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Determination of Effectiveness of Noise Barriers Along I-285, Atlanta

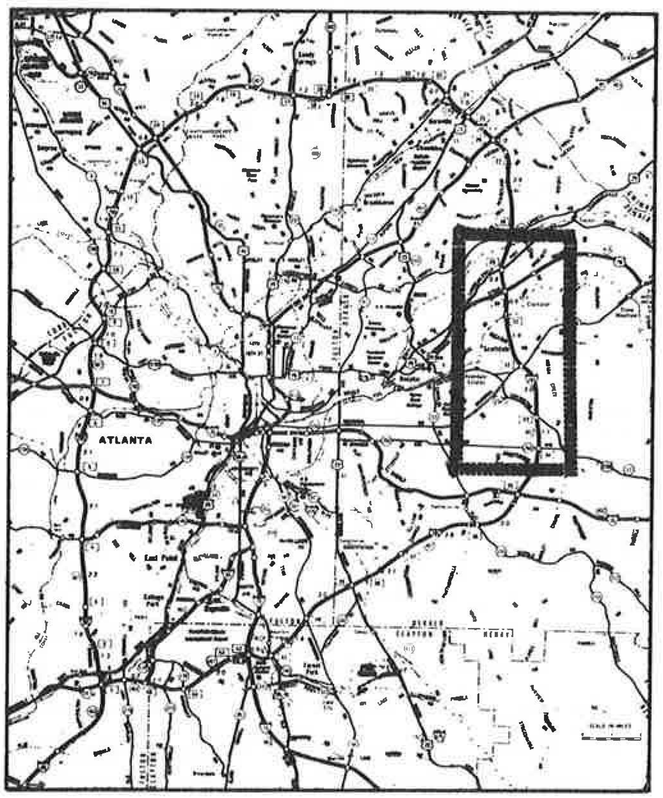
ROSWELL A. HARRIS

A study was conducted to compare the field insertion loss with the calculated insertion loss of four noise barriers along Interstate 285 in Atlanta, Georgia. Field insertion loss was determined in accordance with the latest guidelines promulgated by the Federal Highway Administration (FHWA). The calculated insertion loss was obtained through the use of STAMINA 1.0, the level-2 computer model based on the FHWA highway traffic noise prediction model. The study indicates a high level of confidence in the accuracy of the computer model. Also included are the results of a survey administered to the affected population behind each noise barrier. Results of this survey indicate general public support for a noise-abatement program and the need for more public involvement prior to the construction of a noise barrier.

Highway-generated noise and public reaction to it have become a real problem in recent years, especially in densely populated areas such as Atlanta, Georgia. The ever-growing central business district of Atlanta continues to attract growing volumes of commuter- and production-related traffic. In addition to this business-oriented traffic, thousands of interregional vehicle trips pass through and around the city annually. These high traffic volumes have led to increased noise levels in areas that abut most of the Interstate highway mileage in and around Atlanta.

In an effort to mitigate highway-traffic-induced noise impacts, the Georgia Department of Transportation has constructed noise barriers at selected locations along the Interstate highway system. Four of these barriers have recently been constructed along Interstate 285, east of Atlanta (see Figures 1 and 2). The intent of this paper is to compare the measured insertion loss with the insertion loss predicted by state-of-the-art computer modeling techniques. In addition, public reaction to this abatement effort is examined in order to determine whether support exists for an active noise-abatement program.

Figure 1. Project location.

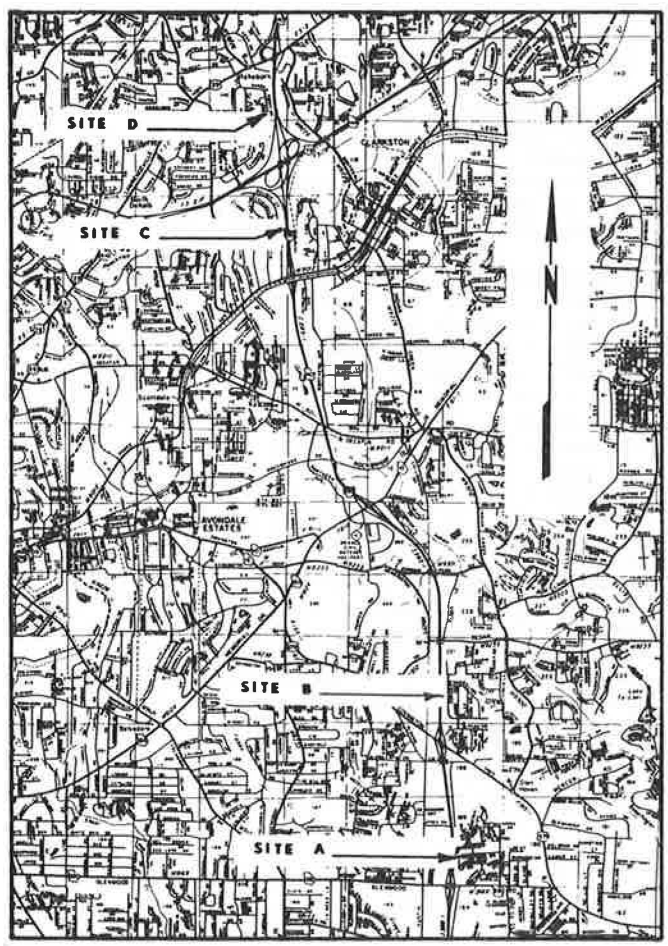


PROBLEM STATEMENT

Barrier acoustic design was accomplished through the use of STAMINA 1.0 (1), the level-2 computer model based on the Federal Highway Administration (FHWA) highway traffic noise prediction model (2). This model considers actual site geometry along with vehicle mix and operating characteristics and, through a series of adjustments to a reference energy-emission level, calculates the noise level at a receiver before and after the construction of a barrier. The difference in these two calculated noise levels is the predicted insertion loss.

Since these barriers were constructed on an existing highway, a set of before and after noise measurements was made at sites representative of

Figure 2. Site location.



each location. These sound levels were then used to calculate the field insertion loss for each barrier, which was then compared with the predicted insertion loss as determined by the computer model. An evaluation of the expected accuracy of STAMINA 1.0 is then presented.

The physical performance of a noise barrier in reducing traffic-generated noise is important, but the perceived effectiveness of the barrier by the people who live behind it is a more meaningful measure of the success of the abatement attempt. In the absence of any quantifiable data on citizen reaction to traffic noise before the barriers were constructed, only the results of a survey conducted after the barriers were completed will be included in this paper. Although a valid comparison of reaction to traffic-generated noise before and after construction of the noise barrier cannot be made with these data, useful conclusions can be drawn from it.

METHODOLOGY

Since construction of the barriers took a short amount of time, we could closely duplicate the ambient conditions during the before and after field measurements. On-site measurements of temperature, wind speed, and wind direction were recorded throughout the sample period on both occasions. Relative humidity was obtained from a local office of the National Oceanic and Atmospheric Administration. These data are presented in the table below. Meteorological conditions did not vary significantly enough to introduce an appreciable source of error in the measurements of noise level for this study.

Item	Before	After
Wind speed (mph)	1-7	1-9
Wind direction (north azimuth)	180	300
Temperature (°F)	60-62	80-85
Relative humidity (%)	71	89

Measurement of noise levels in this area during the 12 months prior to the beginning of this test indicated that average traffic flow conditions are consistent for the same day of week and the same time of day for similar seasons. Traffic flow conditions vary with time. However, past experience with this section of highway revealed that noise levels rarely varied by more than 2 dB at the same location and for the same sample period. For this study, all sample periods were 10 min. We therefore assumed that traffic count, mix, and speed would not change significantly in the short period of time between the before and after field measurements. Consequently, care was taken to make the field measurements on the same day of the week and same time of day. The time period between field measurements was short enough so as not to be influenced by seasonal variations in traffic flow.

Under this assumption, traffic flow conditions were measured only during the after set of noise level measurements; these data are presented in the table below and are incorporated into the STAMINA model for both the pre- and post-barrier conditions. Note that this assumption is not valid unless sufficient past experience indicates that little variation in measured noise levels exists for a given section of highway at the same location. All four barriers were geographically close enough so that the same traffic flow conditions were assumed to apply equally to each site.

Traffic	Vehicles per Hour	Speed (mph)
Automobiles	3980	53.8
Medium trucks	190	53.8
Heavy trucks	624	51.8

Field measurements of noise levels were conducted in a manner similar to procedures contained in the report, Determination of Noise Barrier Effectiveness (3). A reference microphone was established 50 ft from the centerline of the nearest travel lane at a point longitudinally beyond the end of the noise barrier for both sets of measurements. This microphone was used to detect any significant changes in the noise source that might have occurred between the two measurement dates. A second sound level meter (microphone 1) was placed in the backyard of a home determined to be typical of the topography in the neighborhood behind the noise wall. Simultaneous measurements were made at each location for both the before and after conditions. A Metrosonics dB-602 sound level analyzer was used as the reference microphone in all cases; a General Radio 1565-B sound level meter was used for the simultaneous measurement in all cases. Both meters were set up in accordance with the report, Sound Procedures for Measuring Highway Noise (4), and were calibrated before and after each measurement to ensure accuracy.

A survey questionnaire was constructed by using examples contained in the report, Proceedings of Conference on Highway Traffic Noise Mitigation (5). As mentioned previously, no suitable data are available to quantify citizen reaction to highway-traffic-generated noise before construction of the noise barriers. However, an attempt was made to determine how the affected citizens perceived the effort to mitigate their noise problem. The questionnaire was administered through a door-to-door survey to preselected homes identified from aerial photography. The areas were chosen with the intent of obtaining information on how perceived effectiveness differed between those people who live adjacent to the Interstate and those who live at greater distances from the facility. Interviews were conducted during late afternoon and evening hours to ensure that a maximum number of people could be reached.

FINDINGS

Field Insertion Loss

The field insertion loss was calculated in a manner similar to that recommended by Reagan and Hatzi (3). The Leq(h) measured at the reference microphone after the barrier was constructed was subtracted from the Leq(h) at the same location before the barrier was constructed. Mathematically, this is stated as

$$\Delta L = Leq(h)_B^R - Leq(h)_A^R \quad (1)$$

where $Leq(h)_B^R$ is the hourly Leq measured at the reference microphone before the barrier was constructed and $Leq(h)_A^R$ is the hourly Leq measured at the reference microphone after the barrier was constructed.

In cases where $|\Delta L|$ is 1 dB(A) or less, the field insertion loss (IL) is calculated according to Equation 2:

$$IL = Leq(h)_B^1 - Leq(h)_A^1 \quad (2)$$

where $Leq(h)_B^1$ is the hourly Leq measured at the location behind the noise barrier before the barrier is constructed and $Leq(h)_A^1$ is the hourly Leq measured at the same location after the barrier is constructed.

In cases where $1 < |\Delta L| \leq 3$ dB(A), field IL is calculated according to Equation 3:

$$IL = [Leq(h)^1_B - \Delta L] - Leq(h)^1_A \quad (3)$$

The field insertion loss for each site (refer to Figure 2) is presented in Table 1.

Calculated Insertion Loss

Calculated insertion loss is simply the difference in the calculated Leq(h) at the location behind the noise barrier before and after construction of the barrier. These data are also presented in Table 1.

Attitudinal Survey

The interviews were conducted by personnel from the

Table 1. Insertion loss.

	Before		After		Insertion Loss	
Site	Measured	Calculated	Measured	Calculated	Measured	Calculated
Reference microphone						
A	79	79	80	79	10	9
B	76	79	78	79	10	8
C	82	79	80	79	8	7
D	80	79	78	79	8	7
Microphone one						
A	71	73	61	64		
B	66	71	58	63		
C	70	70	60	63		
D	69	69	59	62		

Figure 3. Sample questionnaire.

I-285 NOISE BARRIER SUVEY

1) HOW LONG HAVE YOU LIVED AT THIS ADDRESS? ____ Years ____ Months

2) HOW OFTEN DO YOU USE I-285? ____ Trips Daily

TYPE OF TRIP: ____ Work ____ Shopping ____ Pleasure

3) PRIOR TO THE IMPROVEMENTS TO I-285, DID YOU NOTICE NOISE AS A PROBLEM IN THE FOLLOWING ACTIVITIES?

___ Conversation or TV
___ Work or Study
___ Sleep
___ Outside Activities
___ Other: ____________

4) AFTER THE IMPROVEMENTS, HAVE YOU EXPERIENCED ANY BENEFITS OF REDUCED TRAFFIC NOISE?

___ Conversation is easier
___ Improved Sleeping Conditions
___ More Relaxing Environment
___ Use Yard More
___ Other: ____________
___ None

5) HOW WOULD YOU DESCRIBE THE VISUAL EFFECTS OF THE NOISE BARRIER?

___ Enhances Facility Appearance
___ No Effect
___ Limits or Restricts View
___ Creates Closed-in Feeling
___ Visual Eyesore: Unsightly
___ Other: ____________

6) WHAT IMPROVEMENT ELEMENTS TO I-285 HAVE/WILL BENEFIT YOUR NEIGHBORHOOD?

___ Improved Riding Surface
___ Reduced Congestion
___ Improved Safety
___ Noise Barrier
___ Quieter or Reduced Noise Levels
___ Other: ____________

7) IF QUIETER RESPONSE WAS GIVEN, WHAT ATTRIBUTED TO THIS EFFECT?

___ Smoother Surface
___ Improved Operating Conditions (ie: Speeds and/or Congestion)
___ Noise Barrier
___ Other: ____________

8) IT HAS BEEN DETERMINED THAT NOISE BARRIERS COST $11,200 PER PROTECTED RESIDENCE. DO YOU THINK DOT WAS JUSTIFIED IN SPENDING THIS AMOUNT?

___ Yes ___ No ___ No Opinion

TO BE COMPLETED BY INTERVIEWER AFTER SURVEY:

SEX OF RESPONDENT: ___ Male ___ Female

RACE: ___ White ___ Non-White ___ Other

ESTIMATED AGE OF RESPONDENT:

___ 29 or under ___ 40 - 49 ___ 65 or older
___ 30 - 39 ___ 50 - 64

TYPE OF DWELLING: ___ Wood ___ Masonry

DESCRIBE ATTITUDE OF RESPONDENT: ___ Positive ___ Neutral ___ Negative

ADDRESS: ______________________________

Planning Data Services Section, Systems Usage Branch, Georgia Department of Transportation, and the results were tabulated in the final report (6). A total of 233 homes at the four sites (see Figure 2) were chosen to be surveyed. Of this total, 49 either were not at home or would not respond to the questions, which left a total response of 79 percent of the population of interest. The results of this survey are considered an accurate indication of the affected citizens' perception of the effectiveness of the noise barriers constructed for their community. A sample questionnaire is shown in Figure 3. The consensus of all four communities is presented in the following paragraphs.

The noise problem was perceived in a similar manner by residents who had lived in the area more than 10 years and those who had just moved in during the last few years. The average time of residence in the area was 6.6 years, which indicates that a number of people have willingly moved into an area that has high noise levels. Further analysis shows that 55 percent of the residents have lived there less than 10 years and 78 percent of these found noise to be a problem; 87 percent of those who lived there more than 10 years complained of a noise problem.

Nearly 50 percent of the respondents indicated that noise was a problem in conversation or sleep, 17 percent listed interference with work or study, and 33 percent said noise was a problem in outdoor activities. We also determined that 13.7 percent of the residents did not consider noise a problem.

Approximately 40 percent of the residents listed improved communication and sleeping conditions as a benefit of the noise wall. In addition, 44 percent found the environment more relaxing, and 37 percent said they used their yards more as a result of the noise wall. In describing the visual effects of the noise barriers, 65 percent of the respondents felt the barrier actually enhanced the appearance of the facility; only 10 percent felt they were detrimental.

An interesting item was that 32 percent of the residents thought that the reduced noise levels would benefit their community. However, almost 62 percent thought this would be a result of a smoother riding surface from the widening of I-285 and only 4 percent attributed the quieter environment to noise barriers.

By counting only those houses expected to experience noise levels in excess of 70 dB(A) (L10), we determined that the noise barriers cost $11 200/residence protected. More than 82 percent of the respondents thought this cost was justified and only 12 percent were not in favor of this expenditure.

CONCLUSIONS

The data in Table 1 show that the STAMINA 1.0 model provides an accurate means of calculating highway traffic-generated noise. In every case except at site B, the difference in field measured and calculated noise levels was no more than 3 dB(A). Site B consisted of hilly terrain that broke the line of sight between source and receiver. The terrain was modeled to illustrate this shortcoming of the STAMINA 1.0 program. In fact, all cases in which a barrier was inserted yielded calculated noise levels higher than measured noise levels. This is apparently due to the loss of excess attenuation provided by surrounding trees and shrubs, since STAMINA 1.0 ignores this factor when the line of sight is broken. However, the STAMINA 1.0 model is still an accurate tool when used with this deficiency in mind. It provides the user with conservative estimates of the expected insertion loss.

Results of the survey indicate public support for a noise-abatement program. Also apparent is that efforts are needed to educate the public on what noise barriers are and how they are expected to work. This could be accomplished through meetings with affected communities after it has been determined that noise abatement is feasible for a given location.

A distinct difference in the perceived noise problem between residents adjacent to the Interstate and those beyond the second row of houses from the Interstate was found at sites A and B. Site C displayed virtually no difference over the entire sample area and site D exhibited only a slight decrease in the perceived noise problem with increased distance from the source. This inconsistency is believed to be a result of inexperience in constructing and administering the survey as well as lack of public awareness of what the noise barriers were and why they were erected.

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Evaluation of Noise Barriers

RUDOLF W. HENDRIKS AND MAS HATANO

This study was performed to evaluate Federal Highway Administration (FHWA) noise prediction and barrier design model 77-108, used by the California Department of Transportation. Barrier costs and community attitudes to barriers were also studied. Nine microphones were positioned at various heights and distances behind the barrier location before and after the barrier was constructed. One microphone was positioned 5 ft above the barrier to serve as a control. Sound levels were measured before and after the barrier was constructed at seven locations. Two sets of measurements were obtained at four

locations where the barrier was already constructed: one measurement behind and one measurement adjacent to the barrier. Traffic was counted simultaneously during the measurement periods. The data indicate that the FHWA model predicts about 3 dB(A) higher than field-measured sound levels. However, current practice is to make field measurements and adjust the model where barriers are constructed on existing freeways. The barrier design part of the model predicts about 1 dB(A) higher than field-measured levels after the prediction part of the model is adjusted. Questionnaires were used to collect information on community attitudes toward barriers. The data indicate that the residences that received the most insertion loss from barriers were the most satisfied. Although most residents were satisfied with the barriers, many adverse comments were received from individuals who were concerned about view, aesthetics, and cost. Cost per residence per dB(A) ranged from $626 to $2085. Variables such as length, height, location of barrier, and other work such as landscaping and irrigation systems affected the cost.

Requirements for abating noise are covered in various state and federal laws. These are further detailed by regulations, policies, and practices developed by experience. Noise barriers are the primary means used by highway departments to mitigate noise.

Federal-Aid Highway Program Manual 7-7-3 (1) is the Federal Highway Administration (FHWA) document that covers the two major federal participating noise-abatement programs that the California Department of Transportation (Caltrans) is currently pursuing. These fall into type 1 (new or major reconstruction) and 2 (existing highway) categories and consist of constructing barriers in almost all cases. The procedure for designing barriers is covered in the FHWA Highway Traffic Noise Prediction Model (2).

Caltrans has constructed about 19 miles of noise barriers under the type 1 category program. No estimate is available for future barrier construction under this category; however, construction will probably continue to be significant.

Caltrans policy and procedure on freeway traffic noise reduction (no. P74-47, July 23, 1974) covers the retrofitting of noise barriers under the type 2 category projects. It was codified into law in 1979 and is in the California Streets and Highways Code Section 215.5. About 50 miles of barriers have been constructed to date under this category. More than 400 miles of barriers remain to be constructed under this program.

The need for a detailed study of current procedures for barrier design was recognized for several reasons. Limited feedback from the districts indicated good-to-poor correlation between design and actual field measurements. Design procedures specified by FHWA (2) are relatively new and were not officially adopted until January 1980 although they were published in December 1978. They had never been field validated in California. The most-important factor was the large inventory of barriers yet to be designed and constructed under the type 1 and 2 categories and the costs involved. Therefore, the primary objective of the study was to evaluate the FHWA procedure. Barriers that are underdesigned or overdesigned by an inaccurate procedure either provide inadequate protection or costs are unnecessarily high.

There were two secondary objectives:

1. To examine public reaction to noise barriers because of varied comments from residents who already had or were about to have barriers and
2. To evaluate costs for constructing barriers.

Because of a limited amount of suitable sites and barrier construction schedules that fall outside the study's time frame, only 11 barriers were selected (see table below). For the same reasons, barriers at sites 5, 8, 10, and 11 were existing barriers. Barrier and site geometries at the existing installations allowed satisfactory before-construction simulations by measuring noise levels on open areas adjacent to the barriers.

Site	Name	District	Route	Post Mile	Location
1	Chapman	4	17	15.8	San Jose
2	Dana	4	17	15.4	San Jose
3	Fruitridge	3	99	22.1	Sacramento
4	Glenbrook	3	50	5.3	Sacramento
5	Meadowview	3	5	16.2	Sacramento
6	Alhambra	7	10	23.6	Los Angeles
7	St. Jerome	7	405	24.4	Los Angeles
8	Manteca	10	99	7.9	Manteca
9	Marlesta	11	805	21.4	San Diego
10	Parkway	11	8	9.9	San Diego
11	Guasti	8	10	7.7	Guasti

The limited amount of suitable sites also narrowed the selection of available materials used in barriers. Only two basic materials could be studied: concrete walls (concrete block or precast concrete panels) and steel panels with concrete blocks. Community attitudes were not studied at each location because some barriers were already constructed, protected schools, or were surrounded by few residences. Cost evaluations were made for eight barriers. Costs for such things as landscaping and irrigation systems were not included.

INSTRUMENTATION AND TYPICAL SETUP

All sound level meters (SLM) used in this study met the requirements for type 1 precision SLM per American National Standards Institute SI.4 (1971). The SLM were connected to a data logger designed for this study. The data logger has the capability of processing the output signals from 16 SLM simultaneously in descriptors of Peak, L_{eq}, L_{10}, and L_{50}. It also prints a histogram and various statistical values.

Instrument calibrations were performed by the Caltrans Transportation Laboratory and are traceable to the National Bureau of Standards. In addition, calibrations were performed in the field before and after the measurement period. Figure 1 shows typical instrument setups at the individual sites, microphone numbering, and site layout. In some instances the typical layout was not feasible because of space limitations, equipment availability, or breakdowns. Cross sections for each site are shown in Figures 2 and 3.

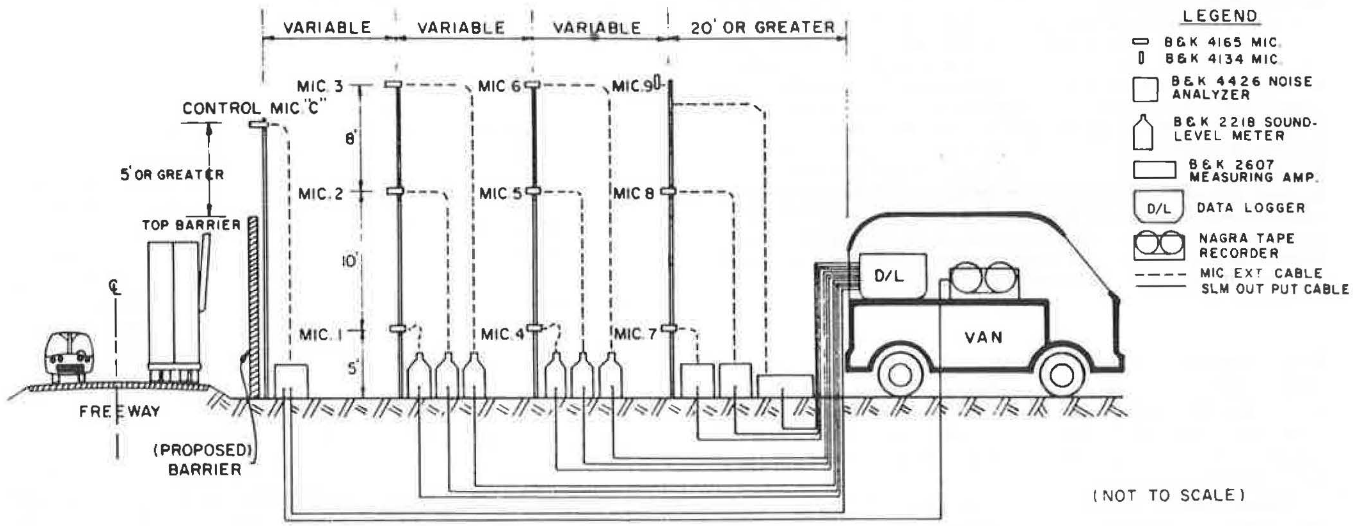
Sites 1, 2, and 6 had noise barriers on both sides of the highway. Calculations showed small [<1 dB(A)] noise contributions from reflections by the opposite barriers at these sites. A previous Caltrans study indicated that small changes due to reflected noise could be calculated but not measured in the field. No attempt was made, therefore, to measure the reflections from the opposite walls.

MEASUREMENT RESULTS

Sound level data are not normally reported in 0.1 dB(A) increments because this implies an accuracy that is beyond the capability of the instrument. However, the data are shown in this report to 0.1 dB(A) as printed out by the recorders. The results of the before- and after-barrier L_{eq} are summarized in Table 1.

The barrier field insertion losses (FIL) were calculated from before- and after-barrier measurements, by first normalizing before- and after-barrier data. In the normalization process, the difference between before- and after-noise levels of the control microphone were applied as a constant to

Figure 1. Typical instrument setup for noise barrier evaluation.



the noise levels of the remaining microphones of the same set.

At all measuring sites, noise levels were measured in terms of L_{eq} dB(A). Measurement periods lasted a minimum of 20 min/run, with two or more runs taken before and after barrier construction. Simultaneous measurements with 10 or fewer microphone locations of varying heights and distances from the highway traffic source provided spatial resolution. Control microphones mounted at least 5 ft above the proposed or finished barrier were used to normalize before- and after-barrier traffic noise. The noise levels measured at these control microphones were assumed to be unaffected by the barrier due to their height. Differences between before- and after-noise levels at the control microphones were therefore assumed to be caused by differences in traffic volumes, mix, or distribution.

During the L_{eq} measurements, traffic volumes were counted lane-by-lane and classified as automobiles, medium trucks, and heavy trucks. Traffic speeds were obtained by radar gun and by a car traveling with traffic. No measurements were made unless traffic was free flowing. Wind speeds were measured to ensure that no noise measurements were attempted during periods when wind speeds averaged more than 5 mph.

Noise Levels Versus Heights and Distances

In general, the data indicate an average increase in before-barrier noise levels with an increase in microphone height and an average decrease with distance (Table 1 and Figure 4). However, the increases and decreases are not uniform due to different distances from the source, terrain features, and hard or soft site. The same trends are illustrated for the after-barrier average noise levels as for the before condition. As expected, heights and distances affected after-barrier noise levels more than for the before condition, depending on whether they were in the clear or shadow zone.

Average FIL (before and after) showed the expected trend of the greatest noise level decrease at the close tower (5-ft height) and the least decrease at the 23-ft height. The trends are less clear at towers 2 and 3. A detailed examination of the data at the individual sites indicates some reversal of the expected trends. These seemed to occur at the sites that were in cut. A few microphones in the clear zone even showed a slight increase in normalized noise levels after barrier construction (sites 4, 8, and 11).

A specific reason for each anomaly is not known but could be due to things such as berm effect (cut section) and dropoff rates as a function of barrier, ground cover, height, and distances. These factors affect FIL.

Predicted Versus Measured Noise Levels

Predicted noise levels were determined by using the Caltrans computer program Sound 3, which is the same as the FHWA Stamina 1.0 program. Both programs are based on the FHWA noise prediction model (2). Table 2 shows the dropoff rate (hard and soft site) for each site and microphone height. The predicted noise levels before and after barrier construction are shown in Table 1.

Before Barrier

A plot of predicted versus measured noise levels for all sites and microphones before barrier construction is shown in Figure 5. In general, the predicted noise level averages 3 dB(A) higher than the measured levels at around 70 dB(A). A skewed regression line indicates predicted levels 4 dB(A) and 2 dB(A) higher than measured levels at 65 and 75 dB(A).

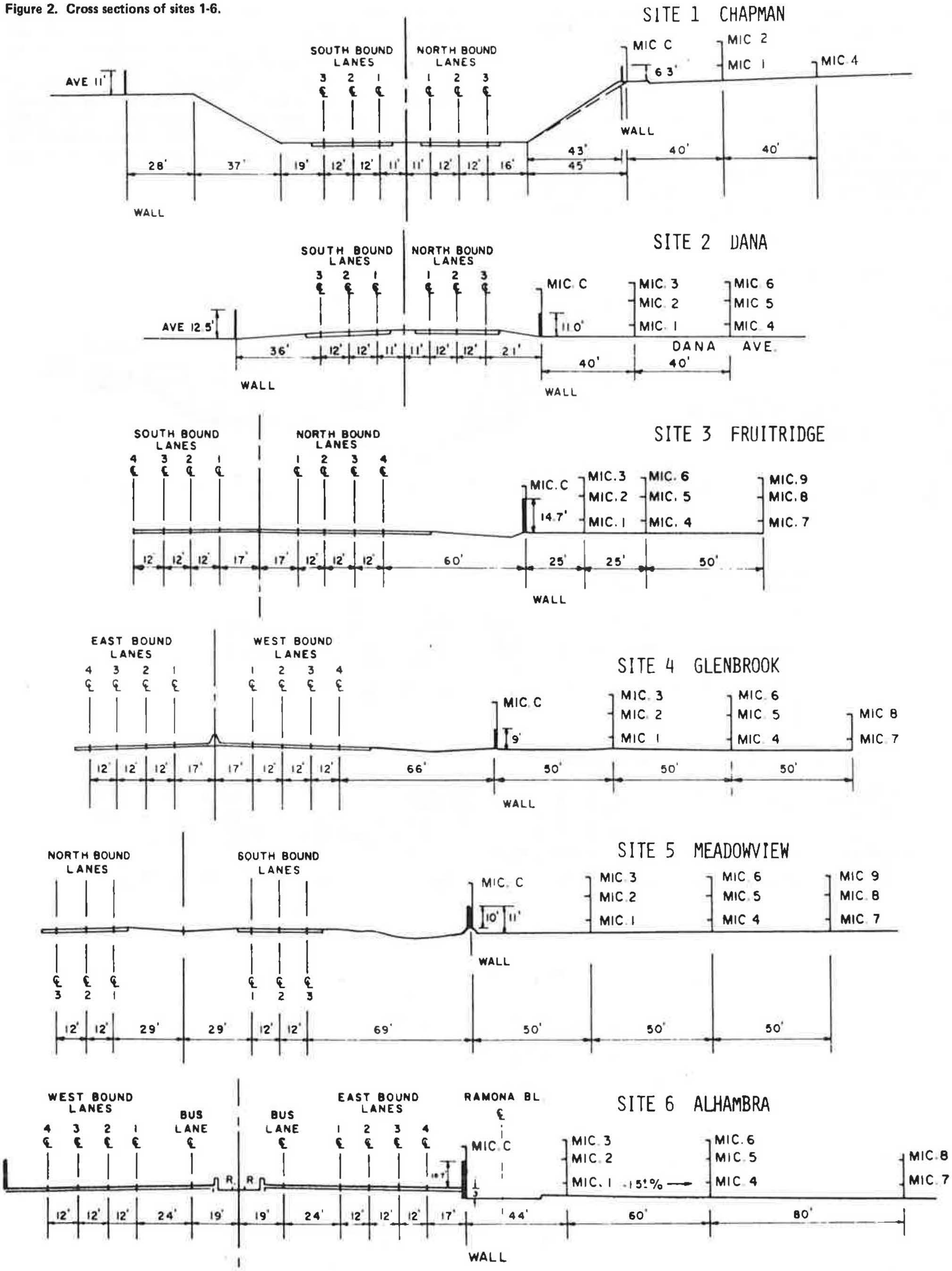
Figure 6 shows a plot of predicted versus measured noise levels for all sites at the low microphone location before barrier construction. This also shows an average 3 dB(A) higher predicted level and the regression line generally parallel to the balance line.

After Barrier

A plot of predicted versus measured noise levels for all sites and microphones after barrier construction is shown in Figure 7. In general, the predicted noise levels average 4 dB(A) higher than measured levels at around 65 dB(A). A skewed regression line indicates predicted levels 6 dB(A) and 3 dB(A) higher than measured levels at 60 and 70 dB(A).

Figure 8 shows a plot of predicted versus measured levels for all sites at the low microphone location after barrier construction. The predicted noise levels average 5 dB(A) higher than measured

Figure 2. Cross sections of sites 1-6.



levels at 62 dB(A). A skewed regression line indicates predicted levels 7 dB(A) and 1 dB(A) higher than measured levels at 57 dB(A) and 67 dB(A).

FIL

A plot of normalized predicted versus measured FIL for all sites and microphones is shown in Figure 9. The skewed regression line for the data indicates that predicted levels average 4 dB(A) as compared with measured levels of 5 dB(A). These levels vary depending on the magnitude of the insertion loss. A similar plot for all sites and low microphones (Figure 10) shows the same general trends for all sites and all microphones [average predicted FIL of 5 dB(A) and average measured FIL of 6 dB(A)].

Figure 11 shows a frequency distribution of predicted minus measured noise levels (deviations) before and after barrier construction. The FHWA model overpredicted before-barrier noise levels by an average of 2.9 dB(A) and after-barrier noise levels by 3.8 dB(A).

Figure 3. Cross sections of sites 7-11.

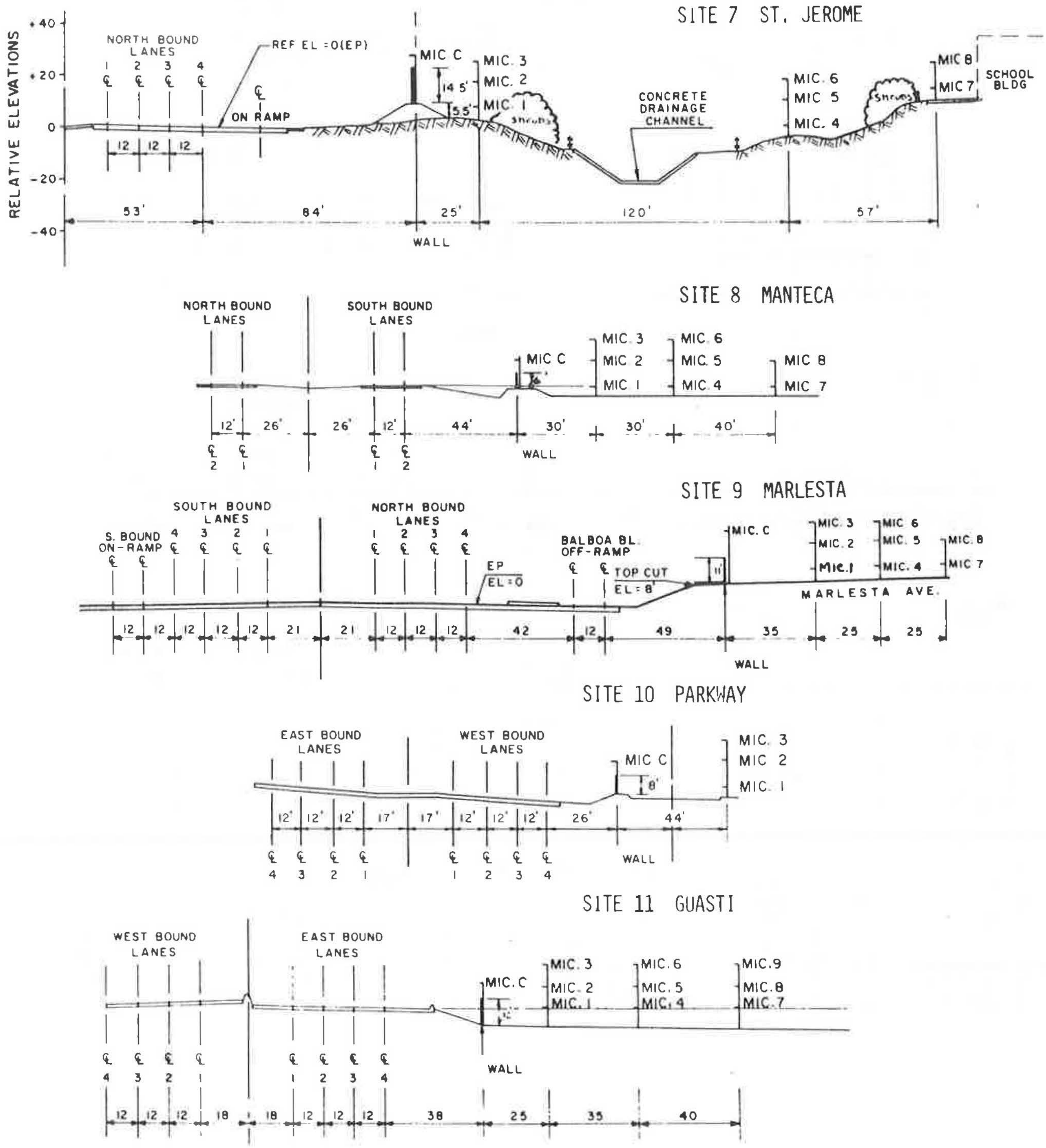


Table 1. Summary of measured, predicted, and field insertion loss.

Tower	Microphone	Sound Level [L_{eq} dB(A)]																							
		Site 1		Site 2		Site 3		Site 4		Site 5[a]		Site 6		Site 7		Site 8[a]		Site 9		Site 10[a]		Site 11[a]		Site X	
		Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted
Control	Before	78.4	78.4	80.4	81.5	77.1	78.9	78.8	77.8	75.3	76.0	83.0	83.8	78.9	80.0	75.2	77.7	75.9	74.8	80.4	79.6	78.9	79.8	78.4	79.0
	After	78.8	78.0	81.1	81.0	77.1	78.7	77.0	77.2	74.0	75.7	80.9	80.5	77.9	80.2	75.5	78.2	75.9	74.8	80.0	79.8	78.7	79.4	77.9	78.5
1	1																								
	Before	64.9	68.2	72.7	78.8	72.4	75.1	71.1	72.5	68.4	70.7	75.5	79.7	73.5	76.0	69.4	73.5	68.6	68.8	74.6	74.5	71.4	75.1	71.1	73.9
	After	62.5	65.5	66.4	70.0	61.2	64.3	62.5	68.2	56.7	65.6	64.3	67.1	61.1	62.5	61.8	69.7	62.9	63.1	66.6	68.7	64.0	70.8	62.7	66.9
	Field insertion loss	2.8	2.3	7.0	8.3	11.2	10.6	6.8	3.7	10.4	4.8	9.1	9.3	11.4	13.7	7.9	4.3	5.7	5.7	7.6	6.0	7.2	3.9	7.9	6.7
	2																								
	Before	68.2	75.6	75.1	78.8	75.4	77.8	76.0	75.7	71.3	73.9	78.3	80.5	76.7	79.1	72.1	75.9	73.3	73.3	76.9	76.7	73.9	77.7	74.3	76.8
	After	66.5	70.4	69.0	73.1	68.4	71.7	70.3	73.3	62.1	69.4	67.8	71.5	64.1	68.2	68.6	75.8	69.3	69.0	71.5	73.5	69.3	76.6	67.9	72.1
	Field insertion loss	2.1	4.8	6.8	5.2	7.0	5.9	3.9	1.8	7.9	4.2	8.4	5.7	11.6	11.1	3.8	0.6	4.0	4.3	5.0	3.4	4.4	0.7	5.9	4.2
	3																								
	Before			75.8	78.7	76.7	77.8	75.7	75.8	72.6	73.8	78.5	80.4	76.7	79.1	73.2	75.8	74.3	73.5	77.4	76.7	75.7	77.9	75.7	77.0
	After			73.9	76.6	74.9	77.2	75.8	75.2	68.8	73.5	72.7	74.7	72.1	74.0	73.7	76.4	74.0	73.3	74.6	75.7	76.1	77.5	73.7	75.4
	Field insertion loss			2.6	1.6	1.8	0.2	-1.9	0	2.5	0	3.7	2.4	3.6	5.3	-0.2	-0.1	0.3	0.2	2.4	1.2	-0.6	0	1.5	1.1
	4																								
	Before	63.3	64.8	71.2	76.3	71.7	73.7	69.3	70.2	65.2	68.6	69.4	76.1	63.7	68.6	68.6	71.6	67.2	66.9			69.3	72.3	67.9	70.9
	After	60.1	62.5	64.1	68.7	62.8	65.1	61.7	67.2	55.7	65.8	61.5	65.6	61.0	65.2	61.4	69.7	62.5	63.3			63.0	70.0	61.4	66.3
	Field insertion loss	3.6	1.9	7.8	7.1	8.9	8.4	5.8	2.4	8.2	2.5	5.8	7.2	1.7	3.6	7.5	2.4	4.7	3.6			6.1	1.9	6.0	4.1
2	5																								
	Before			72.0	76.3	74.4	76.9	72.1	74.1	69.5	72.3	71.0	77.2	67.8	72.3	70.9	74.6	73.1	72.3			71.0	75.6	71.3	74.7
	After			66.0	70.7	66.7	70.3	66.1	69.7	59.3	67.7	64.4	68.6	62.9	66.2	64.8	74.6	67.2	68.2			66.5	73.2	64.9	69.9
	Field insertion loss			6.7	5.1	7.7	6.5	4.2	3.8	8.9	4.3	4.5	5.3	3.9	6.3	6.4	0.5	5.9	4.1			4.3	2.0	5.9	4.3
	6																								
	Before			72.1	76.4	74.4	76.9	73.2	74.4	70.7	72.3	74.9	77.6	69.8	75.1	71.6	74.6	73.4	72.7			72.8	75.8	72.5	75.1
	After			68.6	72.5	71.5	73.9	69.5	73.0	62.9	70.9	67.5	70.6	63.6	67.4	69.1	75.0	72.1	71.7			70.7	75.0	68.4	72.2
	Field insertion loss			4.2	3.4	2.9	2.7	1.9	0.8	6.5	1.1	5.3	3.7	5.2	7.9	2.8	0.1	1.3	1.0			1.9	0.4	3.6	2.4
3	7																								
	Before					67.9	71.7	63.9	68.4	62.1	66.9	65.2	72.7	67.0	71.6	67.8	69.8	65.0	65.7			67.3	70.0	65.8	69.5
	After					62.5	65.1	60.0	66.3	55.0	65.6	59.2	63.9	61.8	66.0	62.3	68.9	61.4	63.1			62.0	69.0	60.5	65.6
	Field insertion loss					5.4	6.4	2.1	1.5	5.8	1.0	3.9	5.5	4.2	7.8	5.8	1.4	3.6	2.6			5.1	0.6	4.8	3.4
	8																								
	Before					71.2	75.5	69.5	72.7	67.4	71.0	67.3	73.9	70.0	73.9	68.5	73.3	71.4	71.0			68.4	73.9	69.2	73.2
	After					65.3	68.5	64.2	68.6	57.8	66.8	61.5	66.4	63.6	66.5	62.9	72.7	66.2	67.5			64.4	71.5	63.2	68.6
	Field insertion loss					5.9	6.8	3.5	3.5	8.3	3.9	3.7	4.2	5.4	7.6	5.9	1.1	5.2	3.5			3.8	2.0	5.5	4.1
	9																								
	Before					72.3	75.5			68.5	71.0											69.9	74.0	70.2	73.5
	After					67.2	70.3			60.3	68.5											67.2	73.5	64.9	70.8
	Field insertion loss					5.1	4.9			6.9	2.2											2.5	0.5	4.8	2.2

[a]Barriers already in place; before levels are simulated.

Summary and Comments

A detailed examination of the data from each site indicates that noise levels for the various conditions were affected by dropoff rates due to hard and soft sites, effect of barriers on soft sites, heights of microphones, and cut section (berm effect). As an example, depending on the magnitude of the ground effect and barrier attenuation, some high receivers far from the barrier may benefit from a greater FIL than will lower receivers at the same distance (Table 1). Other barriers showed a FIL

Figure 4. Average measured noise levels for various microphone heights and distances.

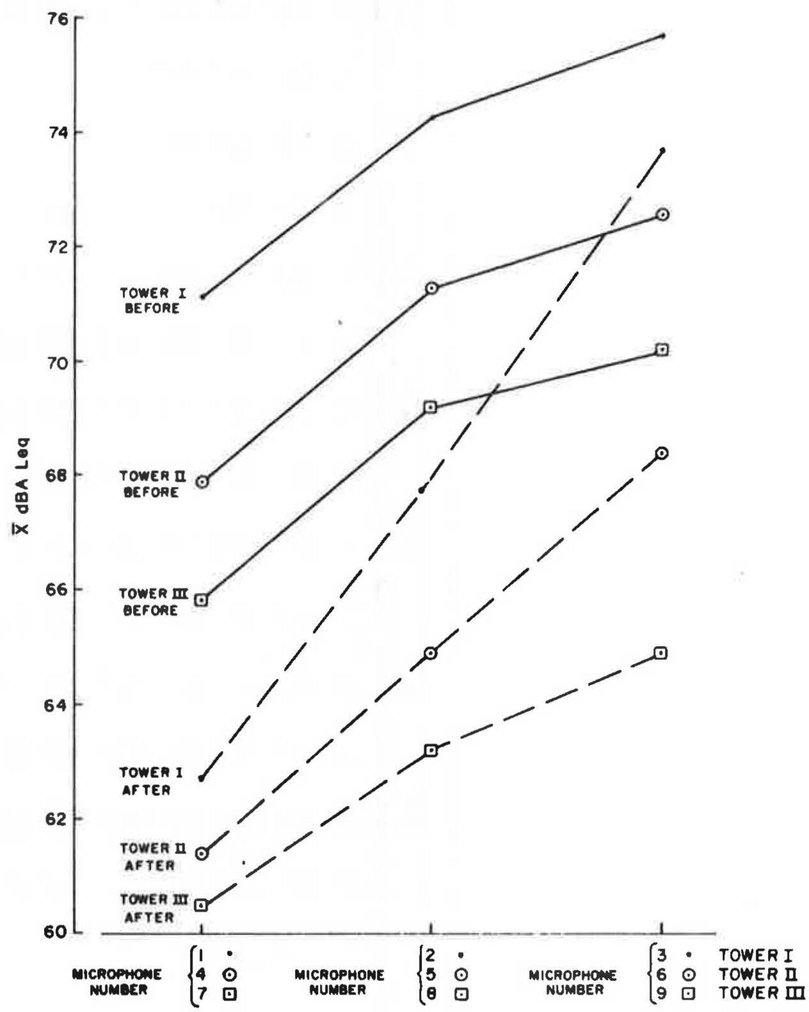


Table 2. Dropoff rates as distance is doubled.

Site	Dropoff Rate [dB(A)]								Comments
	Before				After				
	Control	Low	Middle	High	Control	Low	Middle	High	
1. Chapman	3	3	3	3	3	3	3	3	Soft site cut section
2. Dana	3	3	3	3	3	3	3	3	Hard site
3. Fruitridge	3	4.5	3	3	3	3	3	3	Soft site
4. Glenbrook	3	4.5	3	3	3	3	3	3	Soft site wall <10 ft
5. Meadowview	3	4.5	3	3	3	3	3	3	Soft site wall <10 ft
6. Alhambra	3	3	3	3	3	3	3	3	Hard site
7. St. Jerome	3	3[a]	3	3	3	3	3	3	Soft site before berm
8. Manteca	3	4.5	3	3	3	3	3	3	Soft site wall < 10 ft
9. Marlesta	3	3	3	3	3	3	3	3	Soft site before berm
10. Parkway	3	3	3	3	3	3	3	3	Hard site
11. Guasti	3	4.5	3	3	3	3	3	3	Soft site wall <10 ft

Note: SOUND 3 is Caltrans' version of STAMINA 1.0 computer program. All present computer programs default to a dropoff rate of 3 dB(A)/DD when barrier attenuation is encountered. This is different from FHWA Manual 77-108 (2), which recommends retaining soft-site dropoff rates (or alpha factors) for barriers less than 10 ft high.

[a]Used 4.5 dB(A) for microphone 1 at St. Jerome's before (did not receive attenuation from before berm).

Figure 5. Predicted versus measured dB(A) for all sites, all microphones, L_{eq}, before.

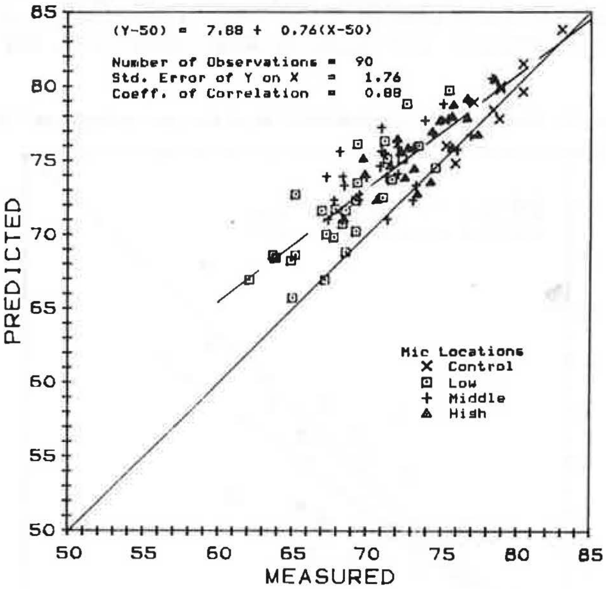


Figure 6. Predicted versus measured dB(A) for all sites, low microphones, L_{eq}, before.

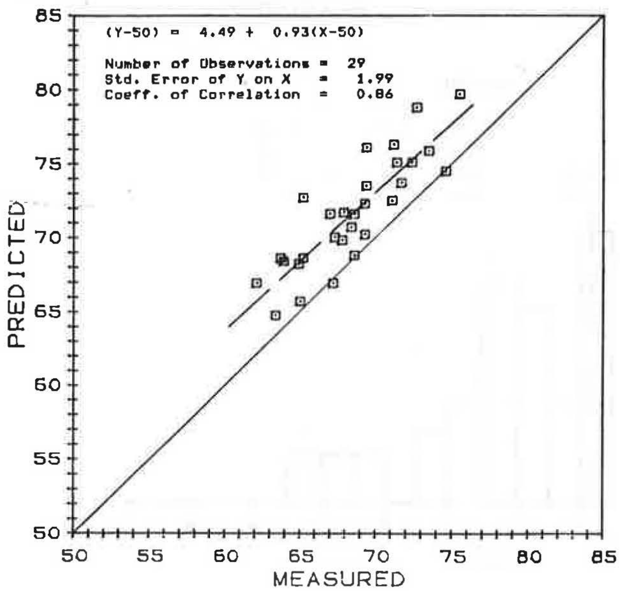


Figure 7. Predicted versus measured dB(A) for all sites, low microphones L_{eq}, after.

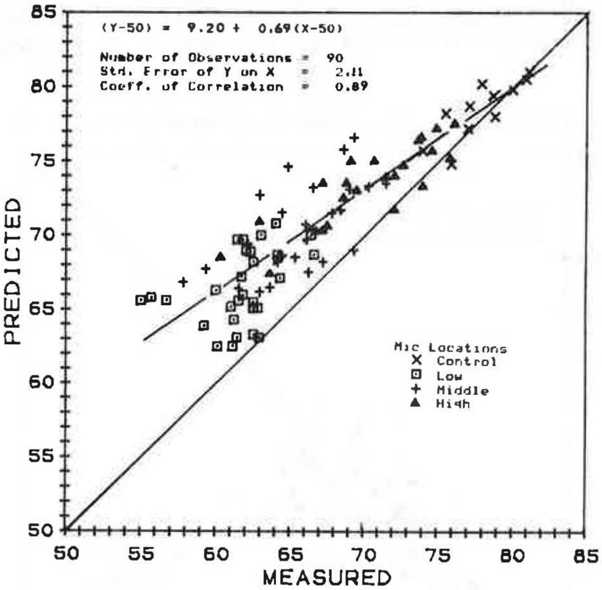
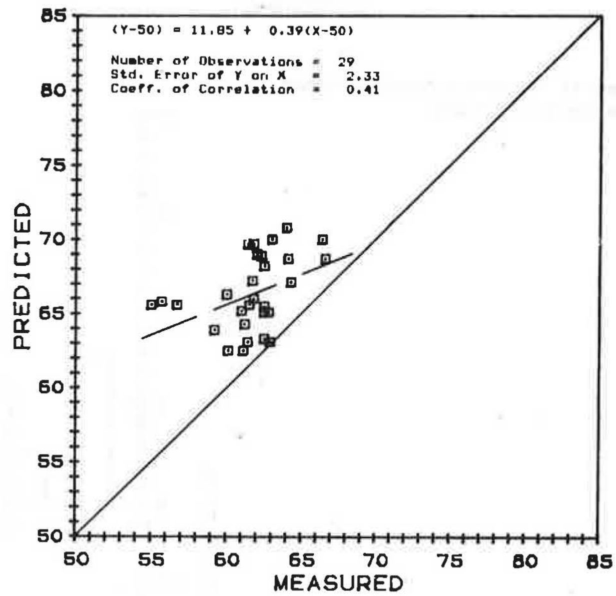


Figure 8. Predicted versus measured dB(A) for all sites, low microphones, L_{eq}, after.



less than 3 dB(A), which is not effective from either a cost or acoustic standpoint.

The tendency is for all calculated regression lines between measured and predicted noise levels to be skewed with the least difference at the higher levels. An estimated regression line parallel to the 45° line may be more illustrative of the difference between measured and predicted levels. However, all the data indicate that the predicted levels are higher than measured levels, regardless of how the regression line is drawn.

COMMUNITY ATTITUDES

Community acceptance of barriers was also evaluated. Some dissatisfactions were expressed by residents before and after a barrier had been built. The extent of this problem was to be defined. Three major issues were to be evaluated:

1. Barrier acceptance,
2. Change in attitude toward the barrier before and after construction, and
3. Perceived versus measured noise response.

Evaluation of community acceptance of barriers was accomplished by using a questionnaire mailed to residents in the first three and four rows of houses behind the wall. The questionnaire was mailed before and after construction of the barrier. The weaknesses of mailed questionnaires were recognized, but they were considered the most cost-effective way to gather this information.

At several locations in the community behind the barriers, noise measurements were taken 5 ft above the ground in terms of 20 min L_{eq} dB(A) to characterize ambient noise levels before and after the barrier. These were averaged with the barrier performance measurements and were useful in placing the first three or four rows of residences near each site in the following noise reduction categories: <3, 3-5, and 6-9 dB(A) (Table 3). Responses to questions concerning perceived noise reduction could then be compared with measured noise reductions. For

Figure 9. Predicted versus measured dB(A) for all sites, all microphones, FIL.

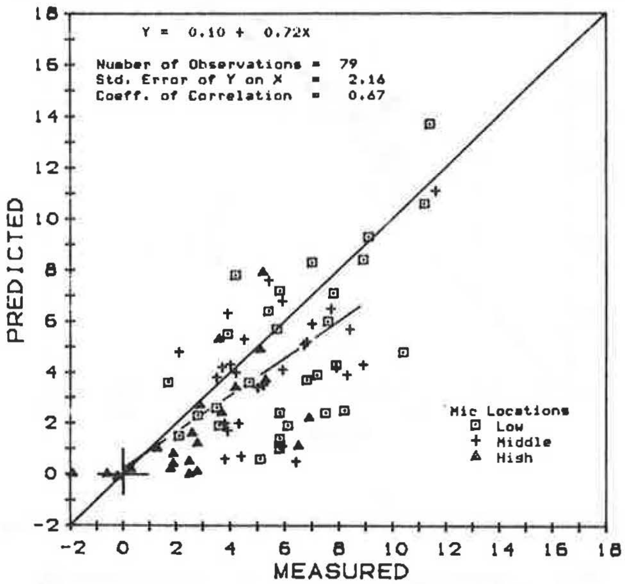


Figure 10. Predicted versus measured dB(A) for all sites, low microphones, FIL.

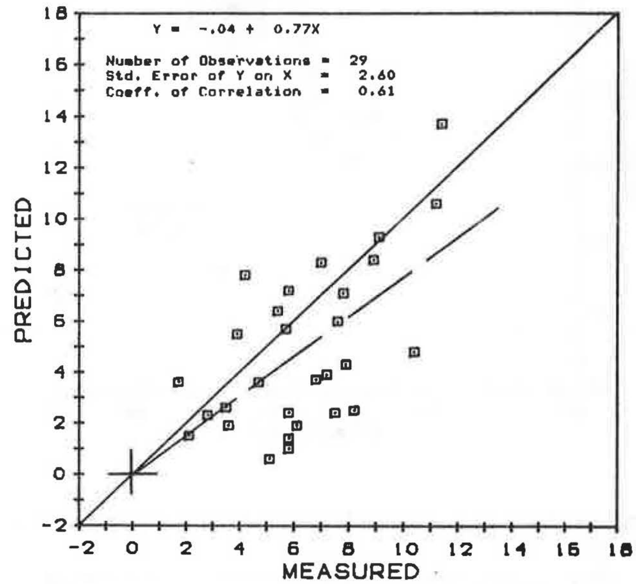


Figure 11. Frequency distribution of FHWA model deviation before and after.

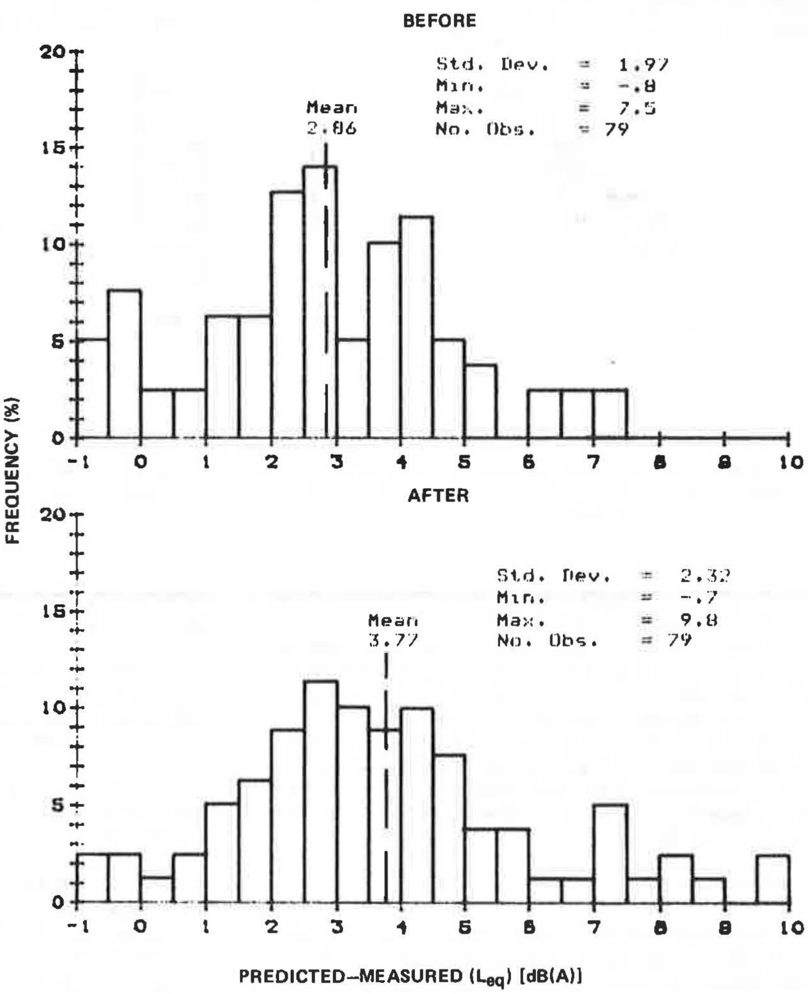


Table 3. Average noise reduction.

Site	Row	Measured Noise Reduction [dB(A)]	Site	Row	Measured Noise Reduction [dB(A)]
1	1	<3	3	2	3-5
	2	<3		3	<3
	3	<3		4	<3
2	1	6-9	6	1	6-9
	2	3-5		2	6-9
	3	<3		3	3-5
3	1	6-9		4	<3

Table 4. Community response to questionnaire.

Site	Questionnaire Response (%) Row 1	Row 2	Row 3	Row 4	Total No.	Total Percent
1 and 2					438	
Before	61	55	58		256	58
After	80	56	65		299	68
3					46	
Before	50	50	44	41	21	46
After	53	33	70	56	23	53
6					110	
Before	39	14	24	40	35	32
After	41	41	35	27	42	38

Table 5. Significance of difference between numbers of before and after responses.

Survey Area	Barrier Stage	No. Responded	No. Not Responded	Calculated Chi²[a]	Chi²[b]	Reject	Significant
Row							
1	Before	144	116	10.83	3.841	Yes	Yes
	After	180	78				
2	Before	91	93	7.97	3.841	Yes	Yes
	After	117	64				
3 and 4	Before	77	73	0.98	3.841	No	No
	After	86	63				
Site							
1 and 2	Before	256	182	8.67	3.841	Yes	Yes
	After	299	139				
3	Before	21	25	0.28	3.841	No	No
	After	23	20				
6	Before	35	75	0.72	3.841	No	No
	After	42	68				

[a]df = 1. [b]df = 0.05.

Table 6. Acceptance of barrier appearance.

Question	Response by Row (%) 1 (n = 180)	2 (n = 98)	3 and 4 (n = 87)	Total (n = 365)
Barrier appearance				
Very acceptable	51	46	56	51
OK	37	43	33	38
No	12	11	11	11
Overall barrier acceptance				
Like	73	64	65	69
Dislike	9	9	11	9
Neutral	18	27	24	22

Table 7. Overall barrier acceptance.

Question	Response by Site (%) 1 and 2 (n = 306)	3 (n = 23)	6 (n = 42)	Total (n = 371)
Barrier appearance				
Very acceptable	50	65	52	51
OK	38	26	43	38
No	12	9	5	11
Overall barrier acceptance				
Like	67	83	75	69
Dislike	10	4	10	10
Neutral	23	13	15	21

Table 8. Attitude change—advantage versus disadvantage.

Survey Area	Advantages Outweigh Disadvantages: Yes (%) Before	Yes (%) After	No (%) Before	No (%) After	No. of Respondents Before	No. of Respondents After
Row						
1	85	84	15	16	125	172
2	82	79	18	21	60	94
3 and 4	86	72	14	28	59	75
Site						
1 and 2	85	80	15	20	194	279
3	89	77	11	23	18	22
6	78	85	22	15	32	40

this purpose the San Jose barrier location was separated into barriers represented by site 1 (Chapman) and site 2 (Dana).

Responses

Table 4 summarizes the number and percentage of questionnaires mailed and returned, before and after construction of the barrier.

Chi-square tests were performed to detect any significant differences between two variables. A chi-square test determines the probability that any difference between observed sample data and expected data could have occurred by chance. It can be implied that there is a significant difference between the two variables if the chi-square value exceeds a certain critical value at a selected confidence level. A 95 percent confidence level ($\chi^2 = 0.05$) was used for this report.

The chi-square test on before versus after responses indicated that, within row 1 and row 2 (all sites combined), responses increased significantly after the barriers were constructed. There was no significant difference in rows 3 and 4. The calculated chi-squares were highest in row 1 and lowest in rows 3 and 4. This demonstrated that interest in responding to the questionnaire declined as the distance from residences to barrier increased.

An analysis of all rows combined by site indi-

Table 9. Overall attitude change.

Survey Area	Like (%) Before	Like (%) After	Dislike (%) Before	Dislike (%) After	Neutral (%) Before	Neutral (%) After	No. of Respondents Before	No. of Respondents After
Row								
1	79	73	5	9	16	18	136	180
2	72	64	8	9	20	27	89	97
3 and 4	61	65	8	11	31	24	77	86
Site								
1 and 2	71	67	8	10	21	23	249	299
3	79	83	0	4	21	13	19	23
6	82	75	3	10	15	15	34	41

Table 10. Cost-effectiveness of Caltrans barriers.

Barrier Sites	Length (ft)	First Row Frontage Units	FIL [L_{eq} dB(A)]	Cost ($) Total (000s)	Explicit (000s)	Per Linear Foot	Per dB(A)[a]	Per FRU.dB(A)[a]
1 and 2	11 456	190	6	2063	1120	180		982
3	2 650	17	9	477	319	180		2085
6	17 318	207	9	2840	1167	164		626
7	1 280	School	5	291	258	227	51 600	
9	870	15	5	134	102	154		1360
10	768	4	8	78	60	102		1875
11	385	School	7	57	45	148	6 428	

[a]Explicit cost only.

cated a significant increase in after-barrier responses (sites 1 and 2) and no significant difference at sites 3 and 6. The results of the latter two sites may have been caused by insufficient data. Table 5 summarizes the calculated and critical chi-squares, degrees of freedom, and significance used to arrive at the above conclusions.

Analysis and Discussions

The results of the questionnaires were also tested statistically for significance by using the chi-square test with 95 percent confidence level. However, the results may not represent the views of all the residents who live in the first three or four rows behind the barriers. The results represent only the views of the residents who responded. Evaluation was performed by combining all sites by row and all rows by site. The data are shown on tables for various cases and conclusions are drawn on the basis of the chi-square analysis.

Barrier Acceptance

Table 6 shows data about the appearance of the barrier and its overall acceptance by row. Table 7 gives the same data by site. An overwhelming number of respondents by row (89 percent) and site (91 percent) thought that the barrier appearance was OK or very acceptable (combined). The percentages of acceptance by row (67 percent) and site (75 percent) were also high. Neither table showed significant differences in response between rows or between sites.

The table below gives data relating to barrier acceptance versus measured noise reduction. The data indicate a significant difference in response among residents in the three categories. The respondents' overall feeling toward the barrier was governed by the amount of noise reduction.

Measured Noise Reduction [dB(A)]	Response (%) Like	Dislike	Neutral
6-9 (n = 178)	75	7	18
3-5 (n = 84)	68	6	26
<3 (n = 101)	58	16	26

The table below gives data that relate barrier acceptance and neighborhood improvement. Residents were asked, "Has the barrier met your expectations in improving your neighborhood?"

Survey Area	Response (%) Yes	No	Undecided
Row			
1 (n = 182)	58	26	16
2 (n = 86)	58	27	15
3 and 4 (n = 86)	64	15	21
Total (n = 354)	60	23	17
Site			
1 and 2 (n = 289)	56	26	18
3 (n = 23)	83	13	4
6 (n = 42)	74	12	14
Total (n = 354)	60	23	17

The responses showed no significant difference among rows, although a higher percentage of respondents in rows 3 and 4 thought that the barrier improved the neighborhood. Responses by sites showed a significant difference; those at sites 3 and 6 showed the highest favorable response.

Attitude Change

Table 8 shows the response to the question, "Do the advantages of the barrier outweigh the disadvantages?" Both the before and after respondents by row and site overwhelmingly considered the barriers to be an advantage. However, note that, in every case, the number of respondents after the barrier was greater than the number before the barrier was constructed.

Table 9 shows the response to the question, "How do you feel about the barrier overall?" The percentages were generally lower than for Table 8 but showed the same favorable opinion of barriers before and after construction. Again, the number of respondents after barrier construction increased.

Measured Versus Perceived Noise Reduction

The table below gives data related to measured versus perceived noise levels before and after barrier construction. The respondents indicated a substantial quieting of the neighborhood in the 6-9 and 3-5 dB(A) categories. There was also a 14 percent increase in the <3 dB(A) category, but it was not statistically significant.

Measured Noise Reduction [dB(A)]	Opinion of Neighborhood Noise (%): Little Noisy to Very Quiet	Noisy to Very Noisy	No. of Respondents
6-9			
Before	27	73	126
After	73	27	185
3-5			
Before	59	41	69
After	77	23	71
<3			
Before	65	35	84
After	79	21	103

A significant difference can be seen in the before and after responses in the 6-9 dB(A) and 3-5 dB(A) but not in the <3 dB(A) categories. There is a significant difference in the before and after change in responses among the three categories.

BARRIER COST-EFFECTIVENESS

The emphasis on reducing highway construction costs on state and federal levels has always been a consideration but has increased steadily under pressure of inflation and reduced revenues. The greatest challenge in noise barrier design lies in providing acoustically and aesthetically adequate noise barriers for the least cost. Before the cost-effectiveness of the Caltrans barriers could be analyzed, we needed to define the effectiveness of each barrier and the associated barrier costs.

Barrier effectiveness was defined by the amount of FIL in L_{eq}, dB(A), at the sites in this study. The FILs measured by the low microphone located at representative distances to the first row of houses were multiplied by the number of first-row residences to get an indication of barrier effectiveness.

A special problem occurred when the first row behind the barrier included apartments or commercial property. In this case, the frontage length of the property was equated to the number of frontage lengths of adjacent single-family homes. Thus, the affected property was assigned an equivalent number of frontage units. (One single-family residence is one frontage unit or FRU.) The unit for effectiveness was therefore FRU dB(A); [i.e., a barrier that protects 20 first row FRUs that has a FIL of 10 dB(A) would have an effectiveness of 200 FRU dB(A)].

This method of defining barrier effectiveness implies that the only benefits from barriers are acoustical benefits and the first-row residences are the only recipients of the barriers' benefits. In reality, the barrier benefits are more complex. The findings on community acceptance clearly indicate that benefits of barriers should not only be measured by acoustical effects but also by nonacoustical effects such as aesthetics, physical and visual separation from freeway, safety, and air pollution. Some of these nonacoustical effects may enhance the acoustical benefits; others may partly or entirely offset them. Ideally, the net total of acoustical and nonacoustical benefits should be studied in a cost-effectiveness analysis. Unfortunately, the nonacoustical effects are mainly subjective perceptions and cannot be readily quantified. For this reason, only acoustical benefits were considered.

Assigning all benefits to the first row was another simplification. Although the greatest impact of the barrier is perceived at the first row, the second and possibly third row also enjoy some FIL. There is, however, a greater variation of impacts in these rows, depending on the amount of shielding by first row residences. An assessment of the noise attenuation value for rows two or three would be difficult. Therefore, all benefits were assessed at row one, which results in a lower benefit than actually achieved.

The term explicit cost was used to determine the acoustical cost-effectiveness for first-row frontage units. Explicit cost is only for barrier cost and does not include items such as landscaping and irrigation systems.

Table 10 presents the results of the analysis. Barrier sites 7 and 11 were school noise projects. For these, only the explicit cost per dB(A) noise reduction in terms of L_{eq} were determined. The remaining barriers were compared in terms of cost per FRU dB(A) [explicit cost divided by number of FRU dB(A)]. Also presented are the total costs per linear foot. The Caltrans barriers evaluated in this report ranged from $626 to $2085/residence dB(A).

The large variations in costs and cost-effectiveness were due to the site geometry, barrier length and location, and community layout. Barriers that protect few homes are obviously less cost effective (i.e., sites 3, 9, and 10). Long barriers that protect many homes are more cost effective (i.e., sites 1, 2, and 6).

Caltrans District 7 in Los Angeles reported the cost-effectiveness of 12 barrier projects in terms of cost per residence dB(A) and cost per person dB(A) based on 2.6 persons/residence. The cost per residence dB(A) ranged from $675 to $2290 and showed general agreement with the results from this study. According to the District 7 study, a major factor that affects the cost of noise barriers is the location. In general, noise barriers located on the freeway shoulder were more expensive than those on the right-of-way line. The cost differential (approximately $40/linear foot) was due to additional requirements for barriers constructed at the edge of shoulder, including concrete safety barriers; maintenance access gates or overlapping openings; and revisions to existing signs, light standards, guardrails, utilities, landscaping irrigation, and traffic control.

Other major factors concerning the costs of barriers in general are accessibility to the work site, irregular terrain, and, of course, the height of the barrier.

CONCLUSIONS

The FHWA procedure (2) for predicting noise levels is satisfactory when traffic noise levels can be validated in the field. These conditions occur when field noise measurements can be made on traffic that currently uses the facility. Adjustments are made to the model in these cases. All type 1 and many type 2 projects fall under this category. This procedure predicted noise levels about 3 dB(A) higher than field-measured levels for a before-barrier condition at a microphone height of 5 ft and noise level around 70 dB(A). It is slightly higher and lower than 3 dB(A) at noise levels below and above 70 dB(A). Similar trends were noted for microphone heights of 15 and 23 ft. No adjustments to the model can be made on new alignments because no traffic noise can be measured. This can result in over-design of barrier height by around 5 ft.

The FHWA procedure predicted noise levels about 4 dB(A) higher than field-measured levels for an after-barrier condition at a microphone height of 5 ft and noise levels around 61 dB(A). Other variables showed similar trends as for the before-barrier conclusion. The net result is about 1 dB(A) more insertion loss after barrier construction if the model can be field-validated before barrier construction.

Responses to questionnaires indicated general satisfaction with barriers. Residents in the second and third row of houses next to the freeways were generally not affected by traffic noise. Some individuals did not want walls or were not satisfied for various reasons. The overall feeling of the residents appeared to be governed by the amount of noise reduction provided by the barrier. Many individual comments were received by persons concerned about things such as view, aesthetics, and cost.

Total cost of barriers per house per dB(A) ranged up to $3115; explicit barrier costs were up to $2085. The maximum cost per linear foot was $227.

ACKNOWLEDGMENT

This study was performed in cooperation with FHWA. The contents of this report reflect our views and we are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of FHWA or Caltrans and do not constitute a standard specification or regulation. A copy of the detailed report for this study is available from Caltrans.

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Transparent Noise Barriers Along I-95 in Baltimore City, Maryland

ROBERT D. DOUGLASS AND JEFFREY K. DRINKWATER

The Archbishop Keough Noise Barrier Project is classified as a category 2 experimental project by the Federal Highway Administration because of the barrier material (Lexan) used in the project. Lexan, a clear plastic panel system, has never been used as a noise-abatement measure in this area and its inclusion in this project provides cost and performance information for future project comparisons. Lexan was chosen for this project because of its effectiveness in attenuating highway noise levels while at the same time not interfering with the natural, scenic vista from a highway. It was incorporated into the system of noise barriers along Interstate 95 and protects Archbishop Keough High School from elevated noise levels due to the highway. The Keough noise barrier consists of 58 transparent panels, each 10 ft high by 0.25 in thick, supported at a 7.5-ft on-center width. The panels are held in place by steel posts that are attached to a concrete footing that runs the entire 435-ft length of the project. The project was built at a cost of $151 770. The cost of the barrier itself was $87 000. Delays in the delivery of materials and our underestimation in the number of working days were not totally unexpected due to the experimental nature of the project.

In 1968 a multidisciplinary concept team was assembled in Baltimore City, Maryland, to study its future transportation needs and problems and to recommend solutions. Environmental and aesthetic concerns were carefully evaluated by the teams of architects, engineers, and urban planners. Early in the process the need for transparent noise barriers on elevated highway sections was identified. Two benefits were attributed to transparent barriers over their opaque counterparts. The first, and most obvious, reason is that the motorists' vista and sunlight penetration to the roadway and ground are not blocked. The second benefit is that the highway and barrier would look much less imposing with a transparent barrier when viewed from the ground. On one preliminary expressway plan prepared for Interstate 83, a transparent noise barrier was shown in the area of the Canton and Fells Point communities. Even though this roadway alternative was rejected, the benefits and desire for transparent barriers remained.

As plans for I-95 progressed, the requests for transparent noise barriers on elevated expressways continued. The Interstate division staff made repeated inquiries for information on transparent barriers but were unable to find similar projects. Transparent barriers were not considered for I-95 due to unanswered questions such as,

1. Are the transparent materials available suitable for noise barriers?
2. How can they be supported?
3. How much will they cost?
4. Are there maintenance problems?
5. How will the material hold up in urban environments?
6. Will they increase reflections of sun and headlights?
7. Will they work from an acoustical standpoint?

Since our inquiries did not produce any similar projects, but we felt that the concept of transparent noise barriers was valid, we decided to look for a test project site.

THE PROJECT

The Archbishop Keough High School was identified as a potential noise-mitigation site because of elevated noise levels due to increasing traffic on I-95. Concerned school officials prompted a noise study by the Interstate division for Baltimore City. The study did, indeed, identify a noise problem once I-95 was fully opened. It was decided that, because of the pleasing vista of the school property from the highway and the limited length of barrier needed to protect the school, this project provided an ideal situation in which to implement a transparent barrier.

The Maryland Division of the Federal Highway Administration (FHWA) agreed and approved the project as a type 2 experimental project. FHWA funding participation on this project totaled 90 percent; Baltimore City contributed the local share of 10 percent.

Once the site was selected, the Interstate division for Baltimore City proceeded to search for a suitable transparent material that was applicable to a barrier situation. After considerable research, Lexan, a polycarbonate material supplied by the Fanwall Corporation, was selected. Considerations that entered into the selection of Lexan were cost, shatterability, wearing characteristics, aesthetics, and maintenance. Lexan compared favorably in all these areas with its glass and plastic counterparts.

The acoustic properties needed for the Lexan barrier were evolved for the Fanwall Corporation as a panel mass law study by the acoustic engineers, Bolt, Beranek, and Newman (1). This study determined the minimum thickness of material necessary to achieve the desired transmission loss of a 10dB minimum. Because of the relatively high cost of plastic materials as compared with typical construction material, (for example, plastic-concrete cost ratio = 100/1) it was imperative to avoid costly over-design. Bolt, Beranek, and Newman concluded that 0.25-in thickness of Lexan material would achieve the desired transmission loss.

Additional product testing included wind loading and shatterability. In shatterability testing, samples of the polycarbon sheets were subjected to pellet guns, 0.22 longs, and 0.38 police missiles. There was no shattering in any of the tests and only 0.22 longs penetrated and left tiny holes of inconsequential acoustic concern. Simulated wind load testing was performed by Arnold Greene Testing Laboratories, Inc. Tests showed that the panels withstood a loading of 170 lb/ft² with no failure or pull out from the posts. A loading of 170 lb/ft² is roughly equivalent to a wind velocity of 258 mph.

Design on the Archbishop Keough Transparent Acoustical Barrier Project was carried out by the Interstate division for Baltimore City. The final plans consist of 58 Lexan panels, each 10 ft high and 7.5 ft wide. Width of each panel was dictated by the maximum panel width available, which was 8 ft. The thickness of each panel as called for in the plans is the recommended 0.25 in. The panels are held in place by 6 W 16 steel posts and 3/16-in bent plate zee bar panel retainers (see Figure 1). The panel ends are curved to partly wrap around a 1-in diameter closed cell urethane rod. The zee bar is attached to the steel post by a 3/8-in bolt and nut (see Figure 1).

Each post has a baseplate that is attached to a 20x20-in concrete pedestal by four 3/4-in anchor bolts. Each pedestal is attached to a concrete footing that runs the 435-ft length of the project. Fifty-one railroad ties were used for cribbing on the rear slope of the project. Select backfill was used around each pedestal between the existing Jersey barrier and the cribbing (see Figure 2). Crusher run (CR-6) was then used over the backfill as a base for the top layer of asphalt (see Figure 2).

Approximately 2 in of asphalt was placed over the CR-6 and the 2:1 slope was maintained. Due to the low melting point of the Lexan panels (275° F), the hot asphalt could not be allowed to contact the panels directly. This resulted in a 0.5- to 2-in gap between the panel and the asphalt. At this time, several highway joint sealers are being tested to fill this gap.

In early 1980 a local contractor, Highways Incorporated, was awarded the contract for the Keough transparent barrier for the low bid of $151 770.40. This bid included (a) all excavation to construct footings and pedestal for acoustical barrier, (b) furnishing and placing all concrete required for constructing the footings and pedestal, (c) fabrication and erection of the barrier, and (d) final grading. The Fanwall Corporation, the material supplier for Highways Incorporated, was responsible for producing the transparent barrier.

EVALUATION

The Archbishop Keough Noise Barrier Project is classed as a category 2 experimental project by FHWA because of the barrier material (Lexan) used in the project. Since Lexan had never been used as a noise-abatement measure in this area, its inclusion in this project provided cost and performance information for future project comparisons.

FHWA funding participation on this project totaled 90 percent; the Interstate division for Baltimore City picked up the remaining 10 percent. To date the cost of the Archbishop Keough Transparent Barrier Project is $173 193.48. The cost of the barrier was $87 000, or $20/ft². The latter cost included the panel, posts, all hardware, and panel erection. The cost of the concrete work was $20 800, including footings and pedestals. Approximately 104 yd³ of concrete was used for this project. An additional $2500 will be necessary to place a silicone-based joint sealer in the gap between the Lexan and the asphalt.

The Archbishop Keough Noise Barrier Project was started in March 1980 and completed in April 1981. The project took longer than the proposed 92 calendar days by 336. This lengthy overrun was chiefly attributed to delays in the delivery of materials and also to an underestimation in the number of working days required. Delay in the delivery of materials was caused by problems encountered in forming the curved ends of the Lexan. This can be expected in an experimental project where unforeseen problems often arise in the manufacture of materials and their assembly.

In October 1981 FHWA performed an insertion loss test on the Keough barrier as part of their barrier analysis program. This test measures noise levels in the same location, before and after the insertion of the barrier. The Lexan barrier was found to give a 10 dB insertion loss.

Noise level readings taken at five sites approximately 1-500 ft behind the barrier registered well below the FHWA guideline of 67 dB L_{eq}. The highest reading of 62.6 dB L_{eq} was registered directly behind the barrier. All readings were taken by FHWA personnel and are the product of four 15-min periods averaged into one hourly level. It is expected that traffic volumes and, consequently, noise levels on I-95, will be higher when the Fort McHenry Tunnel is opened.

Maintenance, durability, retention of transparency, and related problems can only be addressed if and when they occur. Concern for Lexan's durability was raised in a report by the California Business and Transportation Agency (2). In this study, four materials were submitted for testing. Three of the materials were plastics and one was tempered glass. Under accelerated and natural weathering conditions, the tempered glass was favored because of its ability to better withstand abrasion and discoloring. In the same tests it was found that polycarbonate materials were more susceptible to abrasion and loss of transparency than were acrylics. However, at this time (approximately 6 months since the erection of the barrier), we have found no evidence of these potential problems.

Figure 1. Detail of post attachment.

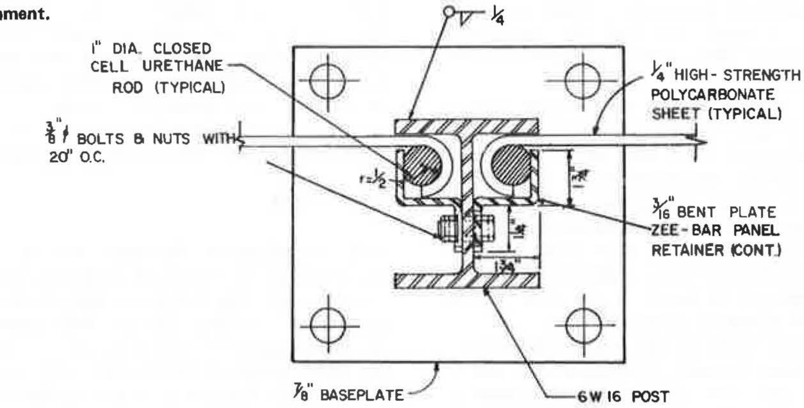
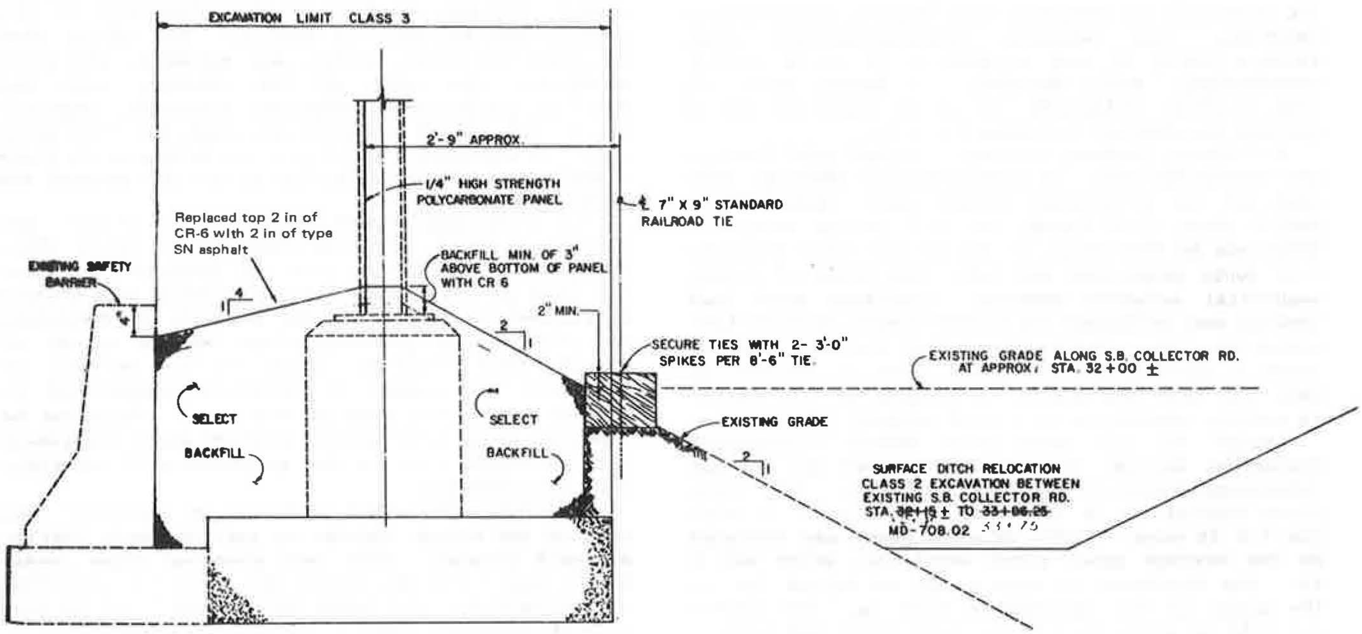


Figure 2. Detail of typical foundation.



PROBLEMS AND DESIGN CHANGES

The main design change that should be considered for future transparent barrier projects is an edge detail at the bottom or top of each panel for support. This is expected to decrease the rippling movement of the Lexan that results from gusts of wind generated by the larger trucks on I-95. The concern for the rippling of the Lexan is not that it is deleterious from a noise standpoint, but that it may have an adverse effect on wear and longevity. Other options that may effectively alleviate this problem could be either to increase the thickness of the panel itself or, if practical, to move the barrier farther away from the road. However, both of these options would require an increase of materials and, therefore, an increase of project cost.

Another problem that will require a design change is the edge detail at the bottom of the panel where the Lexan meets the asphalt. As mentioned previously, several highway joint sealants are currently being tested to fill the gap between the Lexan and the asphalt. This gap needs to be filled so that standing water could not fill the trench and, when it freezes, possibly crack the asphalt. It is hoped that some additional stabilization of the Lexan panel will be achieved with the implementation of this bottom edge detail. A top edge support has also been considered for added stability. However, this could be aesthetically objectionable as it would detract from the panels openness by framing the observer's vista.

CONCLUSION

The Archbishop Keough Transparent Noise Barrier Project not only met its objectives from acoustical and aesthetic standpoints, it also provided cost and performance information for future project comparisons. Lexan, the clear polycarbon panel material, seems to be feasible for use in a transparent barrier system.

With the addition of the edge detail, the barrier should have more stability, and the rippling should decrease appreciably or be eliminated. The inclusion of joint sealer along the bottom edge of the barrier should preclude any maintenance problems and also aid in stability. Problems encountered by the material supplier when forming the curved edges of the Lexan panel were alleviated and should not cause delays in the delivery of materials in the future.

Overall, the Keough noise barrier maintains the pleasing vista of the school's property for motorists along I-95 and effectively protects the school population from elevated noise levels. From this standpoint, in addition to the cost and performance data acquired, the Archbishop Keough transparent noise barrier should be considered a successful project.

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NJ-18 Freeway and Rutgers University Classrooms: Unique Construction Noise Mitigation Experience

DOMENICK J. BILLERA AND BRUCE C. CUNNINGHAM

This paper presents the identification and solution of a severe construction noise problem at Rutgers University classrooms created by the NJ-18 Freeway. The design, construction, and testing of sealed, modular metal walls attached to the buildings, which have sound-absorbing properties and window panels, are discussed.

The purpose of this report is to relate the knowledge and experience the New Jersey Department of Transportation has gained in the design and construction of a unique solution to a severe noise problem at a construction site. Our solution to mitigate construction noise impacts at university classrooms adjacent to the NJ-18 Freeway project was to attach a sound-absorbing, sealed, and ventilated wall with windows onto the affected buildings.

The NJ-18 Freeway extension project in New Brunswick is a 2.3-mile, six-lane roadway that will extend from the existing interchange at New Street along the Raritan River on the filled bed of the Delaware Raritan Canal. It will pass three Rutgers University dormitory buildings and Buccleuch Park. It will then cross the river into Johnson Park and terminate at River Road (see Figure 1). The 1972 noise impact study predicted a significant noise impact of L_{10} 77 dB(A) to the three Rutgers University river dormitories from traffic in the design year.

To mitigate this impact and also to replace land taken from Johnson Park by the project, a landscaped deck cantilevered over the roadway was proposed that was predicted to provide approximately 21 dB of noise attenuation. This deck will pass the three dormitory buildings between two access ramps for an uninterrupted 1530 ft. The estimated cost of the deck alone is $12 million. The total project cost is estimated to be $47 million.

Before construction on the project could begin, the transportation department was required to perform a construction noise study (1). This study determined that, for the three-year construction period, noise impacts would be significant and would range from L_{eq} 75 dB(A) to 86 dB(A) in the 25 classrooms and four seminar rooms that occupy the basement levels of the dormitory buildings. These high noise levels result from construction activity within 40 ft of the buildings. Ironically, one of the noisiest construction periods was found to be during the construction of the cantilevered deck, which is intended to be a noise-abatement measure.

Once the problem was identified, 13 alternative schemes were developed for dealing with the construction noise problem. These schemes were then presented to the Federal Highway Administration (FHWA) and Rutgers University officials, and an agreement on a single scheme was negotiated.

DESIGN

Three criteria were used to assess the impact of construction noise on the classrooms. The first criterion was the overall hourly L_{eq}. Although FHWA does not specify a noise level for construction, the L_{eq} was used to determine the degree of noise attenuation for all the abatement measures considered.

The speech interference level (SIL) was one criterion selected for impact assessment (2). It is defined as the arithmetic average of the sound levels in the 500 Hz, 1 kHz, and 2 kHz octave bands. These bands are used because nearly all the information contained in speech is distributed between 200 Hz and 6 kHz. The SIL is also easily determined. The table below relates SIL, distance from speaker to listener, and intelligibility for face-to-face communication. For the lecture environment in the classrooms, an SIL of 35 dB was the design goal.

Voice Level	SIL	Distance from Speaker to Listener (ft)	Intelligibility
Normal	40	16	Possible
Raised	50	8	Possible
	60	3	
Loud	70	1	Possible
Very loud	80	1	Possible
Shout	90	0.5	Possible
Maximum vocal effort	100	1	Difficult

Another approach used for impact assessment was the noise criteria (NC) for the classrooms (3). These are a set of curves of sound pressure level versus frequency, based on the averaged opinions of a large group of people (see Figure 2). The distribution of sound pressure level with frequency was adopted because it was judged to be the least objec-

Figure 1. NJ-18 Freeway extension project.

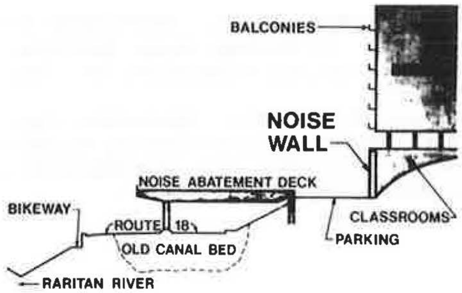
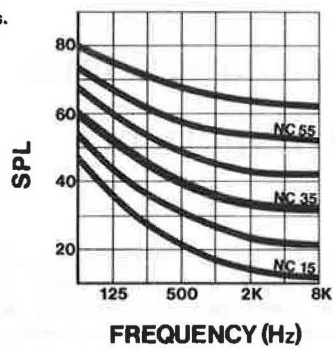


Figure 2. NC curves.



tionable. The list below shows the suggested NC values for various activities. To determine the NC value, an anticipated sound distribution is compared with the standard NC curves. An NC number is assigned to the sound that corresponds to the nearest NC curve that lies entirely above it. The design goal for the classrooms was an NC value of 35.

NC	Application
25	Recording studio
30	Theater
35	Classroom
40	Office
45	Department store
50	Typing pool
60	Light industry
70	Heavy industry

The use of these three criteria required the estimation of the overall construction noise levels. The hourly L_{eq} noise levels were calculated by using the design plans, a preliminary construction schedule, and the anticipated equipment types as input to Equation 1 (4,5).

$$L_{eq(h)} = 10 \log \sum_{i=1}^{n} UF_i \times N_i \times (10^{L_p/10})_i \times (D_o/D)_i^2 \quad (1)$$

where

- UF = usage factor for a piece of equipment expressed as the ratio of time in use to time on the job,
- N = number of similar pieces of equipment,
- L_p = maximum noise level of equipment,
- D = distance between equipment and the dormitory buildings, and
- D_o = 50 ft.

As a result of our calculations, we estimate that the hourly L_{eq} noise levels will range from 75 dB(A) to 86 dB(A) at the river dormitories during the anticipated three-year construction period.

The construction noise levels were further broken down into octave band levels shown in Figure 3 in order to use SIL and NC criteria. The octave band data were determined by using the spectra of the noisiest pieces of equipment (6) and combining them logarithmically to develop a typical construction noise spectrum.

Following the determination of the exterior construction noise levels, it was necessary to determine the noise levels within the classrooms. Because of the large expanse of glass and the low-frequency content of the construction noise, it was decided that the building noise reductions specified in the Federal-Aid Highway Program Manual (1) were not valid. Based on detailed acoustic analyses, the calculated classroom noise reduction with the windows open is 7 dB and with closed windows is 15 dB. These reductions result in predicted classroom L_{eq} noise levels that range from 60 to 71 dB(A) with closed windows and from 68 to 79 dB(A) with open windows.

The sound-reduction index of the building facade was calculated by dividing the wall into elements that have similar transmission loss characteristics. The transmitted sound pressure level (SPL_T) was determined by subtracting published transmission loss values from the exterior sound-pressure level or, where published values were not available, the result of Equation 2 (3) was subtracted from the exterior sound pressure level.

$$TL = -27.3 + 15 \log(\sigma f) \quad (2)$$

where

- TL = transmission loss (dB),
- σ = wall element density (lb/ft²), and
- f = octave band center frequency (Hz).

Equation 2 is an empirical relation that yields a lower initial value of TL and does not increase with wall element density and sound frequency as rapidly as the mass law predicts. This is because it accounts for resonance effects, induced vibrations, nonplanar wave propagation, and nonperpendicular wave incidence.

The sound pressure level transmitted to the classrooms was determined by logarithmically combining the transmitted sound pressure levels of the various wall elements by using Equation 3.

$$SPL_c = 10 \log \Sigma [S_i \times 10(SPL_{Ti}/10)] / \Sigma S_i \quad (3)$$

where

- SPL_c = composite SPL transmitted into classrooms (dB),
- S_i = area of each wall element (ft²), and
- SPL_{Ti} = SPL transmitted through each wall element (dB).

After determination of the transmitted sound pressure level, we considered the effects of the classroom acoustics by using Equation 4 to finally determine the building noise reduction.

$$SPL_R = SPL_c + 10 \log(4/S\bar{\alpha}) + 10\ dB \quad (4)$$

where

- SPL_R = the interior sound pressure level (dB),
- SPL_c = the composite transmitted sound pressure level (dB),
- S = surface area of room (ft²), and
- $\bar{\alpha}$ = average absorption coefficient.

This equation is based on the Sabine formula,

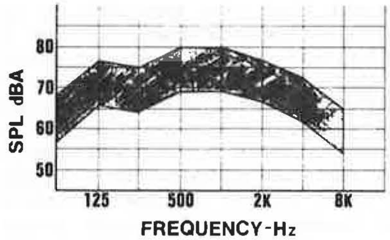


Figure 3. Construction noise spectrum.

which assumes that the rate of energy removal is constant proportional to the intensity. This equation also assumes that there is no change in the area of the wavefront that enters the classrooms. The average absorption coefficient is calculated by using published frequency-dependent Sabine absorption coefficients in Equation 5.

$$\bar{\alpha} = \Sigma S_i \alpha_i / \Sigma S_i \quad (5)$$

where

$\bar{\alpha}$ = average Sabine absorption coefficient,
α_i = published Sabine absorption coefficient of individual room elements, and
S_i = area in ft² of individual room elements.

As part of the acoustic analysis, the reverberation time of the classrooms was found to range from 0.8 to 1.4 s. These times were calculated by using Equation 6, based on assumptions in the Sabine theory.

$$T_R = 0.049V/S\bar{\alpha} \quad (6)$$

where

T_R = room reverberation time (s),
V = room volume (ft³),
S = room surface area (ft²), and
$\bar{\alpha}$ = average Sabine absorption coefficient from Equation 5.

The optimum reverberation time for speech intelligibility in rooms of this size is generally acknowledged to be approximately 0.5 s (3). According to these calculations, the noise impact to students during lecture would be severe and would be aggravated by the rather poor acoustics of the classrooms. Based on this information, 13 alternative schemes were developed to mitigate the noise impact. The alternatives considered included do nothing with open windows, do nothing with closed windows, classroom relocation, source control, individual window ventilators, a large fan with exterior duct work, building ventilation modifications, air conditioning, temporary noise barriers, interior acoustical curtains, double-glazed windows, and a sealed and ventilated wall.

Several of these alternatives were eliminated because they could not meet the noise-reduction criteria. Those that remained, including classroom relocation, interior vinyl acoustical curtains, double-glazed windows, and exterior sealed wall, were presented to the FHWA regional office and Rutgers University officials.

The criteria used by the New Jersey Department of Transportation and FHWA for review were the cost, effectiveness, and energy use of the abatement. Based on these criteria, the double-glazed window alternative was eliminated. This alternative was ruled out because of its cost, which was estimated at $600 000. The noise levels would have been acceptable if two panes of 3/16-in glass were separated by a 4-in air space. This alternative would also require extensive modifications to the buildings' existing ventilation systems, which would involve reversing the flow of each system to change it from an exhaust to a supply system. As designed, the fresh air supply for the classrooms is through the openable windows. Obviously, with windows open the noise-reduction goals could not be realized and, thus, the ventilation modifications would be necessary.

An energy use analysis (7) required by FHWA (8) indicated that the double-glazed windows would reduce the total heat requirements of each dormitory building by 4 percent. However, if the windows were sealed, the classrooms would require positive ventilation and air conditioning, which would increase the climate-control costs for each building by nearly 40 percent.

Several constraints on the designs were imposed by Rutgers University. They insisted on minimal class disruption and return of the buildings to their original condition on completion of the project. School officials were also concerned about vandalism and so required that the system be relatively vandal-resistant.

Based on these constraints, the university rejected the classroom relocation proposal because of the logistics problems of class scheduling, disruption of student busing schedules, the loss of revenue from classroom rental between semesters, and concern for an adequate learning environment.

Vinyl acoustical curtains mounted inside the existing windows with a 4-in airspace were also rejected by the school officials. This alternative provided marginally acceptable classroom noise levels and, at an estimated cost of $300 000, was moderately expensive. The officials thought that the vinyl curtains would be easily vandalized and present a constant maintenance problem.

The exterior sealed wall was acceptable to the university, although it meant the loss of several parking spaces behind each dormitory building. The modular absorptive wall system would be attached to an overhang on the building and sealed at the ends. The advantage of this system was that all construction was external to the building, which minimized classroom disruption. Once the freeway construction is completed, the wall can be removed for reuse elsewhere and the building can easily be returned to its original condition.

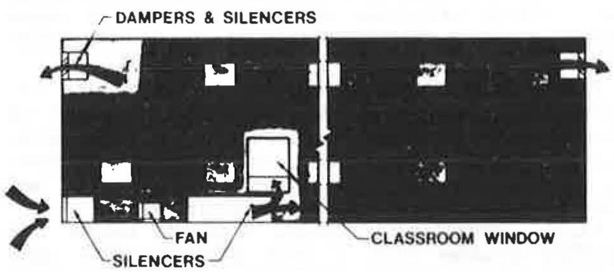
This alternative also met the acoustic design goals set at the outset of the investigation. During the noisiest phases of construction, with the fans operational and classroom windows open, the NC value for the classrooms is predicted to be 35, the SIL will be 29 dB, and the peak hourly L_{eq} will be 56 dB(A). The estimated cost for this alternative was $225 000.

The wall consists of a supporting steel framework bolted to a concrete leveling curb and to a concrete ledge that overhangs the classrooms and serves as the floor of an open-air colonnade for the dormitories. Modular, 4-in thick absorptive panels were slipped into the supports and interlocked by an integral tongue-and-groove design. The wall was sealed to completely isolate the classrooms from the construction noise. Windows were provided in several of the panels to allow for natural lighting and to minimize the feeling of claustrophobia in the classrooms caused by the wall (see Figures 4 and 5.)

A vaneaxial fan was installed in the lower part of each wall (below the first-floor windows) and its intake was located away from the building entrances. The fan was incorporated to provide positive fresh-

Figure 4. Partly constructed wall.

Figure 5. Schematic of air flow.



air ventilation through the openable windows without modification to the buildings' existing ventilation systems. The fan was isolated with intake and exhaust silencers, a 2-in absorptive cover panel, and solid steel safe-off panels, where required, to prevent short circuiting of air flow.

Barometric dampers were installed in the upper ends of the noise walls to modulate the air flow into the classrooms. A 3-ft medium-pressure drop silencer was attached to each damper to attenuate construction noise entering through the open dampers to a level sufficient to meet the acoustic design goals.

A modular absorptive barrier system with the absorptive surface facing the classrooms was specified for several reasons. The primary reason was that the speed and blade configuration of the fans were unknown when the wall proposal went out to bid. Since the fan acted as a steady source of noise with many discrete tonal components (especially at harmonics of the blade-passage frequency), there was concern that some of these components would coincide with the eigen frequencies of the plenum. This would result in resonances that cause large noise-level magnifications at specific frequencies.

A second reason for absorption was that, after the construction noise enters the plenum, the plenum becomes a noise source room to the classrooms. By using a technique often used for noise control in receiver rooms, absorptive material was used in the plenum room to lower the plenum sound level and thus to reduce the sound energy transmitted to the classrooms. Finally, a modular panel system was specified because it is relatively inexpensive, easily erected, and can be disassembled for future use after the project is completed.

The major constraint to fan selection was an adequate flow rate provided by a relatively small fan. The space allowed for the fan is 39 in wide and 43 in deep. The fan was placed inside the wall to minimize the chances of vandalism. Additional reasons for selecting the vaneaxial fan included lower installed cost, wide operating range, relatively low noise levels, and energy-saving design.

A 3-ft low pressure drop silencer was placed on the inlet side of the fan to attenuate the fan noise that reaches the dormitory rooms at night. The silencer was sized to reduce the noise to 40 dB(A) at the dormitory rooms. A 10-ft low pressure drop silencer was placed on the outlet side of the fan to meet the acoustic design goals for the classrooms. A smaller silencer could have been used that has similar attenuation characteristics; however, it would have a higher pressure drop and require more energy to operate the fan.

CONSTRUCTION

As part of the contract specifications required by FHWA, no construction activity was permitted when classes were in session for approximately the 2000 ft along the freeway that was near the dormitories until the construction-noise-abatement wall was in place and operational. A second restraint was the university's desire that erection of the wall take place during a school recess period to avoid interrupting classes.

The concrete curb for the wall was placed in January during the semester break (see Figure 6). This was a leveling curb poured on top of the existing bituminous parking lot surface and fixed by steel dowels into the pavement. Protruding from the curb were the bolts used to attach the wide flange beam-support structure.

Because of delays in the approval of the shop drawings submitted by the panel manufacturer, the erection of the support structure did not take place until the spring recess in early March. These 5-in wide flange beams, located on 12-ft centers, were bolted to the leveling curb at the bottom and welded to a steel angle bracket bolted to the 12-in concrete overhang (see Figure 7).

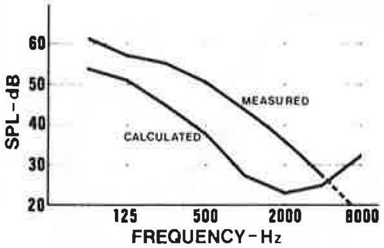
A neoprene gasket was also glued to a flange on each beam at this time. A 16-gauge steel U-channel over a neoprene gasket was ramset along the concrete curb between the vertical supports. This channel is used to provide a positive seal at the bottom of the first wall panels (see Figure 8).

The exterior skin of the panels is constructed of 18-gauge galvanized steel and the inner face is 22-gauge perforated (3/32-in holes staggered on 3/16-in centers) stainless steel. The panels are constructed with a 4-in cavity filled with 4.25-in thick fiberglass. Stainless steel is used for the inner skin to prevent corrosion in the unprotected perforations. The inner and outer panel skins are Tedlar-coated colonial red. In order to prevent unprotected holes in the Tedlar and galvanizing coatings that would be made with spot-welded assembly, the panels were assembled with stainless-steel rivets.

At the request of the university, window panels were added to the design. Two 3/16-in tempered glass panes separated by a 3.5-in air space were used. These panes were set in a neoprene gasket to provide a positive seal and excellent vibration isolation from the remainder of the panel. Each of these window areas was also framed with an 18-gauge steel channel to stiffen the assembly.

The silencers were also delivered to the site with the wall panels. They are constructed of 26-gauge perforated galvanized steel inner surfaces and 22-gauge steel outer shell. They are also

Figure 12. Fan sound level.



possible through the dedicated efforts of the many New Jersey Department of Transportation, FHWA, and Rutgers University personnel involved. Special thanks go to Fred Bogdan and Joe Maiorino, both of Bureau of Surface Design, Area 3, for their input, guidance, and support; to Paul Wygovsky and Robert Lane of the Bureau of Quality Control, for their monitoring data; to Al Ari, resident engineer, construction, and his staff for supervising and coordinating the wall installation; to Lloyd Jacobs, FHWA Environmental Specialist, for his comments; and to Bruce Whitehead, superintendant of plant and equipment, Rutgers University, for his input and coordination with the university. Thanks are also in order to personnel in special engineering, construction practices, and structural design for their input during various phases of the project.

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Role of Airport Noise Allocations in a Regional Airport System

CHRIS BRITTLE

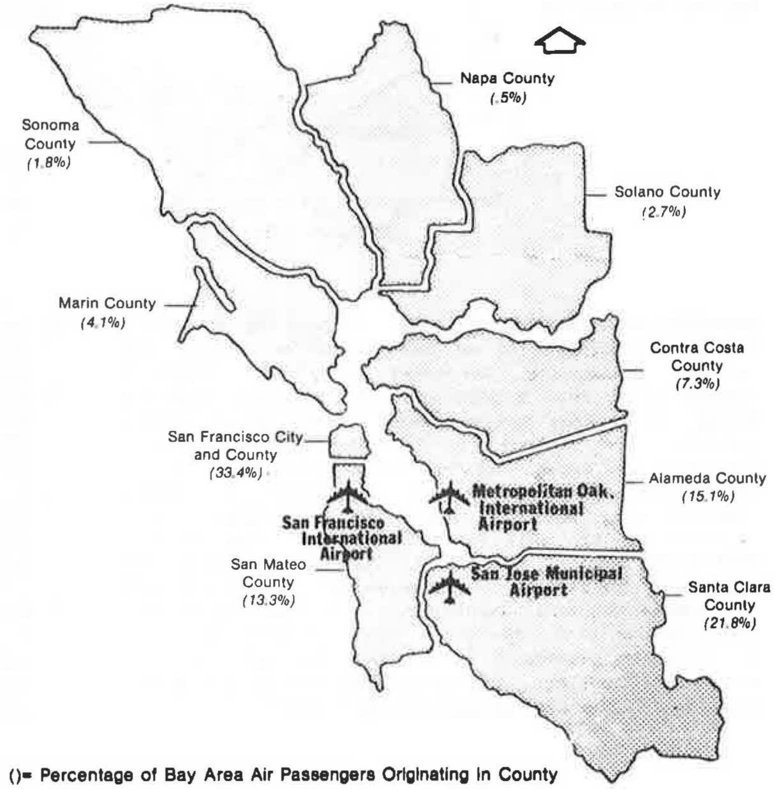
This paper describes an approach developed in the San Francisco Bay Area to manage aircraft noise at the three major air carrier facilities—San Francisco International Airport, Metropolitan Oakland International Airport, and San Jose Municipal Airport—and to implement policies to develop regional air service. Airport noise allocations, defined by the number of residential dwelling units exposed to noise levels in excess of mandated California state noise standards, represent the noise capacity of each airport. Noise allocations are established at the regional level in a two-step process. First, projected Bay Area air passenger and air cargo demand are assigned to each airport in order to make optimum use of the three regional airports and to expose a minimum of the total Bay Area population to excessive airport noise. Next, noise levels are projected at each airport, with the assumption that aircraft that do not meet federal aircraft noise certification standards are either replaced or retrofitted with quieter engines, and the number of dwelling units in the noise impact area is calculated. Regional noise allocations are designed to accommodate increased aviation demand as well as to encourage airlines to expand their services at Oakland Airport, which is convenient and has the least noise impact of any Bay Area airport. The regional noise allocation is implemented through the power of the individual airports to establish appropriate restrictions on use if annual allocations are not being achieved.

The San Francisco Bay Area is served by three major air carrier facilities: San Francisco International (SFO), Metropolitan Oakland International (OAK), and San Jose Municipal (SJC). Airport noise affects a large number of persons in the Bay Area, hence additional growth in regional aviation demand must be accompanied by a coordinated approach to areawide airport noise problems. Airport system planning studies conducted by the Association of Bay Area Governments and the Metropolitan Transportation Commission, and funded by the Federal Aviation Administration (FAA), have addressed the noise-control problem and the optimum distribution of traffic among the three air carrier airports to handle future demand.

Two major areas that will provide significant noise relief include a redistribution of airline flights among the Bay Area airports as traffic grows and a reduction in the noise levels of the aircraft. Federal law provides a phased schedule for the retirement of aircraft that do not comply with Federal Aviation Regulation (FAR), part 36, aircraft noise certification standards. Regional studies since 1972 have highlighted the need for greater use of Oakland and San Jose Airports (1,2); however, like other multiairport hubs, most service is concentrated at a single airport--San Francisco International. Since the passage of the Airline Deregulation Act of 1978, service at Oakland and San Jose Airports has declined significantly, due partly to competitive forces and partly to national economic problems.

In spite of the current economic malaise, the long-range outlook is for significant growth in air traffic, which, in turn, will produce increased pressure for effective noise control. The regional noise-allocation strategy is designed to encourage

Figure 1. Location of Bay Area airports and origins of air passengers.



efficient use of the Bay Area airports by the airline industry and to respond to local concerns about airport noise levels. In effect, the noise allocation represents an annual noise capacity or noise budget for each airport, measured in residential dwelling units exposed to noise levels in excess of mandated noise standards for California airports.

Noise allocations are established at the regional level in a two-step process. First, projected Bay Area air passenger and air cargo demand is assigned to each airport in order to make optimum use of the three regional airports and to expose a minimum of the total Bay Area population to excessive noise levels. Next, noise levels are projected at each airport, based on assumptions about the aircraft fleet mix and the noise characteristics of these aircraft. The number of residential dwelling units within the projected airport noise contours can easily be determined and used to define the noise allocations.

Although the noise allocation strategy is discussed in the context of a regional airport system, this approach also provides a useful and practical method for any airport (a) to quantify noise-control objectives, (b) to assess progress by comparing actual noise-monitoring data with annual noise allocations and (c) to define additional noise-control measures necessary to achieve the desired results.

REGIONAL ASSIGNMENTS OF AIR TRAFFIC

The relative location of the three Bay Area airports is shown in Figure 1. San Francisco International is the region's major airport facility. It handles 80 percent of the air passengers and 95 percent of the air cargo. Approximately 18 percent of the passengers who use the airport are connecting or through passengers. The airport is located 15 miles south of San Francisco. A large percentage of the aircraft take off over water; however, prevailing winds from the west cause about 24 percent of the flights to take off over land. These operations impact a densely populated area.

A satellite airport, Oakland International Airport, handles about 9 percent of the air passengers and 1 percent of the air cargo. Service from Oakland International is concentrated in the California corridor between the San Francisco Bay Area and the Los Angeles metropolitan area. Because takeoffs and departures are over water, noise impacts from airport operations are minimal. A major residential development is under construction near the airport, and it will be the only area significantly affected by airport noise in the future.

San Jose Municipal, the Bay Area's other satellite airport, handles 11 percent of the air passengers and 3 percent of the air cargo. Service from this airport is also concentrated in the California corridor. Urban development surrounds the airport; therefore, noise has been a major concern for a number of years. The airport is currently removing homes near the main air carrier runway due to airport noise and safety problems.

Regional planning studies indicate that Bay Area air traffic could increase from 1980 levels of 27 million annual passengers to 37-43 million annual passengers in 1987, and to 45-56 million annual passengers in 1997 (see Figure 2). Recommended air traffic assignments for the Bay Area airports for 1987 and 1997 are shown in Table 1. Regional traffic assignments would result in a substantial redistribution of air traffic, as discussed below.

Air passenger surveys conducted in 1975 and 1980 have shown that the market will support substantially greater service at the Oakland and San Jose airports (3,4). The service areas for these airports each generate approximately 25 percent of the region's air travelers, considerably less than the number currently served. This overall passenger distribution is typical of most city pair markets as filled with fiberglass (see Figures 9 and 10). Each dormitory enclosure required four silencers as part of the ventilation system.

The barometric dampers are set to open when the plenum pressure exceeds 0.1 in water gauge. This pressure is sufficient to meet the American Society of Heating Refrigeration and Air Conditioning Engineers ventilation requirements for the classrooms. The dampers also provide a constant air flow into the classrooms regardless of the number of open windows.

Also erected at this time were the steel angle supports for the silencers that are mounted against the barometric dampers located in the upper ends of each enclosure. To improve the aesthetics of the completed wall, all these structural elements were painted to match the modular wall panels.

The installation of the wall panels into the steel supports was started as soon as panels were received by the contractor. Because this was a relatively quiet operation and required only a small crane, the university agreed to allow installation of the panels while classes were in session.

A crane was used to lower the panels into place between the support beams. The neoprene strips on the beam flanges and silicone caulk provided a good acoustical seal and prevented rattling of the modular assembly (see Figure 11). Additional fiberglass fill was placed in the channel area where the panels interlock to absorb any sound energy passing through the panel joints before entering the plenum area.

All the panels were placed during April, except in the fan and intake silencer area. At this point, work was stopped because the fan manufacturer could not supply the specified fans due to a back order of the low-vibration motors. The fans specified were direct-drive adjustable vaneaxial and provided a flow rate of 8000 to 14 000 ft^3/min from 0.25 to 1.5 in water gauge and operating at 1750 revolutions/min. The specification also called for a vibration level not to exceed one mil double amplitude at design-rated speed. These fans caused a substantial delay in completing the project. The fans were received in late May and the installations were completed and operational by July.

The fans were bolted to a concrete pad and isolated with 1-in thick neoprene and cork composite vibration isolation pads. The intake silencers were then set in place and the cover panel was attached over the fans and silencers. The remaining wall panels were then inserted and sealed, which completed the installation.

The bid price for the complete wall installation was $340 000. Because the classrooms were now protected from construction noise, the university accepted a value engineering proposal submitted by the contractor to substitute driven piles for drilled, cast-in-place caissons to support the cantilevered deck. The minimum cost saving of this construction method is $210 000. This saving, when applied to the cost of the wall, brings the net cost of the mitigation down to $130 000, which compares favorably with the estimated cost of $225 000.

TESTING AND VERIFICATION

Several tests have been made to verify the performance of the walls and the accuracy of the predictions. During the spring semester break, when work was proceeding in the canal bed and the structural steel members were being installed on the dormitories, the building noise reduction was measured. The measurements were made by using two B&K 2218 precision integrating sound level meters: one located outside the building 10 ft from the wall and one located inside a classroom 5 ft from the windows. During the measurements a Koering backhoe model 866E was operating approximately 180 ft from the building and generated an L_{eq} of 70 dB(A) outside the classrooms. The A-weighted noise level was sampled until the L_{eq} stabilized on both meters. The average measured building noise reduction was 8 dB for open windows and 15 dB for closed windows. These compare with calculated reductions of 7 dB for open windows and 15 dB for closed windows.

After the wall was completed, building noise reduction was measured again. During the measurements, a pile driver (manufacturer and size unknown) drove 20-ft test H-piles. A B&K 2218 was positioned 10 ft outside the completed wall, and a second was in a classroom 5 ft from the windows. The fast meter response was used and the peak noise levels [86 to 94 dB(A)] generated by the driver blows were measured and compared. The results showed a 36 dB reduction with the windows open and a 38 dB reduction with the windows closed. Note that the closed windows condition is only 2 dB better than the open windows condition. There are two explanations for this. First, the noise level within the classrooms due to the mechanical equipment within the building was less than 10 dB below the peak pile driver levels. Second, the pile driver noise levels were noticeably louder in the hallways. Apparently, the noise infiltrated through the building entrances and propagated down the hallways and into the classrooms. The calculated noise reduction with open windows was 38 dB; with closed windows, it was 46 dB. Whether these attenuations are actually achieved cannot be determined because of the complications encountered during the measurements.

The fan noise levels were also measured in the classrooms closest to the fan enclosures. These measurements were made for all six fans by using a B&K 2209 impulse precision sound level meter on fast response and a B&K 1613 octave filter set 5 ft from the open windows. The results showed wide variations between the spectra for each fan--some fans were noisy at low frequencies and others were noisy at the midfrequencies. The average overall level is 52.3 dB(A) with a standard deviation of 2.4 dB (see Figure 12). Unfortunately, we have been unable to determine why such wide variations occurred.

The fan noise levels measured in the six classrooms adjacent to the fan enclosures and outlets result in an NC value of 45 and an SIL of 43 dB. At all the remaining rooms, the design criteria of NC 35 and SIL 35 dB were met due to distance attenuation from the fan.

SUMMARY

The major goals for abatement of construction noise have, for the most part, been achieved. The project can be considered successful at this time. To date, all comments received from the university, which cover aesthetics to noise reduction, have been favorable. Up to 8000 students/day are shielded from high levels of construction noise during lecture; therefore, the cost-effectivensss of the wall justifies its inclusion in the project. The added benefits of panel salvage and possible reuse will make the wall even more cost effective.

Whether the need for this type of construction noise mitigation will occur again in New Jersey is not known; however, the experience gained from this project will prove to be invaluable in future construction and traffic noise evaluations.

ACKNOWLEDGMENT

Completion of this mitigation proposal was only

Figure 6. Concrete curb for wall.

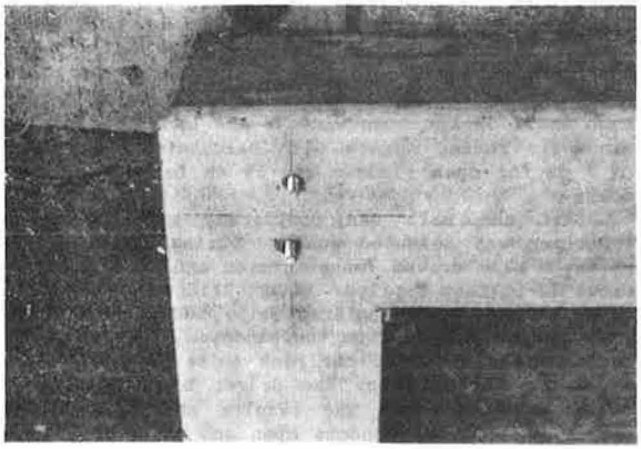


Figure 7. Steel support structure.

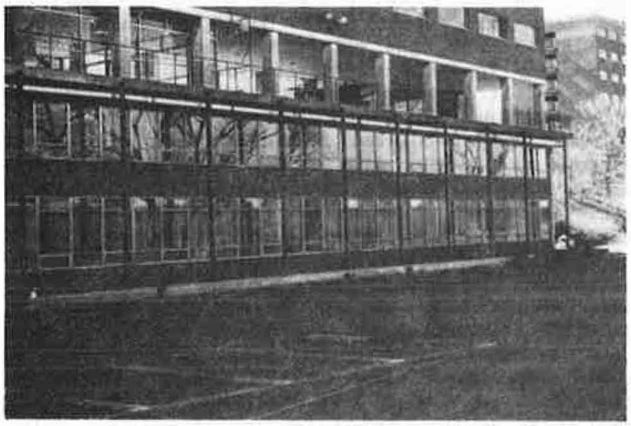


Figure 8. Closeup of support structure, which shows curb, steel H-beam bolted to curb, and 16-gauge U-channel ramset on curb.

Figure 9. Ten-ft long silencer used on output of ventilation fan.

Figure 10. Completed installation of silencer outlet and steel safe-off panels.

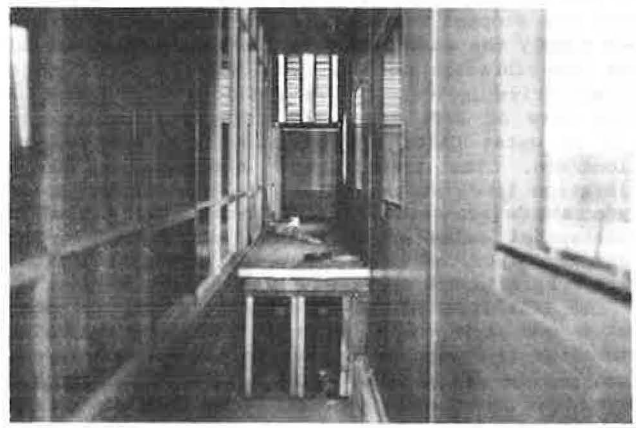


Figure 11. Panel placement.

Figure 2. Air passenger forecast for San Francisco Bay Area.

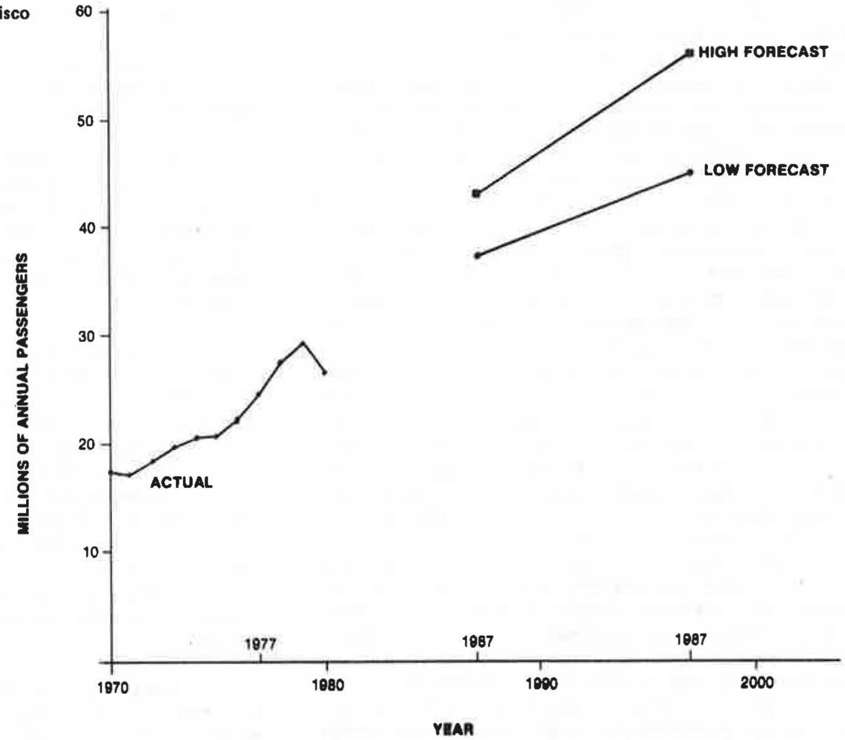


Table 1. High forecast of regional air traffic assignments.

		Air Passengers		Air Freight	
Year	Airport	No. (000s)	Percent	Tons (000s)	Percent
1980	San Francisco	21 338	80.1	318.7	95.4
	Oakland	2 417	9.1	4.7	1.4
	San Jose	2 877	10.8	10.7	3.2
	Total	26 632		334.1	
1987	San Francisco	27 000	63	753.0	90.2
	Oakland	8 000	19	43.0	5.1
	San Jose	7 000	16	36.0	4.3
	North Bay[a]	1 000	2	3.0	0.4
	Total	43 000		835.0	
1997	San Francisco	31 000	55	1524.0	85.4
	Oakland	13 000	23	151.0	8.5
	San Jose	10 000	18	105.0	5.9
	North Bay[a]	2 000	4	5.0	0.2
	Total	56 000		1785.0	

[a]Possible joint use of Travis Air Force Base or a new airport in the North Bay.

well; hence, the larger markets could support expanded service at the satellite airports. In addition, Oakland International's proximity to San Francisco (the origin of 33 percent of the region's airport users) makes this airport a reasonable alternative for air passengers in San Francisco.

Studies of airspace capacity and delay have shown that the airspace system would operate more efficiently if the available capacity at Oakland and San Jose airports is used better. If traffic continues to be concentrated at the San Francisco airport, substantial delays will be experienced in the future during instrument flight rules (IFR) weather conditions (5).

Balancing of the demand among the three regional airports will also balance the demand on the airport ground-access systems and minimize congestion on the regional highways (6). Local and regional air quality effects will be minimized with a redistribution of airline service (7). Most importantly, the total population in the region exposed to excessive airport noise levels will be minimized by the recommended regional traffic distribution (8).

DEVELOPMENT OF AIRPORT NOISE ALLOCATIONS

California has promulgated airport noise standards that govern the level of airport noise in residential areas that surround an airport (California Transportation Title 21, section 5000). Community tolerance to noise is measured in Community Noise Equivalent Levels (CNELs) in dB(A). State law requires that an airport either operate with a zero noise impact area (i.e., no residential units within the applicable CNEL standard) or obtain a variance (other incompatible land uses include schools and hospitals). To obtain a variance, airports must show progress toward meeting the standards and how they intend to achieve compliance. The noise standard becomes more stringent over time, as shown below:

Effective Date	CNEL Standard
January 1, 1976	75
January 1, 1981	70
January 1, 1986	65

The 65 CNEL was used to define the future noise-impact area for each airport because this is the standard with which all airports in California must ultimately comply. Noise levels were projected for each airport to determine the future noise impact area exposed to noise of 65 CNEL or greater. Other noise descriptors, such as the day-night average sound level (L_{dn}), can also be used to define the airport noise-impact area.

Units of Measurement

The preferred unit of measurement for the regional noise-allocation system is the number of residential dwelling units within the 65 CNEL contour. In addition to providing a quantitative measure of the community impact of airport noise, the dwelling unit count defines the number of homes that must ultimately be removed, be treated with sound insulation, or be subject to a noise easement in order to comply with the noise standards for California airports.

Since the residential dwelling unit count is used to measure the size of the noise-impact area, one data base can be selected (e.g., U.S. census data) and used for successive updates of the airport impact area. The main purpose of the dwelling unit count is to track changes in the size of the noise-impact area and not necessarily to serve as an accurate inventory of current housing within the noise-impact area. Also, although there will probably be some in-fill construction within existing residential areas that surround an airport, local building standards typically require either sound insulation or the granting of noise easements to the airport for this new construction. As a practical matter, these dwelling units should not add to the potential noise liability of the airport.

Another reason for using dwelling units as the metric for the noise-allocation system is that the effectiveness of various proposed mitigation measures (e.g., airport operational controls, changes in flight procedure, and pricing incentives) can be defined in terms of the anticipated reduction in the dwelling unit count. These reductions can further be broken down by communities that receive the noise relief. Communities need to know how much noise reduction can be provided and whether noise is being reduced or merely shifted from one community to another. Airline decisions may also be affected by the dwelling unit count. For instance, airlines may need to decide whether to accept additional operating constraints at an airport or pay for expanded sound insulation off the airport through landing fees if the stated airport policy is to achieve an equivalent amount of noise reduction.

An alternative unit of measurement to determine the noise-impact area is the number of acres within a noise contour. One problem in using acres is the potential for reducing the size of the noise contour without substantially changing the airport noise impact. This situation would occur if the area of the 65 CNEL contour was reduced over water, over open space, or in an area developed for office and commercial use. The number of acres within the projected noise contour may be useful for defining noise allocations when the density and distribution of residential dwelling units within the noise-impact area of an airport is fairly uniform.

Projecting Airport Noise Contours

A predictive noise model was used to estimate future airport noise levels in the Bay Area for two time frames, 1987 and 1997 (8). The principal variables that need to be considered in airport noise modeling are as follows:

1. Air traffic demand--the overall demand projections and distribution of traffic among the three air carrier airports,
2. Airline fleet mix--the projected airline fleet mix associated with each airport traffic level and the noise characteristics of this fleet mix,
3. The distribution of aircraft operations by time of day--the CNEL standard weights aircraft noise emissions more heavily between 7:00 and 10:00 p.m. and between 10:00 p.m. and 7:00 a.m. to reflect lower community tolerance for noise in the evening and late night,
4. Flight procedures--engine thrust and flap settings for individual aircraft types,
5. Flight track use--airport arrival and departure routes, and
6. Airport operational controls--restrictions on noisy aircraft and curfews.

Of major interest from a regional planning perspective is the population in the region exposed to excessive airport noise, given different traffic assignments among the Bay Area airports. To address this question two major airport system alternatives were compared based on the future forecast of Bay Area air traffic.

1. Alternative 1: Existing airport traffic shares. The traffic distribution among the three Bay Area airports duplicates the existing traffic distribution. San Francisco International would continue to handle close to 80 percent of all air passengers and 95 percent of all air cargo.
2. Alternative 3: Regional airport plan. Oakland and San Jose airports would serve a significantly greater share of regional demand and a North Bay airport would provide limited air carrier service in the California corridor (noise impacts associated with the proposed North Bay Airport would be minimal).

In addition to the proposed redistribution of airline flights among Bay Area airports, another major airport noise-mitigation measure incorporated in the regional noise allocation was the phase out of all older, noisier aircraft currently in operation. It was assumed that all aircraft would comply with FAR Part 36 aircraft noise certification standards by 1987. Current federal statutes require aircraft that do not meet FAR Part 36 to either be replaced or retrofitted with new technology engines by 1987. New technology aircraft (e.g., B737-300, B757, B767, and DC-9-80) are generally assumed to meet the more-stringent stage 3 noise levels and estimates were made of the noise characteristics of these aircraft.

In order to clearly identify changes in regional noise impacts due to alternative airport traffic distributions and aircraft technology, other variables were held constant. For instance, it was assumed that airlines would continue to schedule flights at the preferred arrival and departure times for passengers and cargo and that current aircraft operational procedures and airport flight track use would not change in the future. As a matter of policy it was also assumed that any decisions regarding curfews, maximum aircraft noise limits, changes in flight procedures, and economic incentives to reduce noise would be the responsibility of the airports and federal agencies and would not be incorporated in the regional noise allocation. This assumption is based on the fact that regional strategy incorporates noise reduction at the source--the aircraft--as the major mitigation measure while leaving the door open to the airports and communities to implement other measures if the regional noise allocations are not achieved or if further noise reduction is desired.

Counting Dwelling Units Within the 65 CNEL Noise-Impact Boundary

Determination of the population and number of dwelling units within an actual or projected noise contour can be a fairly time-consuming process unless modern computer techniques are employed. This process has been completely computerized in the Bay Area through the use of the Bay Area spatial information system (BASIS) program developed by the Association of Bay Area Governments (9). In brief, BASIS is structured around an array of grid cells, each of which represents a land area of 1 hectare (100 m^2 in the Universal Transverse Mercator coordinate system or about 2.5 acres). Each cell on the ground corresponds to a unit of computer storage. The unit contains data codes that represent the characteristics of that cell. Data of importance to airport noise assessment include census data, dwelling units and population, school sites, hospital sites, and noise levels. Noise contours are entered into the computer via a digitizer that quickly translates mapped data into the cell format. Once the information is entered, BASIS can overlay one data set (e.g., noise levels) on another (e.g., dwelling unit) and produce a quick analysis of the effects of changing noise contours on residential areas.

Recommended Noise Allocations for Each Airport

Figures 3 and 4 show how the population exposed to noise levels of 65 CNEL or greater varies at each airport as a function of the number of aircraft operations and projected aircraft fleet mix for 1987 and 1997. Estimated differences in regional airport

Figure 3. High forecast of noise impacts versus annual jet air carrier operations in 1987.

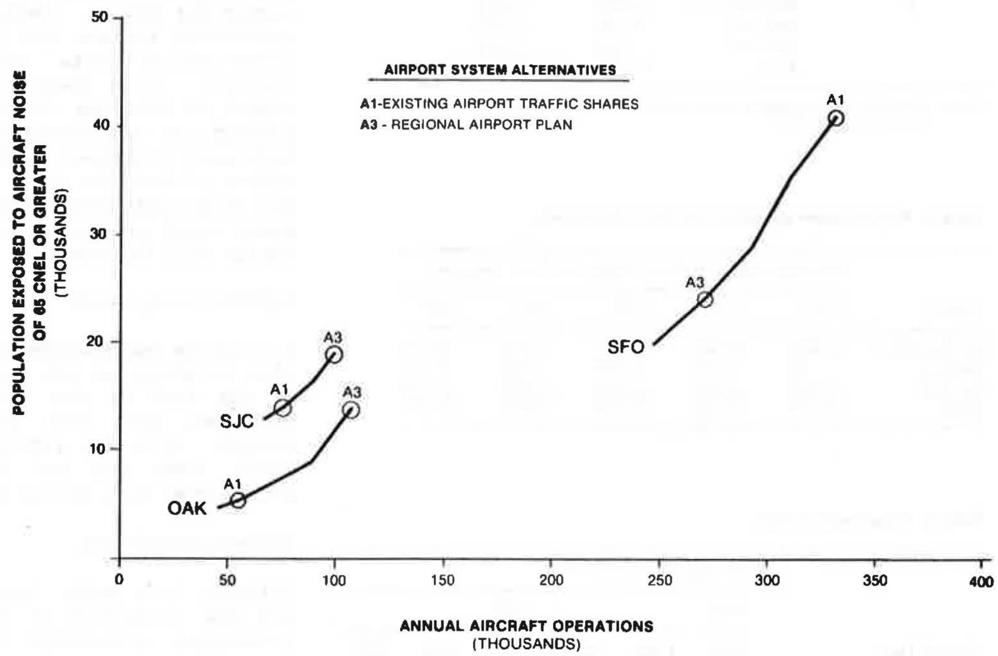


Figure 4. High forecast of noise impacts versus annual jet air carrier operations—1997.

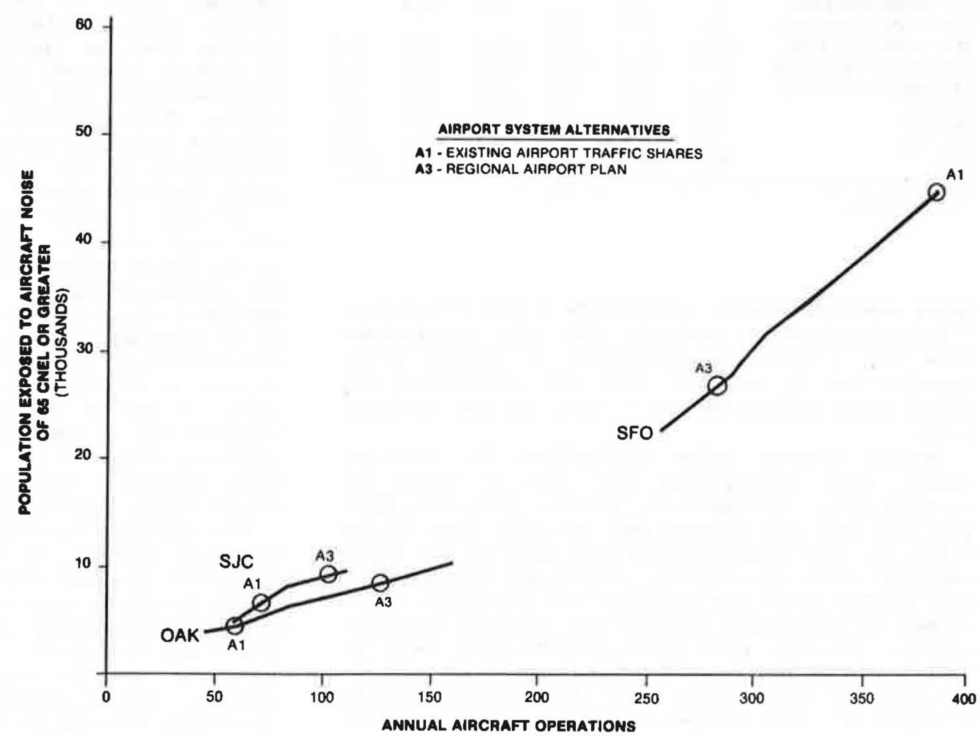


Table 2. Population and dwelling units exposed to airport noise levels of 65 CNEL or greater.

Year	Alternative	Airport	Population	Dwelling Units
1987	1	San Francisco	41 460	14 530
		Oakland	5 530	2 130
		San Jose	14 410	4 850
		Total	61 400	21 510
	3	San Franciso	23 560	8 630
		Oakland	13 720	5 340
		San Jose	18 660	6 400
		Total	55 940	20 370
1997	1	San Francisco	45 440	15 640
		Oakland	4 450	1 730
		San Jose	6 730	2 060
		Total	56 620	19 430
	3	San Francisco	27 090	9 610
		Oakland	8 740	3 320
		San Jose	9 350	2 990
		Total	45 180	15 920

Notes: Alternative 1 is the existing airport traffic shares. Alternative 3 is a regional airport plan.

Table 3. Regional noise allocation for Bay Area airports.

	Projected Dwelling Units Within 65 CNEL Contour				
Airport	1976	1981	1986	1987	1997
San Francisco	12 400	10 690	8 970	8 630	8 630
Oakland	80	1 730	3 390	3 720	3 320
San Jose	1 630	3 800	5 970	6 400	2 990
Total	14 110	16 220	18 370	18 750	15 920

Table 4. Projected fleet mix.

	Average Daily Operations					
	1987			1997		
Aircraft Type	SFO	OAK	SJC	SFO	OAK	SJC
Four-engine wide body	73.9	1.2		93.0	23.6	
Four-engine regular body	94.6	26.1	18.6			
Three-engine wide body	109.3	22.3	10.5	126.4	51.8	43.2
Three-engine regular body	281.5	165.4	154.6	180.0	91.0	91.2
Two-engine regular body	118.2	52.6	66.4	59.8	40.6	30.2
New 200[a]	40.6	12.1	8.0	132.4	50.8	48.7
New 150[a]	15.6	0.5	6.2	79.3	34.1	32.6
New 125[a]	9.3	5.2	3.5	101.4	54.7	34.0
Total	743.0	285.4	267.8	772.3	346.6	280.0

[a]New technology.

noise exposure between alternative 1 and alternative 3 are summarized in Table 2. The noise projections show that substantial reductions in airport noise exposure can be achieved with the recommended regional distribution of air traffic in the regional plan.

Annual airport noise allocations (in dwelling units) were established for interim years by straight-line interpolation between the 1976 base year and 1987 and between 1987 and 1997 (see Tables 3 and 4). Two modifications were made in the final regional noise allocations. First, one Oakland Airport flight track was modified and overflight noise caused by eastbound traffic was reduced significantly. Second, 1997 noise impacts were held to 1987 levels at San Francisco Airport. These modifications were incorporated into the regional plan as a result of local studies that showed potential for significant noise mitigation based on changes in flight procedures, flight track use, and aircraft noise restrictions (10).

There has been discussion concerning the validity of a linear interpolation procedure since such a procedure does not consider the timing of individual airline aircraft delivery programs or major federal aircraft compliance dates for replacement or retrofit of non-Part 36 aircraft. The precise effect of airline aircraft acquisition programs on a specific airport would be difficult to determine; however, and the straight-line approach is reasonable public policy.

Monitoring Progress

Each Bay Area airport is equipped with a noise-monitoring system. Data recorded from these noise-monitoring systems can be used to prepare airport noise-contour maps either annually or semi-annually. Once these contours are developed, the number of dwelling units within the actual 65 CNEL contour can be counted (by using the computer-based technique discussed above) and compared with the number of dwelling units targeted for the airport in the noise-allocation process. If the actual measured count exceeds the desired count, further mitigation will be required.

INSTITUTIONAL ROLES

A complete explanation of the regional noise-allocation strategy is not possible without a discussion of the role of the various actors. A number of questions have been raised concerning this approach: Will the regional noise allocation really work? Have the Bay Area airports adopted this plan? What will be the impact on the airlines?

Airport Proprietor

Although this paper focuses on California airports and the regulation of noise through administrative procedures established by California, all airports throughout the country are potentially liable for personal injury or property damage resulting from airport noise. Noise-control programs are an important means for limiting airport liability and are of general interest for this reason. Airports can take reasonable and fair actions to limit their liability. This authority provides the backbone of the regional noise-allocation strategy. Regional noise allocations do not tell an airport how to reduce noise, just the overall objective.

Although a number of airports have projected future noise contours, they have not used the contours in the manner suggested in this paper; that is, for the purpose of setting specific, quantifiable noise-abatement objectives over a period of years. One major advantage to the airports is that the noise allocations can be related to noise monitoring data so that a continuous report on progress is available. A second advantage is that a variety of measures can be considered to meet the annual objectives, depending on local conditions. A significant, intangible benefit is that community relations can be vastly improved by having such a program.

The regional approach addresses cumulative noise exposure; however, a comprehensive airport noise-mitigation program needs to consider other irritating problems, such as noise in the late evening and extremely noisy aircraft whose single event levels are disruptive to residents who live in the area and to teachers and students in nearby schools. A more-comprehensive set of noise-control strategies may also be necessary if the noise reductions anticipated through the airlines' fleet reequipment program do not materialize. One measure available to the airport operator for controlling noise is the use of standardized aircraft noise-emission data to exclude the noisiest aircraft from an airport. A variation of this control measure--elimination of noisy aircraft from the late evening--will have a dramatic effect on the size of the noise contour and will offer a real measure of relief to persons who live around airports.

At the time of this writing, San Francisco International formally adopted a noise-mitigation program and a series of yearly noise budgets (11). San Jose Municipal has suggested a lower allocation for its airport due to community pressure to reduce airport noise levels. Since the noise allocation for San Jose airport may be reduced, the noise allocation for Oakland International would have to be increased to provide an equivalent noise capacity for the region. This possibility was anticipated in adopting a stepwise approach to establishing noise allocations for each airport. By starting with the airports that have the greatest noise problem (San Francisco and San Jose) and leaving the final adjustments for the airport with the least noise problem (Oakland), the total noise capacity of the region can be preserved.

Some legal protection from liability for noise damages might also be considered to provide both airlines and airports with incentives for accomplishing the noise-allocation program.

Communities

The regional noise-allocation strategy primarily addresses the airport side of the noise problem by concentrating on the amount of noise that will be generated at each airport and how this noise can be controlled. Most communities in the Bay Area now understand that noise levels may be reduced but airport noise will not disappear and airports may not get appreciably quieter. The regional noise-allocation strategy helps communities understand the role of each airport in the regional airport system and the magnitude of the residual noise impacts once airlines have retired their noisier aircraft. Implicit in the regional noise allocation is a sharing of responsibility for noise problems between the community and the airport. Once the airport has agreed to do its fair share in reducing noise, local communities need to help plan methods for preventing new incompatible land uses and for correcting existing incompatible land uses. Correction of existing incompatible land uses is a lengthy process and can take several forms: removal of homes, sound insulation, voluntary relocation assistance, or purchase of noise easements. Regional agencies have encouraged the airports and communities to jointly prepare a program for continuing remedial action in the airport noise-impact area. Legislative changes may be necessary to mandate more-effective land use planning in the airport environs.

Bay Area communities like the regional noise-allocation concept because it is easily understood and because the progress of the airports in controlling noise can be monitored through the preparation of periodic noise-contour maps. Communities have become involved in the establishment of the noise allocations (a) to ensure that all reasonable operational controls are evaluated by the airports and (b) to protect their interests if it appears that noise will be shifted from one community to another.

A recent joint study that involves the San Francisco airport (which is located in San Mateo County) and the cities in San Mateo County resulted in a noise-allocation program that exceeds the regional objective (11).

Airlines

Airlines that serve the Bay Area have a major investment in airport facilities and their aircraft fleets. The regional noise allocation provides sufficient noise capacity for new carriers to enter the Bay Area, for existing carriers to expand service, and for carriers to continue to operate during most hours of the day--provided the airlines continue to invest in new, quieter aircraft. Due to national economic problems and the current slowdown in air travel, noise levels at all Bay Area airports are significantly below their annual allocations. At San Francisco airport, for instance, the number of dwelling units in the 65 CNEL contour is 40 percent lower in 1981 compared with 1980.

As traffic increases in the future, the noise allocation will come into play at various times at each airport. The airlines could continue to concentrate service at San Francisco airport by collectively agreeing to undertake more-extensive forms of noise mitigation. If San Francisco airport is unsuccessful in negotiating additional mitigation measures with the airlines, unilateral actions could be considered to reduce airport noise levels to the yearly allocation. For example, one action might be to prohibit noisier aircraft (based on manufacturer certification data) from using the airport. Carriers that have such aircraft could use them at other Bay Area airports, provided those airports had not exceeded their own noise budgets.

Federal Agencies

Based on past experience, FAA and Civil Aeronautics Board (CAB) have expressed concern when an airport's noise restriction policy (a) placed a significant burden on interstate commerce, (b) was unreasonable, (c) discriminated against a particular carrier or group of carriers, or (d) preempted federal authority. The regional airport noise-allocation strategy avoids all of these concerns. In particular, the regional noise-allocation strategy deals directly with the noise issue and avoids limiting access to Bay Area airports by new or incumbent carriers for arbitrary reasons.

Regional Agencies

The success of the regional noise-allocation strategy in achieving regional air service objectives depends on the persuasive power of the regional agencies to convince the Bay Area airports to adopt a coordinated set of noise budgets. The trend in current noise control debates at most airports is to seek reductions in airport noise below current levels. The regional noise-allocation strategy, therefore, involves a difficult and politically sensitive process of building consensus for increased noise at some airports (Oakland and San Jose) while noise is reduced at San Francisco airport.

Regional interest in having the individual airports adopt the noise budget concept as a noise management tool is strong. Regional agencies may become involved in the granting of variances to the Bay Area airports. The noise variance process in California provides for public hearings on whether or not a variance should be granted to an airport that is not in compliance with the airport noise standards. A further part of the variance process is to determine what conditions, if any, should be attached to the variance. Regional agencies will vigorously support the granting of a variance when an airport demonstrates that it is achieving its noise-allocation objectives. Alternatively, the regional agencies will argue for more-stringent conditions to be included in the variance if sufficient progress is not being achieved.

CONCLUSION

This paper has outlined the major elements of a regional noise-allocation program that provides an areawide approach to development of airline service and airport noise control. Future experience will determine the success of this concept. The methodology is straightforward and requires only the monitoring of noise levels on an annual or semi-annual basis and a comparison of actual noise impacts with the annual noise allocations. The approach relies on the proprietary powers of the three Bay Area airports to achieve the desired results. It is easily understood by local communities and provides considerable flexibility to the airports in determining how to meet the annual objectives. In addition, this approach has significant merit as a noise-management tool--not just for a regional system of airports, such as the Bay Area, but for individual airports in other parts of the country as well.

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Comparison of Irritation Caused by Noise Generated by Road Traffic and Aviation Traffic

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Acoustic measurement methods are necessary in order to measure noise objectively. On the other hand, the use of decibel values to determine the degree to which persons subjectively perceive noise to be disturbing is a distortion because no acoustic measurement methods can objectively reflect how persons perceive noise. In light of this, one is justified in wondering whether dB(A) measurement can possibly account for the level of discomfort that intervals of quiet or noise cause to humans. The answer can be found if one compares the effects that two sources of noise that have the same dB(A) but different intervals of quiet between the noise have on persons exposed to the noise. In this paper, two different sources are discussed—noise generated by road traffic (which is continuous noise) and noise generated by aviation traffic (which is noise interspersed with longer or shorter periods of quiet). For our study a sample group of persons was first exposed to noise caused by aircraft traffic and then to noise caused by road traffic; the dB(A) for both was the same. The test persons then filled out questionnaires that dealt with their reactions to these different sources of noise. A laboratory situation was deliberately avoided, since this can never be comparable to the actual conditions found in real-life situations and, thus, necessarily results in errors. The hypothesis of the study—that the same dB(A) can be very differently perceived by persons when the source of the noise is different—was clearly proven to be true. Not only were a greater number of persons irritated by noise from road traffic than by aircraft noise, but the perceived degree of disturbance was also more intense. The study discussed here was a pretest that used a sample of only 107 persons and could not take into consideration the long-term effect of their past experiences with noise.

A whole spectrum of social scientific and acoustic studies explain and analyze specific aspects of the problem of noise as an environmental pollutant. These studies usually deal with the irritation to persons who are exposed to noise daily or, at least, regularly. Thus, noise is directly dealt with; that is, persons who have been exposed to noise over a long period of time are studied, and the sample group usually knows that its reactions to noise are being tested. The present study, sponsored by the German Federal Office of Environment (1) was structured so that test persons would be exposed to noise generated by road traffic and by aviation traffic on the same day. (This was to ensure that the results be as comparable as possible.) The conditions under which the persons experienced the different types of noise were also to be as similar as possible. However, this approach, like most approaches, had its limits. The experiment was restricted to one day (literally, since it was impossible to do the testing at night) and previous experiences with noise of the test persons were, initially, ignored.

The design of the study required that a number of factors be taken into consideration:

1. Test persons had to be selected irrespective of any experiences that they had had with noise,
2. Test persons were not to know what the purpose of the study was since this knowledge would sensitize them to noise and would influence the results of the study, and
3. Test persons needed to be studied under controlled conditions in which a specific routine had been established and in which conditions were not totally different from those at home or at work.

Since this type of comprehensive standardization of the external conditions and daily routine is somewhat problematical, the requirements for the methodological design of the social scientific study were thus very specific.

METHODOLOGICAL DESIGN

It was of utmost importance that the following be clarified:

1. Type and structure of activities for the periods in which the test persons were exposed to noise,
2. Composition of the sample,
3. Choice of survey methods,
4. Length of time exposed to noise, and
5. Size and sociodemographic composition of the group of test persons on each of the six sampling days.

Furthermore, a fundamental question needed to be answered, Should the test persons be informed about the purpose of the study or should the study be done as a blind analysis?

The pros and cons of telling the test persons the reason for the study were considered. Both alternatives had definite advantages and disadvantages; therefore, the two alternatives were combined and tested. The first study of exposure to noise (which took place in the morning) was done as a blind analysis. In the second exposure to noise (in the afternoon), the test persons knew that noise was relevant to the study because they had to fill out a questionnaire at noon that contained questions concerning the effect that the noise in the morning had on them.

However, the purpose of the study was deliberately never explicitly explained to the test persons. However, as was desired, all of the test persons did make use of the lunch break to talk with each other about noise.

This approach made it possible to determine whether, and to what degree, being informed about the goal of the study had an effect on the responses made by the test persons. In order to compare results with that of a control group, the entire group was divided into two. The one half began in the morning in the room exposed to road traffic noise; the other half began in the room exposed to aircraft noise. This made an analytical observation of subsample groups possible. The following table is a schematic depiction of the course of events as they occurred:

	Sequence of Traffic Noise	
Day	Morning	Afternoon
1	Road	Aviation
2	Road	Aviation
3	Aviation	Road
4	Road	Aviation
5	Aviation	Road
6	Aviation	Road

The sample was split into groups that were to come on different days. The groups were approximately the same size and their sociodemographic characteristics were comparable. The approach selected ensured that those errors that could result from exposure to one source of noise before exposure to another source of noise would be eliminated.

The definition of specific activities and times for these activities was as important as the decision about whether test persons should be told the reasons for testing. Thus, two similarly structured sets of activities were designed for the persons to participate in while they were exposed to the noise generated by the two different sources. The course of the two sets of activities had to be similar in content, time, and chronological order. This was a necessary prerequisite if the actual perception of noise and the perception of the irritation caused by the noise in the two different rooms was to be compared directly.

The design of a differentiated series of activities had to comply with the following requirements:

1. The activities had to be somewhat similar to activities that might take place at home or at work,
2. The activities should make it possible to measure perception of noise by persons involved in a broad spectrum of activities that are perceived differently by the individuals and result in a variety of emotional and vegetative states, and
3. Boredom was to be avoided.

Activities needed to be varied and call for different responses--physical exercise and mental concentration, passive reception and action, individual activities, and group activities. The chronological sequence of the activities had to be logically structured. A specific amount of time was to be spent on each activity. The length of time spent on different activities should also not be too divergent, since the amount of time spent on an activity is related to the way in which an activity is perceived.

The planning of the activities was somewhat difficult because, for methodological reasons, the activities in the morning and afternoon had to be as similar to one another as possible and the mental states of the persons in response to the activities also had to be the same for the different activity sets. However, a physiological given is that persons tend to be a bit drowsy after lunch. Therefore, an after-lunch pep pill was served. The second half of a Hitchcock thriller (A Lady Disappears, 1938) was shown after lunch; the test persons had seen the first half of the film in the morning.

The entire day's program was carefully structured to induce specific physical and mental states. The activity program used is depicted below. Included are the times for different activities and the times when the questionnaires were presented. Although the times fluctuated a bit, they were basically adhered to.

8:55 a.m. Greeting; persons were told where to sit for the remainder of the session;
9:05 a.m. Film, part 1;
9:50 a.m. Exercise break;
10:10 a.m. Questionnaire 1;
10:25 a.m. Break;
10:45 a.m. Drawing and writing task on dream house;
11:25 a.m. Music played (a record);
12:00 p.m. Questionnaire 2a;
12:20 p.m. Questionnaire 2b;
12:35-2:15 p.m. Communal lunch, then drive to second test room;
2:15 p.m. Film, part 2;
3:00 p.m. Exercise break;
3:20 p.m. Questionnaire 3;
3:35 p.m. Break;
3:55 p.m. Essay and sketch on conserving energy;
4:35 p.m. Music played (a record);
5:10 p.m. Questionnaire 4;
5:25 p.m. Questionnaire 5; and
5:40 p.m. Farewell; test persons driven back to meeting place.

The daily program consisted of six activity blocks in the morning and six activity blocks in the afternoon. Type of activity, time of activity, and order of activities was the same in the morning and in the afternoon.

The study used written questionnaires. This made it possible to question all of the test persons simultaneously directly after a certain activity had taken place. The written questionnaires also guaranteed that the responses would not be influenced by the interviewers. In an area as soft and sensitive as noise perception, it is especially important that the possibility that the interviewers might bias the responses is avoided. The experiment leader and an assistant were trained to avoid influencing the responses under all conditions. In order to reinforce the data supplied in the questionnaires, the respondents were also carefully observed for any noise-related behavior they might show.

An average of 18 test persons were in each group. The largest group consisted of 21 persons and the smallest group consisted of 15 persons. Group size is important because, if the group is too small, the members of the group will interact with one another and with the group leader. However, a large group of persons will produce its own background noises. This might interfere with the perception of background noises. Also, in a large group, the situation is hardly comparable with an average person's home or work situation.

The length of exposure to the source of the noise was directly related to the time available. Thus, in the given experiment, three hours were available in which persons participating in carefully structured activities could be exposed to a particular type of noise.

The different activity blocks lasted a minimum of 15 min in order to give the test persons enough time to register the activity and their perception of the noise to which they were exposed during this activity. The maximum time block was limited to 45 min to ensure that boredom would not set in.

The sociodemographic composition of the sample was carefully selected in order to ensure that the sample was as similar as possible to the population as a whole; only the very young were excluded. The desired sociodemographic structure was nearly attained (see Table 1).

SUMMARY OF RESULTS

Even when the dB(A) level is the same, the table below shows that the degree to which persons are irritated by noise generated by aviation traffic and by noise generated by road traffic is different. This is because different types of noise are perceived differently, and this noise perception cannot be measured by measuring dB(A).

	Perception of Test Persons (%) (n = 107)	
Classification	Noise Generated by Aviation Traffic	Noise Generated by Road Traffic
Very great nuisance	24	40
Great nuisance	28	42
Nuisance	42	17
Hardly or not a nuisance	6	1

In identifying those factors that determine the degree to which noise is perceived to be irritating, factors that have to do with the source of the noise and factors that have to do with the respondents themselves must be differentiated. This is of primary interest here--the existence or lack of periods of quiet between periods of noise is important when studying the effect that noise sources have on persons. The majority of the test persons responded to periods of quiet positively (i.e., it reduced the irritation caused by the noise). Only a minority of persons perceived irregular sources of noise, rather than steady noise, to increase the irritation effect of noise. However, for persons who were particularly sensitive to noise, it was irrelevant whether the noise was interspersed with periods of quiet or not. These persons were equally irritated by both sources of noise.

Noise Disturbance of Test Persons	Perception of Nuisance Effect (%)		
	Morning (n = 49)	Afternoon (n = 58)	Total (n = 107)
More by aviation traffic	14	21	18
More by road traffic	78	67	73
Equally by aviation and road traffic	6	10	8
Not by either aviation or road traffic	2		1

A differentiation of different sources of noise showed the main factors that influence noise perception

Noise Perception of Test Persons	Noise Generated by Aviation Traffic (%) (n = 106)	Noise Generated by Road Traffic (%) (n = 106)
Noise increased	6	21
Noise decreased	11	
Noise occasionally increased and occasionally decreased	69	36
Noise stayed the the same	9	42
No response	5	1

Thus, the following cause particular irritation when noise is generated by aviation traffic (see Table 2):

1. Intensity of the noise, especially since it is possible to compare the periods of sudden noise with intervals when it is quiet;

Table 1. Number of test persons in sample.

Day of Sampling	Number of Test Persons: Percent	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Ideal No.[a] (%)
Age								
15-18	6	2	1	2		2		6
18-21	7	1	2	1	1	2	1	6
22-45	44	7	8	10	13	6	3	42
46-60	17	5	4		3	3	3	22
61-65	6		2		2	1	1	5
65 and over	20	3	2	4	2	3	7	19
Total		18	19	17	21	17	15	
Sex								
Male	57	13	11	12	12	9	4	53
Female	43	5	8	5	9	8	11	47
Total		18	19	17	21	17	15	
Occupation								
Employed or now unemployed	42	7	7	9	13	5	4	42
Housewife	20	5	3	3	4	5	2	20
School	15	3	4	3	1	4	1	19
University	2		1		1			2
Retired	20	3	4	2	2	3	8	17
Total		18	19	17	21	17	15	

Note: Sampling was done from November 6 to November 13, 1979.

[a]According to secondary statistics.

Table 2. Description of noise.

Reason for Disturbance	Responses to Aviation Traffic (%) (n = 17)[a]	Reason for Disturbance	Responses to Road Traffic (%) (n = 56)[a]
Noises were very loud	35	Never a minute's peace, constant background noise	48
Noise makes one afraid, nervous, sick, startled; difficult to concentrate; one feels like screaming, cursing, closing one's ears	35	Noise volume and type vary, multiply, and are so different (screeching brakes, acceleration, blowing horns, big trucks)	34
Noise comes suddenly	29	Noise makes one feel afraid, helpless, aggressive; cannot concentrate	21
Roar, boom, thunder, fizzle, whiz	23	Noise always equally loud, monotonous	5
Noise come so quickly and unexpectedly	6	Noise is very loud	4
Noise increases, decreases, echoes	6		
Total	134	Total	112

[a]Multiple responses given.

Table 3. Activities during noise exposure.

Responses	Comparison of Degree to Which Noise Perceived to Be a Nuisance: Exposure to Aviation Traffic (%): Persons More Disturbed by Aviation Traffic (n = 19)	Exposure to Aviation Traffic (%): Persons More Disturbed by Road Traffic (n = 78)	Exposure to Road Traffic (%): Persons More Disturbed by Aviation Traffic (n = 19)	Exposure to Road Traffic (%): Persons More Disturbed by Road Traffic (n = 78)
While film was playing				
Very great	37	14	5	32
Great	42	32	32	39
Total	79	46	37	71
While exercising				
Very great	10	1	0	3
Great	0	6	5	9
Total	10	7	5	12
While questionnaire was filled in				
Very great	21	5	0	20
Great	26	14	21	39
Total	47	19	21	59
During coffee break				
Very great	21	3	0	4
Great	16	3	11	13
Total	37	6	11	17
While drawing or writing				
Very great	21	3	10	8
Great	21	13	11	44
Total	42	16	21	52
While music was playing				
Very great	32	17	37	61
Great	37	37	26	31
Total	69	54	63	92

2. Character of the noise (slowly increasing sound volume, loud noise, decreasing volume, sound echoes); and
3. Effects such as fear or that persons are startled by the sudden noise.

When noise is generated by road traffic, the following cause particular irritation (Table 2):

1. Consistency of the noise, since there are no intervals when it is quiet;
2. Effect of different types of noise and different sound volumes; and
3. Problems such as not being able to concentrate even a moment because the noise never lets up.

An analysis of the relation between irritation caused by noise and activity in which a person is involved showed the following (see Table 3):

1. During recreational periods (e.g., coffee break, exercise periods), the irritation caused by noise is minimal;
2. Purely acoustic occupations (such as listening to music) are affected the most severely by noise; during these activities road traffic noise was considered to be much more irritating than aircraft noise;
3. Activities in which acoustics and optics were combined (e.g., the movie) are affected by road traffic noise more than by aircraft noise;
4. In activities that require mental concentration (e.g., drawing, describing a problem), noise caused by road traffic is perceived to be more irritating than noise generated by aviation traffic; and
5. For all types of activities, persons generally perceive that type of noise to be more irritating to which they are basically more sensitive.

A study of the effect that prior experiences with noise at work and at home had on the present perception of noise is shown in the following in-text table and Table 4.

Table 5. Socioeconomic characteristics of test persons.

Characteristic	Disturbance (%) More by Aviation Traffic (n = 19)	More by Road Traffic (n = 78)	Equal (n = 9)	Total (n = 106)
Sex				
Male	52	41	56	44
Female	48	59	44	56
Age				
18-21	23	65	12	
22-45	13	76	11	
46-60	19	76	5	
>61	22	74	4	
Education				
Grammar school	50	24	11	27
High school diploma or better	50	76	89	73
Total	18	74	8	

Table 4. Comparison of test noise with noise in usual environment.

Perception	Disturbance (%) Total (n = 106)	More by Aviation Traffic (n = 19)	More by Road Traffic (n = 78)	Equal (n = 9)
Aviation traffic in comparison with usual environment				
Much louder	44	90	33	45
Somewhat louder	18	0	22	22
Just as loud	10	0	13	11
Somewhat quieter	9	0	12	0
Much quieter	13	5	14	22
No response	6	5	6	0
Road traffic in comparison with usual environment				
Much louder	55	37	59	56
Somewhat louder	8	16	5	11
Just as loud	11	16	9	11
Somewhat quieter	3	5	3	0
Much quieter	9	16	6	22
No response	14	10	18	0

Table 6. Perceptions of test persons.

Perception	Disturbance (%) More by Aviation Traffic (n = 19)	More by Road Traffic (n = 78)	Equal (n = 9)	Total (n = 106)
Sensitive to noise				
Yes	42	61	67	58
No	58	39	33	42
Too little or nothing is being done				
To reduce noise from aviation traffic	63	63	67	63
To reduce noise from road traffic	69	76	78	74
Noise from aviation traffic is unhealthy				
Yes	84	53	89	61
No	16	47	11	39
Noise from road traffic is unhealthy				
Yes	63	85	89	86
No	37	15	11	14

Table 7. Results of technical noise level measurements for aircraft noise area and road traffic noise area.

Measurement Area	Outside Measurement [dB(A)] L_{AFm}	L_1	L_{95}	Inside Measurement [L_{AFm} dB(A)] Window Closed	1 Window Open	1 Window Tilted	2 Windows Tilted
Aircraft noise							
Area 1	72.3					53.3	56.0
Area 2	57.4					43.2	46.0
Area 3[a]	70.1					52.5	55.0
Road traffic noise							
Area 1	72.2	77.3	63.0	53.0[b]	60.5		
Area 2[a]	71.4	76.6	62.0	44.8	57.5	52.2	
Area 3	72.2	77.3	62.8	50.6	60.8		

[a]Selected noise area.
[b]Volume is 1-2 dB(A) too high because, on the testing day, extra noise was created by road construction.

At Work-place	Response to Study (%) More Disturbed by Aviation Traffic (n = 19)	More Disturbed by Road Traffic (n = 78)	Equally Disturbed (n = 9)	Total (n = 106)
Disturbed by aviation traffic	32	19		20
Not disturbed by aviation traffic or not employed	68	81	100	80

Prior experiences with aircraft noise at work increased the sensitivity to such noise. Prior experiences at work with noise generated by road traffic increased sensitivity to such noise only minimally. If a person is exposed to much noise at his or her place of work, he or she is generally less sensitive to noise generated by road traffic (see table below):

Response to Study	Respondents (%) Exposed to Noise at Workplace (n = 20)	Total (n = 106)
More disturbed by aviation traffic	20	18
More disturbed by road traffic	65	74
Equally disturbed	15	8

In general, prior experiences with noise at home cause a person to be less affected by the noise generated by sources to which he or she is frequently exposed. Persons who have prior experience with aircraft noise react to aircraft noise, as well as to noise generated by road traffic, more than do persons who have prior experiences with road traffic noise. Prior experiences with aircraft noise result in a stronger sensitivity toward aviation traffic noise than does prior experiences with road traffic noise to road-traffic-generated noise.

An analysis of sociodemographic variables is given in Table 5. In general, women perceive noise generated by road traffic to be much more irritating than do men. Youngsters are less sensitive to road traffic noise than are other age groups. The elderly are more irritated by aircraft noise than are other age groups. Persons without formal higher education are more irritated by aircraft noise than are persons who have higher degrees.

Table 6 gives attitudes to noise pollution policies. It shows that persons who consider themselves to be sensitive to noise are relatively more irritated by noise generated by road traffic than by noise generated by aviation traffic. The belief is widespread that less is done to deal with noise generated by road traffic than with aircraft noise. However, a relation between this opinion and the degree to which different noise sources were considered to be irritating could not be established. When the dB(A) is the same, the noise caused by road traffic is considered to be more irritating than aircraft noise. Persons consider that source of

Table 8. Aircraft noise area.

Date (1979)	Time	L_{AFm} [dB(A)]	Noise Without Street Construction[a] [dB(A)]
Nov. 6	2:00-5:30 p.m.	72.3	72.0
Nov. 7	2:00-5:00 p.m.	76.1	74.0
Nov. 8	8:30 a.m.-12:00 p.m.	72.4	71.5
Nov. 9	2:00-5:00 p.m.	75.0	
Nov. 12	8:45-11:45 a.m.	74.5	
Nov. 13	9:00 a.m.-12:00 p.m.	70.9	
Energetic mean		73.9	73.3

[a]Estimated by using results of trial measurement.

Figure 1. Road traffic noise area 2.

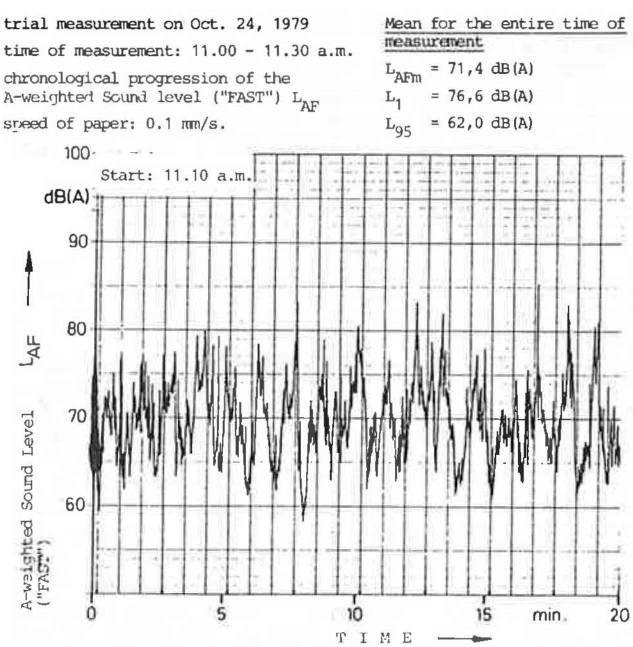
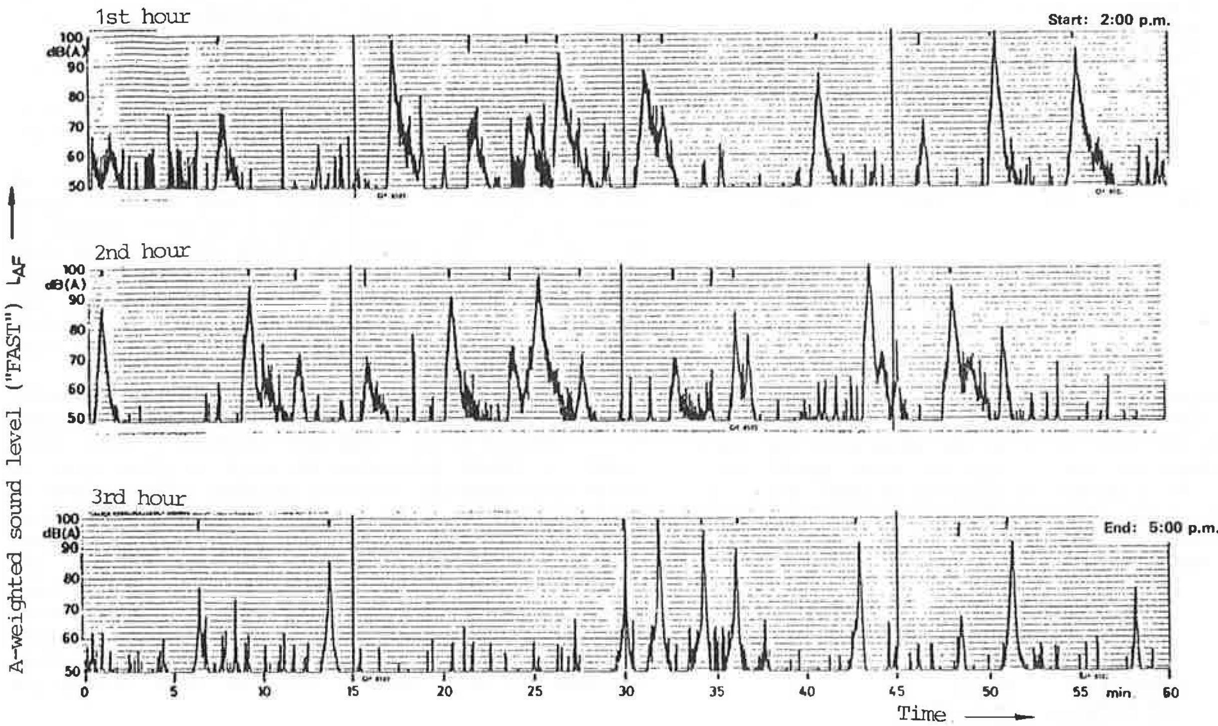


Table 9. Calculation and measurement for road traffic noise area 2.

Date (1979)	Time	Vehicles per Hour[a] n_{PKW}	n_{LLKW}	n_{SLKW}	Measurement Value [dB(A)][a] L_m	L_1	L_{95}
Nov. 6	10:35-10:50 a.m.	1668	176	48	71.7		
Nov. 7	9:35-9:40 a.m.	1696	244	36	72.1		
Nov. 12	3:00-3:30 p.m.	1872	164	22	71.3		
Nov. 13	3:00-3:30 p.m.				71.7	77.8	63.0
Oct. 24[b]	11:00-11:30 p.m.				71.4	76.6	62.0

Note: Calculated equivalent sound level of long-term counts is 71.5 dB(A).
[a]See Equation 1 (2). [b]Trial measurement.

Figure 2. Aircraft noise area 3.



4th sample: 11/9/79; time of measurement: 2:00-5:00 p.m.; and chronological progression of the A-weighted Sound level ("FAST") L_{AF} speed of paper: 0.1 mm/s.

noise to be more unhealthy, which generally irritates them more.

Finally, we should once again emphasize that these results were obtained by using a very small sample of only 107 persons. The study was a pretest and the results must be tested again with a larger sample.

OVERVIEW OF TECHNICAL NOISE LEVEL MEASUREMENTS

A detailed description of technical noise level measurement was deliberately avoided in this study. However, some of the basic information pertinent to such measurement is summarized below for those who might be interested in the technical measurement techniques that were used (1). The measurements were done by a group of specialists (Müller BBM Company) under the direction of Rüdiger Wettschureck, who has much experience in the field. First, three different areas were selected to study noise generated by road traffic and three different areas were selected to study noise generated by aviation traffic. In each of these areas, three different values were measured: the outside decibel, A-weighted, equivalent sound level, measured with time constant fast (L_{AFm}), the sound volume L_1, which was exceeded 1 percent of the time while the measuring was being done, and the sound volume L_{95}, which was exceeded 95 percent of the time while the measuring was being done. The results of the measurements are summarized in Table 7.

While the social scientific tests were taking place, the noise made by aircraft was measured continuously. For noise generated by road traffic, on the other hand, some of the values were measured, but others were calculated. The calculation was done by using a formula that had been developed in a special study that took 400 measurements of the dB(A) in urban streets (2):

$$L_m = 32.2 + 10 \log(n_{PKW} + 8 \cdot n_{LLKW} + 20 \cdot n_{SLKW}) + 10 \log(25/S) + \Delta L_F \quad (1)$$

where

L_m = equivalent sound level (L_{eq}) dB(A),
n_{XXX} = number of vehicles that belong to class XXX per hour,
PKW = all vehicles with two axles that weigh less 2.8 tons,
LLKW = trucks that weigh between 2.8 and 9 tons and buses,
SLKW = trucks that weigh more than 9 tons and agricultural tractors,
S = distance from middle of the road (m), and
ΔL_F = facade correction, ΔL_F = 2.5 dB(A) in front of a facade.

The results of these measurements and calculations are shown in Tables 8 and 9. In order to depict the exact noise volume, the records of two measurements are depicted as an example in Figures 1 and 2.

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Enhancement of Highway Noise Modeling Through Computer Graphics

LOUIS F. COHN, LEONARD W. CASSON, AND WILLIAM BOWLBY

Predictive modeling of highway noise has evolved dramatically in recent years. Current state-of-the-art models require extensive use of three-dimensional (X, Y,Z) coordinate data to represent roadways, barriers, and receivers. Introduction of incorrect data is all too common when such models are used because of the need to transfer information from maps to coding forms to computer files. To overcome these problems, the Vanderbilt University Transportation Research Group has developed an interactive computer graphics program, VUPLOT, designed to plot coordinate data in plan (X,Y) or profile (X,Z) view. One subroutine of VUPLOT permits the plotting of STAMINA-type input files or the selective plotting of roadways, barrier, or receiver files. Another subroutine overwrites roadway segment noise level contributions to the overall L_{eq} value at a particular receiver on a plan view plot of the prediction scenario. This paper discusses in detail the interactive use of VUPLOT and its subroutines.

Within the past 10 years, advances in software development have paralleled the significant growth in the sophistication of highway noise-prediction models (1). Opportunities for the noise analyst manifest themselves in the refinement, level of detail, efficiency, and overall accuracy achievable through such computer programs as STAMINA 1.0 (2) and STAMINA 2.0 (3). The advances also created problems for the analyst, primarily related to data management. Because of the complexity of the models, thousands of separate pieces of input data may be required to represent a given highway configuration. With such large numbers of input data values, two separate but equally significant problems inevitably come about: input errors and analyst disorientation.

Three opportunities exist for the accidental introduction of errors into an input file:

1. When reading coordinates from plans,
2. When coding coordinates onto forms, and
3. When typing data into the computer.

In using either of the STAMINA versions, input errors can be troublesome because, for fatal errors, error messages are unable to pinpoint bad coordinates. This can result in a kind of hit or miss, time-consuming debugging process. For nonfatal errors, use of either version of STAMINA can prove disastrous because execution will proceed and erroneous noise levels will be generated.

While attempting to maintain control of extensive data bases, it is not uncommon for the analyst to lose the ability to visualize or conceptualize input and output. Figuratively speaking, the analyst may become awash in a sea of numbers. Once the orientation of the numbers is lost, judgmental errors are possible.

Various members of the Vanderbilt University Transportation Research Group (VUTRG) have had extensive experience in using the STAMINA models on complicated highway projects and have often fallen victim to both of the problems discussed above. In its efforts to eliminate both problems and in its desire to significantly advance the state of the art in highway noise modeling, VUTRG has developed an interactive computer graphics package for plotting STAMINA and STAMINA-type input and output data in several forms. The package is the Vanderbilt University Plotting Package, called VUPLOT.

VUPLOT

VUPLOT is an independent FORTRAN computer program that allows the user to access two main graphics subroutines, SCHEME and LEVEL. SCHEME plots coordinate input data for STAMINA in plan (X,Y) or profile (X,Z) view, by using either a standard, complete STAMINA input file or a file that contains only a list of roadways, barriers, or receivers. LEVEL plots a plan view (X,Y) of selected roadways showing noise level contributions by individual segment at a selected receiver.

On execution of VUPLOT, the computer writes

```
STAMINA PLOTTING ROUTINES

YOU MAY:
    GENERATE A SCHEMATIC PLOT        (ENTER -1)
    GENERATE A NOISE LEVEL PLOT      (ENTER 1)
    END PLOTTING PROCEDURE           (ENTER 0)

TYPE OF PLOT:
```

To activate the SCHEME subroutine, the appropriate response is -1. The computer responds with

```
YOU MAY PLOT SELECTIVELY (PLOTTING ITEMS OF YOUR
CHOICE) OR FROM A SPECIFIC DATA FILE.

DO YOU WISH TO PLOT FROM A SPECIFIC FILE? (YES):
```

Should the analyst desire to plot a STAMINA input file, he or she simply hits carriage return to default to yes. This type of plot is often used when the analyst wishes (a) to examine the plan or profile orientation; (b) to examine interrelations among roadways, barriers, and receivers; or (c) to prepare a graphical illustration of the prediction scenario.

In the plotting of the specific file (i.e., defaulting the above question) the computer next writes,

```
PLEASE ENTER THE NAME OF THIS FILE:
```

The response to this would be something like RUN2B.DAT, where RUN2 may indicate the second in a sequential set of prediction scenarios and B may indicate the second modification of RUN2. The DAT simply reminds the analyst that the file is an input data file.

After the analyst enters the file name, the computer asks,

```
TO WHICH FILE SHOULD THIS DATA BE OUTPUT?
(PLOT.PLT):
```

Default to this question sends the output data to the general plotting file named PLOT.PLT. Reexecution of VUPLOT later will cause PLOT.PLT to be written over, so if the analyst desires to save a plot, he or she should create a new output file, such as RUN2B.PLT. In either case, the data in this output file are in such a format as to be suitable for use with the CALCOMP plotting system used by Vanderbilt.

Next, the computer writes,

ENTER SCALE: 1 INCH = FEET (250):

The default is 250 ft equals 1 in. Scale is only important when the analyst desires to obtain a hard copy printout of the plot. The computer then asks,

DO YOU WISH TO VARY THE HEADING SIZE WITH THE PLOTTING SCALE? (NO):

Default to this question causes the heading characters (e.g., titles and numbers) to be 0.3 in high, both on the cathode ray tube (CRT) screen and in the hard copy. For purposes of report preparation, it may be advantageous to alter this dimension.

The next command from the computer requires that the analyst select either plan or profile plotting,

ENTER AXES TO BE PLOTTED, SEPARATED BY A COMMA (X,Y):

Default to this command will result in a plot of the plan view of the scenario. The only other response acceptable to the computer is X,Z, which results in a profile or elevation plot. For a profile plot (X,Z) one additional question must be addressed,

BY WHAT FACTOR DO YOU WISH TO EXPAND THE VERTICAL AXIS SCALE IN TERMS OF THE HORIZONTAL AXIS SCALE? (10):

The analyst will ordinarily default to this question so that the vertical axis will be expanded tenfold with respect to the horizontal axis. Otherwise, it would be difficult to perceive subtle changes in elevation. One situation where the analyst will want to use no expansion for the vertical axis is when he or she seeks a profile plot of the top of a barrier. This could be accomplished by deleting all but one roadway and the barrier in question and expanding the plotting scale to 50 ft equals 1 in or 100 ft equals 1 in. Representation of the barrier's top geometrics will then be excellent.

When plotting either plan or profile, the next question asked by the computer is,

DO YOU WISH TO USE MULTICOLOR PLOTTING? (YES):

A default to yes on this question will cause the hard copy plots to show the roadways in black, the barriers in green, and the receivers in red. Headings will still be in black. Multicolored plots are especially useful in complex scenarios that include large numbers of roadways, barriers, and receivers.

By using the coordinate data entered via the input file, along with the plotting scale in feet per inch entered in response to a previous question, the computer will calculate internally the width of the vertical axis and print

THE VERTICAL AXIS IS XX. INCHES LONG

where XX is the length as determined by the computer. This information is helpful in two cases. First, when the plot is viewed on the CRT screen, the maximum height of the vertical axis is 7 in, so it may be necessary to increase the scale before executing the program that actually draws the plot on the screen (TEKPLT). Second, the drum plotter used to generate hard copy plots can print on either 15- or 36-in paper. Knowledge of the maximum vertical dimension will help the analyst to select the appropriate paper width.

The final three questions in the SCHEME subroutine of VUPLOT pertain to labeling:

DO YOU WISH TO LABEL THE ROADWAYS? (YES):
DO YOU WISH TO LABEL THE BARRIERS? (YES):
DO YOU WISH TO LABEL THE RECEIVERS? (YES):

A default on these questions will cause the programs to print the names of the roadways, barriers, and receivers, as given in the comment section of the STAMINA input data.

At this point the plot has been created and stored in the output file (i.e., PLOT.PLT or RUN2B.PLT). In order to view the plot on the CRT screen or obtain a printed copy, the analyst must engage the program TEKPLT or PLOT, respectively.

Selective Plotting for SCHEME

A most important feature of VUPLOT is its ability to eliminate coding errors prior to STAMINA execution. This is accomplished by using a data storage file system that contains open-ended files for roadways, barriers, and receivers. On the Vanderbilt system these are named RDWYS.DAT, BARS.DAT, and REC.DAT, respectively. RDWYS.DAT may contain an unlimited number of roadways, complete with traffic data and speeds, suitable for STAMINA use. Similarly, BARS.DAT and REC.DAT may contain an unlimited number of barriers and receivers ready for STAMINA. When the analyst is prepared to make noise predictions, he or she simply copies the appropriate roadways, barriers, and receivers from RDWYS.DAT, BARS.DAT, and REC.DAT into a new file, inserts the other information required by STAMINA, and executes.

Use of the selective plotting feature of VUPLOT will allow the analyst to visually inspect the coordinates and identify miscoded points easily. After specifying SCHEME (TYPE OF PLOT: -1), VUPLOT states and then asks,

YOU MAY PLOT SELECTIVELY (PLOTTING ITEMS OF YOUR CHOICE) OR FROM A SPECIFIC DATA FILE.

DO YOU WISH TO PLOT FROM A SPECIFIC FILE? (YES):

To initiate selective plotting, this question is answered, no. The computer will then ask,

DO YOU WISH TO PLOT ANY ROADWAYS? (YES):

Unless the interest is only in barriers and receivers, default is usually the response to this question. The computer then asks,

HOW MANY ROADWAYS DO YOU WISH TO PLOT? (DEFAULT PLOTS ALL EXISTING ROADWAYS):

Since the roadways file RDWYS.DAT will likely contain a large number of roadways, the answer to this question will be an integer between one and the total number of roadways in the file. For example, to plot the first five roadways in the RDWYS.DAT file, the following dialogue would take place

HOW MANY ROADWAYS DO YOU WISH TO PLOT? (DEFAULT PLOTS ALL EXISTING ROADWAYS): 5

ENTER A DESIRED ROADWAY NUMBER (NUMBERS MUST BE ENTERED SEQUENTIALLY!): 1

ENTER A DESIRED ROADWAY NUMBER (NUMBERS MUST BE ENTERED SEQUENTIALLY!): 2

ENTER A DESIRED ROADWAY NUMBER (NUMBERS MUST BE ENTERED SEQUENTIALLY!): 3

ENTER A DESIRED ROADWAY NUMBER (NUMBERS MUST BE ENTERED SEQUENTIALLY!): 4

ENTER A DESIRED ROADWAY NUMBER (NUMBERS MUST BE ENTERED SEQUENTIALLY!): 5

Similar interaction then takes place for data in the barrier and receiver files (BARS.DAT and REC.DAT). For example, to include the fifth barrier in BARS.DAT and the third, eighth, and twelfth receivers in REC.DAT the dialogue would be

DO YOU WISH TO PLOT ANY BARRIERS? (YES):

HOW MANY BARRIERS DO YOU WISH TO PLOT? (DEFAULT PLOTS ALL EXISTING BARRIERS): 1

ENTER A DESIRED BARRIER (NUMBERS MUST BE ENTERED SEQUENTIALLY!): 5

DO YOU WISH TO PLOT ANY RECEIVERS? (YES):

HOW MANY RECEIVERS DO YOU WISH TO PLOT? (DEFAULT PLOTS ALL EXISTING RECEIVERS): 3

ENTER A DESIRED RECEIVER NUMBER (NUMBERS MUST BE ENTERED SEQUENTIALLY!): 3

ENTER A DESIRED RECEIVER NUMBER (NUMBERS MUST BE ENTERED SEQUENTIALLY!): 8

ENTER A DESIRED RECEIVER NUMBER (NUMBERS MUST BE ENTERED SEQUENTIALLY!): 12

Following this interaction, the same questions pertaining to output file name, scale, heading size, plan or profile axes, color, and labeling discussed earlier for SCHEME, are asked and answered.

Once the subroutine SCHEME has been used, the output file created, and the labeling decided on, the command

TYPE OF PLOT:

is again put forth. In order to initiate the subroutine LEVEL, the response to this command is 1. LEVEL allows the analyst to examine the contribution of individual roadway segments to the overall L_{eq} value at specific, individual receivers. This type of plot is valuable late in the design phase where barrier-top elevations are being finalized in an optimization procedure. This concept was originally developed by VUTRG in an earlier study (4), when such plots were hand drawn.

LEVEL Plotting

On initiating the subroutine LEVEL, the computer asks,

WHICH INPUT DATA FILE IS TO BE USED?:

The analyst responds with the name of the STAMINA input file he or she wishes to examine. For example: RUN2B.DAT. The computer then responds with

WHICH OUTPUT DATA FILE IS TO BE USED?

Because the program must correlate predicted segment noise levels with output plots, the answer to this question must match that of the previous question. That is, the output file specified must be the plot file created by the STAMINA input. For example, if the STAMINA file was RUN2B.DAT, the output file to be used in the plot must be RUN2B.PLT. This is because LEVEL writes over STAMINA-produced noise level segment data onto a plot of that STAMINA data.

After specification of the appropriate data file, the computer asks,

TO WHICH FILE SHOULD PLOTTING OUTPUT BE SENT? (PLOT.PLT):

As with the SCHEME subroutine, defaulting to this question will cause the output to be sent to the general plotting file named PLOT.PLT. Should the analyst desire to save the plot for later use, he or she should create a new output file. For example, an appropriate output file name for data generated from RUN2B.DAT and RUN2B.PLT would be LRUN2B.PLT, signifying a LEVEL plot of the data in those files.

The next three questions in the dialogue are identical to those discussed in the SCHEME subroutine. These are as follows:

DO YOU WISH TO USE MULTICOLOR PLOTTING? (YES):

ENTER SCALE: 1 INCH = FEET (250):

DO YOU WISH TO VARY THE SIZE OF THE HEADING WITH THE CHOSEN SCALE? (NO):

Since LEVEL plots segment noise level values at only one receiver, the computer asks,

ENTER RECEIVER NUMBER FOR WHICH LEVELS ARE DESIRED (1):

Defaulting to this question results in the calculation of levels for the first receiver in the STAMINA input list. Should the analyst desire levels for any other receiver, he or she simply inputs its number (sequence) from the STAMINA input list of receivers.

One problem with writing noise level values directly onto graphical plots is the likelihood of writing over numbers on those of adjacent segments and roadways. To solve this problem, the program allows the analyst to specify only those roadways for which he or she has an interest. For example, if only interested in roadways 4 and 5 from a STAMINA input file, the dialogue would appear as

HOW MANY ROADWAYS DO YOU WISH TO PLOT? (ALL): 2

NOTE: ROADWAYS ARE REFERENCED SEQUENTIALLY AS THEY APPEAR IN THE DATA FILE

ENTER DESIRED ROADWAY NUMBER: 4

ENTER DESIRED ROADWAY NUMBER: 5

Should the analyst desire to include all the roadways in the STAMINA input, he or she simply defaults to this question. Regardless of whether all of the roadways are plotted in the input file, the total L_{eq} value for all roadways is shown in the heading.

At this point, the output plotting file has been constructed and the execution of the LEVEL subroutine is completed. The command,

TYPE OF PLOT:

is once again given. To disengage VUPLOT, the analyst simply defaults.

Drawing Plots with VUPLOT

The Vanderbilt DEC1099 system works via file storage, retrieval, and editing. Since the output from both subroutines of VUPLOT (SCHEME and LEVEL) is in the form of files stored in the system, it is necessary to use separate programs designed to physically construct the plots. Two such programs are available. The first, TEKPLT, is for use with a remote

Figure 1. Plan view of example plot from VUPLOT subroutine scheme.

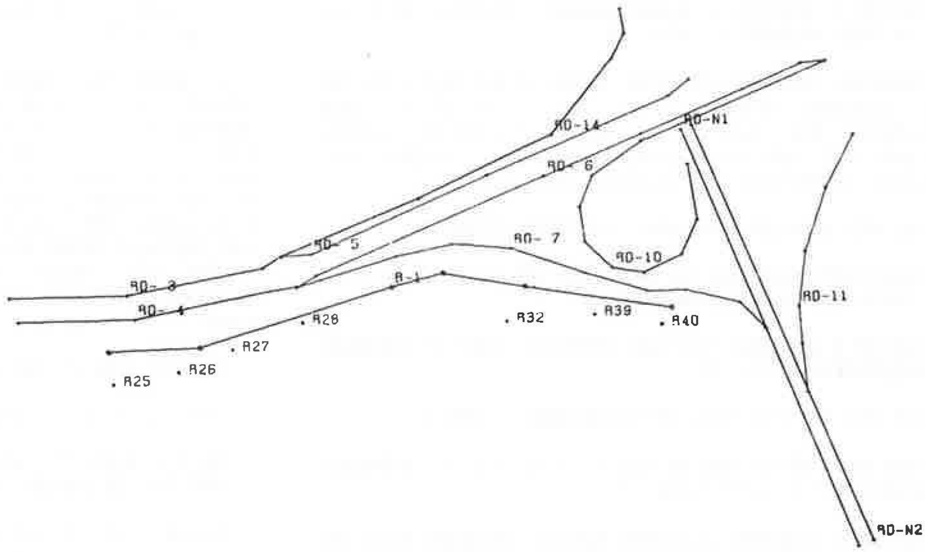


Figure 2. Profile view of example plot from VUPLOT subroutine scheme.

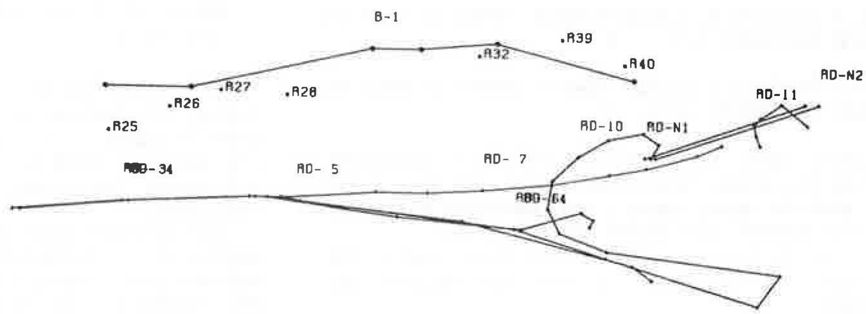
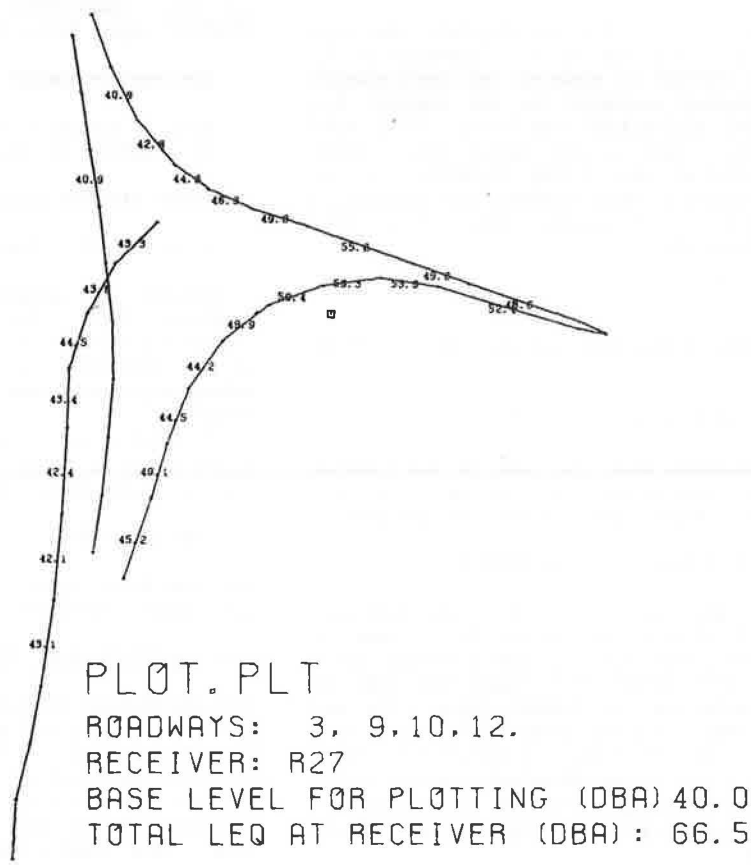


Figure 3. Plan view of example plot from VUPLOT subroutine LEVEL.



CRT terminal. The second, PLOT, is for use with a CALCOMP-type hard-copy plotter. Because these programs are system specific and because their use is quite simple, they will not be discussed here.

Figure 1 shows an example of a plan (X,Y) view plot of a STAMINA input file named EX4.DAT. Figure 2 shows the profile plot (X,Z) for the same file. Figure 3 shows a levels plot (in plan X,Y) for a receiver in the STAMINA input file.

SUMMARY

Use of coordinate-based computer models for highway noise prediction has become widespread in recent years, with resulting increases in accuracy and design flexibility as well as in error potential. For such programs as STAMINA 1.0 and STAMINA 2.0, these errors can manifest themselves as resulting from reading coordinates from plans, from coding coordinates onto forms, and from typing data into computer files. Another problem associated with such models is analyst disorientation, where a preponderance of numbers may cause the analyst to lose his or her ability to visualize the physical meaning of the input and output.

VUTRG has developed an interactive computer graphics package named VUPLOT that allows the analyst to plot, either on a CRT screen or hard copy, plan or profile representations of roadways, barriers, and receivers. The SCHEME subroutine of VUPLOT allows the analyst to plot a labeled series of roadways, barriers, and receivers from either a standard STAMINA input file or from separate unlimited storage files for roadways, barriers, and receivers. The LEVEL subroutine allows the analyst to overlay segment noise level contributions for a particular receiver, on a plan view plot of selected roadways near that receiver.

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Highway Construction Noise Modeling

WILLIAM BOWLBY AND LOUIS F. COHN

A model and interactive computer program for predicting highway construction noise levels have been developed and evaluated for the Federal Highway Administration (FHWA), as part of its on-going efforts to provide state-of-the-art tools for highway-noise analysis. The model addresses noise sources as points, lines, or areas and has a built-in data base for 53 different sources. Noise barrier attenuation may also be analyzed. The results of the calculations are the total 8-h equivalent sound levels [L_{eq}(8h)] at noise receptors as well as the individual contributions from each source. Use of the model will not be required by FHWA; however, the model can serve as a useful tool for meeting the requirements of the FHWA noise standards for impacted areas and for evaluating abatement measures. It may also be used during construction as a diagnostic tool for investigating citizen complaints and for designing mitigation strategies, if necessary.

In its efforts to provide the latest tools for analysis of highway noise, the Federal Highway Administration (FHWA) conducted a research project to develop a model and computer program for predicting levels of highway construction noise (1). At the completion of the project, Vanderbilt University was asked to evaluate the model and prepare a user's manual (2) and construction noise-analysis handbook. This paper outlines the highway construction noise model and program. It discusses basic features, data input requirements, program output, and several applications.

BACKGROUND

FHWA has recognized the need to address the impacts of highway construction noise from federal-aid projects for many years. The FHWA noise standards state that the following steps are to be performed when doing a highway noise study (3):

1. Identify receptors that are sensitive to highway construction noise;
2. Determine mitigation measures for those receptors impacted by construction noise, considering the cost and feasibility of such measures; and
3. Incorporate the needed abatement measures into the plans and specifications for the project.

The states were given total flexibility to meet the requirement of this paragraph. No maximum permitted noise levels were included in the noise standards, and the use of specific procedures to determine impact was neither specified nor required. FHWA thought that the level of effort applied for mitigation of construction noise depended on the type of project and its circumstances. Requirement of specific analysis techniques or imposition of maximum permitted noise levels would be an added regulatory incumberance that would often be more extreme than warranted.

However, FHWA recognized its leadership role in providing guidance to state noise analysts. As a result, it embarked on a program to provide state-of-the-art information on construction noise. The first part of this effort was an in-house staff study on highway construction noise measurement, prediction, and mitigation (4). This report presented simplified measurement and prediction tools and sample contract specifications for different categories of construction noise control. The report has served as a useful reference to state noise analysts for the last six years.

FHWA's second effort in the study of highway construction noise was a symposium held in 1977 on construction noise mitigation. It brought together experts from federal and state governments, contractors, equipment manufacturers, and consulting firms. The purpose of the symposium was to evaluate potential strategies for mitigation of construction noise and then develop a reference guide on mitigation. The resulting report has also served as a useful reference to state noise analysts (5).

The latest part of the FHWA efforts in the study of construction noise has been a research contract to develop a highway construction noise-prediction model and to demonstrate noise-abatement techniques at actual construction sites. Wyle Laboratories conducted the study and produced a series of unpublished reports that document its work. The study included extensive noise level and equipment operation monitoring at four major construction sites around the country. An analytical model for predicting construction noise was then developed by using the field operations to calibrate and validate the model. The abatement demonstrations included equipment muffling, equipment shielding, and equipment substitution.

Vanderbilt University was then called on by FHWA to take the Wyle Laboratories work and develop a clear, comprehensive reference for construction noise analysis. Work tasks included (a) evaluation of the Wyle results, (b) recommendations for computer program changes, (c) implementation of those changes, (d) preparation of a user's manual for the program, (e) preparation of simplified calculation methods, and (f) preparation of the comprehensive construction noise-analysis guide.

The final products of these efforts will give state noise analysts a set of state-of-the-art tools for addressing construction noise when deemed necessary and appropriate. The model permits detailed analysis of the impact of construction noise and permits analysts to design abatement measures for specific problem sites. However, by not requiring its use on federal-aid highway project studies, FHWA continues its efforts to minimize regulation while providing up-to-date analysis tools.

FEATURES

A review of previous attempts at modeling construction noise (both highway and industrial) reveals that such models contained numerous assumptions that reduced user flexibility (6). The intent, then, in this model's development was to maximize flexibility and applicability, which suggested implementation as a computer program. The model and resultant program developed by Wyle Laboratories was called HICNOM for highway construction noise model.

The model's basis for calculation is the 8-h equivalent sound level [$L_{eq(8h)}$]. An 8-h period was deemed approriate to represent a construction workday for the purpose of noise analysis. The results of the calculations would be the $L_{eq(8h)}$ at one or more noise receptors (receivers) from the variety of operations occurring on a construction site throughout the day.

Geometric Representation

Three geometric configurations were defined to represent noise sources

1. At a point,
2. Along a line, and
3. Over an area.

Examples of each would be a compressor, a motor grader or haul truck, and a bulldozer, respectively.

Attenuation of sound propagating from these sources is addressed in three ways:

1. Geometric wave spreading,
2. Excess attenuation due to interference with absorbing ground, and
3. Shielding by a physical barrier.

The excess ground attenuation feature allows the user to specify an excess attenuation rate in terms of decibels per doubling of distance (dB/DD) from a reference distance of 50 ft (15.2 m). Vanderbilt expanded this feature so that a separate rate could be specified for each receiver.

Barrier Attenuation

Barrier shielding is modeled by using Maekawa's formulation for point sources and the Kurze-Anderson incoherent line source method for nonpoint sources (1). Single equivalent frequencies are assigned to each source for the attenuation calculations.

Product Rate Coordination

The model is also designed to consider the situation where the operation of one type of equipment is dependent on another piece of equipment. An example would be where the number of trucks on a haul road would depend on the ability of a front-end loader to fill them. The model addresses such a situation through coordination of production rates. In the case just cited, the model would compute the number of trucks (N) based on their capacity (C_1) and the bucket capacity (C_2), cycle time (t_2), and duration of operation (T_2) of the loader.
Mathematically,

$$N = T_2 (C_2/C_1)(1/t_1) \qquad (1)$$

where N is in terms of vehicles per hour.

Data Base

Based on the literature review and the data collection done as part of the model development, a noise level data base for 53 different equipment models was compiled. These models were grouped into 16 types of sources, as shown in Table 1. Examination of Table 1 reveals that a source type may represent a type of equipment (e.g., scraper) or a type of operation (e.g., concrete). The model numbers in Table 1, therefore, refer to particular equipment or operations, as appropriate.

Both the basic construction noise model and the computer program have flexibility for the addition of new sources or models for which the user has noise level and operational data. These sources may be permanently added to the program or specified on each computer run through use of a user-defined source entry.

Certain of the source types are automatically assigned to a particular geometric type. For example, pumps may only be analyzed as point sources. Other sources, such as a loader, may be analyzed as a point, line, or area source, depending on the situation.

Interactive Format

To facilitate use and provide flexibility, the computer program was written in an interactive format. The computer makes data requests to which the user responds. Based on the responses, the appropriate next question is asked. For example, if the user responded to the request, "enter source type", with "pump", the program would recognize

Table 1. Noise source data.

Type	Model No.	Description	Allowable Geometry Types[a]	Reference Level [dB(A)]	Source Acoustic Height (ft)	Source Acoustic Frequency (Hz)
Backhoe	1	Nominal[b,c]	1, 2, 3	83.5	6	500
	2	Caterpillar, Koehring	1, 2, 3	85	6	500
	3	P&H	1, 2, 3	89	6	500
	0[d]	Defined by user	1, 2, 3	UD[e]	UD[e]	UD[e]
Loader	1	Nominal[b,c]	1, 2, 3	84	6	500
	2	3-yd capacity	1, 2, 3	76	6	500
	3	5-yd capacity	1, 2, 3	77	6	500
	4	7-yd capacity	1, 2, 3	78	6	500
	5	10-yd capacity	1, 2, 3	80	6	500
	0[d]	Defined by user	1, 2, 3	UD[e]	UD[e]	UD[e]
Compressor	1	Nominal[b,c]	1	89.3	4	1000
	2	Standard	1	86	4	1000
	3	Quiet, doors open	1	75	4	1000
	4	Quiet, doors closed	1	65	4	1000
	0[d]	Defined by user	1	UD[e]	UD[e]	UD[e]
Pile driver	1	Nominal[b,c]	1	91.3	20	1500
	2	Current data	1	107	20	1500
	0[d]	Defined by user	1	UD[e]	UD[e]	UD[e]
Pump	1	63 dB at 50 ft	1	63	4	800
	2	76 dB at 50 ft	1	76	4	800
	3	Nominal[b,c]	1	71	4	800
	0[d]	Defined by user	1	UD[e]	UD[e]	UD[e]
Crane	1	Nominal[b,c]	1	81.5	15	500
	2	Low	1	65.5	15	500
	3	Medium	1	74	15	500
	4	High	1	77.5	15	500
	0[d]	Defined by user	1	UD[e]	UD[e]	UD[e]
Breaker	1	Rock drill, nominal[b,c]	1, 2, 3	89	2	1500
	2	Standard jackhammer, nominal[b,c]	1, 2, 3	80	2	1500
	3	Muffled jackhammer	1, 2, 3	69	2	1500
	0[d]	Defined by user	1, 2, 3	UD[e]	UD[e]	UD[e]
Concrete	1	Concrete pour[b]	1	73	10	500
	2	Nominal batch plant[b,c]	1	90	10	500
	3	Batch plant	1	82	10	500
	4	Pump[b]	1	85	6	500
	5	Cement mixer[b]	1	82.8	8	500
	0[d]	Defined by user	1	UD[e]	UD[e]	UD[e]
Generator	1	Low level	1	73.5	4	1200
	2	Nominal[b,c]	1	81	4	1200
	0[d]	Defined by user	1	UD[e]	UD[e]	UD[e]
Miscellaneous	1	Grinder[b]	1	71	2	1200
	2	Concrete saw[b]	1	88	1	1200
	3	Fan[b]	1	83	4	1200
	4	Welder, nominal[b,c]	1	71	4	1200
	0[d]	Defined by user	1	UD[e]	UD[e]	UD[e]
Bulldozer	1	Nominal[b,c]	1, 2, 3	88.1	6	500
	2	Caterpillar D6, D7, D8	1, 2, 3	78	6	500
	3	Caterpillar D9	1, 2, 3	83	6	500
	4	D9 without muffler	1, 2, 3	94	6	500
	0[d]	Defined by user	1, 2, 3	UD[e]	UD[e]	UD[e]
Grader	1	Nominal[b,c]	1, 2, 3	83	8	500
	0[d]	Defined by user	1, 2, 3	UD[e]	UD[e]	UD[e]
Compactor	1	Low	3	80	8	500
	2	Nominal[b,c]	3	86	8	500
	3	High	3	93	8	500
	0[d]	Defined by user	3	UD[e]	UD[e]	UD[e]
Paving	1	Nominal[b,c]	1, 2, 3	83.8	4	500
	2	Concrete paver	1, 2, 3	82.8	4	500
	3	Asphalt paver	1, 2, 3	82.5	4	500
	0[d]	Defined by user	1, 2, 3	UD[e]	UD[e]	UD[e]
Trucks	1	10-yd dump, quiet	4	-[f]	8	500
	2	10-yd dump, noisy	4	-[f]	8	500
	3	Dual 20-yd trailers	4	-[f]	8	500
	4	Nominal[b,c]	4	-[f]	8	500
	0[d]	Defined by user	4	UD[e]	UD[e]	UD[e]
Scraper	1	Caterpillar 631, muffled	4	84	6	500
	2	Caterpillar 631, not muffled[b,c]	4	95	6	500
	3	Caterpillar 623	4	90	6	500
	4	Caterpillar 637	4	81	6	500
	0[d]	Defined by user	4	UD[e]	UD[e]	UD[e]

[a] 1 = point, 2 = nonhaul line, 3 = area, and 4 = haul line.
[b] Use this model number if a generalized value is needed.
[c] "Nominal" means that the data represent an averaging of data from previous literature.
[d] A model number of zero means that the user has different reference level height and frequency data.
[e] UD = user-defined.
[f] See Figure 3.

"pump" as a point source and respond with, "point source - enter location (X,Y,Z)."

Cartesian Coordinates

All geometric data are specified in terms of Cartesian coordinates. For example, line sources are defined by a series of endpoints that are connected by straight-line segments. Although use of coordinates complicates data input, it allows specification of many receivers, sources, and barriers in the same computer run, which ultimately leads to saving analyses time. Current program limits are set at 10 receivers, 10 point sources, 6 line sources, 5 area sources, and 3 barriers; however, these limits are easily modified.

POINT-SOURCE MODEL

The first type of source geometry to be discussed is the point source. Examples of point source include stationary equipment such as a compressor, quasi-mobile equipment such as a rock drill, and mobile equipment such as a backhoe. The particular source types in the program that may be analyzed as points, as listed in Table 1, are as follows:

1. Crane,
2. Pump,
3. Compressor,
4. Generator,
5. Pile driver,
6. Paving,
7. Concrete,
8. Backhoe,
9. Loader,
10. Breaker,
11. Bulldozer, and
12. Miscellaneous

The point source model is as follows:

$$L_{eq(8h)} = \text{Maximum reference emission level} - \text{Cycle time adjustment} - \text{Usage factor} - \text{Distance adjustment} - \text{shielding adjustment} \quad (2)$$

The first two terms represent the L_{eq} over the duty cycle of the equipment. They are specified in this manner because most of the data on emission levels in the literature are reported as maximum levels. The usage factor accounts for equipment operation for less than a full 8-h day. The distance adjustment is based on a 6 dB/DD rate plus an excess ground-attenuation rate, if specified by the user. As previously stated, barrier shielding calculations are based on Maekawa's formulation.

In analyzing barriers at absorptive sites, the program compares the excess ground attenuation to the barrier attenuation and does not show any noise reduction due to the barrier until barrier attenuation exceeds the soft site ground attenuation. This is a simplistic, yet reasonable, attempt to address the real-world problem of the possible loss of excess ground attenuation due to the insertion of a barrier because of the elevation of the effective height of the source to the top of the barrier.

LINE SOURCES

The model and program classify line sources as either haul or nonhaul; each is analyzed differently. The haul sources in the program are trucks and scraper. The nonhaul sources are backhoe, loader, bulldozer, grader, and paving.

Nonhaul Line Sources

A nonhaul line source may be considered conceptually as a point source that has its sound intensity spread out along a line. As such, it is modeled by

$$L_{eq(8h)} = \text{Maximum reference emission level} - \text{Cycle time adjustment (if appropriate)} - \text{Usage factor} - \text{Source density adjustment} - \text{Distance adjustment} - \text{Finite line segment adjustment} - \text{Barrier shielding} \quad (3)$$

The first three terms are similar to those for the point source. The source is spread along the line through the source density adjustment. This adjustment is simply a logarithmic function of the inverse of the length of the line along which the source is traveling.

The distance adjustment is based on a 3 dB/DD rate with excess ground attenuation, as appropriate. The finite line-segment adjustment scales down the contribution of a finite segment from the theoretically infinitely long line on which the calculation is initially based. Barrier shielding is done by using the Kurze-Anderson incoherent line-source model. To analyze sources and barriers accurately with changing vertical profiles, the program divides the barrier into successively smaller segments until the change in total attenuation from additional divisions is less than 0.4 dB.

Note that the speed of the nonhaul line source does not affect the L_{eq}. This is because the emission levels for these sources are independent of speed. Thus, the L_{eq} contribution from a fast-moving source that makes many passes by a receiver (e.g., a grader) would equal that from a slow-moving source that makes one pass (e.g., paving), all other parameters being equal.

Haul Line Sources

The second type of line source in HICNOM is the haul line source, that is, equipment involved in earth-hauling operations. The two specific source types in the model are trucks and scrapers. The modeling is analogous to that used in the FHWA highway traffic noise prediction model (7). In its simplest form, the 8-h equivalent sound level may be predicted by,

$$L_{eq(8h)} = \text{Reference emission level} + \text{Flow adjustment} - \text{Distance adjustment} - \text{Finite line segment adjustment} - \text{Barrier shielding} \quad (4)$$

For trucks, the reference emission level is a logarithmic function of vehicle speed; for scrapers, it is independent of speed. The flow adjustment is a logarithmic function of the ratio of the average hourly volume of vehicles to their average speed. The distance, finite segment, and barrier adjustments are the same as for the nonhaul line sources.

One feature of the HICNOM program is the capability of generating a turn-around loop at the end of the haul road. Figure 1 shows the seven types of loop recognized by the program (type 7 is actually not a loop but more of a U-turn). Given the type of loop and its radius by the user, HICNOM will compute the coordinates of a series of points on the loop. In this manner, the loop is approximated as a series of straight-line segments.

Another feature of HICNOM is then put into use. The program has an acceleration-deceleration profile built into it that will compute an average speed on each segment of the loop based on the loop type and approach and departure speeds. Figure 2 illustrates loop generation, where three line points (A,B, and C) and a type-6 loop with radius r were given.

The acceleration-deceleration feature is also useful where the haul vehicles are dropping their loads without immediately turning around. The program can be instructed to decelerate and accelerate the vehicles around some loading-unloading point along the line.

Figure 1. Types of haul road loops recognized by HICNOM.

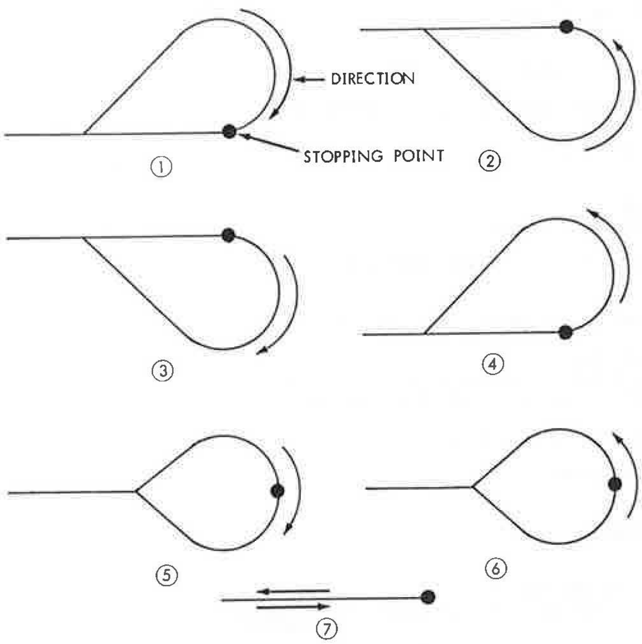
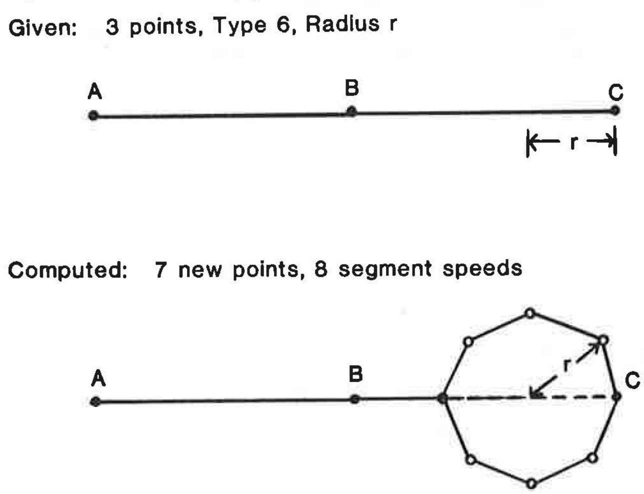


Figure 2. Illustration of loop-generation concept in HICNOM.



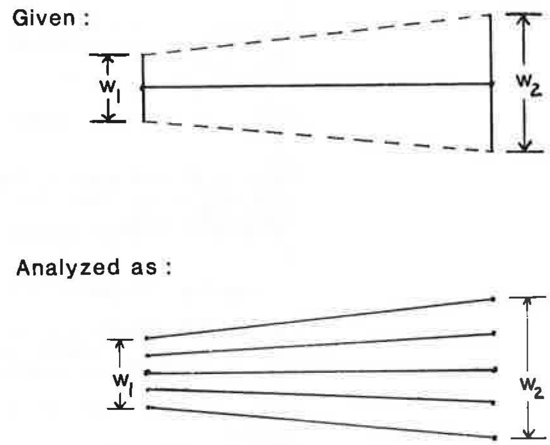
AREA SOURCE

The third geometric category is the area source. Examples would include bulldozers involved in clearing and grubbing or compactors working in a fill area. Six sources may be analyzed by the computer program as area sources:

1. Compactor,
2. Bulldozer,
3. Loader,
4. Backhoe,
5. Paving, and
6. Grader.

Area sources are analyzed by representing the area as a series of four-sided subareas and then breaking each subarea into a series of strips. Each strip is then represented as a nonhaul line source. Figure 3 illustrates schematically the area source approximation for one subarea. The number of strips that the area is divided into is a function of the area's width and the distance from the area's centerline to the nearest receiver. The intensity of

Figure 3. Area sources defined by a centerline and end widths and simulated as a series of nonhaul line sources.



the source is then divided among these lines and spread along them as is done for a regular nonhaul line source.

PROGRAM FORMAT

HICNOM is an interactive FORTRAN program. The user enters data by responding to program requests. The creation of a data file for a one source-one receiver problem is illustrated in Figure 4. The first line of each pair of lines represents the computer request, and the second line is the user response, which has been underlined. During this data entry, HICNOM will make decisions based on the responses as well as some intermediate calculations. It will then create an intermediate data file that contains three types of data:

1. User-supplied (coordinates, source types description, and user-defined data);
2. Program-supplied (source frequency and height); and
3. Program-calculated [L_{eq} (reference), source density, and loop point coordinates].

The user may obtain a printout of this file for project documentation. Figure 5 illustrates the data file report for the data illustrated in Figure 4.

HICNOM will then read from this intermediate file to do its final L_{eq} calculations and produce a report on the results. This report contains the total $L_{eq(8h)}$ for each receiver as well as the contributions from each source. For line and area sources, these contributions are broken down by segment. This breakdown provides a good diagnostic tool for assessing problem areas and evaluating abatement measures. Figure 6 presents the results report for the data in Figures 4 and 5.

MODEL APPLICATIONS

FHWA does not require that construction site noise be analyzed through modeling; the analyst is left to judge the need for modeling. However, the federal highway program manual (3) does require that the potentially impacted sensitive areas be identified and abatement measures be developed where needed and feasible. HICNOM is an appropriate tool for meeting either of these requirements.

First, it may be used during project planning and design as a screening tool for potentially impacted areas. Construction noise is generally studied by

Figure 4. Interactive data input for example problem.

```
ENTER TITLE FOR THIS PROBLEM:
EXAMPLE OF ONE SOURCE AND ONE RECEIVER
ENTER NUMBER OF RECEIVERS (MAXIMUM IS 10)
1
ENTER A DESCRIPTION OF RECEIVER # 1
(MAXIMUM OF 16 CHARACTERS - BLANK IF NONE)
1012 MAIN ST
ENTER X, Y, Z AND EXCESS ATTENUATION (DB/DD) FOR  RECEIVER # 1
0 0 0 1.5
ENTER SOURCE TYPE - BLANK IF FINISHED

PUMP
ENTER A DESCRIPTION OF THE SOURCE
(MAXIMUM OF 16 CHARACTERS - BLANK IF NONE):
NEAR PROP. LINE
ENTER MODEL NUMBER (ENTER 0 TO DEFINE NEW MODEL NUMBER)
1

PROGRAM HAS AUTOMATICALLY ASSIGNED A GEOMETRY TYPE TO THIS SOURCE

ENTER HOURS WORKED DURING 8-HOUR DAY
(ENTER -1 TO COORDINATE THIS SOURCE'S PRODUCTION RATE WITH THAT OF
THE LAST PREVIOUSLY ENTERED SOURCE HAVING A  PRODUCTION RATE)
8
POINT SOURCE:  ENTER X, Y, Z OF SOURCE LOCATION
30 30 0
ENTER SOURCE TYPE - BLANK IF FINISHED
______
ENTER NUMBER OF BARRIERS (MAXIMUM IS 3)
0

ENTER THE NAME OF THE FILE FOR HICNOM USE;
MAXIMUM OF 10 (6.3) CHARACTERS, DEFAULT = HICNOM.DAT :  EXTRB.DAT
```

Figure 5. Example of input data file.

```
EXAMPLE OF ONE SOURCE AND ONE RECEIVER
  1  RECEIVERS
     X            Y            Z        EX. ATT.(DB/DD)      DESCRIPTION
      0.00         0.00         0.00     1.5000000        1012 MAIN ST.
  1  POINT SOURCES
     X            Y            Z         LEQ(REF)    FREQ.      SOURCE            DESCRIPTION
     30.00        30.00        4.00        63.00      800   PUMP      1         NEAR PROP. LINE
  0  LINE SOURCES
  0  AREA SOURCES
  0  BARRIERS
```

Figure 6. Example of results report.

```
EXAMPLE OF ONE SOURCE AND ONE RECEIVER

RECEIVER NUMBER              LEQ              DESCRIPTION


            1                64.8          1012 MAIN ST.

COMPONENT CONTRIBUTIONS FOR RECEIVER NUMBER:  1

INDEX    INTENSITY     LEVEL        SOURCE              DESCRIPTION

    1    0.300839E+07   64.8      PUMP      1         NEAR PROP. LINE

KEY TO INDEX:
    X - POINT SOURCE, WHERE X OR XX IS INPUT SEQUENCE # OF POINT SOURCES.
   XX
  YXX - LINE SOURCE, WHERE XX IS INPUT SEQUENCE # OF LINE SOURCES
 YYXX                       AND Y OR YY IS SEQUENCE # OF POINTS FOR THE XXTH LINE.
1YYXX - AREA SOURCE, WHERE XX AND YY ARE ANALAGOUS TO LINE SOURCE VARIABLES.
```

construction phase (1,4,5). With some knowledge of project features, such as location of structures and major cuts and fills, and with some general assumptions about duration of phase and typical equipment used in the phase, an initial assessment of potential problem areas can be made.

During final design, where exact locations of cuts, fills, and structures are tied down and where there is better knowledge of needed construction operations such as rock drilling or pile driving, the model may be used to refine impact assessments and quantify impact. At this point, use of the model as an abatement design tool would be appropriate. Temporary noise barriers near sensitive sites may be analyzed and designed. The effectiveness of a strategy of building traffic noise barriers early in the project construction may be evaluated. The use of work-hour limitations or alternative equipment or processes may be studied. Recommendations or restrictions on the location of haul roads, material stockpiles, or stationary equipment can be developed.

When construction is under way, the model may be used as an assessment tool if citizens complain about the construction noise levels. The model would allow the major noise sources and their sound level contributions to a particular receiver to be identified. If the severity of the impact or the strength of the complaint warrants action, the model may be used to evaluate the effectiveness of potential abatement measures.

For example, use of the model near a rock drill site might show that a requirement to use compressors that meet U.S. Environmental Protection Agency standards would be ineffective because they contribute little to the total level that is dominated by the drills. Instead, the model might show that a temporary noise barrier of a certain height along the right-of-way line would provide adequate noise reduction. In another situation, for example, the model might show that a temporary barrier would be ineffective but that a strategy such as shifting the location of the haul road to take advantage of terrain shielding would provide significant noise reduction.

SUMMARY

A model and interactive computer program for predicting highway construction noise levels, called HICNOM, has been developed for FHWA. The model addresses noise sources as points, lines, and areas and also calculates noise-barrier insertion loss. A data base for 53 types of equipment and models has been developed from extensive field measurements and a literature review. The final product of the computer program is a list of $L_{eq(8h)}$ at each noise receptor as well as the contribution from each noise source.

Although use of the model is not required by FHWA, HICNOM can serve as a useful tool for identifying potentially impacted areas, quantifying that impact, designing abatement measures, and evaluating their potential effectiveness. Vanderbilt University has developed a manual calculation method and a series of programs for a handheld programmable calculator (Texas Instruments TI-59) based on the HICNOM model.

ACKNOWLEDGMENT

This work was performed under contract to FHWA. We gratefully acknowledge the assistance of FHWA contract manager Fred Romano. He should be contacted regarding the status of this work and plans for implementation. We also gratefully acknowledge the work of Wyle Laboratories in the development of the model under FHWA contract.

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Noise Control Through Land Use Planning: The Calgary Case

D.L. PARSONS

Noise attenuation measures are not often seen as an integral part of roadways. The need for attenuation, however, is determined by the adjacent land use and its noise sensitivity. Calgary, Alberta, Canada, uses land use planning and land use development as a major way of providing attenuation for surface transportation noise sources. Through enabling provincial legislation, the city has the mandate to negotiate attenuation measures as a condition of residential developments. Three scenarios provide opportunities to attain the design noise level objective of 60 dB (A) L_{eq}(24): (a) construction or upgrading of a roadway adjacent to existing development, (b) development or redevelopment adjacent to an existing transportation corridor, and (c) development or redevelopment adjacent to a future transportation corridor. To take advantage of these three opportunities, the concept of potential noise impact zones was developed and is being integrated into the normal planning process to assist in flagging potential noise problems. The procedures and practices have been in place on an informal basis for several years and have proved successful in obtaining livable residential noise environments.

Calgary is becoming the economic center of Alberta's oil-based prosperity and a major financial center in western Canada. Located on the eastern edge of the Canadian Rockies, it is similar to Denver, Colorado, in terms of location, prosperity, and growth. Alberta's tremendous oil resources and resultant booming petroleum industry liken it to Houston and Dallas, Texas.

Calgary typifies growth and economic opportunity, perhaps better than does any other major center in Canada. The oil industry and a prosperous agricultural community provide both a strong regional economy and a vibrant local economy. The favorable employment market has created a growth rate of roughly 5 percent/year; some 2000 people take up residence in Calgary each month.

To provide the necessary services, utilities, and urban amenities for a rapidly growing population of 600 000 is both a challenge and a nightmare for planners, engineers, politicians, and citizens. The demand for housing has made the Calgary area a desirable place for land developers. During the 1970s, Calgary's total area grew to approximately 195 miles^2 through annexation, primarily initiated by the development industry. This reserve of developable land was needed to provide Calgarians with housing and associated urban amenities. One of these amenities is the provision of a good transportation network.

CALGARY: WESTERN UNI-CITY

Control of development and its integration with the existing built-up area and existing utilities could be a horrendous task. Calgary, along with other major cities in Alberta, is fortunate in that it operates as a uni-city with almost total jurisdiction over all municipal matters within its boundaries.

The system of government and constitution does not provide for control and funding from the federal level of government. In the Canadian system of government, the constitution delegates and defines jurisdictions between the federal government and the provinces. Each province in turn can then allocate responsibilities to the municipal level. In the context of provision of transportation services and land use planning and control in Alberta, there is little interplay between the federal government and the municipality. The primary relation on these matters is between the province and the individual city or other urban or rural municipality.

Provincial legislation, like the Alberta Planning Act of 1977 and the Alberta Municipal Government Act of 1968, provides a framework within which local municipalities can operate with considerable latitude. Procedures with respect to subdivision approval and routes of appeal, for example, are laid out at the provincial level but the actual decision-making power on particular proposals is municipal.

Funding of transportation facilities usually implies that some form of control lies with the funding agency. Within Alberta, the provincial government may share costs with the municipality on particular capital projects. For example, of the transportation capital expenditures during 1979 through 1981, the provincial government contributed between 27 and 31 percent of the total. Contributions to operating costs constitute a much smaller proportion of the total, and range between 4 and 7 percent. The application of these funds to particular transportation projects is at the discretion of the municipality.

With the exception of adherence to international design standards and practices, the planning, design, construction, and maintenance of our road and transit network is a municipal matter. Combined with total control over land use planning, Calgary has far-reaching powers that enable it to control and direct the development of our city.

CONTROL OF SURFACE TRANSPORTATION NOISE

Working within the kind of jurisdictional framework described, Calgary is in an excellent position to control surface transportation noise. Approval of a formal policy, Surface Transportation Noise Policy for the City of Calgary, provides consistency in the efforts to obtain our maximum design noise level of 60 dB(A) equivalent noise level for 24 h [$L_{eq(24)}$] for residential land uses.

With the magnitude of downtown development and associated transportation improvements needed to service development, three opportunities exist for control of surface transportation noise within Calgary:

Case 1--Construction or upgrading of a roadway adjacent to existing development,

Case 2--Development or redevelopment adjacent to existing transportation corridors, and

Case 3--Development or redevelopment adjacent to a future transportation corridor.

Case 1 employs the standard use of barriers, berms, and combinations thereof to effect noise control. The city is clearly responsible for funding any noise attenuation in this instance. Calgary continues to benefit from the design, construction, and maintenance experience of the American states and of large Canadian metropolises like Toronto.

Cases 2 and 3 can be described as noise control through joint negotiations between the city and the development industry. The benefit of negotiating the form of attenuation is the flexibility that is afforded to both the city and to the developer. Provided that the development adjacent to the noise source meets the acoustical requirements established by the city, the range of options for achieving the design noise level of 60 dB(A) $L_{eq(24)}$ is significant. From the perspective of the land developer, marketing of lots, for example, can be considered in the negotiation process and may be reflected in the site design and aesthetic treatment of any barriers.

Where a residential subdivision or development is proposed adjacent to an existing noise source, the developer is required to provide any necessary attenuation facilities, whatever their form. In numerous examples of case 2 situations, the developer has employed setbacks, frontage roads, grade change, or barriers to effect noise mitigation. Less conventional approaches have also been used successfully.

The residential subdivision of Ranchlands is a good example. The subdivision was planned adjacent to a six-lane expressway that was in the detailed design stages at the time of subdivision approval. The roadway was depressed to obtain both reasonable grades as well as some noise attenuation. In addressing the noise issue, the developer and the city negotiated a solution that incorporated a berm and barrier combination. The matter of negotiation was the placement of the property line. By placing the property line at the top of the berm, right-of-way acquisition costs to the city were minimized, the amount of developable land in the subdivision was maximized, and sufficient attenuation was achieved. The lots back onto the right-of-way such that maintenance of the community side of the berm and any landscaping is at the discretion of the homeowner. Maintenance of the roadway face of the berm and barrier is the city's responsibility.

Case 3 recognizes that development is occurring in areas where the final roadway, and hence, the ultimate noise problem, may not be constructed for many years. In this instance the developer is required to design and construct the project so as to either achieve the design noise level or provide the opportunity to do so at some future date. Completion of attenuation becomes the responsibility of the city and would occur at the time of construction of the transportation facility.

The city recognizes that not all residential developments adjacent to transportation corridors will experience traffic noise problems. To assist in processing case 2 and 3 development applications, a methodology has been developed that allows for the identification of potential surface transportation-related noise problems. If the potential is identified by some criterion, more detailed analysis is required to determine the extent of the noise problem and possible solutions for it.

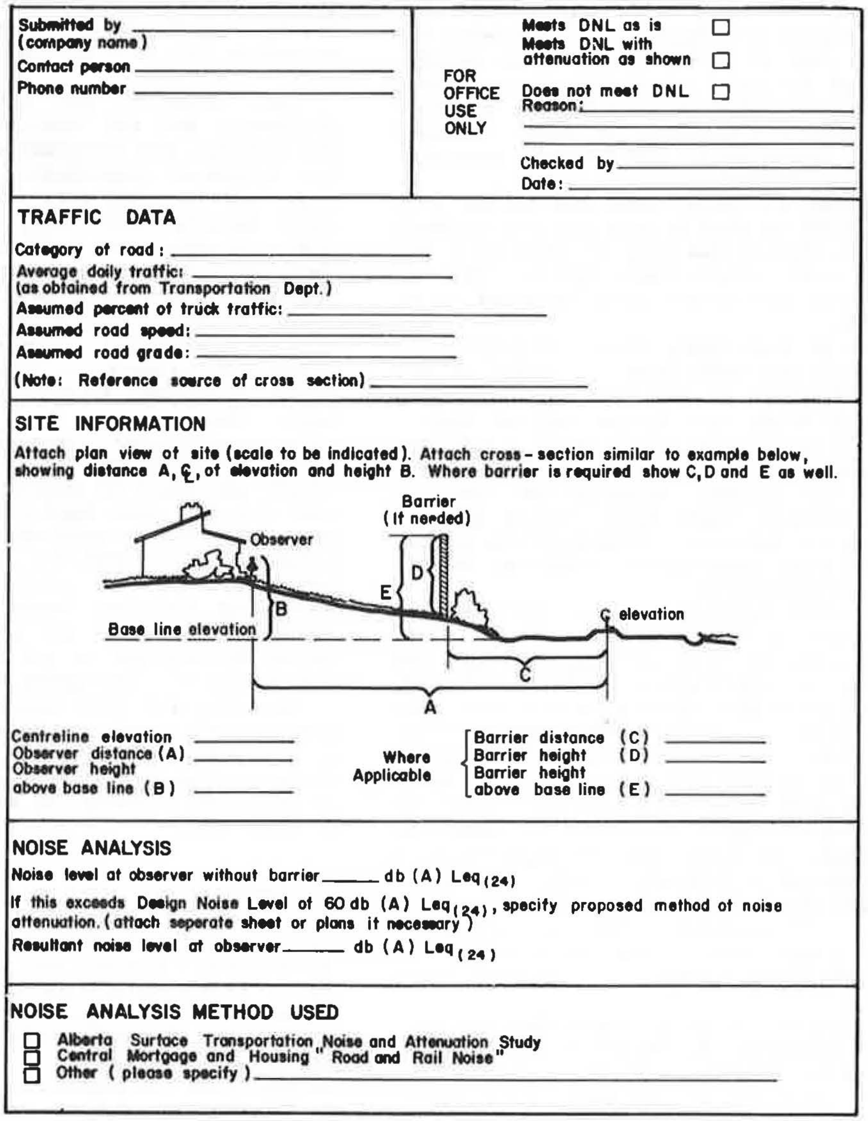
The criterion most appropriate to Calgary was found to be related to the standard of roadway. Traffic noise is a function of traffic volumes, speed, and type of vehicle--factors that are also used in determining the standard of roadway design. By using the maximum expected values for volume, speed, and traffic mix for each roadway category, the distance at which the day-night sound level (DNL) of 60 dB(A) $L_{eq(24)}$ occurs can be deter-

Table 1. Determination of PNIZs.

Road Classification	Maximum Expected Volume (vehicles/day)	Posted Speed (km/h)	Distance from Centerline (m)	L_{eq}(24) [dB(A)]	Recommended PNIZ (m)
Freeway	120 000	100	51[a]	68.4	135
			100	62.5	
			120	60.7	
			135	60.0	
			140	59.0	
Expressway	100 000	70	30[a]	70.1	100
			70	62.4	
			90	60.3	
			100	59.9	
Major	40 000	60	24[a]	68.7	60
			40	63.2	
			60	59.5	
Primary collector	10 000	50	17[a]	57.1	NA
Collector	5 000	50	17[a]	54.1	NA
Residential	1 000	50	14[a]	49.0	NA

[a]Property line plus a standard 6-m building setback.

Figure 1. PNIZ noise data sheet.



Submitted by
(company name)
Contact person
Phone number

FOR OFFICE USE ONLY
Meets DNL as is ☐
Meets DNL with attenuation as shown ☐
Does not meet DNL ☐
Reason:
Checked by
Date:

TRAFFIC DATA

Category of road:
Average daily traffic:
(as obtained from Transportation Dept.)
Assumed percent of truck traffic:
Assumed road speed:
Assumed road grade:
(Note: Reference source of cross section)

SITE INFORMATION

Attach plan view of site (scale to be indicated). Attach cross-section similar to example below, showing distance A, ℄, of elevation and height B. Where barrier is required show C, D and E as well.

Centreline elevation
Observer distance (A)
Observer height above base line (B)

Where Applicable
Barrier distance (C)
Barrier height (D)
Barrier height above base line (E)

NOISE ANALYSIS

Noise level at observer without barrier____ db (A) Leq(24)

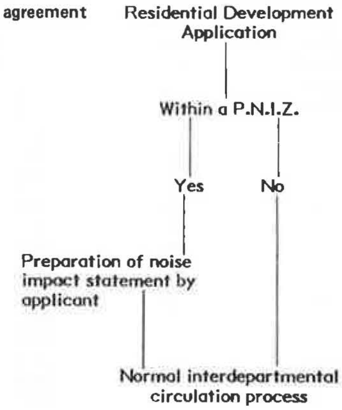
If this exceeds Design Noise Level of 60 db (A) Leq(24), specify proposed method of noise attenuation. (attach seperate sheet or plans if necessary)

Resultant noise level at observer____ db (A) Leq(24)

NOISE ANALYSIS METHOD USED

☐ Alberta Surface Transportation Noise and Attenuation Study
☐ Central Mortgage and Housing "Road and Rail Noise"
☐ Other (please specify)

Figure 2. Flow chart of development agreement for a project.



mined. These in turn are used to define potential noise impact zones.

An analysis of various roadway standards in the city was undertaken. These standards are reflected in several policy documents as well as in the standard development agreements negotiated between the city and the development industry. In reviewing the six recognized road classifications, three categories were found to have the potential to create noise problems for adjacent residential developments. The analysis summarized in Table 1 formed the basis for establishing recommended potential noise impact zones (PNIZs).

In establishing the PNIZ, consideration of rail noise was important in that Calgary has two national lines that pass through the city as well as a developing light rail transit (LRT) system. The potential for heavy and light rail oriented noise problems exists.

In the case of both heavy rail and light rail facilities, PNIZs are much more difficult to define. The variability in the composition, speed, and frequency of heavy rail trains implies that a standard PNIZ is not appropriate. Rather, each development proposal adjacent to a rail line is reviewed on its own merits. Although LRT vehicles generate substantially lower noise levels than do heavy rail trains, individual investigation of all proposed residential developments adjacent to LRT lines ensures compatibility.

The design noise guideline and the PNIZ concept or way to identify or flag potential noise problems are in the process of being incorporated into the normal development application approval process. The requirement of a simplified potential noise impact sheet achieves this goal without significantly effecting the processing of development applications.

Development or redevelopment proposals for PNIZs and adjacent to both heavy and light rail lines require that a noise impact statement be submitted with the proposal. By specifying the type and format of data required to adequately assess the noise environment and the analysis methodologies acceptable to the city transportation department, the use of the simple summary sheet shown in Figure 1 enables the development industry to address noise issues rapidly.

The flow chart in Figure 2 illustrates the simplicity of the approach. Any forms of noise attenuation that may be necessary and their funding are negotiated and finalized in the development agreement for the project.

DOES NOISE CONTROL THROUGH NEGOTIATIONS WORK?

The procedures and concepts described in this paper have been largely in place on an informal basis for the past few years. The PNIZ concept is to be implemented in early 1982. Amicable relations between the city and the development industry and its representative organizations, the Urban Development Institute (UDI) and the Housing and Urban Development Association of Canada (HUDAC), are critical in attaining controlled growth and good quality developments. Considerable discussions were held with UDI and HUDAC on the philosophy, procedures, and practices associated with surface transportation noise control. Although agreement was reached on the need for such control and the options available to achieve a recognized design noise level, the underlying philosophies differed.

The city's philosophy is that land use determines the need for noise protection and that the proponent of a noise-sensitive use is largely responsible for providing attenuation. For a hypothetical piece of roadway, only those adjacent uses that are noise sensitive need protection. For a roadway like Barlow Trail in Calgary, residential development on the west side needs some form of noise attenuation, but the light industrial uses on the east side are not noise sensitive. The development industry's position, however, is that the roadway is the source of the problem and that the responsibility for attenuation lies with the city as the developer of the road.

Notwithstanding the fundamental difference in philosophy and the implications for responsibility for funding, the development industry, in practice, has displayed considerable cooperation and enthusiasm for ensuring that their residential subdivisions provide good noise environments. A sensitivity to potential noise sources is exhibited very early in the planning stages, such that most developments are designed accordingly.

The aesthetic nature of barrier materials available in Calgary has led to more resistance than the concept of attenuation. The fledgling barrier industry in Calgary is beginning to address this concern. They recognize that attractive barriers facilitate marketing. The issue of noise attenuation through architectural acoustics has not been extensively addressed in Calgary. The existing provincial building code does not allow the city to require additional construction standards. The city recognizes that there are areas where desirable exterior noise levels cannot be obtained. Although acceptable interior levels are attainable through architectural design and acoustical insulation, enabling legislation is not in place to make this a requirement of development.

The city can only encourage attenuation through architectural design. Redevelopment in our inner-city areas is extensive; therefore, the need for incorporating this alternative form of noise attenuation has been recognized and is under investigation at this time.

CONCLUSION

Calgary has been progressive in its approach to noise control through land use planning and development. It has benefited from the technical work developed in the United States by adapting it to our own needs. Although the magnitude of our transportation noise problems is not comparable, fortunately, with the problems in cities like Los Angeles or Toronto, the average Calgarian perceives a noise problem that must be acknowledged and dealt with. The procedures and methodology described in this paper have proved to be successful.