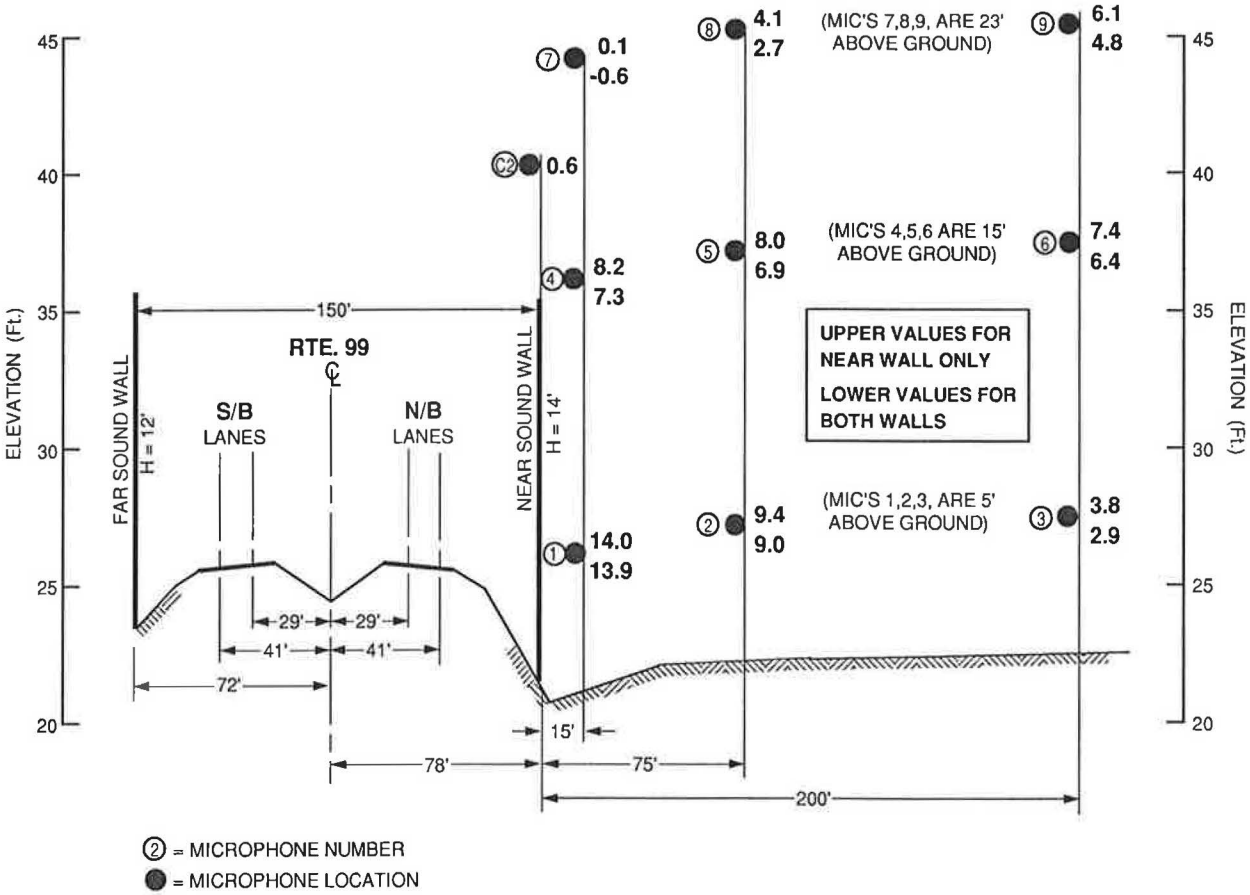

FIGURE 6 Mean insertion loss for near wall only and for both walls.

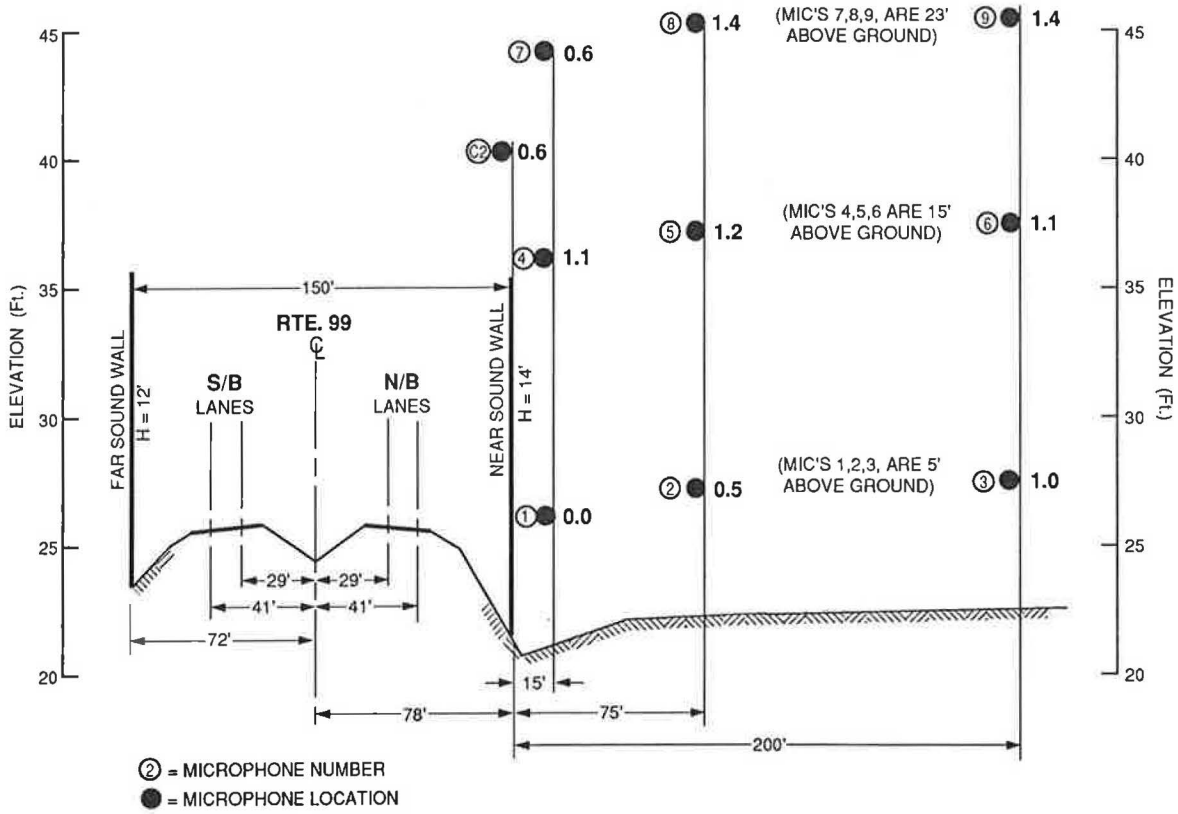

FIGURE 7 Mean insertion degradation due to far sound wall.

TABLE 1 Summary of Regression Slopes: C2 − *i* Differences Versus Crosswind Vector Velocity

Mic No.	Statistic	Stage 1	Stage 2	Stage 3
1	b=Slope (dBA/Mph) r = Coeff. of Corr.	-0.15* 0.57	-0.10* 0.65	-0.06* 0.51
2	b r	-0.21* 0.59	-0.38* 0.91	-0.37* 0.91
3	b r	-0.48* 0.78	-0.60* 0.93	-0.57* 0.95
4	b r	-0.03 0.15	-0.15* 0.92	-0.17* 0.85
5	b r	+0.07 0.23	-0.35* 0.92	-0.38* 0.95
6	b r	-0.03 0.13	-0.42* 0.95	-0.44* 0.96
7	b r	+0.03 0.11	+0.06* 0.71	+0.10* 0.86
8	b r	-0.02 0.07	-0.14* 0.78	-0.11* 0.69
9	b r	-0.02 0.08	-0.34* 0.91	-0.38* 0.96

Note: * Slope is significant ("F" test, level of sig.= 0.05)

effect in decibels per miles per hour at the mic location. To deal with noise levels, the signs of the slopes need to be reversed instead of the differences in noise levels.

Table 1 shows a summary of the regression line slopes and correlation coefficients of all data by mic and stage. Also shown are the results of statistical *F*-tests performed on the slopes of the regression lines (*18*). The *F*-test examines the validity of the hypothesis that the data do not show a regression, that is, that the slope of a regression line is zero.

The summary shows that Stage 1 wind effects were limited to the low mics (1, 2, and 3). After a barrier was constructed between the highway and receivers (Stages 2 and 3), the middle and high mics also showed significant wind effects within 200 ft behind the barrier.

Tables 2 and 3 were developed from Table 1. Shown are the wind effects on noise level during Stages 1, 2, and 3. The effects of Stages 2 and 3 were averaged because the regression slopes were very similar. No crosswind vectors of more than 6 mph were observed during Stage 1.

Other data in this project indicated the following observed extreme differences in noise levels at the Mic 3 location, by stage:

TABLE 2 Vector Wind Effects on Noise Levels, Stage 1

	CROSSWIND VELOCITY				
MIC.NO.	-2 MPH	0 MPH	+4 MPH	+8 MPH	+12 MPH
1	-0.2	0.0	+0.3	+0.6	+1.0 dBA
2	-0.8	0.0	+1.5	+3.0	+4.6 dBA
3	-1.2	0.0	+2.3	+4.7	+7.0 dBA
4	-0.3	0.0	+0.6	+1.3	+1.9 dBA
5	-0.7	0.0	+1.5	+2.9	+4.3 dBA
6	-0.9	0.0	+1.7	+3.4	+5.1 dBA
7	-0.2	0.0	+0.3	+0.6	+1.0 dBA
8	-0.3	0.0	+0.5	+1.0	+1.5 dBA
9	-0.7	0.0	+1.4	+2.9	+4.3 dBA

TABLE 3 Vector Wind Effects on Noise Levels, Stages 2 and 3

	CROSSWIND VELOCITY				
MIC.NO.	-2 MPH	0 MPH	+2 MPH	+4 MPH	+6 MPH
1	-0.3	0.0	+0.3	+0.6	+0.9 dBA
2	-0.4	0.0	+0.4	+0.8	+1.3 dBA
3	-1.0	0.0	+1.0	+1.9	+2.9 dBA
4-9	NO WIND EFFECTS				

- Stage 1, Mic 3, maximum noise level difference for 0- and 6-mph crosswind vector was +4 dBA.
- Stage 2, Mic 3, maximum noise level difference for −3 and 11-mph crosswind vector was +9 dBA.
- Stage 3, Mic 3, maximum noise level difference for 0- and 9-mph crosswind vector was +6 dBA.

The human ear can readily perceive these noise-level variations.

The ANSI S12.8 (1987) recommendation of comparing noise levels within a maximum allowable variation of average vector wind velocities of 2.4 m/sec (5.4 mph) appears to be too liberal, in light of the given data. As a member of the ANSI work group, the author has helped prepare a recommendation for revising the given standard on the basis of wind and noise data in this study.

CONCLUSIONS

The data in this report point toward two major findings:

1. The measured reductions in acoustical performance of one of two parallel noise barriers in this project are less than can be perceived by normal human ears.

2. Wind speed and direction can have a profound effect on noise measurements within 250 ft of a highway.

A summary of specific findings and conclusions in each of the two categories follows.

Reduction in Acoustical Performance (Insertion Loss Degradations)

- Degradations by wind class ranged from 0 to 1.9 dBA, depending on mic location.
- Mean degradations averaged over all wind classes ranged from 0 to 1.4 dBA, depending on mic location.
- Mean degradations increased with distance behind the barrier and height above the ground; the lowest mean of 0 dBA occurred 15 ft behind the near barrier, at a height of 5 ft (Mic 1); the highest mean of 1.4 dBA occurred at 200 ft behind the near barrier, at a height of 23 ft.
- Degradations were statistically significant at all mic locations, except for Mic 1 (t-test, level of significance = 0.05); in terms of human perception, however, none of the degradations was significant.
- With the results of the Los Angeles study and other data (*1*), this study concludes that reflective parallel barriers used in typical Caltrans configurations do not reduce the performance of each individual barrier perceptibly. However, there may be some unusual situations in which complex barrier or terrain configurations cause noise reflection problems.

Wind Effects

- Stage 2 and Stage 3 insertion losses tended to be wind-dependent; they generally decreased as the positive crosswind vector increased and increased as the negative crosswind vector increased.
- Degradations did not show any wind dependency.
- Within the observed ranges of crosswind vector wind speeds of −1 to +6 mph during Stage 1, −3 to +11 mph during Stage 2, and −1 to +9 mph during Stage 3, linear regression lines best described plots of noise levels normalized for source strengths versus crosswind vector velocity.
- Within these wind ranges, good correlations existed for Stage 1, low mics only, and all Stage 2 and 3 mic data. Noise levels increased downwind from the source and decreased upwind from the source.
- Wind effects increased with distance from the source, although not linearly.
- Construction of a noise barrier between source and receiver tended to enhance the wind effects.
- Without a barrier, wind effects at a normal receiver height of 5 ft above the ground were slightly less than the same receiver with a barrier. This accounted for the wind dependency of barrier insertion losses.
- Without a barrier, wind effects decreased rapidly with mic height. At a receiver height of 15 ft and above, no wind effects could be detected without a barrier.
- Comparing the "near barrier only" and "both barriers" conditions, the wind effects were nearly identical and extended to much greater heights than without barriers. At a receiver height of 23 ft, the wind effects were still large.
- These findings imply that second-story or higher dwellings could experience an increase in noise levels due to a noise barrier if they are located downwind from a highway. However, ground-level residences that are elevated above the highway by virtue of sloping terrain will not experience such an increase because the before-barrier wind effects are greater because of the proximity to the ground. By the same token, a second-story or higher dwelling upwind from the highway could benefit from a greater noise reduction due to the barrier.

RECOMMENDATIONS

This paper recommends that no mitigation of reflected noise will be attempted in California until controlled field studies indicate an actual problem with reflections, or until subsequent research, performed under real-world conditions, identifies under what conditions parallel barrier reflections will degrade the performance of a barrier by 3 dBA or more. On the basis of the data in this report and others (*14*), the author suspects that degradations of this amount occur when the ratio of the separation distance and height of the barriers is less than 10 to 1.

If such research is accomplished, a suitable FHWA-approved computer model needs to be available to predict the degradations and to include mitigation strategies in the future design of noise barriers where appropriate.

Future research in identifying parallel barrier problems should be done only under real-world conditions with extensive documentation of source, site, and atmospheric conditions. Such research is very expensive and should be done on a national scale.

The findings in this project also indicate an urgent need for more research in meteorological effects of noise levels with and without noise barriers, in the immediate vicinity of a highway as well as farther away. A better understanding of atmospheric effects on noise levels will help Caltrans districts address the scores of noise complaints received by the public each year. Many of these complaints may be caused by atmospheric phenomena.

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REFERENCES

1. M. M. Hatano. *Evaluation of Noise Barrier Reflection, 04-SC1-101-30.7.* Report CA-TL-7287-78-02. Office of Transportation Laboratory, California Department of Transportation, Sacramento, Jan. 1978.
2. W. Bowlby, L. F. Cohn, and R. A. Harris. A Review of Studies of Insertion Loss Degradation for Parallel Highway Noise Barriers. *Noise Control Engineering Journal*, March–April 1987.
3. R. Hendriks and J. Hecker. *Parallel Noise Barrier Report: A Noise Absorptive Demonstration Project—San Diego Freeway, Interstate Route 405 in the City of Los Angeles, Community of*

Brentwood. District 7 Environmental Investigations Section (and Transportation Laboratory), California Department of Transportation, July 1989.
4. C. Menge. Sound-Absorption Treatments for Highway Noise Barriers. In *Transportation Research Record 740*, TRB, National Research Council, Washington, D.C., 1980.
5. J. J. Hajek. Effects of Parallel Highway Noise Barriers. In *Transportation Research Record 933*, TRB, National Research Council, Washington, D.C., 1983.
6. W. Bowlby and L. F. Cohn. Insertion Loss Degradation For Parallel Traffic Noise Barriers. *Proc., Inter-Noise 84, Vol. I*, Noise Control Foundation, Inc., Poughkeepsie, N.Y., 1984.
7. D. A. Hutchins and H. W. Jones. Parallel Barriers in the Presence of Ground Surfaces. *Proc., Inter-Noise 84, Vol. I*, Noise Control Foundation, Inc., Poughkeepsie, N.Y., 1984.
8. C. G. Balachandran, R. G. Patching, and C. Andrew. Traffic Noise Attenuation Due to Single and Parallel Barriers. *Proc., Inter-Noise 84, Vol. I*, Noise Control Foundation, Inc., Poughkeepsie, N.Y., 1984.
9. W. Bowlby and L. F. Cohn. Image-3: Computer-Aided Design for Parallel Highway Noise Barriers. In *Transportation Research Record 933*, TRB, National Research Council, Washington, D.C., 1983.
10. *Effectiveness of Parallel Noise Barriers—An Iowa Study*. Planning and Research Division, Iowa Department of Transportation, Ames, Feb. 1984.
11. M. A. Staiano. Parallel Barrier Attenuation Degradation. Presented at Summer Meeting of TRB Committee A1F04, St. Petersburg, Fla., July 1985.
12. S. Slutsky and H. L. Bertoni. Some Insertion Loss Curves for Vertical and Tilted Barriers. Presented at Summer Meeting of TRB Committee A1F04, 1986.
13. W. Bowlby and L. F. Cohn. *Sound-Absorptive Highway Noise Barriers*. Report FHWA-TS-86-214. Office of Implementation (HRT-10), FHWA, U.S. Department of Transportation, May 1986.
14. G. G. Fleming and E. J. Rickley. *Parallel Barrier Effectiveness—Dulles Noise Barrier Project*. Report FHWA-RD-90-105. Office of Engineering and Highway Operations Research and Development, FHWA, U.S. Department of Transportation, May 1990.
15. R. L. Wayson and W. Bowlby. Atmospheric Effects on Traffic Noise Propagation. In *Transportation Research Record 1255*, TRB, National Research Council, Washington, D.C., 1990.
16. T. M. Barry and J. A. Reagan. *FHWA Highway Traffic Noise Prediction Model*. Report FHWA-RD-77-108. FHWA, U.S. Department of Transportation, Dec. 1978.
17. A. H. Bowker and G. J. Lieberman. *Engineering Statistics*, 2nd ed. Prentice-Hall, Inc., Englewood Cliffs, N.J., 1972.
18. N. R. Draper and H. Smith. *Applied Regression Analysis*. John Wiley & Sons, Inc., New York, N.Y., 1966.
19. R. W. Hendriks. *Field Evaluation of Acoustical Performance of Parallel Noise Barriers Along Route 99 in Sacramento, California*. Report FHWA/CA/TL-91/01. Division of New Technology, Materials and Research, California Department of Transportation, Sacramento, Jan. 1991.

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