TRANSPORTATION RESEARCH RECORD 1033

Issues in Transportation-Related Environmental Quality

TRB
TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1985

Transportation Research Record 1033
Price $14.60
Editor: Catherine Dorn Nizharadze
Compositor: Lucinda Reeder
Layout: Marion L. Ross

modes
1 highway transportation
4 air transportation

subject areas
12 planning
17 energy and environment

Transportation Research Board publications are available by ordering directly from TRB. They may also be obtained on a regular basis through organizational or individual affiliation with TRB; affiliates or library subscribers are eligible for substantial discounts. For further information, write to the Transportation Research Board, National Research Council, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

Printed in the United States of America

Library of Congress Cataloging-in-Publication Data
National Research Council. Transportation Research Board.

Issues in transportation-related environmental quality.

(Transportation research record; 1033)
1. Transportation–Environmental aspects–Congresses.
2. Transportation noise–Congresses. 3. Environmental impact analysis–Congresses. I. National Research Council (U.S.). Transportation Research Board.
II. Series.
TE7.H5 no. 1033 380.5 s 86 5106
[TD195.T7] [363.7'31]
ISBN 0-309-03924-X ISSN 0361-1981

Sponsorship of Transportation Research Record 1033

GROUP 1–TRANSPORTATION SYSTEMS PLANNING AND ADMINISTRATION
William A. Bulley, H. W. Lochner, Inc., chairman

Environmental Quality and the Conservation of Resources Section
Carmen Difiglio, U.S. Department of Energy, chairman

Committee on Environmental Analysis in Transportation
Louis F. Cohn, Vanderbilt University, chairman
J. Paul Biggers, Illinois Department of Transportation, secretary
Charles B. Adams, Martin J. Bernard III, David Gates Burwell, James F. Charlier, Camille Cleveland, Denise Constantopoulou, Robert S. De Santo, John H. Gastler, William C. Grenke, Roswell A. Harris, C L. Leroy Irwin, Rajendra Jain, Walter A. W. Jetter, Wayne W. Kober, Leon N. Larson, Peter A. Lombard, George E. Mouchahoir, Fred M. Romano, Earl C. Shirley, Malcolm L. Steinberg, Thomas L. Weck

Committee on Transportation and Air Quality
Norman L. Cooper, U.S. Department of Transportation, chairman
Salvatore Bellomo, Paul E. Benson, Joseph M. Bishop, David L. Calkins, Walter F. Dabberdt, Denis E. Donnelly, Alan Eschenroeder, Gary Hawthorn, Joel L. Horowitz, Howard A. Jongedyk, William C. Lockett, Paul F. Maxwell, Roderick D. Moe, Carlton Thomas Nash, Kenneth E. Noll, Susanne M. Pelly, Ronald J. Piracci, Tom K. Ryden, Phillip S. Shapiro, Mark T. Stahr, N. Thomas Stephens, John H. Suhrbier

Committee on Transportation-Related Noise and Vibration
Mas Hatano, California Department of Transportation, chairman
William Bowlby, Vanderbilt University, secretary
Charles B. Adams, Grant S. Anderson, Domenick J. Billera, Clifford R. Bragdon, Peter C. L. Conlon, Michael G. Dinning, Richard G. Dyer, J. J. Hajek, C. Michael Hogan, Harvey S. Knauer, Bernard G. Lenzen, Win M. Lindeman, Nicholas P. Miller, James R. O'Connor, Joseph B. Pulaski, Fred M. Romano, Myles A. Simpson, Simon Slutsky, Eric Stusnick, Roy E. Turner, Stephen Urman; liaison representative, Louis F. Cohn

Stephen E. Blake, Transportation Research Board staff

Sponsorship is indicated by a footnote at the end of each paper. The organizational units, officers, and members are as of December 31, 1984.

1033

Contents

Addresses of Authors

Bowlby, William, Vanderbilt University, P.O. Box 96-B, Nashville, Tenn. 37235
Bragdon, Clifford R., Georgia Institute of Technology, Cherry and North Swann Building #108, Atlanta, Ga. 30332
Cohn, Louis F., University of Louisville, Louisville, Ky. 40292
Crossan, A. Brook, Louis Berger & Associates, Inc., 100 Halsted Street, P.O. Box 270, East Orange, N.J. 07019
Fisher, Gordon P., Department of Environmental Engineering, Cornell University, 309 Hollister Hall, Ithaca, N.Y. 14853
Grealy, P. J., John Collins Consulting Engineers, 852 Commerce Street, Thornwood, N.Y. 10594; formerly with Polytechnic Institute of New York
Harris, Roswell A., University of Louisville, Louisville, Ky. 40292
Hatano, Mas, California Department of Transportation, 5900 Folsom Boulevard, Sacramento, Calif. 95819
Hendriks, Rudolf W., Transportation Laboratory, California Department of Transportation, 5900 Folsom Boulevard, Sacramento, Calif. 95819
Hogan, C. Michael, Earth Metrics Incorporated, 859 Cowan Road, Burlingame, Calif. 94010
Hotopp, John A., Louis Berger & Associates, Inc., 100 Halsted Street, P.O. Box 270, East Orange, N.J. 07019
Kamerud, Dana B., Societal Analysis Department, General Motors Research Laboratories, Warren, Mich. 48090
Lidman, J. Kirby, Iowa Department of Transportation, 800 Lincoln Way, Ames, Iowa 50010
Lindeman, Win, Florida Department of Transportation, 605 Suwannee Street, Tallahassee, Fla. 32301
McShane, W. R., Polytechnic Institute of New York, 333 Jay Street, Brooklyn, N.Y. 11201
Menge, Christopher W., Harris Miller Miller & Hanson Inc., 429 Marrett Road, Lexington, Mass. 02173
Ravnkilde, Jorgen, Earth Metrics Incorporated, 859 Cowan Road, Burlingame, Calif. 94010
Saricks, C. L., Center for Transportation Research, Argonne National Laboratory, 9700 South Cass Avenue, EES 362 2B, Argonne, Ill. 60521
Singh, M. K., Center for Transportation Research, Argonne National Laboratory, 9700 South Cass Avenue, EES 362 2B, Argonne, Ill. 60521
Slutsky, S., Polytechnic Institute of New York, 333 Jay Street, Brooklyn, N.Y. 11201
Stoddard, Albert T. III, School of Engineering, University of Alaska, Anchorage, 3211 Providence Drive, Anchorage, Alaska 99508
von Buseck, Calvin R., Societal Analysis Department, General Motors Research Laboratories, Warren, Mich. 48090
Weck, Thomas L., Louis Berger & Associates, Inc., 100 Halsted Street, P.O. Box 270, East Orange, N.J. 07019
Zahn, Howard, New Jersey Department of Transportation, 1035 Parkway Avenue, CN 600, Trenton, N.J. 08625

Tire-Pavement Noise Measurement Using Transfer Functions

S. SLUTSKY, P. J. GREALY, and W. R. McSHANE

ABSTRACT

An investigation of the use of transfer functions in the measurement of tire-pavement noise is reported. A large variety of tire types and several pavement types were studied. It was found that all transfer functions for automobile tires that have been determined so far cluster into a band approximately 1 dBA wide. This result makes it possible to predict wayside tire noise levels from on-board measurements, thereby reducing the cost and complexity and increasing the range of tire-pavement combinations that can be investigated in a modestly budgeted program. It was also found that test tires must be cured before reliable on-board (near-field) measurements can be expected.

Summarized in this paper is a phase of the work that was carried out (and some of which is still in progress) in connection with the measurement of tire-pavement noise attributable to automobiles, light trucks, and heavy trucks. Of the results obtained during this phase, the following are included:

- Characterization of the tire-pavement component of total vehicle noise emission
- Assessment of the effects of different tire-pavement combinations
- Development of a measurement methodology that may be more convenient than those currently available

In the following sections, some of the past practices and their perceived shortcomings are discussed, followed by an outline of the on-board methodology used. Then, the transfer function idea, which is required to extrapolate from on-board to the wayside impact location, is discussed. Finally, some of the results of the study are presented.

BACKGROUND

The importance of tire noise as a source of automotive vehicle noise emission has been recognized for some 30 years or more. Both government and industry have been concerned with it as one of the currently limiting elements in the control and reduction of noise on and in the vicinity of our nation's highway system. Thus, it is apparent that automobile noise emission levels above approximately 40 mph cannot be significantly improved by improvements in the vehicular engine system (including casing, intake, exhaust, fan, and other auxiliary components) without at the same time (or first) addressing the tire as a noise emission component.

On the other hand, it has already been noticed that the range of tire noise (keeping pavement fixed) can be as much as 10 dBA for different tires. Conversely, noise made by the same tires on different pavements has also been found to differ by as much as 10 dBA (1-3). It must be added that these were outer limits and that most variations found were smaller.

Early programs of tire noise testing carried out by the American Trucking Associations and by General Motors established the importance of some of the basic parameters governing tire noise, such as the dependence on speed, tire tread pattern, and pavement type. Since then, increased attention has been given to prediction of the sound power output anticipated for a given tire-pavement combination. It was found that "rank ordering of passenger tire noise can only be made when referenced to a specific identifiable surface" (4).

Thus, the result of recent years of effort (in Europe and Canada, as well as in the United States) has been to recognize that the tire-pavement interaction mechanism is complex; that its dominant components change significantly with tire type, pavement type, and operating condition; and that many parameters play an important role. Studies by Nilson (5) and Sandburg (6) are especially relevant in this regard.

A further difficulty encountered in the effort to characterize tire noise is the lack of uniqueness of the usual outdoor noise test measurement procedures of tires and difficulties in the indoor procedures as well. These difficulties are briefly reviewed in the following subsections.

Wayside Measurements

Most measurements have, until recently, been made outdoors as coastby measurements (engine off) on standard concrete by using the Society of Automotive Engineers recommended practice on Sound Level of Highway Truck Tires (SAEJ57a).

Miller and Thrasher (7) note that many uncertainties are present in the coastby technique. They find (a) the use of fast response increases error; (b) a change of 2 to 3 dBA with direction of travel; (c) successive passby variations on hot, cloudless days of up to 3 dBA in 1 min; (d) the occurrence of after peak, that is, large pressure fluctuations experienced by the microphone 4 to 5 sec after vehicle passby.

Large site-to-site variations of 5 to 7 dBA were found for a given vehicle (8). Variations were approximately 1 to 3 dBA at a given site. It was found that results showed a lack of reproducibility of an absolute tire sound level among test sites, and that there existed too many variables of surface and environment. It was further concluded that the

SAEJ57a coastby noise test is limited because it is not repeatable.

Nevertheless, informal discussions with tire noise groups from tire companies and from FHWA are in agreement that care in observing stable micro-weather conditions (uniform air and ground temperature, and low wind speeds) could favorably affect reproducibility of test results at a given site.

Indoor Roadwheel Measurements

Indoor roadwheel measurements of tire noise are widely discussed in the literature, and are particularly attractive to tire companies as a means of comparing tires under highly controlled and reproducible conditions. The facility is generally an anechoic chamber with a roadwheel that has a large diameter; this roadwheel is coated with various textured materials to simulate road materials. It was found that a significant degree of care (and expense) was necessary to test a variety of road surfaces.

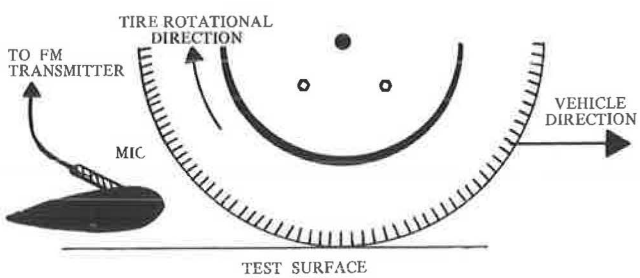
On-Board Measurements

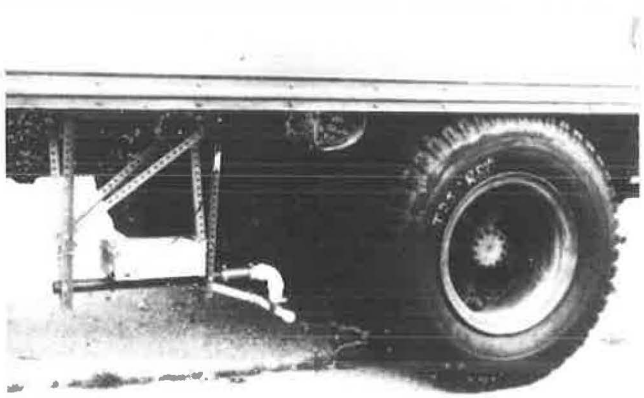
The third principal method of tire noise measurement is that achieved by attaching the microphone to the vehicle in the vicinity of one of the test tires. Figure 1 shows a typical microphone location (9) as used in recent studies (10,11). A variant of this procedure is the placement of the test tire and microphone on a trailer pulled along at some distance from the tractor vehicle (12).

The goals of precision and speed in measurement of tire-pavement noise led the authors to base their procedure on the on-board measurement technique for a number of reasons:

- Reiter and Eberhardt found that the on-board and far-field (50-ft) measurements correlated very well (10). They also found that on-board and laboratory roadwheel measurements correlated very well, despite the on-board microphone experiencing wind noise.
- The capital equipment and operating expenses for an on-board measurement program are modest compared with the alternatives.
- The on-board signal-to-noise ratio is high.
- The signal is not subject to microweather instabilities.
- The test site need not be restricted to a single strip, but may be sampled from a large range of pavement types.

The difficulty caused by wind noise on the on-board microphone was solved (down to 200 Hz) by constructing a teardrop-shaped foam windscreen 7 in. wide and 16 in. long (see Figure 2), similar to the Rosenheck, Hoffman, and Wittwer design (12).





Note: Windscreen not shown in photograph.

FIGURE 1 Typical mounting of on-board microphone for measurement of tire noise.

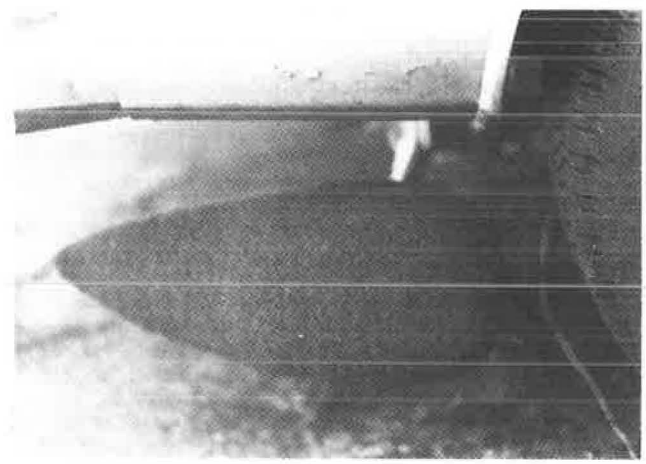


FIGURE 2 Windscreen used for on-board tire noise measurements.

The noise spectra obtained with the windscreen shown in Figure 2 for a vehicle speed of 55 mph is presented in Figure 3. The first set of data (solid circles) represents measurements made behind a moving tire; the other set (open circles) represents a nonrotating tire mounted on the roof of a vehicle, reproducing the turbulent wake but eliminating the tire-pavement noise. As can be seen from the plots, a separation of at least 5 dB exists between wind noise and tire noise, down to a frequency of about 200 Hz. These results indicate that on-board, near-tire measurements can be made with good signal-to-noise ratio, without masking wind noise.

Transfer Functions

The methods used by Reiter and Eberhardt (10), by Plotkin, (9) and by Hajek et al. (3) involving the measurement of the tire near field by using an on-board microphone needed one further element to adapt

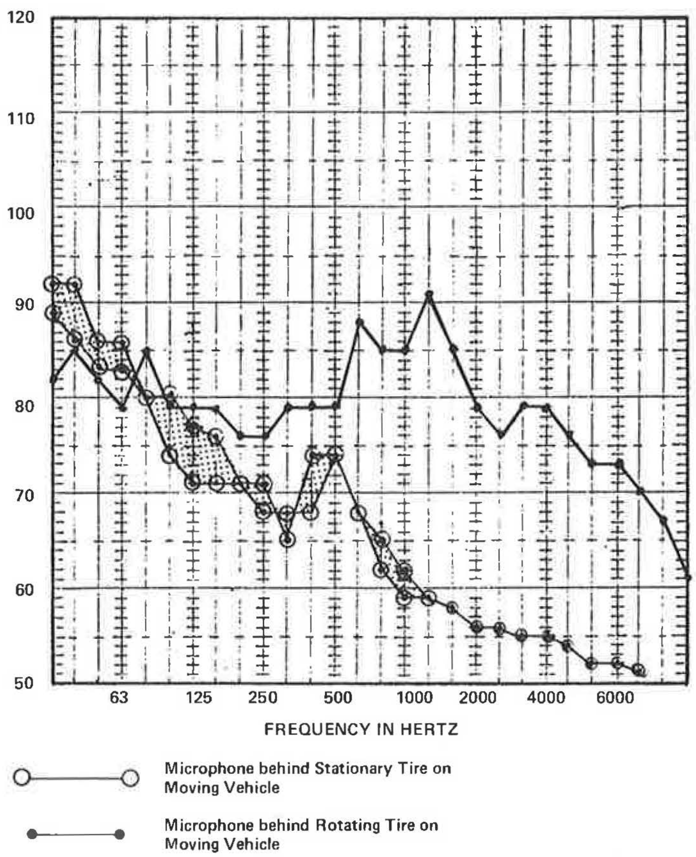


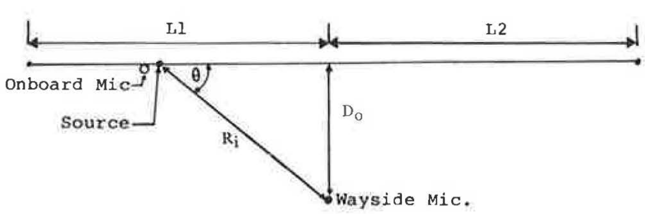
FIGURE 3 Third-octave data for teardrop-shaped windscreen.

them for use as wayside noise indicators--a relationship between the wayside measurement and the on-board measurement (see Figure 4).

A correction factor or a simple functional operation, which would yield a prediction of the standard 50-ft wayside sound pressure level, is needed that could be performed on a noise measurement made on a moving vehicle. The correction the authors were led to is the arithmetic difference between the on-board measurement and that at a 50-ft wayside receptor, L(50). This correction is labeled "transfer function" (TF) and it is defined operationally as

$$TF = L_{on\text{-}board} - [L(50)] \quad (1)$$

It is necessary to caution that this is not the usual definition from linear system theory [such as used in Reiter and Eberhardt (10)] inasmuch as no phase data is preserved. Rather, the form of Equation 1 corresponds to the level differences described by Reiter and Eberhardt (10).



Note: R_i is the radial distance to the wayside receiver.

FIGURE 4 Source-receiver geometry.

It was hypothesized that the variation between TFs for various tire-pavement combinations would prove to be small compared with the variation in sound emission strength between the combinations. It was hypothesized that at worst only a small number of TF classes might be required, perhaps 1 or 2 for automobile tires and a similar number for light truck tires and for heavy truck tires.

To investigate this hypothesis and place it on a firm foundation, simultaneous on-board and wayside measurements had to be made, TFs had to be deduced, and their variability had to be studied. This investigation involved 9 tire types for automobiles, 9 tire types for light trucks or vans, and 7 tire types for heavy trucks, as well as 4 different pavement strips. Furthermore, because it was necessary to avoid the errors and uncertainties due to previously noted micrometeorological instabilities, the measurements were carried out under conditions of low windspeed and nighttime hours between sunset and sunrise.

EXPERIMENTAL CONFIGURATION

Instead of following the usual order of presentation, that is, starting with the theoretical basis and following with the procedure, that order will be reversed in this paper: the experimental methodology will be reviewed and then the theoretical ideas, alternatives, and questions will be discussed.

The instrumentation configuration was reported previously (13) and is shown again for convenience in Figures 5 and 6. Figure 5 shows the transit of a test vehicle past a wayside microphone at a perpendicular distance of 50 ft. Two tapeswitches placed

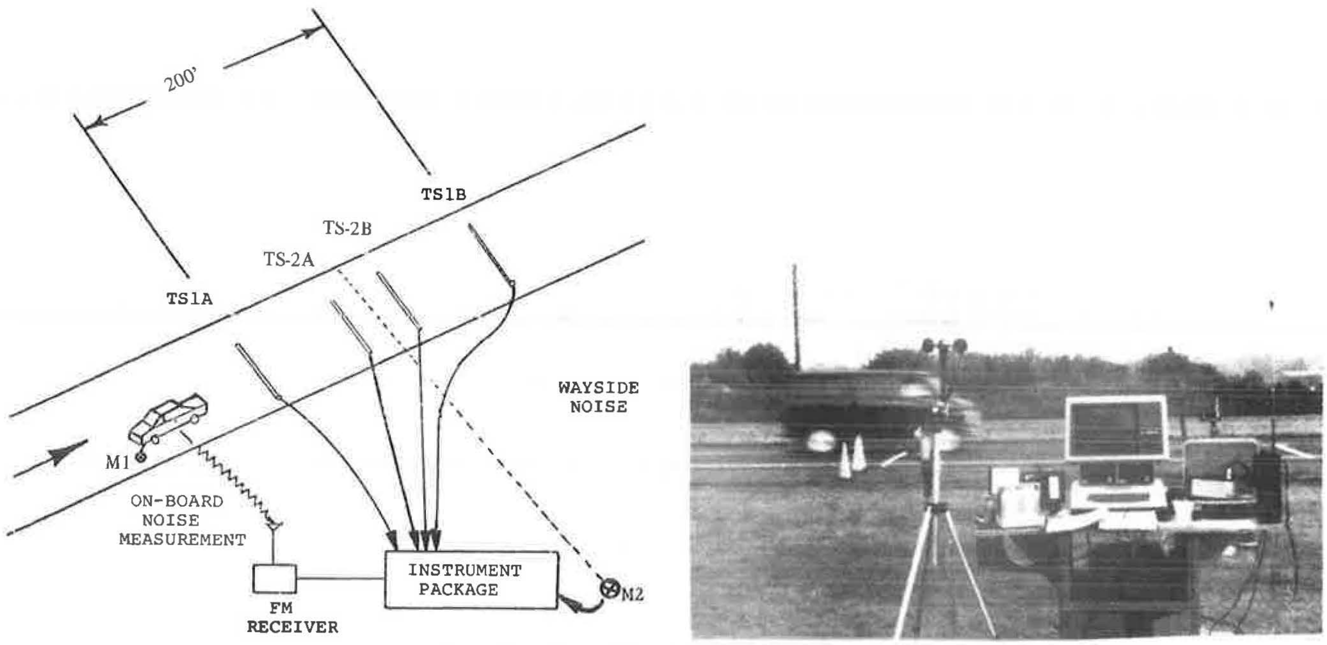


FIGURE 5 Equipment configuration for passby on-board/wayside noise measurements.

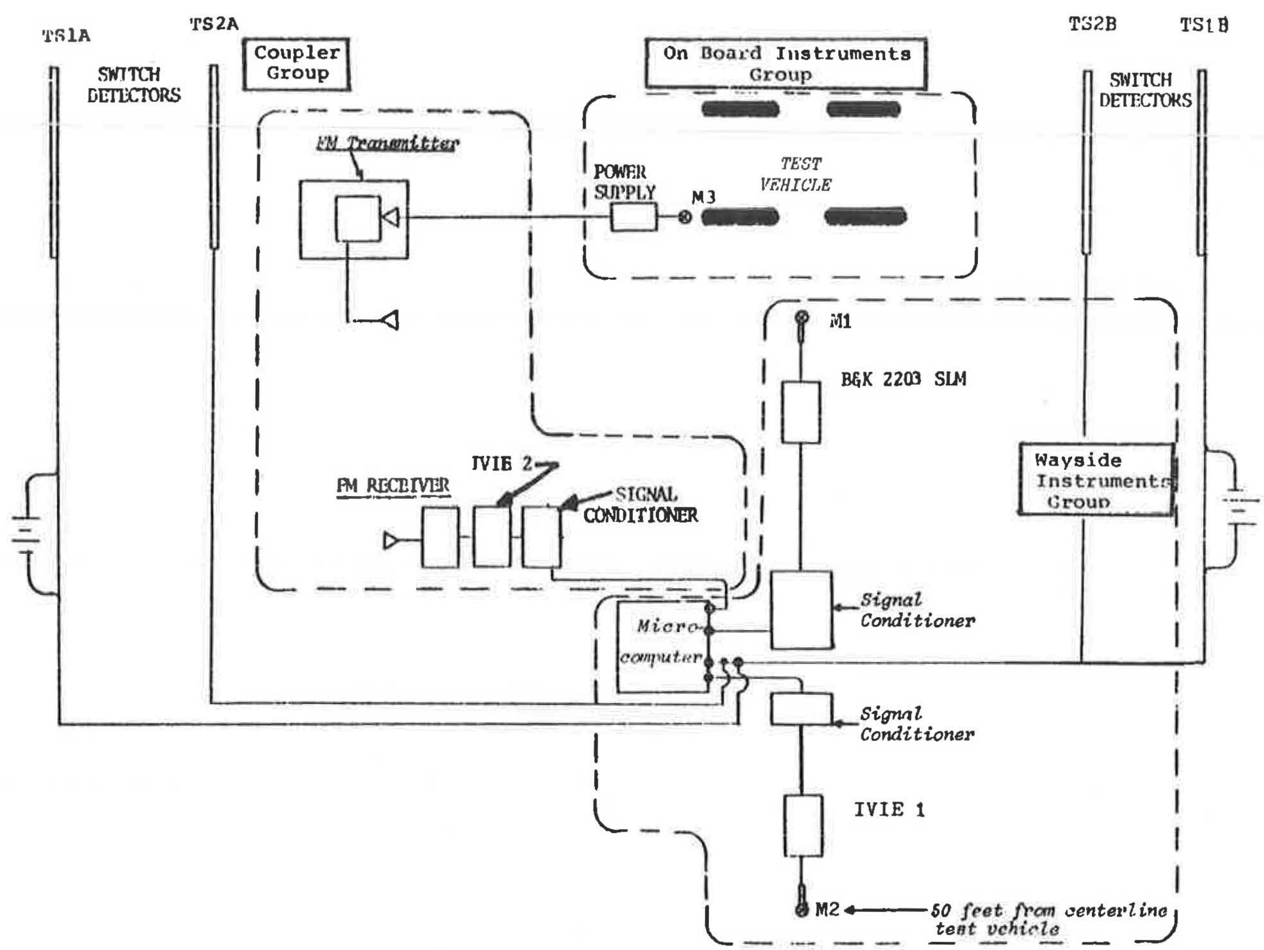


FIGURE 6 Block diagram of passby data acquisition instrumentation.

on the road pavement are spaced 200 ft apart and are centered over the perpendicular from the microphone, thereby furnishing a reproducible roadway test strip. (Two additional tapeswitches placed 30 ft apart furnish an additional smaller subsection useful for verifying vehicle speed and position). The tapeswitches activate a trigger circuit in the microcomputer incorporated within the instrument package, which scans the third octave and A-weighted output levels of an IVIE IE-30A sound level meter and third octave analyzer. The signals (up to 30 discrete 1/3 octave bands) are digitized and recorded in the microcomputer memory.

At the same time, the on-board microphone signal is monitored, amplified, and telemetered to the wayside, where it is processed by a second IVIE IE-30A sound level meter to yield corresponding third-octave and A-weighted data. The computer does not record the two data sets simultaneously; instead, it alternately makes one sweep of IVIE 1 (wayside) in about 11.5 ms, waits for the timing clock of IVIE 2 (on-board signal) to reach its starting position, and then makes a sweep of the IVIE 2 data channels. Because the two IVIEs are independent and unsynchronized, the waiting time is between 0 and 11.5 ms. This sampling waiting time between the two signals and the IVIE outputs being rms-DC-logarithmic processed signals make it impossible to use conventional cross-spectral data processing techniques such as those described in Reiter and Eberhardt (10). On the other hand, the logarithmic data are processed at relatively great speed and low cost.

When the test vehicle passes the second of the principal (200-ft) tapeswitches, the data collection stops, the computer core memory is transferred to diskette, and the system becomes ready for the next passby. About 20 passbys can be stored on one single-sided, single-density floppy disk. Each passby at 55 mph consists of about 75 complete cycles of on-board and wayside data, with each cycle containing 67 data points. The diskettes accumulated over one collection session are then generally processed automatically overnight.

ALTERNATIVE TF FORMULATIONS

Four TF formulation options have been identified:

1. Find the maximum wayside A-weighted level and corresponding third octave levels, and subtract them from the on-board values for the same cycle sweep to obtain TF.
2. Find the A-weighted and third octave levels for each of the (approximately 75) time cycles, correct them to equivalent 50-ft values, subtract each of these from the on-board values for the same cycle, and average the corresponding differences to obtain average TF.
3. Find L_{eq} (equivalent sound level) for the passby for the A-weighted and third octave wayside data and subtract from the corresponding on-board L_{eq} to obtain L_{eq} TFs.
4. Find the average of the 50-ft corrected wayside data and the on-board data, and subtract to obtain an average TF.

Fault was found with Option 1 because there was much data in each passby, which together should be more reliable than the single data point. Option 2 was found useful for analyzing directionality patterns, but is more cumbersome than Options 3 and 4. Option 3 has the conceptual defect that it apparently does not give predictions for other wayside distances. Option 4 appears to be quite reasonable, but it weights source points close to the receiver equally with those at the beginning and end of the test run. Problems with each of Options 1 to 4 led to the development of Option 5:

5. Find the difference of the L_{eq} measured at the wayside receiver (Figure 2) during a passby and the L_{eq} that would exist if the sources were omnidirectional and with constant strength. This can be expressed as

$$TF' = 10 \log 1/N \Sigma 10^{L_{OBi}/10} \times (D_o^2/R_i^2) + K - 10 \log 1/N \Sigma 10^{L_{wi}/10} \qquad (2)$$

where

L_{OBi} = on-board sound pressure level at time $t = t_i$,
D_o = offset distance from wayside microphone to centerline of lane,
R_i = radial distance from observer to noise source,
K = constant, and
L_{wi} = noise level observed for wayside receiver.

The constant K can be interpreted as depending on the squared ratio of the on-board microphone to source distance and the offset distance D_o. (More information about K is provided in the discussion of directionality that follows.) Because the actual functional form of K cannot be set down in a simple form, it is merged in the overall transfer function, $\overline{TF}$, with the result

$$\overline{TF} = 10 \log 1/N \Sigma 10^{L_{OBi}/10} \times (D_o^2/R_i^2) - 10 \log 1/N \Sigma 10^{L_{wi}/10} \qquad (3)$$

However, L_{OBi} is extremely stable over a passby run, and the second term is recognized as the passby L_{eq}, so that,

$$\overline{TF} = L_{OB} - L_{eq} - \Delta$$

where

L_{OB} = on-board sound pressure level,
Δ = difference in vehicle position from L_0, and

$$-10 \log 1/N \Sigma (D_o^2/R_i^2) \equiv \Delta = 10 \log [|L_1/D_o| + |L_2/D_o|/\arctan |L_1/D_o| + \arctan |L_2/D_o|] \qquad (4)$$

The right-hand side of Equation 4 is obtained by allowing the sum on the left-hand side to approach an integral in the limit of large N. For the trap dimensions used, $L_1 = L_2 = 100$ ft, $D_o = 50$ ft, and $\Delta = 2.6$ dB. It can be seen that Option 5 differs from Option 3 only by the factor Δ, which is the same for all runs with similar pavement length to offset ratio.

It should be noted that the TFs as defined above are for one axle. The effect of adding a second identical axle is that 3 dB is added to the wayside passby L_{eq} and nothing is added to L_{OB}. (The on-board microphone only sees the rearmost axle because of shielding proximity to the source.) Accordingly, the resulting two-axle TF is less by 3 dB. (The actual results are for a two-axle TF.) The contributions of two unequal axles must be found by decibel subtraction of the results from the homogeneous and mixed cases. The energy contribution of multiple axles is similarly obtained by superposition.

AVERAGE TF FOR REPEATED PASSBYS

For each run, the data analysis procedure used involves generating a third octave array of wayside L_{eq}, of on-board L_{OB} (arithmetic) average, and of the corresponding (two-axle) TF (as defined by Equation 3). These runs are repeated between 5 and 10 times for each combination of three conditions: tire-pavement, speed, and either powered engine or idle engine (35 runs per tire-pavement combination).

Question arises about which is the most appropriate procedure for averaging TFs. The procedure that was first choice, for simplicity and ease of error detection, was to calculate the mean value of all the TFs (in a given spectral band) as well as the standard deviation. Any large standard deviation would call attention to a suspicious run and cause a search for the on-board or wayside root of the trouble. Obvious errors (as distinct from possible random effects) could thereby be eliminated.

Assuming now that the data contain only variations that cannot be attributed to error or otherwise discounted, considered should be overall average TFs for runs r = 1 to NR, defined by any one of the following three alternative forms:

$$\overline{TF} = 1/NR \sum_{r}^{NR} TF_r \tag{5}$$

$$\overline{TF} = -10 \log 1/NR \sum_{r}^{NR} 10^{-TF_r/10} \tag{6}$$

$$\overline{TF} = 10 \log 1/NR \sum_{r}^{NR} 10^{\overline{L_{OB}}/10} - 10 \log 1/NR \sum_{r}^{NR} 10^{(EL50)/10} \tag{7}$$

where

NR = total number of test runs,

TF_r = transfer function for test run r, with r varying from 1 to nr, and

$$EL50 = L_{eq} + \Delta \tag{8}$$

EL50 is L_{eq} corrected so that the receiver appears to be at a constant distance of 50 ft during the passby.

The meaning of Equation 5 is obvious: it is the arithmetic average already discussed previously. Equation 7 represents the difference of the energy averages of all of the on-board averages and the wayside EL50 values. Thus, given an on-board reading, a most probable wayside prediction can be made. Equation 6 represents an average of the energy ratios of I_{OB} and I_{wr}:

$$10^{-TF_r/10} = (I_{wr} \times 10^{\Delta/10})/I_{OB} \times (1/NR) \sum_{r}^{NR} 10^{-TF_r/10}$$

$$= 10^{-\overline{TF}/10} = (I_{wr}/I_{OB})\ 10^{\Delta/10}$$

where I_{wr} is the intensity at the wayside receiver and I_{OB} is the on-board intensity. The mean TF follows by taking logarithms.

Although Equations 5, 6, and 7 appear to be quite different, the numerical values of the resulting TF are equal to within 0.1 to 0.2 dB even for large values of sigma (2 or 3).

INSTANTANEOUS TFs

A metric of considerable interest is the radiation directionality, which reflects the influence of tire carcass construction and footprint slip-stick mechanism. The pattern of the instantaneous (time-evolving) TF is therefore of interest for the light that it might shed on this construction and this mechanism.

The geometry of Figure 1 (neglecting ground absorption for the 50-ft wayside position) results in the relation between wayside intensity I_w due to the 4 tires and on-board intensity I_{OB}:

$$I_w = I_{OB} \times (D_O^2/R^2) \times K(\theta) \tag{9}$$

where $K(\theta)$ includes a directionality index and a constant factor depending on the on-board microphone position (angle and distance from the on-board source tire) as well as on the wayside contributions of the other tires. For automobiles and vans, it is assumed that directionality will not be affected much by the presence of 4 tires instead of 1, for 4 identical tires if the wheelbase is small compared with the offset distance D_O = 50 ft. (Characteristics of mixed tires would have to be determined by energy subtraction.)

The instantaneous TF (for 4 tires) would be

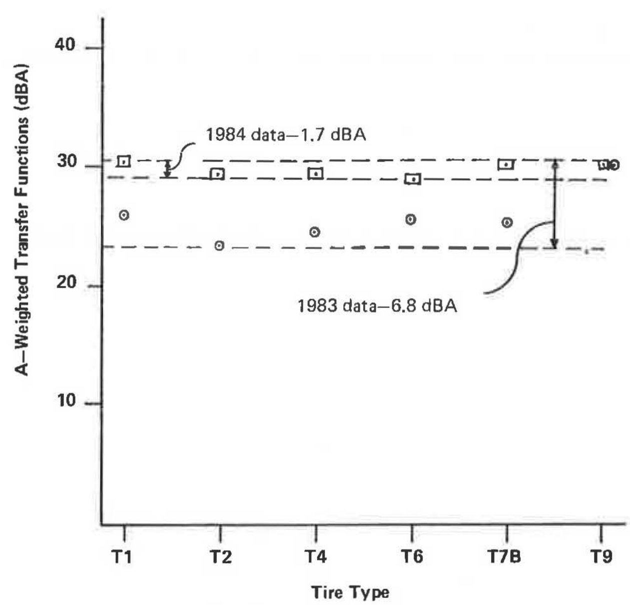
$$TF = 10 \log (1/K_i) \tag{10}$$

$$\equiv 10 \log (I_{OB}/I_{wr})\ (D_O^2/R_i^2) \tag{11}$$

$$\equiv L_{OB} - 10 \log \left[10^{L_{wr}/10} \times (D_O^2/R_i^2)\right] \tag{12}$$

where K_i is the constant energy term that is a function of time.

Figure 7 shows a representation of the instantaneous TF plotted versus axial distance instead of angle.



Note: Tire definitions—T1 = bias rib, T2 = bias mud and snow, T4 = all weather radial, T6 = radial rib, T7B = radial mud and snow, T9 = radial rib. Symbol definitions—⊙ = 1983 data, ⊡ = 1984 data.

FIGURE 7 Instantaneous transfer function versus axial distance.

FINDINGS

Initial Measurement Results

Computations of the A-weighted TF for automobile, light-truck, and heavy-truck tires were carried out for many tire pavement sets during spring, summer, and fall 1983. The authors were surprised and disappointed to find large spreads of about 6 to 8 dB in the TFs. Similar large spreads were found in the on-board and wayside readings, with little apparent reason for the difference in on-board levels of tires (which were expected to be similar) and with equally unexpected reversal of the noise rankings. Many hypotheses were explored, from the effect of strong directionality patterns to the special toughness (hardness) of some of the rubber compositions.

Later Measurement Results

During winter 1983 and early spring 1983-1984, the tires were all stored in a truck where they experienced many significant changes in temperature and humidity. (This was in contrast to spring 1983 when excess tires filled the laboratory to the point of impassibility.) As soon as the spring rains eased, the investigation proceeded on the effect of tire noise directionality by repeating the automobile tire on-board/wayside test procedure but with the microphone in three different positions: successively behind the tire (as before), at 45 degrees (halfway between the wheel axis and the previous trailing position), and at the 90-degree position on the wheel axis.

It was somewhat surprising to find that the on-board microphone readings changed with angular position by at most 3 dBA (see Figure 8c). Also, it was puzzling to find that the TFs for each of the microphone positions now formed a tight (1 dBA) cluster at a value identical to that of the tire that had previously been considered to be most questionable. Upon investigation, it was found that the tire set in question had been the only one purchased locally; its wrapping was old and faded, and its apparent initial age and exposure contrasted dramatically with those of the other tires that had arrived hot from the manufacturers' baking ovens. (The strong odor of rubber had been evident to anyone passing near the laboratory.)

Conversations with polymer chemists and polymer engineers at the Polytechnic Institute of New York and then with people at tire companies verified the hypothesis that aging for 1 year would produce large changes in the physical properties of rubber tires, and, indeed, that some operators of heavy equipment regularly aged their off-the-road tires to toughen them for the hard usage that was anticipated.

Examination of the data for both periods revealed that the change in the TFs was due to a change in the on-board A-weighted level with relatively small (less than 2 dBA) changes in the wayside A-weighted level, as can be seen in Table 1. (Note that all of the runs shown in Table 1 were tested on the pavement type P2, dense graded asphalt overlay.) Furthermore, a general clockwise rotation of the spectral curve about the middle of the range (1,000 Hz) was observed having the effect of increasing the low frequencies, decreasing the high frequencies, and leaving the A-weighted sum relatively unaffected. Figure 9 shows a typical example of this behavior.

The new A-weighted wayside and TF values for the automobile and van tires tested are given in Table 2.

Transfer Functions

A partial summary of the results to date of TFs for various tire types and several pavements is given in Table 2. Note that for each vehicle class there is a well-defined range of TFs that vary only slightly from pavement to pavement.

However, there is a significant variation of the TF from one vehicle class to another. The largest values are found for automobiles; values for vans rank next and those for trucks are lowest. These

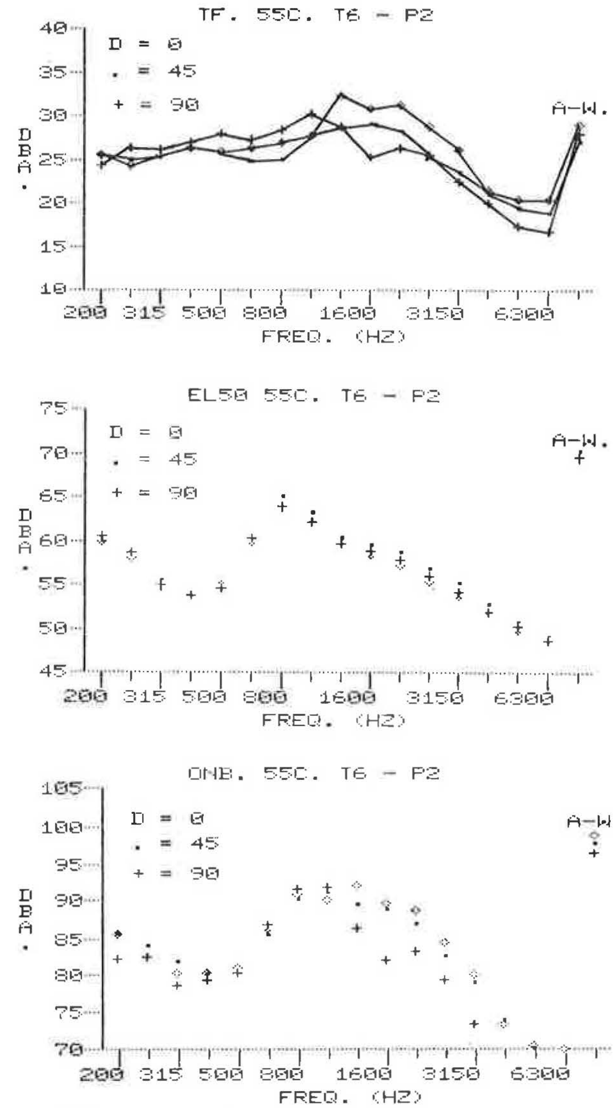


FIGURE 8 On-board/wayside measurements taken with on-board microphone at varying angles.

TABLE 1 Summary of Observed Wayside and On-Board Levels for 1983 Measurements versus 1984 Measurements at 55 mph Coastby

	1983		1984	
Tire Type	Wayside	On Board	Wayside	On Board
Bias rib	70.9	97.1	72.1	102.8
Bias mud and snow	73.3	96.5	74.6	104.2
All weather radial	69.6	93.7	71.3	100.9
Radial rib	70.4	96.1	69.6	98.6
Radial mud and snow	69.4	95.0	70.4	100.6
Radial rib	70.1	100.1	70.1	100.1

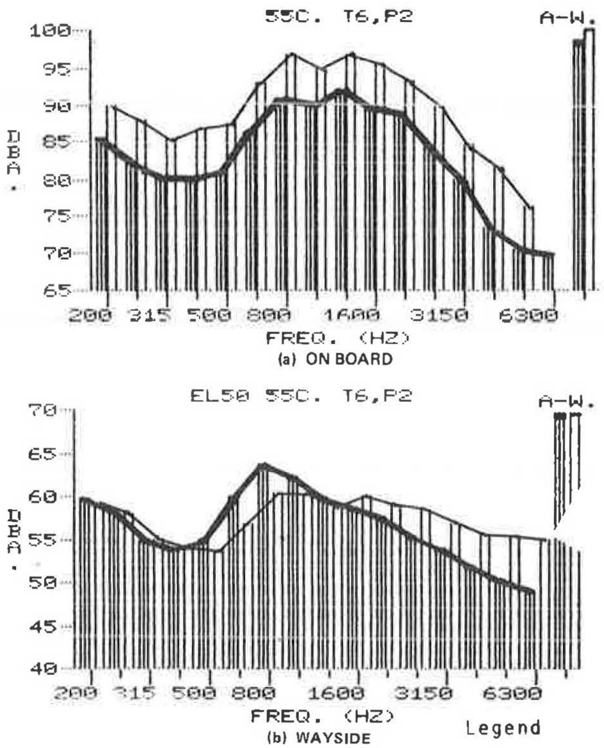


FIGURE 9 Comparison of 1983 and 1984 measurements of automobile tire noise levels.

TABLE 2 Summary of Typical Transfer Functions

Tire Type	Transfer Function
Automobile	
Bias rib	30.8
Bias mud and snow	29.7
All weather radial	29.4
Radial rib	29.0
Radial mud and snow	30.2
Radial mud and snow	29.3
Radial rib	30.0
Van	
Bias mud and snow	25.3
Bias rib	25.5
Bias rib	24.6
Radial rib	24.5

differences appear reasonable for the following reasons:

- The fractional contribution of the on-board measured tire to the total level measured at the wayside decreases for the van and truck because of the increased visibility of the tires on the opposite side of the vehicle.
- In addition to the effect of increased visibility, the truck also has more tires.
- To maintain reasonable and safe geometric configuration of the microphone and tire, the distance from the microphone to the tire patch trailing edge increases from automobile to van to truck.

Note that the full range of available automobile tires were tested on one of the test pavements to be absolutely certain of the validity of the bounded TF results.

To further validate the conclusions of tightly bounded variation, a subset of pavements and tires was chosen to represent the available range of pavements and tires. This need for limiting the number of tire-pavement cases was a consequence of the inability of using the initial, extensive measurements from the uncured tires. The overall reliability of these TFs is confirmed by the inner consistency of the data.

Further reason for confidence in the data is the reproducibility of the individual on-board and wayside data from which the TFs are deduced. Typical data outputs are given in Tables 3, 4, and 5 for on-board, wayside, and transfer function levels, respectively. These tables are for a series of pass-bys and coastbys of a single tire-pavement combination at two speeds. Data are output in third octave bands as well as A-weighted levels. Note that the variations from run to run are very small.

Use of TFs

One of the important applications of the foregoing results is the remarkable facility with which it is possible to make reliable wayside predictions for various tire-pavement combinations by using the on-board over-the-road measurement system. In connection with the research effort, it was possible to collect an extensive tire-pavement noise data base. Table 6 shows a typical sampling from that data base for a subset of the tires and pavements measured. It can be seen in the table that there is a range of about 6 to 8 dBA from the quietest to the loudest combinations encountered. Such a data base would be of value for predicting the tire-pavement noise component to be anticipated by the particular mix in a given region and for assessing reasonable pavement choices.

CONCLUSIONS

The following conclusions can be drawn from the foregoing discussion:

1. Wayside computerized data acquisition allows great flexibility in application of and in choosing varieties of data interpretation.
2. On-board methods allow acquisition of tire-pavement noise data bases at minimal cost.
3. TFs were found to be unique for each vehicle type and are therefore appropriate for measurement programs. Reliability is equivalent to that of existing standard wayside measurement methods as ordinarily employed.

ACKNOWLEDGMENT

The research reported on herein is being conducted under FHWA, U.S. Department of Transportation contract "Tire-Pavement Noise Assessment Procedure" with Fred Romano as technical monitor, and has benefited from comments received from the various tire manufacturers, including Firestone, General, Goodrich, and Goodyear. The authors wish to acknowledge the input of many others associated with the design and implementation of the research reported on here, including personnel of domestic tire manufacturers. Special thanks are expressed to Loyal Chow, Patrick Hanley, James Goon, and Conrad Moses for their ac-

TABLE 3 Summaries of Multiple Data Runs for On-Board Levels

1/3 Octave Band	Test Run No. (dB)				Avg of Test Runs	Sigma
	CC2	CC3	CC4	CC5		
200 HZ	86.7	87.9	87.3	87.4	87.3	.43
250 HZ	85.4	85.6	85.6	85.9	85.6	.18
315 HZ	85.7	86	86.9	86.4	86.3	.45
400 HZ	85.2	86.2	85.2	84.9	85.4	.49
500 HZ	88.4	88.5	88.1	88.7	88.4	.22
630 HZ	94.1	94.8	94.2	93.9	94.3	.34
800 HZ	92	91.7	91.7	91.2	91.7	.29
1 K	92.2	92.5	91.9	92.4	92.3	.23
1.25 K	98	97.7	98.2	98.2	98	.2
1.6 K	97.7	97.5	97.9	97.3	97.6	.22
2 K	95.4	94.8	95.6	94.7	95.1	.38
2.5 K	90.4	90.5	90.8	90.4	90.5	.16
3.15 K	86.5	86.4	86.5	86.4	86.5	.05
4 K	81.8	81.6	81.7	81.6	81.7	.08
5 K	76.5	76.3	76.5	76.3	76.4	.1
6.3 K	72.9	72.8	72.9	72.9	72.9	.04
A-W*	104.3	104.1	104.4	104.1	104.2	.13

Note: Test runs were made on May 9, 1984, using vehicles with tire types 1 (bias rib) and 2 (bias mud and snow). Vehicles were travelling at 55 mph.

TABLE 4 Summaries of Multiple Data Runs for Wayside Levels

1/3 Octave Band	Test Run No. (dB)				Avg of Test Runs	Sigma
	CC2	CC3	CC4	CC5		
200 HZ	63.2	62.5	63.6	62.6	63	.45
250 HZ	62.6	62.2	62.7	61.9	62.4	.32
315 HZ	60.6	61.1	60.6	60	60.6	.39
400 HZ	57.8	57.6	57.1	57.5	57.5	.25
500 HZ	59.2	58.4	59.6	59.3	59.1	.44
630 HZ	64.2	63.7	64.7	63.9	64.1	.38
800 HZ	65.2	65.3	65.2	64.9	65.2	.15
1 K	65.4	65.7	65.2	65.2	65.4	.2
1.25 K	68	67.7	67.8	67.6	67.8	.15
1.6 K	67.3	66.8	67	66.7	67	.23
2 K	63.3	63.2	63.6	63.3	63.4	.15
2.5 K	60.7	60.8	60.8	60.4	60.7	.16
3.15 K	58.2	57.8	58.1	57.8	58	.18
4 K	55.9	54.4	55.4	55.3	55.3	.54
5 K	53.9	52.4	53.4	53.1	53.2	.54
6.3 K	51.6	50.2	51.1	50.7	50.9	.51
A-W*	74.7	74.5	74.6	74.4	74.6	.11

Note: Test runs were made on May 9, 1984, using vehicles with tire types 1 (bias rib) and 2 (bias mud and snow). Vehicles were travelling at 55 mph.

TABLE 5 Summaries of Multiple Data Runs for Transfer Function Levels

1/3 Octave Band	Test Run No. (dB)				Avg of Test Runs	Sigma
	CC2	CC3	CC4	CC5		
200 HZ	23.5	25.4	23.7	24.8	24.4	.78
250 HZ	22.8	23.4	22.9	24	23.3	.48
315 HZ	25.1	24.9	26.3	26.4	25.7	.68
400 HZ	27.4	28.6	28.1	27.4	27.9	.51
500 HZ	29.2	30.1	28.5	29.4	29.3	.57
630 HZ	29.9	31.1	29.5	30	30.1	.59
800 HZ	26.8	26.4	26.5	26.3	26.5	.19
1 K	26.8	26.8	26.7	27.2	26.9	.19
1.25 K	30	30	30.4	30.6	30.2	.26
1.6 K	30.4	30.7	30.9	30.6	30.7	.18
2 K	32.1	31.6	32	31.4	31.8	.29
2.5 K	29.7	29.7	30	30	29.9	.15
3.15 K	28.3	28.6	28.4	28.6	28.5	.13
4 K	25.9	27.2	26.3	26.3	26.4	.48
5 K	22.6	23.9	23.1	23.2	23.2	.46
6.3 K	21.3	22.6	21.8	22.2	22	.48
A-W*	29.6	29.6	29.8	29.7	29.7	.08

Note: Test runs were made on May 9, 1984, using vehicles with tire types 1 (bias rib) and 2 (bias mud and snow). Vehicles were travelling at 55 mph.

TABLE 6 Typical On-Board Noise Levels (dBA) for Various Tire-Pavement Combinations

	Pavement Types			
Tire Type	P1 (PCC)	P2 (DGA)	P3 (DGAO)	P4 (OGA)
Bias rib	102.9	99.9	99.3	98.4
Bias mud and snow	102.4	101.4	100.6	101.9
All weather radial	100.6	98.8	98.9	96.9
Radial rib	101.4	98.9	99.7	97.4
Radial mud and snow	100.7	100.4	100.9	99.4
Radial rib	100.4	98.7	99.4	97.9
Bias mud and snow	97.1	95.6	96.4	95.1
Bias rib	98.0	95.8	96.2	94.6
Bias rib	95.4	95.5	94.4	94.0
Radial rib	99.2	95.4	96.4	94.4

Note: PCC = portland cement concrete, DGA = dense graded asphalt, DGAO = dense graded asphalt overlay, and OGA = open graded asphalt.

complishments related to the design of the hardware and software systems presented here. Appreciation is also extended to Michael Leonard, Nassy Srour, and Horace Patterson for their assistance in the data collection efforts. Special appreciation is expressed for the comments of our reviewers.

REFERENCES

1. J.C. Walker and R.D. Oakes. The Reduction of Tyre Road Interaction Noise. Dunlop Corporation, Birmingham, England, 1981.
2. J.C. Walker. Tyre-Road Interaction Studies to Improve Noise and Grip. Dunlop Corporation, Birmingham, England, 1981.
3. J.S. Hajek, L. Kwan, and C.T. Blaney. Comparison of Tire/Pavement Noise Measurement Methods. Inter-Noise '82, San Francisco, 1982.
4. D.B. Thrasher, R.F. Miller, and R.G. Bauman. Effect of Pavement Texture on Tire/Pavement Interaction Noise. SAE Highway Tire Noise Symposium Proceedings. SAE Report P-70, Paper 762011. San Francisco, 1976.
5. N-A. Nilson. Possible Methods of Reducing External Tire Noise. Presented at International Tire Noise Conference, Stockholm, Sweden, 1980.
6. V. Sandburg. Characterization of Road Surfaces with Respect to Tire Noise. Presented at International Tire Noise Conference, Stockholm, Sweden, 1980.
7. R.F. Miller and D.B. Thrasher. Passby Tire/Pavement Interaction Noise Measurement Problems. SAE Highway Tire Noise Symposium Proceedings. SAE Report P-70. San Francisco, 1976, pp. 81-87.
8. D.G. Anderson, T. Benchea, and F.E. Matyja. Round Robin Testing with SAE J57a. SAE Highway Tire Noise Symposium Proceedings. SAE Report P-70. San Francisco, 1976, pp. 89-100.
9. K. Plotkin. Investigation of the Truck Tire Vibration Sound Mechanism. Wyle Labs, July 1979.
10. W.F. Reiter and A.C. Eberhardt. The Relationship Between Truck Tire Vibration and Near and Far Field Sound Levels. SAE Highway Tire Noise Symposium Proceedings. SAE Report P-70. San Francisco, 1976, pp. 145-154.
11. K.J. Plotkin, M.L. Montroll, and W.R. Fuller. The Generation of Tire Noise by Air Pumping and Carcass Vibration. Inter-Noise '80 Conference Proceedings, Poughkeepsie, N.Y., Dec. 1980, pp. 273-276.
12. A.J. Rosenheck, R.P. Hoffman, and P. Wittwer. Measurement of Automobile Tire Noise in a Moving Vehicle and Comparison with Drum Measurements. Proc., 1979 International Tire Noise Conference, National Swedish Board of Technical Development, Sweden, 1980.
13. P. Grealy, S. Slutsky, and W.R. McShane. The Use of Microcomputers in Highway Noise Data Acquisition and Analysis. In Transportation Research Record 983, TRB, National Research Council, Washington, D.C., 1984, pp. 57-64.

This paper was produced as part of a program of research sponsored by FHWA, U.S. Department of Transportation. The results and views expressed are the product of this research and statements expressed in this paper are those of the authors and do not necessarily reflect those of FHWA.

Publication of this paper sponsored by Committee on Transportation-Related Noise and Vibration.

An Application of Artificial Intelligence in Highway Noise Analysis

ROSWELL A. HARRIS, LOUIS F. COHN, and WILLIAM BOWLBY

ABSTRACT

The highway noise abatement program in the United States is still in the developmental stage, which is demonstrated by only 29 states having constructed one or more noise barriers to date. Explored in this paper is a method of making the expertise in highway noise analysis and control easily accessible to highway noise analysts. This relatively new activity in artificial intelligence is known as an expert system. A general discussion of expert systems is presented, followed by a discussion of a specific prototype system currently under development at Vanderbilt University.

Efforts to mitigate highway noise impacts are still in the developmental stage in this country (1). After more than a decade of federal involvement and the construction of more than 200 linear miles of noise barriers, only 29 states have constructed more than one noise barrier (2). Moreover, it was noted in a 1980 report by the National Cooperative Highway Research Program that 85 percent of the almost 190 linear miles of barriers had been constructed in only 9 states, with 39 percent in only 1 state, California (3). However, as the concept of mitigating highway noise impacts becomes more fully integrated into the project development process, it can be expected that many more states will develop barrier construction programs.

After a highway noise impact has been identified in accordance with FHWA, U.S. Department of Transportation regulations (4), the noise analyst must seriously consider mitigation measures. Information should be gathered from many different sources and then integrated through a series of mathematical and physical steps to form a basis from which to recommend abatement alternatives to administrators in the highway agency. Much of this information is straightforward and available from convenient sources; for example, horizontal and vertical alignment of the roadway many already have been determined and be available from the appropriate design office. However, other information is less evident and may require special knowledge or insight; for example, the corridor under development may be in the vicinity of an upcoming zoning modification that may significantly alter existing land use. Unless the analyst is able to consider such an eventuality, a selected noise abatement measure may become inappropriate.

After the noise analysis has been completed, there is likely to be an array of abatement options from which to choose. To convince the decision maker that an abatement measure is cost-effective and necessary, it is essential that the analyst be able to assign a priority for all of the options in a correct and consistent manner. Without this ability, it is possible that an agency will either make the wrong decision or no decision at all.

To alleviate this problem, the analyst must be able to use the expertise of other professionals in the field. How can this be accomplished most efficiently? Making expertise from a domain-specific area widely available and then easily accessing that expertise is a relatively new activity in the field of artificial intelligence (AI). The mechanism by which this concept is becoming a reality is known as the expert system (5). A general discussion of expert systems will be presented in this paper, followed by a discussion of a prototype expert system, CHINA-1 (Computerized HIghway Noise Analyst), currently under development by the Transportation Research Group at Vanderbilt University. Finally, the utility of the prototype system will be demonstrated by using an example problem.

EXPERT SYSTEMS

An expert system may be defined as an intelligent computer program that uses knowledge and inference procedures to solve complex problems that are difficult enough to require significant human expertise. Both the knowledge and inference procedures may be viewed as a model of the expertise of human experts in their field (5).

The expert system is typically made up of three primary components [see Figure 1 (6)]:

- A knowledge base containing the domain-specific facts and heuristics associated with a particular field
- A rule interpreter, or inference engine, that can utilize the knowledge base in the solution of a problem
- A global data base, or work space, that maintains the status and input data for the current problem.

Each of these components will be discussed further.

The knowledge base of an expert system is made up of two types of knowledge: facts and heuristics. Facts consist of general knowledge that includes the published definitions and theories found in the textbooks and references within the domain of study. However, expertise in a specialty usually involves knowledge that is not in the published literature. This private knowledge consists of rules of thumb that characterize expert-level decision making and has become known as heuristics (5). For example, the expert in highway noise knows that line-of-sight break with truck exhausts will improve the perception of barrier performance, regardless of prediction results. Thus, he may, as a rule of thumb, make certain that such lines of sight are broken where necessary.

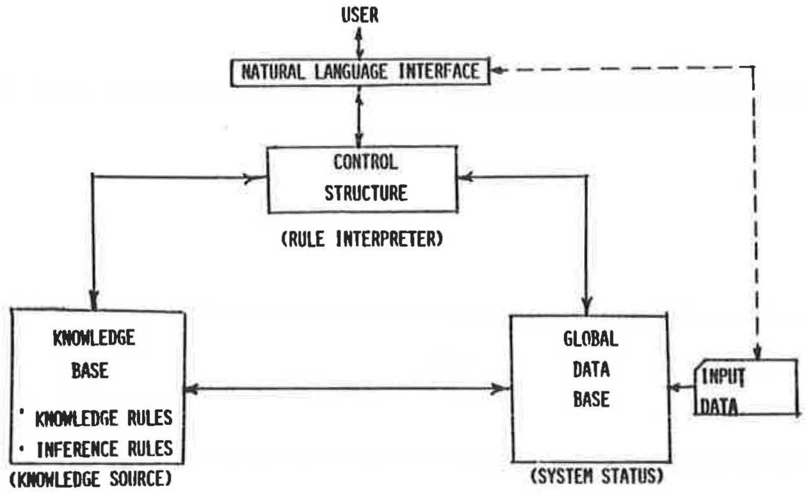


FIGURE 1 Generic expert system.

The rule interpreter, or inference engine, may be described as a type of reasoning mechanism that is capable of applying the heuristics or rules in the knowledge base to the facts about a specific problem (5,7). The performance of an expert system is primarily a function of the size and quality of its knowledge base, not of its particular inference engine. Several inference engines are available as skeletal structures that may be modified to fit the specific needs of a new system (5,8,9). As an option, the engine could be constructed from scratch by using one of the standard AI programming languages.

The final major component of an expert system is the global data base, or work space. This is a working memory that contains information that collectively describes the specific problem and maintains a current assessment of that problem.

The computer language LISP (LISt Processing) is chosen for most work in AI because of its ability to easily manipulate symbols (5). A program written in LISP uses symbolic expressions to work with data and procedures, just as humans work with pencil, paper, and words (10). A symbol manipulation program is able to recognize certain symbolic expressions, tear old ones apart, and assemble new ones. For example, it can interpret a conversational English question from a user by tearing the sentence apart and recognizing predefined technical terms, pronouns, or synonyms.

In LISP, the function to be performed is always given first, followed by the data with which the function is to work. These data are known as the arguments of the function. In the example below, the function SETQ assigns to the expression VANDERBILT the value of the list (A SOUTHERN UNIVERSITY).

```
(SETQ VANDERBILT '(A SOUTHERN UNIVERSITY))
```

In response to the user typing the expression "VANDERBILT", a compiled LISP environment will reply with the list "A SOUTHERN UNIVERSITY". Likewise, in a LISP program, any time the expression "VANDERBILT" is encountered, the list "A SOUTHERN UNIVERSITY" will be returned. A list is defined as an expression enclosed by parentheses. The individual pieces of that list are known as elements. In the example just given, "A SOUTHERN UNIVERSITY" is a list and each word is an element of that list.

The expert system differs from conventional computer programs in several ways (8). Because both functions and data written in LISP have the same form, the system can be more easily modified by users not very familiar with conventional programming techniques. In a conventional program, the data relative to a given problem and the methods of utilizing that data are intertwined so that it is often difficult to change the program. On the other hand, an expert system is usually characterized by a clear separation of general knowledge, information about a specific problem, and the method of applying the general knowledge to the problem. The program itself is only an interpreter and the system can be easily modified by adding or subtracting rules to the knowledge base. Thus, the expert system is not static; rather, it can be said that it learns.

The task of gathering knowledge and assembling it in program form is referred to as knowledge acquisition (5). Because the performance of the expert system is dependent on the completeness of the knowledge base, this task is key to the development of an acceptable system. Sources of knowledge include human experts, textbooks, journal articles, data bases, and personal experience. Because knowledge acquisition is an iterative process, commitment from an articulate expert is important. It is also important that the expert system builder be skilled in the interrogation of the expert to effectively assemble the knowledge base. Feedback from the expert about the performance of the system each time a rule is modified, added, or subtracted is essential. As more and more heuristics are added to the knowledge base, the system will approach (and possibly exceed) the competence of a human expert (6).

Because of the size and complexity of this knowledge base, the development of a prototype is an important first step in constructing an expert system. This prototype is designed to address a subproblem within the overall problem area. Through experimentation and revisions, the prototype will become the model from which the final expert system will be constructed. The remainder of this paper will focus on the prototype system, CHINA-1, currently under development at Vanderbilt University.

CHINA-1

CHINA-1 is written in UCI LISP (11) and is installed on the Vanderbilt University DECsystem 1099 mainframe computer. Access to CHINA-1 is through a Macro Interpreted Command (MIC) file (12).

CHINA-1 is designed to first classify highway noise-related impacts based on existing and future noise levels supplied by the user. This heuristic is based on past experience of the authors and others (13,14) and is meant to illustrate the use of heuristics in this context. Then, reading a file produced by a modified version of OPTIMA, CHINA-1 identifies those barrier segments over which the maximum or minimum sound energy is passing, and makes recommendations on how the barrier may be modified to best reach the design goals specified by the user. How a user might utilize CHINA-1 on a hypothetical problem is described in detail in the following paragraphs.

A fundamental question in any highway noise analysis is whether an impact actually exists. The answer to this question often dictates the type of abatement considered, or just as important, if any consideration will be given to reducing highway noise levels. CHINA-1 was programmed to perform this task based on criteria established by the user and illustrates how the knowledge base can be easily modified. Only exterior activity for single-family residences will be considered in this prototype system. However, this feature will adequately demonstrate the feasibility of expanding the basic concept of building such a model.

In making this impact determination, federal regulations require that an approach that considers absolute noise levels, as well as the increase over existing noise levels, be utilized (4). A number of procedures are available that recommend ways to address this requirement (13,14). A method has been devised for CHINA-1 that will classify noise-related impacts as none, moderate, or severe, on the basis of two rules. Considered in the first rule is the difference between the predicted noise level and a criterion level built into the model; the criterion level is displayed early in the process and the user is given the opportunity to change it. Considered in the second rule is the amount of increase between existing and predicted noise levels. Figure 2 shows the resulting matrix of impact zones.

To illustrate the use of this prototype system and the concept of using expert systems in this area, an interaction with CHINA-1 is described in the following paragraphs. In conjunction with the narrative, the reader's attention is also directed to Figure 3, which presents the actual session with CHINA-1.

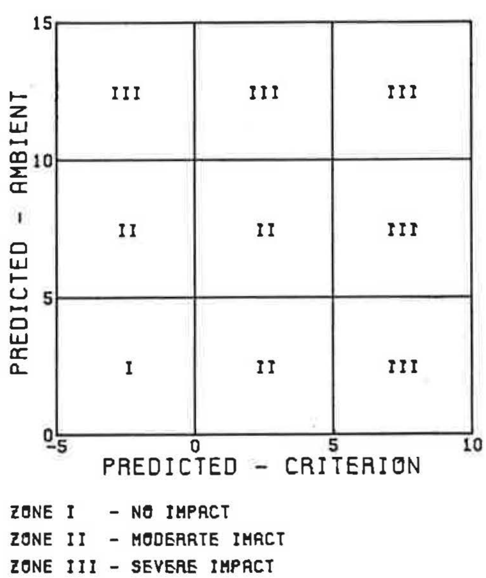


FIGURE 2 Impact classification guide.

It is assumed that the user has an idea about what the existing and future noise levels are at the receptor of interest. CHINA-1 uses this information in determining the degree of impact for a given receiver. After initially deciding not to select the barrier design feature, the user inputs this data to the work space through response to the next two questions asked by the program. Any time the user wants to end the session, he only has to type 'BYE'.

CHINA-1 then requests the user to classify the land use at the site that is under study. As mentioned earlier, abatement strategy can be influenced by land-use type, but for the purpose of the prototype model only single-family residences will be considered. The user is allowed to select between residential and public land use only to demonstrate the feasibility of options at this point. If the land-use type is misspelled, CHINA-1 asks the user to check the spelling.

The design criterion used in classifying the noise-related impact is displayed next, and the user is given the option of changing it. If the criterion is changed, the new level is displayed to verify that the change was as the user wanted. Then, CHINA-1 repeats the land-use type being considered, again to verify it is as the user intended it to be.

CHINA-1 now has enough information to rank the noise-related impact. For the purpose of demonstrating the prototype model, a menu is provided at this point, listing the options available. The user may select the option he desires by asking CHINA-1 the question in concise conversational English. If CHINA-1 does not recognize the request as stated, it will ask the user to rephrase the question. CHINA-1 is designed to recognize a user's question in several different ways. For example, to find out the degree of impact at a particular receptor, the user may simply type "CLASSIFY IMPACT", or he may use "RANK" or "RATE" as synonyms for classify. CHINA-1 looks for certain key words, such as "BARRIER DESIGN", which may be contained in any order within the user's question.

Because the noise barrier is the most common method of noise abatement in this country (3), it was decided that a primary function of an expert system in this domain should be the acoustic design of these structures. The user may access this feature in two ways: by going directly to the barrier design feature at the beginning of the program, bypassing the impact classification, or by proceeding through the impact classification.

At this point, CHINA-1 notifies the user that he must have already run the FORTRAN programs STAMINA 2.0/OPTIMA (15). STAMINA is the basic tool for calculating noise levels at a given location based on unique roadway geometrics and traffic characteristics. OPTIMA then allows the user to select certain combinations of barrier configurations for choosing the one combination that provides the most noise abatement in the most cost-efficient manner.

The human expert follows a certain thought process in this optimization task. CHINA-1 is designed to emulate that thought process. Efforts to integrate CHINA-1 with OTPIMA at this point in the barrier design process are still under development. In the interim, a FORTRAN subroutine has been developed for use in OPTIMA that creates a file containing all pertinent data. CHINA-1 reads the data from that file, recommends ways to change the barrier configuration to reach the optimum design, and prints out a summary of all data relative to a particular barrier design and impact status.

The initial barrier configuration is usually an educated guess by the user based on past experience. He uses the information provided by OPTIMA to change barrier heights or location, or both, in an attempt

```
 DO CHINA
.(CHINA)
*** ALL NOISE LEVELS ARE A-WEIGHTED LEQ VALUES ***
*
*
IF YOU WISH TO GO DIRECTLY TO THE BARRIER DESIGN FEATURE
OF THIS PROGRAM, TYPE 'BARRIER, <CR>'.
OTHERWISE , TYPE 'CONTINUE, <CR>'.
*
*CON
WHAT IS THE  EXISTING NOISE LEVEL AT THIS RECEPTOR ?*61
*
WHAT IS THE PREDICTED NOISE LEVEL AT THIS RECEPTOR ?*64
*
HOW WOULD YOU CLASSIFY THE LAND USE OF THIS SITE
(RESIDENTIAL OR PUBLIC) ?*RESIDENTIAL
*
*
THE DESIGN CRITERION CURRENTLY IN USE IS 60 DBA. IF
YOU WISH TO CHANGE IT, SIMPLY TYPE IN THE NEW LEVEL.
IF NOT TYPE 'NO <CR>'*55
YOU HAVE CHANGED THE DESIGN CRITERION TO 55 DBA.
*
*
YOU HAVE CLASSIFIED THE LAND USE AT THIS SITE AS RESIDENTIAL.
*
CHINA-1 WILL NOW ACCEPT YOUR QUESTIONS REGARDING THE IMPACT
AT THIS RECEIVER AND THE BARRIER OPTIMIZATION PROCESS.
PLEASE STATE YOUR QUESTION CONCISELY AND IN NATURAL ENGLISH.
*
TYPE 'C <CR>' WHEN YOU ARE READY TO CONTINUE.*C
*
FOR THE PURPOSE OF DEMONSTRATING THIS PROGRAM,
A LIST OF AVAILABLE OPTIONS FOLLOW:
*
 1. TYPE 'BYE' TO END SESSION
 2. TYPE 'RESTART' TO BEGIN A NEW CASE
 3. IMPACT CLASSIFICATION
 4. EXPLAIN THE REASONING IN THAT CLASSIFICATION
 5. CONVENTIONAL BARRIER DESIGN
*
*
*
PLEASE TYPE YOUR REQUEST ('LIST' WILL PROVIDE YOU WITH
THE AVAILABLE OPTIONS).
*CLASSIFY THE IMPACT AT THIS RECEPTOR
*
*
PREDICTED NOISE LEVELS AT THIS LOCATION INDICATE THAT EXTERIOR
ACTIVITIES WILL BE SEVERELY IMPACTED.
*
PLEASE TYPE YOUR REQUEST ('LIST' WILL PROVIDE YOU WITH
THE AVAILABLE OPTIONS).
*EXPLAIN THAT RESPONSE
*
*
AN INCREASE OF 3 DBA IN HIGHWAY TRAFFIC NOISE WILL
RESULT FROM THE IMPLEMENTATION OF THIS PROJECT.  IN ADDITION, THE
PREDICTED NOISE LEVEL OF 64 DBA IS  9 DBA ABOVE THE
CRITERION LEVEL YOU SPECIFIED.  THESE NOISE LEVELS ARE CONSIDERED
SUBSTANTIAL CHANGES AND WILL DEFINITELY AFFECT OUTDOOR ACTIVITIES.
*
PLEASE TYPE YOUR REQUEST ('LIST' WILL PROVIDE YOU WITH
THE AVAILABLE OPTIONS).
*DESIGN A BARRIER
*
*
*
BEFORE PROCEEDING YOU MUST HAVE RUN STAMINA2 AND OPTIMA.  THE
OPTIMA RUN GENERATES A TARIF THAT WILL BE USED BY CHINA-1 TO SUGGEST
HOW THE BARRIER SEGMENTS MAY BE ADJUSTED TO ARRIVE AT THE OPTIMUM
BARRIER DESIGN.  NOTE THAT CHINA-1 LOOKS FOR THE FILE OPT.LSP.
*
THE INSERTION LOSS PROVIDED BY THIS BARRIER IS 2.8
DBA BELOW THE MINIMUM YOU SPECIFIED.
*
WITH CONSTRUCTION OF THE BARRIER YOU PROPOSE, THE NOISE
IMPACT AT THIS SITE IS NOW SEVERE.
*
THE MAXIMUM CONTRIBUTION IS 57.3       DBA FROM SECTION 2. IF
YOU WISH TO INCREASE THE INSERTION LOSS AT THIS RECEIVER, TRY RAISING
THAT SECTION AND RE-RUN OPTIMA FOR REVISED NOISE LEVELS.
*
            SUMMARY
*
MATERIAL : CONCRETE
COST     : 98737.0 DOLLARS
INSERTION LOSS : 2.1        DBA
NOISE LEVEL(WITH BARRIER): 61.9       DBA
BARRIER SECTION HEIGHTS (IN FEET) : (10.0 10.0 10.0 10.0)
IMPACT CLASSIFICTION : SEVERE
*
****THE CURRENT SESSION IS ENDED****
```

FIGURE 3 Initial session with CHINA-1.

to obtain the maximum noise reduction for the least amount of money. In this example, the user began the analysis with a barrier of a constant 10-ft height. CHINA-1 noted that the impact was still severe and went on to suggest raising barrier section 2 to further reduce noise levels because the maximum noise contribution was coming from that section. In this prototype system, the model only considers that barrier segment contributing the maximum or minimum noise level at a given receiver. Subsequent work has led to the development of a heuristic that considers not only the maximum and minimum contributions, but also other significant or insignificant contributions at all affected receivers. This heuristic, in its final form, will allow the system to emulate more closely the human expert's thought process.

In this example, the user made the suggested changes, re-ran OPTIMA, and then executed CHINA-1 again. This time, he chose to go directly to the barrier design option. CHINA-1 then requests the existing noise level at the receiver and performs the same analysis as previously described, and again makes the appropriate suggestion.

This example only presents one iteration of the process. As it now exists, this is a somewhat complex procedure, but it does demonstrate the feasibility of emulating the thought process of a human expert with machine reasoning as the user attempts to optimize a noise barrier design. In addition, this prototype system adequately demonstrates the utility of a computer program that contains expert advice on a complex task.

CONCLUSION

A primary purpose of the prototype system at Vanderbilt University is to demonstrate the feasibility of constructing an expanded expert system that would synthesize the knowledge and experience of leading experts in the field of highway noise analysis and abatement. This concept can provide the engineer, who has the fundamental training required for highway noise analysis, with easy access to the experience of recognized experts in the field. This capability has the potential to enable the most inexperienced highway noise analyst to design effective, cost-efficient noise-abatement plans.

Planned enhancements of this concept, which are currently under development, call for the integration of the FORTRAN program OPTIMA into a LISP environment. The next generation of CHINA will be able to execute OPTIMA at the option of the user, analyze the results of an initial design chosen by the user, and then recommend ways to improve that design based on design goals specified by the user. With the expert knowledge encoded in the expert system, the CHINA model will be able to consistently design the optimum barrier directly from within the expert system.

This prototype system, in its present stage of development, also demonstrates the potential that exists for applying artificial intelligence technology to other disciplines of transportation engineering. For example, an expert system could aid in accident reconstruction, airport noise management, transit route maintenance, or traffic management on an urban street system. The potential is also obvious for using expert systems to provide a tutorial for educating users in the use of complex models.

REFERENCES

1. War on Waste: President's Private Sector Survey on Cost Control. J. Peter Grace, chairman. Macmillan Publishing Co., New York, 1984, 608 pp.
2. B.J. Billera. A Survey of Noise Barrier Practices. Presented at Meeting of Committee on Transportation-Related Noise and Vibration, TRB, National Research Council, Los Angeles, Calif., June 26, 1984.
3. L.F. Cohn. Highway Noise Barriers. NCHRP Synthesis of Highway Practice 87. TRB, National Research Council, Washington, D.C., 1981, 81 pp.
4. Procedures for Abatement of Highway Traffic Noise and Construction Noise. In Federal-Aid Highway Program Manual, FHWA, U.S. Department of Transportation, 1982, Vol. 7, Chapter 7, Section 3.
5. F. Hayes-Roth, D.A. Waterman, and D.B. Lenat. Building Expert Systems. Addison-Wesley Publishing Co., Inc., Reading, Mass., 1983.
6. K. Kawamura and B. Tanner. A State-of-the-Art Study of Expert Systems. Vanderbilt University, Nashville, Tenn., Vol. II, 1983.
7. K. Kawamura and J. Close. ROTES: An Expert System for Robot Troubleshooting. Vanderbilt University, Nashville, Tenn., 1984.
8. W.B. Gervarter. Expert Systems: Limited But Powerful. IEEE Spectrum, Vol. 20, No. 8, 1983, pp. 39-45.
9. J. Bourne. GENIE: The General Inference Engine, User's Manual. Vanderbilt University, Nashville, Tenn., 1983.
10. P.H. Winston and B.K.P. Horn. LISP. Addison-Wesley Publishing Co., Inc., Reading, Mass., 1981.
11. J.R. Meehan. The New UCIP LISP Manual. Lawrence Erlbaum Associates Publishers, Hillsdale, N.J., 1979.
12. Macro Interpreted Commands Reference Manual. Hatfield Polytechnic Computer Centre, June, 1980, Edition 7.1.
13. J.A. Reagan. Traffic Noise Impact/Mitigation Criteria. Presented at Meeting of Committee on Transportation-Related Noise and Vibration, TRB, National Research Council, Washington, D.C., Jan. 1981.
14. C.G. Gordon, W.J. Galloway, B.A. Kugler, and D.L. Nelson. Highway Noise--A Design Guide for Highway Engineers. NCHRP Report 117. TRB, National Research Council, Washington, D.C., 1971, 79 pp.
15. W. Bowlby et al. (ed.). Noise Barrier Cost Reduction Procedure, STAMINA 2.0/OPTIMA, User's Manual. Report FHWA-DP-58-1. FHWA, U.S. Department of Transportation, 1982.

Publication of this paper sponsored by Committee on Transportation-Related Noise and Vibration.

The Effects of Traffic Sound and Its Reduction on House Prices

DANA B. KAMERUD and CALVIN R. von BUSECK

ABSTRACT

Sales histories of two residential neighborhoods bordering on an Interstate highway were examined to determine the effect of traffic sound reduction on house prices. Sound levels were reduced in one of the neighborhoods by building a barrier along the highway. The second neighborhood, which remained unshielded, served as a comparison area. Before the barrier was built in the first neighborhood, sound levels in both neighborhoods were determined primarily by proximity to the highway. Analysis of house prices showed that, in the absence of shielding, houses nearest the highway sold for less than equivalent houses farther away. The magnitude of this highway-proximity effect, measured in percent of house value per decibel of sound gradient, was consistent with similar estimates previously reported in the literature. The proximity effect on prices appears to have persisted long after the barrier was built. Hence, although the barrier reduced the level of traffic sound and annoyance in the shielded neighborhood, there was no evidence that these benefits were capitalized into higher house prices. The results of this study therefore suggest that hedonic price regressions (which are not based on true treatment-control data) may overestimate the potential economic benefits of traffic sound reduction.

One way to estimate the potential benefits from traffic sound reduction is to determine the relation between traffic sound and residential property prices. Many analysts view traffic sound as an environmental pollutant that can depress property values. Assuming that purchasers of property exposed to traffic noise trade off annoyance for lower prices, then the difference between the price of a house in a noisy environment and the price of a comparable house in a quieter area is a measure of the value of noise.

Several studies have sought to estimate the value of noise. Nelson (1) recently reviewed 9 empirical studies covering 14 housing sites in Canada and the United States. Among other findings, each study reported some type of property price-reduction rate (or depreciation rate), that is, for each decibel increase in outdoor sound level a corresponding property price reduction was specified. Because some of the studies used different measures of price reduction, Nelson expressed all price changes in percentage terms. Similarly, because the studies used various measures of sound intensity, he converted the sound intensity measures to the LEQ scale. (LEQ stands for equivalent sound level, a measure widely used for describing time-varying environmental noise.) In this way, he was able to compare the 9 studies on the basis of their estimates of the Noise Depreciation Sensitivity Index (NDSI), which specifies the percentage decrease in the value of a residence that would result from a 1-decibel (dB) increase in LEQ.

Nelson's review "suggests noise discounts in the range 0.16% to 0.63% per decibel, with a mean of 0.40%" (1,p.129). A similar NDSI estimate of 0.5 percent per decibel was produced in a more recent study not included in Nelson's review (2,p.540). Another recent study, which used a new data-analysis technique, also found a noise effect on property prices (3). Hence, the evidence suggests that traffic sound can cause a measurable reduction in property prices.

In the research cited here, the sound-level differences were associated with distance from a sound source rather than with any action to reduce sound. Yet, as Taylor et al. (2) have noted, homeowners would also be expected to experience monetary benefits in the form of higher property prices if traffic sound levels were reduced. Accordingly, this study was undertaken to investigate whether homeowners receive monetary benefits from higher property prices when traffic sound levels are decreased in a residential area. The sound-level reductions in this study were obtained by constructing an earth berm between the homes and the sound source, an Interstate highway.

HISTORY AND GEOGRAPHY OF STUDY AREA

During the summer of 1973, a group of residents from the Troy Meadows and Lakewood subdivisions of Troy, Michigan, petitioned their city government to reduce traffic sound and other annoyances associated with nearby Interstate Route 75 (I-75). These homeowners requested construction of a pair of earth berms to shield their houses from roadway-related disturbances. Because the homes in Troy Meadows and Lakewood were built several years after the construction of I-75, the Troy city officers and Michigan state highway authorities decided that the berms should be paid for by the residents who were affected. After a lengthy public debate about the project and its costs, a berm to shield Troy Meadows was completed in the summer of 1974. Lakewood residents, however, abandoned plans to build a berm in their subdivision.

A before-and-after study was conducted to measure sound levels, annoyance, homeowner willingness to pay for noise reduction, and perceived benefits derived from the Troy Meadows berm (4). In this paper, some of these measurements will be combined with data on real estate transactions that have taken place in the two subdivisions from the time of their initial development through May 1980.

Figures 1 and 2 are maps of Troy Meadows and Lakewood that show the location of houses and streets relative to I-75. In both figures, individual homes are labeled by house row number. The two subdivisions lie directly east of I-75 and are separated by Wattles Road, which spans the highway with an overpass. The prevailing wind in this region is from west to east across I-75. Because the land is relatively flat and open, there were no natural barriers to impede the transmission of traffic sound. Each of the two subdivisions will be discussed further.

Troy Meadows is a relatively affluent neighborhood with paved streets and attractive tall trees. It was developed between 1971 and 1973, and contains 65 well-maintained houses aligned in 5 rows approximately parallel to the highway. The near lane of I-75 is 70 m from the abutting property line of the closest home in Row 1 and 230 m from the farthest house in Row 5. All of the houses except two have two stories and most contain 204 to 214 m^2 (2,200 to 2,300 ft^2) of living space. The majority of homes face either directly toward or directly away from I-75.

Lakewood, a somewhat less affluent subdivision, was developed between 1968 and 1971. The homes in this subdivision form 12 rows roughly parallel to I-75, although they actually face side streets perpendicular to I-75; some of these streets are still unpaved. Forty-seven of the 68 houses in Lakewood are single-story houses and 21 are two-story houses, and most have 121 to 158 m^2 (1,300 to 1,700 ft^2) of living space. The near lane of I-75 is 55 m from the closest house in Row 1 and 425 m from the farthest house in Row 12. All of the backyards have some direct view of the highway. Characteristics of typical Troy Meadows and Lakewood houses are summarized in Table 1.

At this location, I-75 is a limited-access divided highway with three lanes in each direction. In 1973, it handled approximately 49,000 vehicles during an average 24-hr period. By 1975, traffic volume had increased to 59,000 vehicles/day. Trucks of all kinds account for about 20 percent of the traffic at times other than those of maximum use, and heavy trucks may constitute as much as 10 percent of the total mid-morning traffic. Traffic flow occasionally exceeds 3,000 vehicles/hr in one direction during the morning and evening rush hours.

TROY MEADOWS EARTH BERM

The homeowners who circulated petitions protesting noise and other annoyances were familiar with traffic sound-reduction methods. They determined that earth berms would be the most cost-effective and aesthetically acceptable sound barriers for the region. Construction of two separate berms was originally proposed because the overpass embankment at Wattles Road divides the I-75 right-of-way between the two subdivisions. As indicated, plans to build a berm on the Lakewood side of Wattles Road were abandoned before construction could begin.

Figure 3 is a photograph of the Troy Meadows berm taken from the overpass spanning I-75 at Wattles Road. The berm is 610 m long and 3.4 m high relative to the pavement surface on I-75 and cost $41,700 to construct in 1974. Table 2 gives the payment schedule for recovery of construction costs. These variable payments were assigned by the Troy city assessor and

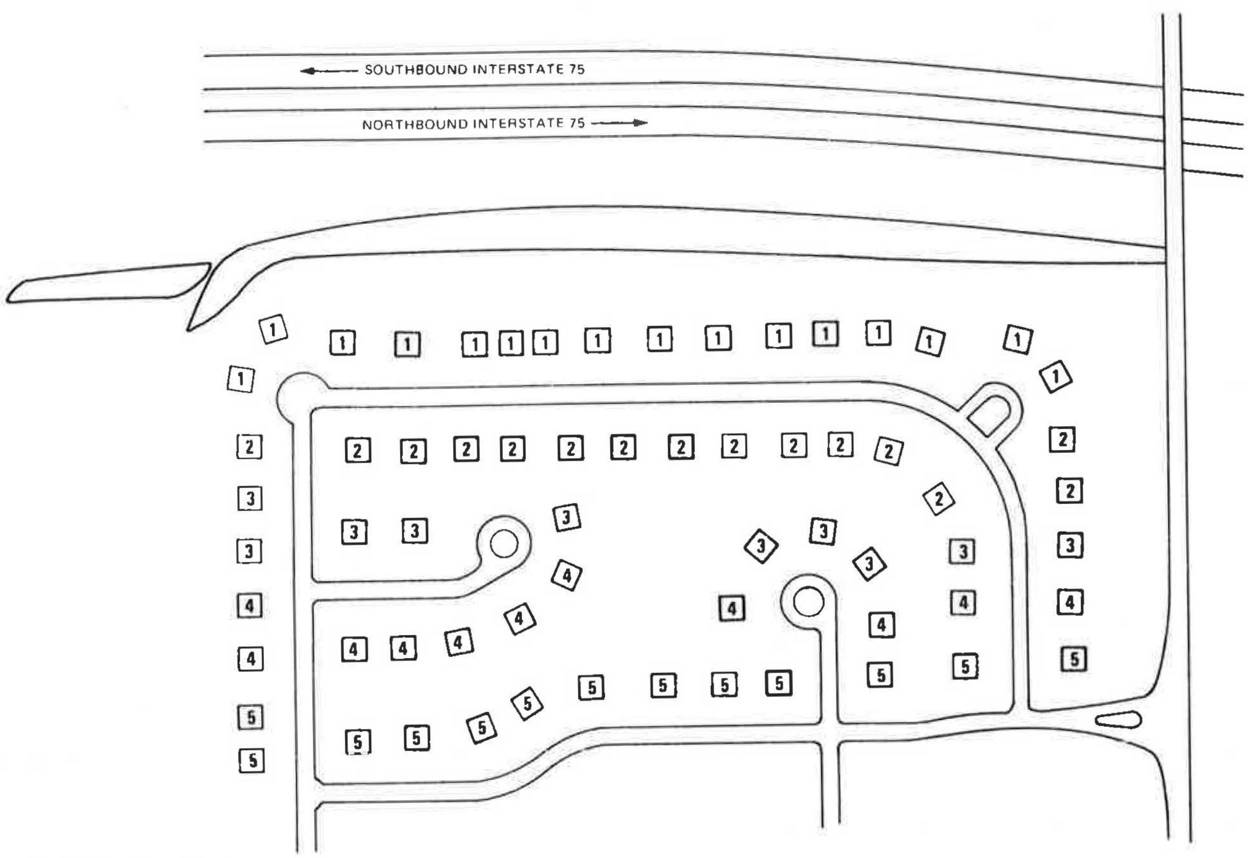


FIGURE 1 Troy Meadows subdivision.

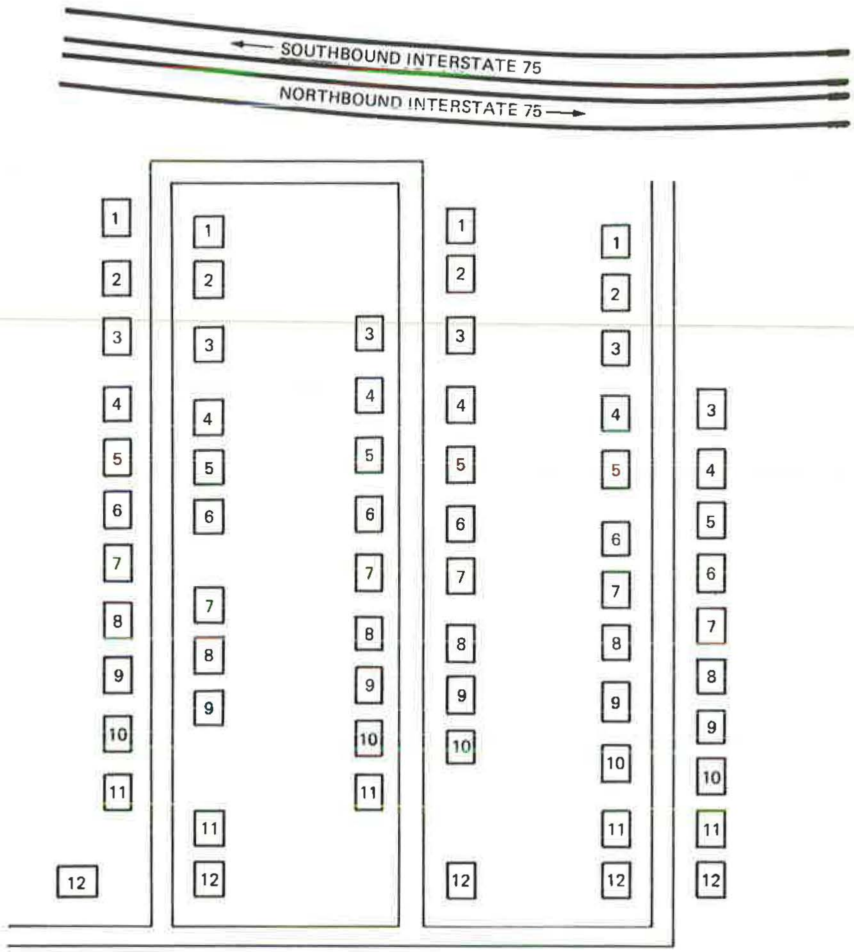


FIGURE 2 Lakewood subdivision.

TABLE 1 Typical Housing Characteristics

	Troy Meadows	Lakewood
Type	Two-story houses	One- and two-story houses
Size	204 to 214 m^2 (2,200 to 2,300 ft^2)	121 to 158 m^2 (1,300 to 1,700 ft^2)
Orientation	Face directly toward or away from I-75	Face at a right angle to I-75
Date built	1971 to 1973	1968 to 1971

could be financed over an 11-yr period at an interest rate of 8 percent.

Effects of Berm on Sound Levels and Homeowners' Perceptions of Effects

The results of the before-and-after study (4) are summarized here. As is suggested in items 3 and 4 in particular, the berm might be expected to have a positive impact on the future resale values of the homes benefiting from it.

1. Originally, significant annoyance from traffic noise was confined primarily to Rows 1 and 2 in Troy Meadows and to Rows 1 to 4 in Lakewood; both of these areas were exposed to an LEQ (24 hr) greater than 60 dB. Moreover, willingness to pay for the berms was concentrated in these high-annoyance areas. In other parts of the subdivisions, LEQ (24 hr) was less than 60 dB and willingness to pay for the berms tended to be low.

2. The berm reduced sound levels in Troy Meadows by 6 to 7 dB at the property line of houses in Row 1, where backyards abut the highway right-of-way. At this property line, maximum LEQ (1hr) sound levels were decreased from 71 to 65 dB, and LEQ (24 hr) levels were reduced from 67 to 61 dB. The reduction in Row 2 was estimated to be between 5 and 6 dB. After installation of the berm, houses in Rows 1 and 2 of Troy Meadows were exposed to an LEQ (24 hr) of 60 dB or less.

3. Annoyance ratings in Rows 1 and 2 of Troy Meadows decreased by a large and statistically significant amount, so that with the berm in place the annoyance ratings in all rows were comparatively low and at approximately the same level.

4. The Troy Meadows homeowners who perceived that they were receiving major benefits from the berm lived primarily in Rows 1 and 2. They believed that they had received their money's worth from the

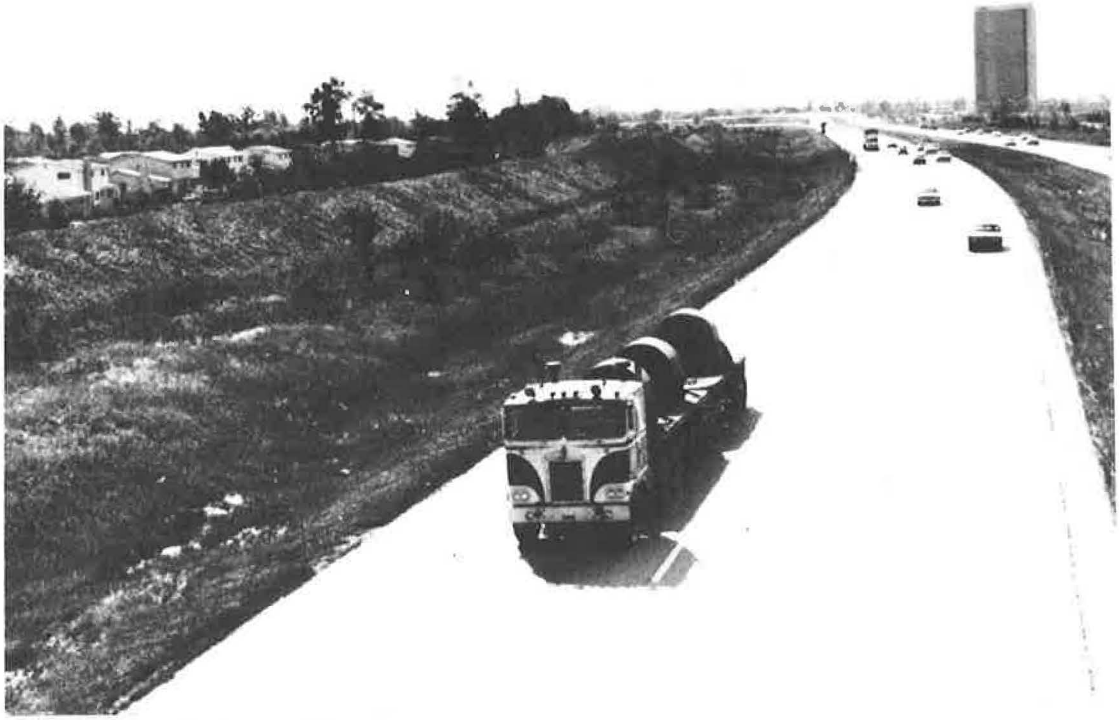


FIGURE 3 Troy Meadows earth berm.

TABLE 2 Payment Schedule for Troy Meadows Earth Berm

Row	1	2	3	4	5
Payment ($)	1,017	814	610	407	203
No. of houses	16	15	10	11	13

berm, while persons in Rows 3 through 5 considered the benefits of the berm to be worth less than their assessed payment.

5. The berm reduced by one-half or more perceived loudness of traffic sound in Rows 1 and 2 of Troy Meadows, but in Rows 3 to 5 there was little change in perceived loudness. Noise reduction was the principal benefit experienced in Rows 1 and 2, while elsewhere residents perceived there to be greater benefits from visual shielding than from noise reduction. These visual benefits included improved appearance of the neighborhood, greater privacy, and elimination of the "visual noise" of seeing passing vehicles.

6. Disadvantages associated with the berm included weeds, unattractive ground cover, and annoying sounds from motorbikes whose riders were attracted to the berm. In addition, a few residents complained about not being able to see traffic on the highway.

ANALYZING REAL ESTATE DATA

Real estate transactions from the first new homes sales through March 1980 were analyzed to determine how prices in the two subdivisions were affected by highway proximity and the berm. For each house, the geographic location, size (ft^2), and sales history (date and price of initial sale and any resales) were included in the data base. However, other attributes affecting house prices--such as decor, condition, air conditioning, swimming pools, and built-in appliances--were not observed. For this reason, comparisons have been made between groups of houses rather than between individual houses, although it has been assumed that the unobserved attributes did not vary systematically between the groups being compared.

Note that, in general, the prices in two different real estate transactions are not directly comparable. First, the houses may be of different sizes, and using cost/ft^2 only partially corrects for size because a large house is generally cheaper per ft^2 than a small house that is otherwise similar. Thus, a comparison of the desirability of two locations using cost/ft^2 would be biased if one of the locations had larger houses than the other. Second, two houses of the same size could differ in decor, appliances, and other attributes. Based on the apparent homogeneity of the houses at these sites, however, it appears reasonable to assume that the unobserved attributes do not vary systematically with location in a given subdivision. Finally, two transactions with different dates of sale require adjustments for inflation before a valid price comparison can be made.

The problems of comparing two different real estate transactions can be handled by treating the variable PRICE as a function of the explanatory variables SIZE, DATE, LOCATION, and ERROR using a different function for each subdivision. Here, SIZE is the square footage of the house, DATE and PRICE refer to the amount that the house would sell for at a given time, and LOCATION is a proxy for distance from the highway. The ERROR variable represents the unobserved differences between transactions, including the possible physical differences already mentioned, the desires and bargaining abilities of buyers and sellers, the input of agents and appraisers, and any other influences on the sale price that are not observed in this data base.

In the calculations in this paper, log(PRICE) rather than PRICE itself will be used as the dependent variable. This has three advantages. First, if two differently priced houses were subject to the same, possibly time-varying, rate of price appreciation (such as during a period of inflation), the dollar gap between the prices would increase but the gap between their log prices would not change. Second, one of the simplest models for the effect of PRICE on DATE is that of exponential growth, under which log(PRICE) is a linear function of DATE. Finally, differences in log prices can easily be reexpressed as percentage price differences.

To summarize, log(PRICE) will be modeled as a linear function of the explanatory variables. The resulting regression coefficients can be interpreted in a way that relates the explanatory variables to percentage price differences; for example, if the coefficient for highway proximity was x units/m, each additional meter of distance would increase prices by 100[exp(x)-1] percent. Furthermore, if it was known that traffic sound decreased at about y dB of LEQ per extra meter of distance, it could be estimated that the NDSI [discussed by Nelson (1)] equals 100[exp(x)-1]/y percent/dB at this site. Estimating the regression coefficients and their standard errors requires that the standard assumptions of regression analysis be made. Also, the data base will be considered as if it were a random sample from some superpopulation of houses.

There is one final assumption made in the calculations in this paper unrelated to those discussed in the preceding paragraph. Since some resale buyers may have taken over the liability of paying the annual assessments for construction of the berm, their willingness to pay might not have been accurately represented by the prices they paid. Note, however, that the assessments (shown in Table 2) are probably too small to be significant, especially if paid monthly along with a mortgage payment. Also, unless the assessment effect varies systematically with location, it will not bias the analysis.

CONFIRMATORY FINDINGS OF PROXIMITY EFFECTS

As noted in the opening section, the evidence in the literature suggests that people will pay extra to locate away from a highway abutting their neighborhood. The disadvantage of highway proximity is usually identified with traffic noise, although visual and other stimuli are also involved. Traffic sound differentials sufficiently large to cause differences in reported annoyance were observed in the two unshielded situations, that is, in Lakewood and in Troy Meadows before the berm was constructed. Therefore, these unshielded situations should be examined to determine whether proximity-induced traffic sound differences affected real estate prices.

In the Lakewood subdivision, after excluding one exceptionally large house and one exceptionally small house, there remain 57 houses in the data base; these houses range in size from 1,300 to 1,920 ft². All of these except three were built during the period 1968-1971. Recall that in Lakewood there are many rows (12) with only a few houses (3 to 6) in each row. The large number of rows makes it reasonable to treat ROW as an interval-scale explanatory variable.

The model

$$\log(\text{PRICE}) = A + (B)(\text{DATE}) + (C)(\text{ROW}) + (D)(\text{SIZE}) \quad (1)$$

has been estimated for the houses in the Lakewood subdivision (57 initial sales plus 32 resales). The fit is quite good ($R^2 = 0.924$), and all three explanatory variables are significant at the 1 percent significance level, indicating the existence of a proximity effect. The parameter values and their standard errors (in parentheses) are: A = 10.053 (0.047), B = 0.066 (0.002) per year, C = 0.00766 (0.00198) per row, and D = 0.00016 (0.00003) per ft². It is implied by these estimates that a 1 percent increase in size yielded roughly a 0.25 percent increase in the price of an average Lakewood home, that prices were increasing at about 6.8 percent/yr during the period 1968 to 1977, and that prices increased by 0.77 percent (standard error = 0.20 percent) per row as one proceeds away from the highway. This last value makes the expected price of a house located in the center of Lakewood subdivision about 5 percent higher than it would be if it were located in Row 1.

During the research for what eventually became the Troy Meadows berm effectiveness study (4), sound contours were obtained for Lakewood as well. When the sound difference between Row 1 and the middle of the subdivision is combined with the 5 percent price difference estimated in the preceding paragraph, an NDSI of roughly 0.4 percent/dB is obtained for Lakewood. This is in agreement with the NDSI estimates cited in Nelson (1) and Taylor et al. (2).

A proximity effect in the neighboring Troy Meadows subdivision during the unshielded pre-berm period was also looked for. Because 47 of the 65 houses in Troy Meadows are of the same style and size (2,262 ft²) and are scattered among all five rows, one can control for house size by restricting attention to these comparable houses. In this group, there were 47 initial purchases during a 2-yr period from 1971 to 1973, and only 8 resales before the berm was built; therefore, little is lost by ignoring the resales and restricting attention to the 47 initial sale transactions. Hence, it is the market for new, nearly identical houses that is being examined.

The observed prices were lowest in Row 1, highest in Row 5, and took intermediate (and essentially equal) values in Rows 2 to 4. The houses were built during a 2-yr period and, generally speaking, Rows 1 and 4 were sold first, followed by Rows 2, 3, and 5, respectively. In a linear regression of log(PRICE) on ROW and DATE, both explanatory variables were significant, so there does appear to be a proximity effect in Troy Meadows. Recall that, while the distance of one row from the highway is a small increment in Lakewood, in Troy Meadows there are only five rows with many houses in each row (see Figure 1). This means that it would be more appropriate to use a dummy-variable approach to represent the row effect in Troy Meadows.

The following statistical model was fit to the 47 data points:

$$\log(\text{PRICE}) = A + (B)(\text{DATE}) + C_2R_2 + C_3R_3 + C_4R_4 + C_5R_5 \quad (2)$$

where C_i is the premium in log(PRICE) that Row i commands over Row 1, and $R_i = 1$ if the house is in Row i and $R_i = 0$ otherwise. The estimates of C_i suggest that there were really only three price levels: Row 1 was cheapest, Rows 2 to 4 were sold at intermediate prices, and Row 5 was the most expensive.

The following reduced model

$$\log(\text{PRICE}) = A + (B)(\text{DATE}) + C_{234}R_{234} + C_5R_5 \quad (3)$$

provides a slightly higher corrected R^2 (0.724 versus 0.716). Its parameter estimates and their standard errors (in parentheses) are: A = 10.659 (0.018), B = 0.019 (0.010) per year, C_{234} = 0.039

(0.009) between Row 1 and Rows 2 to 4, and C_5 = 0.088 (0.013) between Row 1 and Row 5.

Are these values reasonable? It is suggested by the DATE coefficient that price increases for these new homes were 1.9 percent annually (around 1972). This figure appears slightly low, which perhaps is due to the short time period covered by the sample. A low figure would also result if the best houses sold first. If the builders increased their prices at all it was done only occasionally, not continuously. The estimated premium from Row 1 to Rows 2-4 is 4 percent, and from Rows 2-4 to Row 5 it is an additional 5 percent. While the latter difference probably has more to do with the presence of larger lots and cul-de-sacs than it does with highway proximity, it is suggested by the former difference that buyers of houses in Row 1 received discounts of about 4 percent (standard error = 1 percent) as compensation for having their backyards adjoin the highway. Taylor et al. (2,p.533) have also reported some evidence of a first-row discount.

The percentage discounts reported for Troy Meadows are similar to those reported for Lakewood. Because the sound-level difference between Rows 1 and 3 was about 7 dB (67 dB versus 60 dB) before the berm was built, the NDSI estimate is 0.6 percent per decibel for Troy Meadows. Hence, the analyses of Lakewood and of Troy Meadows before the berm was built both support the premise that highway proximity affects housing prices in the manner described by Nelson (1).

DOES TRAFFIC SOUND REDUCTION CONFER ECONOMIC BENEFITS?

It is suggested by the evidence relating real estate values to sound levels that traffic sound abatement would confer monetary benefits on some homeowners by increasing their property values. However, all such evidence is essentially cross-sectional rather than the result of a before-and-after study of property values before traffic sound abatement versus values of these same properties after abatement. Taylor et al. (2) state that the "study of the effect of barrier construction on house prices is [thus] an important topic for inquiry." The study presented here is, to the knowledge of the authors, the first such before-and-after study. It should be noted that only a single site will be reported on and that the findings may not hold in general.

Recall that the Troy Meadows earth berm was built between a traffic sound source and an existing residential neighborhood, that it reduced sound levels in Rows 1 and 2 (previously the high-annoyance area) below the previously observed LEQ = 60 dB annoyance threshold, and that it reduced annoyance ratings in Rows 1 and 2 to essentially the same low level as in Rows 3 to 5. Note also that a price gradient with respect to distance from the highway existed in Troy Meadows before the berm was built. (A price gradient in the nearby Lakewood neighborhood persisted over time, so the price gradients are not merely artifacts of the developers' initial prices.) If sound-level differences due to traffic sound reduction confer the same economic benefits as do sound-level differences due to distance from the highway, then it would be expected that the Troy Meadows earth berm would eliminate, or at least reduce, the price premium for distance from the highway. It might also be possible to detect a house-price increase in Rows 1 and 2 coincident with the construction of the berm.

To test the hypothesis that traffic-sound abatement would confer monetary benefits on some homeowners by increasing their property values, methods discussed in the preceding section will be used to look for proximity effects in Troy Meadows during the post-berm period. Post-berm resales of houses with 2,262 ft² occurred between mid-1975 and early 1980 and were spread among Rows 1 (7 resales), 2 (9 resales), 4 (4 resales), and 5 (4 resales). The full model, which is Equation 2 with C_3 set to 0, revealed no statistically significant difference between C_4 and C_5. The reduced model with Rows 4 and 5 pooled is

$$\log(\text{PRICE}) = A + (B)(\text{DATE}) + C_2R_2 + C_{45}R_{45} \quad (4)$$

This model gave an equally good fit (R^2 = 0.92) and produced the following estimates (and standard errors): A = 10.206 (0.070), B = 0.127 (0.008), C_2 = 0.041 (0.030), and C_{45} = 0.089 (0.031).

The figures in the preceding paragraph suggest that in post-berm Troy Meadows, Row 2 sold for a 4 percent (standard error = 3 percent) premium over Row 1, while Rows 4 and 5 sold at a 9 percent (standard error = 3 percent) premium over Row 1. The DATE coefficient suggests an annual appreciation rate of 13.5 percent, which reflects the strong market for these houses in the late 1970s. Although these premium estimates are somewhat imprecise, they imply that proximity to the highway continued to affect prices even after the berm was built. Indeed, their similarity to their pre-berm counterparts indicates that the berm did little to reduce the existing price differentials between rows. Apparently, any effect of the berm on prices was too small to be detected in the presence of other variation.

SUMMARY

The research reported in this paper concerns the effects of traffic sound and its reduction on house prices. It contains comparative analyses of two adjacent sites bordered on one side by an Interstate freeway. It differs from other such investigations in that the sound differentials arose not only from differences in proximity to the highway, but also from the construction of an earth berm shielding one of the sites.

The data are consistent with the generally accepted idea that, in the absence of shielding, proximity to a highway tends to reduce house prices. It is suggested by this idea that a barrier would confer economic benefits (higher resale prices) along with its acoustic and visual benefits. Accordingly, a test of this hypothesis was performed. However, no significant price effects were found associated with a demonstrably effective earth berm, which residents willingly paid to construct. This raises doubts about the use of hedonic real estate price models to quantify the benefits of sound reduction because these models are generally not based on true treatment-control data. It may be that sound differentials are capitalized into house prices differently depending on whether they arise from distance, from barriers, or from quieter traffic streams. To resolve this issue would require larger samples, perhaps analyzed with Palmquist's repeat-sale technique (3).

REFERENCES

1. J.P. Nelson. Highway Noise and Property Values: A Survey of Recent Evidence. Journal of Transport Economics and Policy, Vol. 16, 1982, pp. 117-138.
2. S.M. Taylor, B.E. Breston, and F.L. Hall. The Effect of Road Traffic Noise on House Prices. Journal of Sound and Vibration, Vol. 80, No. 4, 1982, pp. 523-541.

3. R.B. Palmquist. Measuring Environmental Effects on Property Values without Hedonic Regressions. Journal of Urban Economics, Vol. 11, 1982, pp. 333-347.
4. C.R. von Buseck. Measurements of Reduced Traffic Noise Annoyance Obtained with an Earth Berm. Proc., 1977 National Conference on Noise Control Engineering, Noise Control Foundation, Poughkeepsie, N.Y., 1977, pp. 233-244.

Publication of this paper sponsored by Committee on Transportation-Related Noise and Vibration.

The One-Minute L_{eq} Measurement Method

CHRISTOPHER W. MENGE

ABSTRACT

A noise measurement method for energy-average sound level (L_{eq}) that provides more flexibility and information than most methods in use today is discussed. The one-minute L_{eq} measurement method consists of a series of L_{eq} measurements, each one minute in duration. This method requires an integrating sound level meter or portable noise monitor. Limitations of other commonly used methods and advantages of the one-minute method are discussed. An example of the L_{eq} method's use is presented.

A method for the short-term measurement of the energy-average sound level (L_{eq}) of environmental noise is described. This method uses currently available integrating sound level meters (SLMs) or portable noise monitors. It consists of dividing the measurement period into a series of one-minute intervals. [A similar measurement technique has been described in Sirieys and Commins (1).] L_{eq} is measured and recorded each minute and observations of significant noise events are made. The overall measurement period can be of any duration but is usually one hour or less and always consists of contiguous one-minute intervals. Overall L_{eq} is determined by calculation of the energy average of the valid one-minute L_{eq}s.

The advantages of the one-minute L_{eq} measurement method over more commonly used methods, such as the check-off method and continuous-monitoring method, include increased flexibility, complete sampling of the sound level, and diagnostic capabilities for contributions from various noise sources. In the following sections, limitations of these commonly used methods are discussed further and examples are presented.

LIMITATIONS OF COMMONLY USED METHODS

Check-Off Method

The check-off method (2,3) for measuring environmental noise levels has been in use for many years. Originally developed for statistical sampling of noise levels with hand-held SLMs, this method required reading the SLM instantaneously every 10 sec and checking off a box corresponding to the observed level on a data sheet, thereby creating a distribution of check marks. Statistical descriptors, such as L_{10}, L_{50}, and L_{90}, can readily be determined from such a distribution. L_{eq} can also be determined, typically by using a scientific calculator. Statistical tests are then performed to determine the precision with which the descriptor is known. Described in "Fundamentals and Abatement of Highway Traffic Noise" are the procedure and the tests for determining L_{10} in detail (2).

Although the check-mark method is a relatively straightforward procedure, it has some limitations:

- The method is a coarse sampling of the sound level (one sample every 5 or 10 sec), and therefore fairly long measurement periods are often required before L_{10} or L_{eq} can be determined with reasonable confidence. Determining confidence intervals on L_{eq} requires some calculation and the intervals are often quite large.
- The method is subject to reading error.
- Significant loud events can be missed during attenuator switching. This problem is particularly significant when using the method to determine L_{eq}. L_{eq} is critically dependent on maxima and, if one or more high-level samples are missed, L_{eq} could be significantly underestimated.
- The measurement engineer's attention is often strongly focused on the mechanics of performing the method properly and little time is available for note-taking about noise sources, important events, or traffic conditions.
- Two individuals are required if simultaneous traffic counts are to be made even on a roadway having only a moderate level of traffic.

Continuous-Monitoring Method

Over the past several years, portable noise monitoring systems (and, more recently, integrating SLMs) have been used significantly often for making short-term environmental noise measurements. Most noise monitors (or SLMs) sample the sound level essentially continuously; sampling rate and detector time constant are usually set to avoid missing any level variation. At the end of a selected time period, the monitor prints or displays the sound level descriptors for the previous sample period. For short-term measurements, monitoring is commonly performed for sample periods ranging from 10 to 60 min.

Using monitors for making sound level measurements is much less arduous than using the check-off method and frees the engineer to observe significant events. However, using sample periods of 10 to 60 min substantially reduces the flexibility and amount of information that is available when using shorter sample periods or the check-off method, as can be seen in the following two examples.

• Example 1: Many common noise events cannot be conveniently excluded. Significant noise events such as construction operations, barking dogs, voices, or particularly noisy vehicles nearby may be considered atypical of average conditions. Such events may contribute significantly to the measured L_{eq} but, with some monitors, cannot be excluded from the measurement. Although some monitors or SLMs have standby or pause switches that enable the engineer to avoid an unwanted event, many events such as shouts or dog barks are too sudden to exclude. As soon as an unwanted noise event occurs, the validity of the L_{eq} for that sample period becomes questionable. Typically, the engineer will be unaware of the extent to which the period L_{eq} is affected. The engineer restarts the measurement period after such an intrusion, discarding perhaps many minutes of otherwise useful noise data.

• Example 2: Traffic noise on roadways that are under study cannot be separated from total ambient noise. Frequently, traffic noise measurements are compared with predicted noise levels. These comparisons are most appropriate if the measured noise levels are exclusively due to traffic noise. However, with a continuous monitor accumulating data for the entire measurement period, significant events such as aircraft overflights, railroad passbys, and nearby (nonproject) traffic cannot be separated out. If they are excluded through the use of a pause switch, the engineer loses information about total noise levels.

SUMMARY OF THE ONE-MINUTE L_{eq} MEASUREMENT METHOD

The one-minute L_{eq} measurement method requires the use of an integrating SLM or a portable noise monitoring system. The SLM or monitor is set to operate for one-minute intervals, if it is so equipped. If the instrument must be manually reset, this is done once per minute. L_{eq} can be recorded manually or printed, depending on the capabilities of the instrument.

During each one-minute interval, the engineer is free to note events that may influence L_{eq}. For general environmental noise measurement surveys, notes about specific noise events during each minute can prove valuable for later determination of overall controlling noise sources. For traffic noise measurements, vehicle counts are often valuable. Counts of heavy and medium trucks can often be kept and automobile counts can sometimes be made for moderate- or low-volume roadways. (For automobile counts, a hand counter combined with noting the cumulative automobile count each minute is convenient.)

At the end of the measurement period, the L_{eq} for the entire period is calculated by using Equation 1:

$$L_{eq}(P) = 10 \log \quad (1/N) \sum_{i=1}^{N} \quad 10 \left\{[(L_{eq})i]/10\right\} \qquad (1)$$

where

$L_{eq}(P)$ = the L_{eq} for the measurement period,
N = the number of minutes or one-minute L_{eq}s to be included in the period L_{eq}, and
$(L_{eq})i$ = the ith one-minute L_{eq}.

An example of a field data sheet used for this method is given in Figure 1.

PROJECT: Littleton By-Pass ENGINEER: CWM
SITE NO: 2 DESCRIP: Center School, 190' From ℄ By-Pass DATE: 5 Aug 83

MINUTE STARTING	MEAS. 1-MIN. LEQ	CUMULATIVE LEQ	AIRCRAFT	By-Pass HEAVY TRUCKS	By-Pass MEDIUM TRUCKS	~~AUTOS~~	NOTES
11:52 am	62.7						
11:53	64.1	63.5			I		
:54	63.2	63.4		II			
:55	74.5	69.4	1 Jet	I	I		Noisy Jet Overflight
:56	66.3	68.5		I	I		Some A/C Noise From 2
:57	61.9	68.3			I		Quiet Minute
:58	65.1	68.0		I	II		
:59	64.6	67.7		I	I		
12:00 N	63.2	67.3			I		
:01	63.5	67.1			II		
:02	70.1	67.5	1 LP	I			Fast Overflight
:03	64.6	67.3		I			
:04	63.2	67.1			II		
:05	62.6	66.9					
:06	62.4	66.7			I		
:07	65.3	66.6		II	I		Noisy Med Tr.
:08	64.5	66.5		I	I		
:09	64.8	66.4			II		
:10	64.0	66.3		I	I		
:11	65.2	66.3		II			
:12	67.9	66.3			I		Delivery Truck Parked Nearby
:13	66.8	66.4					left halfway thru this min
:14	65.6	66.3		II	III		
:15	64.2	66.3		I	I		
:16	63.9	66.2		I	I		
:17	64.7	66.1			II		
:18	64.3	66.1		I	I		
TOTAL LEQ =	66.1	dBA (28 min)					
SUBSET LEQ =	64.1	dBA (23 min)	w/o Aircraft & Delivery Truck				

(ADD SKETCH AND WEATHER CONDITIONS TO REVERSE SIDE)

FIGURE 1 Example of field data sheet used in the one-minute L_{eq} measurement method.

Total Length of Sample Period

The duration of the sample period necessary to fairly represent the one-hour L_{eq} varies according to the nature of the noise sources and the distance of the observer from them. In general, a minimum of 15 to 20 min is recommended. Longer periods are advisable if somewhat intermittent noise sources are present. Also, if the variation among the one-minute L_{eq}s is more than a few decibels, then longer sample periods will improve the representativeness of the measurement.

A programmable scientific calculator can be employed in the field to provide additional information to the measurement engineer. The calculator can be programmed to display the cumulative L_{eq} if each one-minute L_{eq} is entered at the end of each minute. The minute-to-minute change in the cumulative L_{eq} can then be used as a guide to the engineer to indicate when the measurement period might be stopped. When the minute-to-minute cumulative L_{eq} becomes a relatively constant value, the engineer may consider ending the measurement period. This procedure requires time, however, and is difficult to employ if traffic counts are desired.

WHY ONE MINUTE?

The one-minute interval for L_{eq} was arrived at through experimentation with many measurement methods and interval durations as well as many hours of field experience with short-term noise measurements.

One minute is long enough to free the engineer for observation for a reasonable length of time; at the same time, the one-minute period is short enough so that individual interval samples of L_{eq} that contain contributions from unwanted or atypical noise sources can be separated out or eliminated without a significant loss of valuable measurement time. Also, the number of interval L_{eq} values that must be energy averaged to obtain the period L_{eq} is not excessive (for short-term measurement periods).

ADVANTAGES OF THE ONE-MINUTE L_{eq} MEASUREMENT METHOD

The major advantages of the one-minute L_{eq} measurement method are efficiency and information. This method allows the engineer to efficiently obtain useful and complete measurement data.

Because the one-minute L_{eq} measurement method allows the separation or exclusion of individual one-minute L_{eq}s, the engineer can perform measurements at less-than-ideal locations and still obtain useful data. Usually, measurement of traffic-only L_{eq} and total ambient L_{eq} can be obtained at the same time, along with simultaneous traffic counts. The engineer only has to note the one-minute periods during which noise sources other than traffic apparently contributed to L_{eq}. (He can do this by listening and estimating the significance of other sources, or by a combination of listening and observing how the L_{eq} for that minute compares with the foregoing L_{eq}s.) Then, those minutes are included only in the calculation of the period L_{eq} for total noise. L_{eq} for traffic noise is calculated excluding those minutes influenced by nontraffic noise. If simultaneous traffic counts were made, they can be used to compare a prediction method with the measured L_{eq} for traffic only.

Another advantage of the one-minute L_{eq} measurement method is that there are inexpensive integrating SLMs available with which one can use the method (such as Bruel & Kjaer Models 2225 and 2226). Until recently, the only methods available for measuring L_{eq} with inexpensive instrumentation have been relatively tedious hand-sampling methods (3) using standard SLMs. These methods are susceptible to operator error and have relatively complex procedures for determining confidence intervals.

The one-minute L_{eq} measurement method doesn't involve a sampling of the sound level; rather, it is effectively a continuous integration (depending on the circuit design). Therefore, sample bias is limited or nonexistent and no confidence interval calculations based on a sampling need be applied. Although recording L_{eq} and resetting an SLM requires a brief pause, this pause can be kept short with practice. The potential measurement error therefore approaches the error in the instrument itself; this error is usually published with the instrument specifications.

Some portable noise monitoring systems can be set up to operate automatically in the one-minute L_{eq} mode (such as Digital Acoustics 607, BBN 614) and can be used to advantage with the L_{eq} measurement method. Although such monitoring systems are more cumbersome than integrating SLMs, their automatic operation and data recording features free the engineer from the recording and resetting tasks.

REFERENCES

1. J.P. Sirieys and D.E. Commins. Short-Term Equivalent Level Series: An Efficient Tool for Environmental Assessment. Proc., International Conference on Noise Control Engineering, Miami, Fla., Dec. 8-10, 1980.
2. Bolt Beranek and Newman Inc. Fundamentals and Abatement of Highway Traffic Noise. FHWA, U.S. Department of Transportation, 1973.
3. W. Bowlby, ed. Sound Procedures for Measuring Highway Noise: Final Report. Report FHWA-DP-45-1R, FHWA, U.S. Department of Transportation, Aug. 1981.

Publication of this paper sponsored by Committee on Transportation-Related Noise and Vibration.

Community Involvement in the Noise Barrier Selection Process: A Case Study

WIN LINDEMAN

ABSTRACT

In response to a community request, the Florida Department of Transportation conducted a survey to determine if a highway noise barrier should be constructed in the Maximo Moorings subdivision of St. Petersburg. Based on this survey and the resulting public workshops, a noise barrier was designed and erected that received a great deal of public acceptance. The procedures used in achieving this acceptance are identified.

In 1956, the Florida Department of Transportation (FDOT) requested that Interstate 4 be extended from the west side of Tampa to the north side of St. Petersburg. After 10 years of study and a change of designation from I-4 to I-75 to I-275, a corridor routing from Tampa through St Petersburg was determined as shown in Figure 1. Part of this corridor would involve an interchange at 54th Avenue South in the vicinity of the Maximo Moorings subdivision. As time and circumstances would show, environmental concerns by people in this subdivision would lead to one of the most intensive and positive community involvement programs related to noise in the history of FDOT.

ORIGINAL ASSESSMENT

In compliance with the National Environmental Policy Act of 1969 and related federal guidelines, an Environmental Impact Statement was completed and approved by FHWA, U.S. Department of Transportation, in 1972. The noise portion of this document consisted of a statement (1) that

> there will be some increase of noise in the northern half of the project due to the retention of U.S. 19 and 31st Street parallel to it. In the southern half of the project the increase in noise level will be

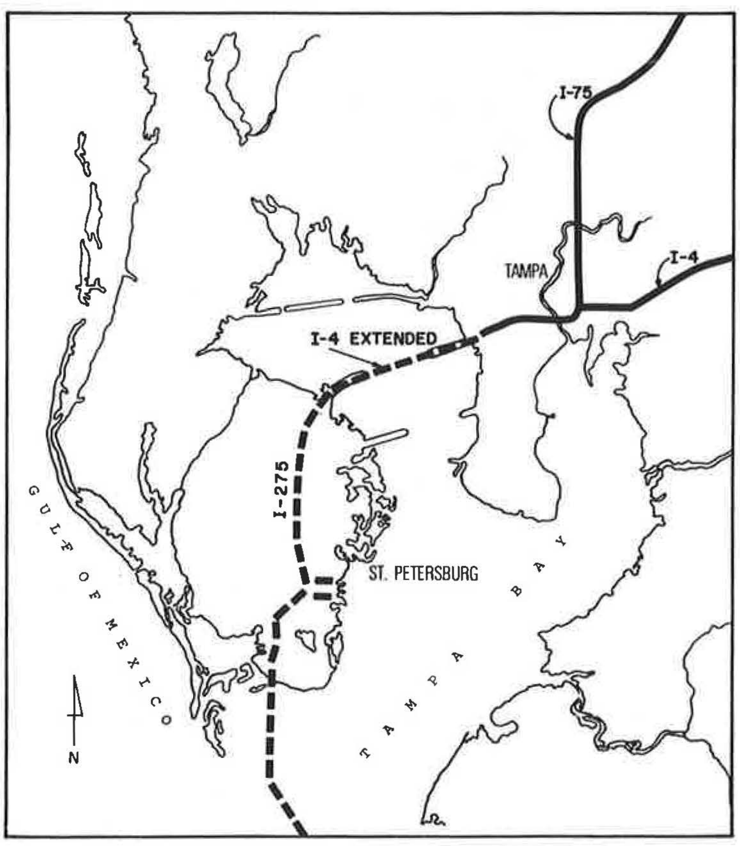


FIGURE 1 Location map of I-275 corridor route.

insignificant due to the rapid, non-stop nature of the traffic flow.

The proximity of the I-275 interchange to 54th Avenue South and the Maximo Moorings subdivision is shown in Figure 2. As I-275 progressed southward from Tampa, growing controversy surrounded the construction of this urban freeway. As reported in a previous study (2), this controversy was widespread and often focused on perceived air and noise impacts of the projects. The development of seven noise barriers along the route of I-275 through the downtown area of St. Petersburg did nothing to diminish the attention focused on noise control.

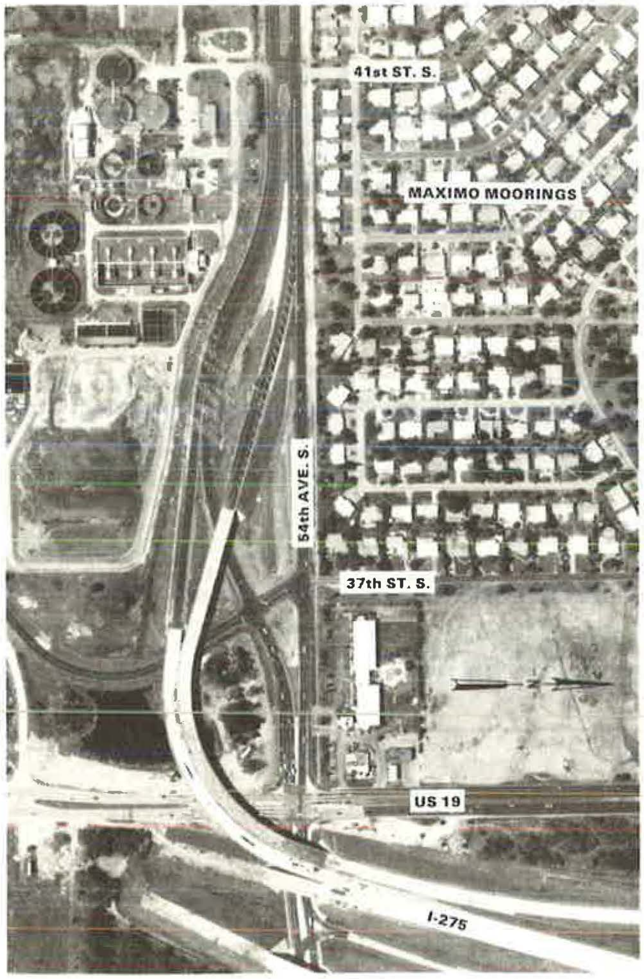


FIGURE 2 Interchange area of Maximo Moorings and 54th Avenue South.

DESIGN CHANGES AND REEVALUATION

After several years of preliminary design concepts and redesigns, the construction of the Interstate in the vicinity of the 54th Avenue South interchange became an approaching reality. A reevaluation of the impact of the design changes was made by FDOT's Bureau of Environment, pursuant to the requirements of Volume 7, Chapter 7, Section 2 of the Federal-Aid Highway Program Manual (FHPM 7-7-2) as it existed in 1980 (3). This reevaluation included an update of the previous noise assessment conducted for the original Environmental Impact Statement. This noise assessment was conducted in accordance with the dictates of FHPM 7-7-3 addressing highway traffic noise analysis and abatement considerations. The noise assessment, summarized in the reevaluation, identified three locations where noise abatement was considered appropriate and feasible. One of those locations was along the north side of 54th Avenue South between 37th and 41st Streets South. This location was adjacent to a portion of Maximo Moorings, a single-family subdivision, which is also the home of a number of citizens concerned about the environmental impacts of the construction of I-275 through the St. Petersburg area. The reevaluation noted (4) that "prior to the employment of any abatement techniques, an attitude survey will be conducted to obtain the viewpoint of nearby residents to determine if they favor abatement and, if so, what type they would desire."

CITIZEN INITIATIVE

Construction on that portion of I-275 involving the Maximo Moorings subdivision began during January 1982. At a public involvement meeting in early May 1982, a Maximo Moorings resident inquired about the status of the public attitude survey regarding noise abatement in the Maximo Moorings subdivision. Because the study area had been broken down into two construction projects, the original intent of FDOT was to conduct the attitude surveys just before the letting of the final project, which was located just south of 54th Avenue South. Because of continued design modifications and other controversy, the letting of the final job was further delayed, thereby postponing the attitude surveys.

A RESPONSIVE FDOT

Because the request for the survey was made in good faith, FDOT's response was to conduct a special survey of the Maximo Moorings subdivision and delay the others until the design was finalized in the southernmost project. With the assistance of the Bureau of Right-of-Way, a list of all owners of property directly abutting the project along 54th Avenue South was made. A letter was written by the Bureau of Environment to each property owner on June 21, 1982, that explained that a recent noise analysis had shown the need for noise reduction. Discussed in the letter were the dimensions of the proposed abatement wall and the need for input from the property owners. In addition, the letter indicated that a telephone survey would be conducted by the Bureau of Environment during the week of June 28, 1982. As scheduled, a telephone survey was conducted on June 28 and 29. This survey was successful in reaching all but one of the residents and that individual was finally contacted early in July after he returned from an extended vacation. A copy of the questionnaire and a summary of the results can be found in Figure 3.

After the telephone survey was conducted, a date was set for an informational workshop at a nearby motel. The time and day of the week selected for this workshop was a result of input gathered during the telephone survey. Two weeks before the workshop, a letter was sent to each property owner, indicating what would be discussed and soliciting their attendance.

Date - June 26-30, 1982 TELEPHONE SURVEY QUESTIONNAIRE

Introduction - Good Day. My name is Win Lindeman with the Florida Department of Transportation. On June 21st, I wrote you a letter telling you about the possible use of barrier walls to reduce the future noise levels from I-275 and 54th Street. If this is a convenient time, I would like to ask you a few questions regarding this matter and then I'll try to answer any questions you might have.

1. Do you feel noise is currently a problem in your neighborhood?
   Yes - 11 No - 2 Don't Know - 0

2. If yes, what types of noise do you notice and how does it affect you?
   Pile Driving - 3 Motorcycles - 6 Trucks - 6 Traffic - 6

3. How would you rate the present noise levels from 54th Avenue?
   Very Annoying - 9 A Little Annoying - 3 Not At All Annoying - 1

4. At what time of day does the traffic noise seem to be the loudest or most annoying?
   Midnight to 7:00 AM - 0 7:00 AM to 7:00 PM - 8 7:00 to Midnight - 0

5. Do you think a properly designed wall along 54th Avenue can effectively reduce traffic noise?
   Yes - 7 No - 2 Don't Know - 4

6. Do you think road users tax money should be spent to reduce traffic noise?
   Yes - 10 No - 1 Don't Know - 4

7. If a barrier wall is constructed, which of the following material types would you prefer?
   Concrete Block - 1 (if stucco) Wood - 2 Metal - 0
   Precast Concrete - 5 Other - 6
   - Cast-in-Place Concrete - 1
   - Earthern Berm and Vegetation - 2
   - Vegetative Screen - 3

8. What color (s) wall would you prefer?
   White - 3 Green - 1 Beige - 6 Gray - 1

9. Would you prefer a vegetative screen to a solid wall?
   Yes - 6 No - 7 Don't Know - 0

10. Would you be willing to release your potential access directly to 54th Avenue to allow the construction of a barrier wall on state-owned right-of-way?
    Yes - 12 No - 0 Don't Know - 1

11. Personal Data
    a. Sex of Respondent
       Male - 7 Female - 6
    b. Length of Residence (in years)
       Range - 2.5 to 25
       Mean - 10.8
    c. Best Time For A Public Workshop
       7:30 PM, Tuesday or Thursday
    d. Name____________________
    e. Address__________________

FIGURE 3 Telephone survey questionnaire and summary of results.

FIRST WORKSHOP

The first workshop was held July 15, 1982, at the site identified in the announcement that had been mailed previously. After an introduction of the FDOT and FHWA representatives and the residents as well, the homeowners (11 of 13 were present) were given a brief presentation on the history of the problem and the magnitude of the situation, the conditions of noise abatement, potential solutions and possible barrier materials, and the results of the telephone survey. Through the use of a tape recording and sound level meters, the residents were able to hear the existing noise levels and what those levels were predicted to be like in the future when the Interstate was completed. In that way, the residents could discern the increase of the noise over time and decide for themselves whether the impact was acceptable. At the end of the workshop, the citizens were asked to make several decisions about noise abatement.

Conditions of Noise Abatement

At the beginning of the workshop, representatives of both FDOT and FHWA established the basic conditions under which the construction of a barrier for noise abatement would take place, including the premise that no additional right-of-way would be purchased by FDOT. If easements of any kind could not be obtained free-of-charge, this would be grounds for discontinuing the pursuit of building the wall. Obtaining easements free-of-charge was the most important condition related to the project because access rights were going to be required no matter what type of barrier was selected. It was also noted that cost was not going to be an immediate consideration but was going to be an item to be dealt with if a preliminary design was chosen that appeared to be cost prohibitive.

Two other conditions for the discussion of abatement considerations were: that an earthen berm not be considered a viable alternative because of limited right-of-way, and that the barrier had to be between 6 and 14 ft high. These limits were based on the results of the computer noise analyses (using STAMINA 2.0) that indicated that a height lower than 6 ft would not give any noticeable reduction in noise and one more than 14 ft would not provide a significant decrease in noise levels compared with the significant increase in cost. The only other major point was that any abatement device would be placed as close to the existing right-of-way line as possible, which would maximize the barrier's effectiveness and also reduce the need for significant utility relocation.

Potential Solutions to Noise Level Problem

Three potential solutions to the increase in traffic noise levels were presented at the workshop: barrier walls, vegetative screens, and no abatement at all.

By using a slide representing the reduction of noise levels for barrier walls of increasing height at the right-of-way line (see Figure 4), the residents were able to discern the level of noise reduction available for any given height between 6 and 14 ft. A discussion was also held about the effect that placing "wings" on the barrier would have in increasing its effectiveness. As explained to the residents, these wings are extensions of the wall that are directed back toward the community at an angle that would reduce the amount of noise that can

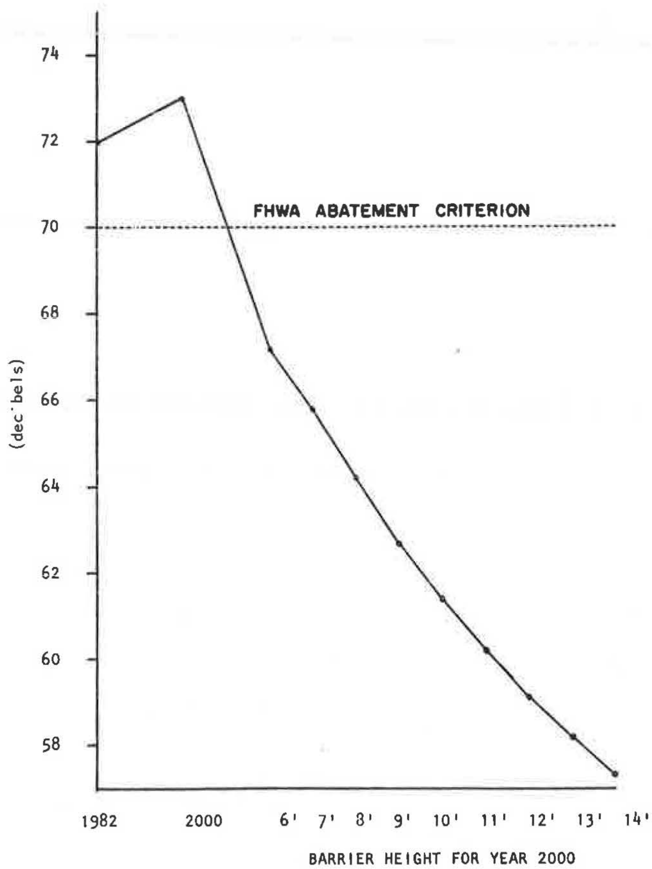


FIGURE 4 Noise barrier reduction guide.

leak around the ends. Also explained to the residents was that the effectiveness of the barrier at either end would be significantly reduced without using these wings even though they would most likely require donation of a right-of-way.

After the reduction in effectiveness as a result of not using wings was highlighted, the discussion moved to the effectiveness of vegetation as a source of noise abatement. The residents were told that within the limited space available, a thick planting of vegetation might be able to reduce noise levels by 3 decibels. This discussion also included the concept of psychological enhancement, which is the notion that if people do not see the source of noise it doesn't bother them as much.

Finally, by using slides, brochures, photograph collections, literature, and actual samples, a broad spectrum of noise barrier wall designs and materials was presented for consideration.

Results of Telephone Survey and Discussion

After the discussion of barrier materials, the results of the telephone survey were announced. These results were basically already known by the residents as a result of internal discussions and took little time to cover. The announcing of the survey results was followed by an open discussion of the pros and cons of a noise barrier, including such topics as the impacts on view, light, air, privacy, graffiti, litter, maintenance, access, and aesthetics. The residents were informed that the time for a decision about noise abatement was rapidly approaching and that their consolidated opinion and recommendation were needed; the meeting was adjourned for about 30 minutes to give the residents an opportunity to review the displays and literature on noise barriers and to discuss this information with their friends and relatives. They also were able to talk with FHWA and FDOT personnel to solicit responses to unanswered questions and to clarify any other matters that had come up.

Decisions by Citizens About Noise Abatement

When the workshop reconvened, the residents were asked to make four decisions about noise abatement.

The first decision made by the residents was whether, based on the information presented, they still wanted a barrier. Three residents said no and offered varying reasons for this decision: one was worried about the collection of exhaust fumes behind the wall and the impact this might have on her ill husband; the other two preferred the open view of the traffic and other activities that take place beyond their property lines. Because the latter two residents lived on the eastern end of the project area, it was stated that the barrier could easily be shortened to accommodate their wishes. Complying with the other resident's request was more difficult to address because she was located between residents who wanted the barrier. After an explanation of the impact such an opening in the barrier would have on both cost and effectiveness, she relented, largely due to neighborhood pressure and lack of a strong conviction that fumes would gather in quantities that could cause serious health effects. (The death of her husband preceded the construction of any barrier and therefore her concern became moot.)

The second decision the residents made was about the desired height of the barrier, as well as the level of attenuation they were willing to accept. After considerable debate over the merits of varying heights, a barrier 8 ft high was selected. Because the terrain varied less than a foot from one end to the other, a uniform height was desired, although a variation in height would have been acceptable to FHWA and FDOT. The residents considered an 8-ft barrier a reasonable compromise between noise reduction and other factors such as view, light, and air flow.

Third, the residents decided that the material for the barrier would be concrete block that would be built on a footing and feature a cap and pilaster design similar to that shown in Figure 5. They wanted a stucco-type finish (referred to by FDOT as Class 5

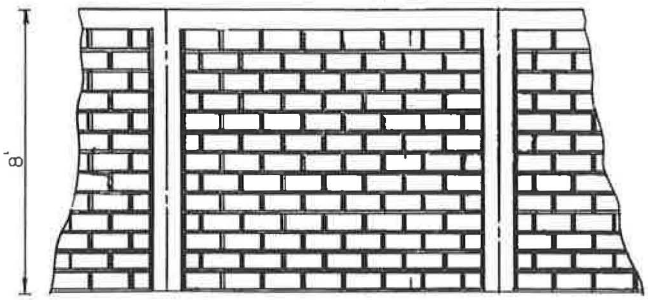


FIGURE 5 Drawing of original noise barrier design.

finish) in a beige color with the alternating panels having a red-brick veneer on the residential side of the barrier. The side facing the highway would be finished in the same beige Class 5 finish without the red-brick veneer.

The fourth decision facing the residents was whether to use wings on the barrier. To increase the effectiveness of the barrier, both affected property owners expressed a willingness to donate the right-of-way necessary for erecting the wings on each end; this gesture typifies the overall spirit of cooperation that the residents brought to this workshop. The owners were informed again that to increase effectiveness and minimize disruption to utilities, the barrier would be placed as close to the right-of-way line as possible and that this would require construction and maintenance easements as well as access rights, as described earlier.

Finally, the residents were informed that many hurdles were still to be overcome, but the information gathered as a result of the first workshop was considered vital and would put FDOT and FHWA on a clearly defined path toward noise abatement. With that qualifier placed on the evening's activities, the workshop was adjourned.

FDOT TAKES CHARGE

Based on the input from the workshop and subsequent contacts with the homeowners in the project area, FDOT initiated an engineering survey, a utility location assessment, and a right-of-way title search to determine property boundaries, deed restrictions, and other items that could affect the abatement project. However, by August 1982, the wheels of progress were starting to bog down: the utility assessment located a transformer pad that would have to be relocated and a sanitary sewer line that was directly below the proposed wall location. Manhole locations were noted and the problem was directed to the design staff. By using some creative engineering, it was decided that the wall could still be built at the right-of-way line by relocating the transformer pad slightly and by incorporating the manhole inlets for the sanitary sewer line into the footing itself.

By mid-September 1982, FDOT had requested formal concurrence from FHWA on the construction of the barrier wall along 54th Avenue South. In this request, FDOT noted that if the donation of right-of-way or construction easements was withheld for any reason, it was their intention to abandon the concept of the abatement wall. FHWA concurrence for the construction of the proposed wall at a cost of approximately $75,000 was received in late September 1982. FDOT requested federal funds to initiate title searches and to do the final design engineering work. This request for federal participation was granted in early October 1982 and the wall was back on track once again.

CHANGING VIEWPOINTS

During the period of conducting title searches and subsequent negotiations with the property owners to obtain construction easements and access rights, one of the residents decided to refuse to grant a construction easement. His reasoning centered on the close proximity of his swimming pool to the right-of-way line--he felt that the construction activity would or could damage his pool, and he did not want the mess and inconvenience of the wall-building operation. However, it was still his desire to have the wall built to protect him from the noise as well as to protect his neighbors.

The FDOT engineer in charge of the preliminary design aspects of the wall met with the various property owners on site to solicit input and attempt to identify a workable compromise. Working through the president of the Maximo Moorings Civic Association, the engineer continued his effort to either pursuade the reluctant owner to change his mind or to devise a reasonable alternative. After receiving a brief education from the Bureau of Environment staff on noise barrier materials and their many pros and cons, the engineer set about trying to find one that would fit the needs of this project.

The FDOT design engineer, based on his study of barrier materials, believed that the use of precast concrete might be a workable compromise. He contacted representatives of the Reinforced Earth Company and the Easi-Set Company and requested additional information and a set of preliminary design concepts from each based on information that he furnished to them. These design concepts were returned and subsequently submitted to the contractor working on the interchange. The contractor then submitted a preliminary bid estimate on all three alternatives (the two designs sent in by the private companies and the original concrete block wall design). Because the preliminary estimates were all considered within an acceptable range, FHWA approved the use of any of the options, depending on the input of the local residents.

Based on the results of the design engineer's efforts, a second workshop was considered necessary. The purpose of this workshop was to reconsider the options available concerning the location, design, and finishes of the wall and to sign construction easements and related documents. The residents were notified by mail that the second workshop would be held at the same location as the first one. To encourage attendance, the Maximo Moorings Civic Association was also requested to actively solicit comments and suggestions and to attend the workshop for the purpose of providing additional input. Representatives of the precast industry were invited to make presentations on their various barrier wall materials. While the workshop was being prepared, FDOT made a decision that if the wall was to be built, an attempt would be made to construct it through a supplemental agreement with the prime contractor for the interchange.

SECOND WORKSHOP

At the second workshop, held in May 1983, slightly more than half of the property owners were present, along with other members of the Maximo Moorings Civic Association, FDOT staff, and a representative of the Reinforced Earth Company. The design engineer in charge of the project explained the nature of the problem, which centered on the construction easement difficulties associated with the conventional block wall design. He offered three alternative design concepts: the conventional block wall and two precast wall designs--Sierra Wall and FANWALL. He explained that a precast wall could probably resolve the dilemma that was facing the residents and FDOT because it could be placed near the right-of-way line without any need for construction activities on the residential side of the wall in most locations. Because precast walls do not require a poured footing and all of the attendant construction activities, the homeowners would not have to worry about damage to their pools, yards, and other fixtures. The representative of the Reinforced Earth Company made a presentation on one of his company's products, FANWALL. Observing a series of slides and handouts showing the wall and its alignment, the residents learned how this wall could be placed along the project without removal of utilities, fences, or anything else through careful design. After explaining how the use of this type of product would eliminate the need for a construction easement from most property owners, and how it would reduce the length of construction time from 3 months to 2 weeks, the residents were much more receptive to this type of product.

A lengthy discussion then ensued about the appearance of the wall. By popular acclaim, the residents opted for the FANWALL product with a mason-cut stone finish on the side facing them. They wanted it to be colored a desert-sand beige and indicated no concern for the general appearance on the highway side. In addition, it was suggested and agreed on that a raked finish on the highway side might discourage graffiti.

The residents present were also given a legal document to sign that indicated that they had given up access rights directly to 54th Avenue South (which no one currently used) and all rights of light, air, and view to a height not to exceed 10 ft above natural ground. They also were to agree to allow FDOT a perpetual easement for the purpose of maintaining the wall; this agreement also spelled out the rights of the property owner to connect fencing to the completed wall and to have any damage to vegetation or improvements arisings out of the construction of the wall repaired by FDOT without any cost to the homeowner. After FDOT legal and right-of-way staff reviewed the agreement with residents, the property owners were encouraged to take it home, study it, present it to their lawyer (if desired), sign it, and return it promptly to FDOT. To aid in this effort, FDOT right-of-way agents were assigned to the task of contacting each property owner to assist them in completing the indenture.

FINAL DESIGN AND PROCESSING

While the right-of-way documents were being processed, the effort to complete the design of the wall continued. The FANWALL Corporation was asked to prepare a final wall design that would incorporate the decisions made at the second workshop, and this design was submitted to the contractor. The contractor then submitted a price quotation to FDOT; however, this quotation was considerably higher than FDOT's estimates.

After negotiation, the contractor submitted a revised price quote within FDOT's estimated range and on November 8, 1983, a supplemental agreement between FDOT and the contractor was signed. This contract called for the project to be completed in 14 working days. After the contract was signed, the FANWALL Corporation located a form-liner in the pattern selected, secured a precasting contractor, and began the process of casting the barrier wall panels (65 in all). The precasting operation took approximately 1 1/2 months to complete. During that interval, the residents were kept informed of the wall's progress through letters and telephone calls to key homeowners and by personal contact with FDOT construction personnel.

CONSTRUCTION PROCESS

Prior to the beginning of the noise barrier's installation, the property owners were contacted by FDOT personnel and advised that construction would begin on or about March 12, 1984. They were informed that if they wanted existing fences removed by the contractor, they were to make this request known to FDOT construction personnel. On March 8, 1984, the contractor began removing fences and preparing the base for the installation of the noise wall. The actual installation began March 13 and was completed March 20, 1984; during the process of the wall's construction, no significant problems occurred. The final appearance of the wall is shown in Figure 6.

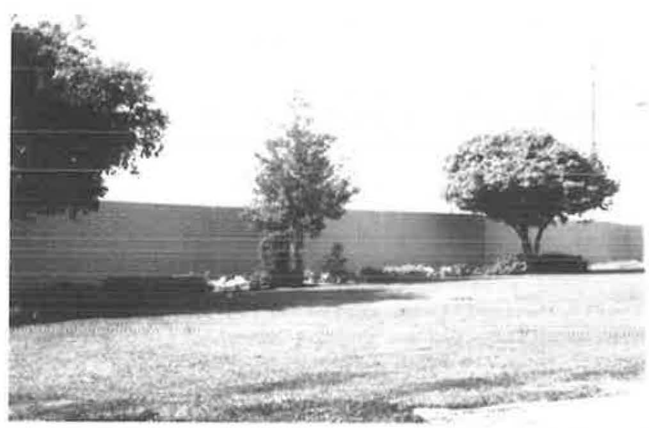


FIGURE 6 Photograph of noise barrier wall after construction.

COMMUNITY REACTION

A survey was formulated and distributed to the residents to determine their level of satisfaction or dissatisfaction with FDOT regarding the noise abatement wall. A copy of the survey form and the results are given in Figure 7.

The survey form was hand-delivered to each available resident, including those adjacent to the wall on the eastern end who elected not to have the wall in front of their property. After a brief explanation of the purpose of the survey, it was left with the resident to fill out with the understanding that

ST. PETERSBURG POST-BARRIER CONSTRUCTION SURVEY
54TH AVENUE SOUTH   STATE JOB NO. 15190-1422

Date April 23-25, 1984

Name ______________________ Address ______________________

Intro- My name is Win Lindeman with the Florida Department of Transportation. I am conducting a follow-up survey regarding your feelings about noise abatement along 54th Avenue South.

1. Were you satisfied with the information concerning the noise barrier that was available prior to the Department of Transportation decision to construct it? (check one)
   - 7 Very Satisified
   - 1 Somewhat Satisfied
   - ___ Neither Satisfied Nor Dissatisfied
   - 1 Somewhat Dissatisfied
   - ___ Very Dissatisfied

2. Did you agree with the Department of Transportation decision to construct a noise barrier at that time? (check one)
   - 7 Yes
   - 2 No
   - ___ Had No Opinion

3. Was the barrier efficiently constructed so that it caused the least possible disruption to the area? (check one)
   - 7 Very Efficient
   - 1 Somewhat Efficient
   - 1 Neither Efficient Nor Inefficient
   - ___ Somewhat Inefficient
   - ___ Very Inefficient

4. Is the barrier effective in reducing traffic noise in your yard? (check one)
   - 2 Very Effective
   - 6 Somewhat Effective
   - 1 Neither Effective Nor Ineffective
   - ___ Somewhat Ineffective
   - ___ Very Ineffective

5. Are you satisfied with the general appearance of the noise barrier? (check one)
   - 6 Very Satisfied
   - 1 Somewhat Satisfied
   - 2 Neither Satisfied Nor Dissatisfied
   - ___ Somewhat Dissatisfied
   - ___ Very Dissatisfied

6. In your opinion, has the construction of the noise barrier affected the value of your property? (check one)
   - 1 Increased Value Greatly
   - 4 Increased Value Somewhat
   - 3 Neither Increased Nor Decreased Value
   - ___ Decreased Value Somewhat
   - ___ Decreased Value Greatly
   - 1 Don't Know

7. Indicate whether you have experienced any of the following frequently mentioned benefits of reduced traffic noise since the construction was completed? (check one or more)
   - 4 Conversation Is Easier
   - 3 Improved Sleeping Conditions
   - 6 More Relaxing Environment
   - 4 Open Windows Fair Weather
   - 1 Use Yard More
   - ___ Other, ______________
   - ___ None

8. Indicate whether you have experienced any of the following frequently mentioned non-noise related benefits since the construction was completed. (check one or more)
   - 3 Cleaner Air
   - 6 Improved Privacy
   - 1 Improved View
   - ___ Lawn/Shrubs Grow Better
   - 1 Sense Of Ruralness
   - ___ Other, ______________
   - 1 None

FIGURE 7 Survey questionnaire after construction of wall and summary of results.

9. Indicate whether you have experienced any of the following frequently mentioned disadvantages of noise barriers since the construction was completed.

(check one or more)

2 Creates Closed-in Feeling
1 Destroys Area Environment
2 Limits/Restricts View
1 More Yard Maintenance
1 Visual Eyesore; Unsightly
___ Other, ___________
4 None

10. In your opinion, do the benefits of constructing noise barriers outweigh the disadvantages?

(check one)

5 Very Beneficial
2 Somewhat Beneficial
1 Neither Beneficial Nor Disadvantageous
1 Somewhat Disadvantageous
___ Very Disadvantageous

If you have any additional comments or suggestions about either the noise barrier program or traffic noise reduction in general, please feel free to include them here. Thank you. Your help is sincerely appreciated. ___________

FIGURE 7 continued.

the form would be picked up later the same day or on the following day. Only two residents failed to fill out the survey form. One of the two had moved out of the neighborhood and the other declined to complete the survey despite several attempts to solicit her input.

As noted previously, the results of the post-construction survey are given in Figure 7. As expected, the results indicated a high degree of satisfaction with the way FDOT presented the information concerning the noise wall and with the decision to build it. Considerable satisfaction with the method of construction was also shown. However, the effectiveness of the barrier at reducing the traffic noise level was not rated as high as might have been hoped for. Because the height of the wall was selected by the residents, their expressed willingness during the first workshop to forego reduction in effectiveness in favor of a lower wall may have led to the modest degree of effectiveness perceived. Concerning appearance of the wall, respondents generally said they were "very satisfied" (recall that the residents also had the opportunity to select the appearance themselves).

The most frequently noted effect on the value of the property was that the noise barrier probably increased it somewhat. The major benefits of having the wall were found to be a more relaxing environment, easier conversation and sleep, and more opportunities to enjoy open windows. Other benefits receiving high ratings were improved privacy and cleaner air. Several residents mentioned that a disadvantage of the wall was that it created a closed-in feeling and limited their view. In the final analysis, most of the residents found the wall to be "very beneficial."

Several residents took the time to write additional comments that expressed their feelings more adequately than they were able to by using the survey form. One resident noted that he appreciated the concern and courtesy of FDOT staff, but wished that the wall had been put up before the beginning of the general construction activities. Another resident noted the efficiency and cooperativeness of the contractor's staff, even though she felt she was going to get more sod installed than was placed. Two residents noted that the wall was very effective at stopping trash and dust from the highway littering their yards. Another resident noted that during the application of the Class 5 finish on the highway side, some overspray was found on his patio furniture and in the pool; nevertheless, he stated that the wall had a very positive impact on their property. Two of the residents who did not favor the wall but went along with it commented on the need to be good neighbors and how they would learn to live with the noise barrier.

CONCLUSIONS

Based on the results of the FDOT effort to involve the community in decision making about a noise barrier, three conclusions can be stated with some level of confidence. First, early public involvement can overcome minor irritations during the construction phase. Second, opening lines of communication in the decision-making process can greatly enhance the acceptability of the noise barrier after the installation is complete. Finally, even though all efforts are reasonably expended, total satisfaction with this process is highly unlikely. To enhance satisfaction, it is strongly suggested that the barrier be built early in the roadway construction process to help reduce the impact of construction noise and dust.

ACKNOWLEDGMENTS

Many people assisted with the preparation of this paper and the field projects associated with it. Special thanks go to James Cunningham, of the Preliminary Plans Section of FDOT, who continued much of the effort that the author began for bringing the noise barrier to the residents. Gordon Morgan, Larry

Barfield, Dick Combs, and Kevin Doyle of FDOT also provided great help in gathering field data and reviewing this paper. Finally, to Roger Eudy, the author owes a special debt of gratitude for field help and graphics assistance.

REFERENCES

1. Florida Department of Transportation Environmental Impact Statement for I-275 in St. Petersburg, Florida. Bureau of Environment, Florida Department of Transportation, Tallahassee, 1971, 151 pp.
2. W. Lindeman. The Birth of a Barrier--A Case Study: I-275 In St. Petersburg, Florida. Proc., Conference on Highway Traffic Noise Mitigation. FHWA, U.S. Department of Transportation, 1978, pp. 19-24.
3. Federal-Aid Highway Program Manual. FHWA, U.S. Department of Transportation, 1980.
4. Florida Department of Transportation Environmental Reevaluation for Design Changes, I-275 in St. Petersburg, 1980. Bureau of Environment, Florida Department of Transportation, Tallahassee, 1980, 31 pp.

Publication of this paper sponsored by Committee on Transportation-Related Noise and Vibration.

Comparison of Noise Barrier Insertion-Loss Methodologies

WIN LINDEMAN

ABSTRACT

Field measurements were conducted before and after the construction of a noise barrier in St. Petersburg, Florida. These noise measurements were made to determine the effectiveness of the barrier by the use of a proposed standard methodology for determining insertion loss. Two methods were used: direct and indirect measured. A computer prediction was also conducted for comparative purposes. Close correlation was found between the two methods and the computer prediction. A recommendation was made to use the computer prediction technique in most instances and the direct method in those cases in which public interest in the barrier is high.

The objectives of the research study were (a) to provide the Florida Department of Transportation (FDOT) with information about the effectiveness of a noise barrier wall built along 54th Avenue South in St. Petersburg and (b) to provide the American National Standards (ANS) Working Group S12-6 with information on the effectiveness of their proposed Standard Method for Determining Insertion Loss of Outdoor Noise Barriers (1).

STUDY LOCATION

To achieve the objectives stated in the preceding paragraph, a before-and-after series of field measurements was planned to determine the insertion loss from the construction of a highway noise barrier wall. The site selected for the field measurements was located along 54th Avenue South in St. Petersburg, Florida. This state highway runs east and west and serves as the major access route to the beaches of southern Pinellas County (see Figure 1).

The existing level of roadway traffic is being increased as a result of an interchange with Interstate 275 as it progresses southward through St. Petersburg. The roadway is bordered on the north by a residential neighborhood known as Maximo Moorings between 37th Street South and 41st Street South. On the south side of this roadway is an open area where a city wastewater treatment plant and Eckerd College are located. The Maximo Moorings neighborhood was selected because of the impending construction of a noise barrier wall at this location and the availability of an existing roadway for before-and-after measurements. In addition, the availability of three vacant lots on which direct before-and-after measurements could be conducted and an equivalent site within 650 ft of the direct site location enhanced the desirability of this location for this type of study. The physical terrain is flat and, on first assessment, met all of the apparent requirements for the ANS study. The homes along the roadway are all single story, single family dwellings that have

FIGURE 1 Interchange area of Maximo Moorings and 54th Avenue South.

backyards facing 54th Avenue South. Profiles of the two measurement sites are shown in Figures 2 and 3.

BEFORE-AND-AFTER STUDIES

The before study was conducted on March 8, 1984, after an effort in February that was aborted when weather prohibited completion of any noise measurements. Two locations along 54th Avenue South were selected for the field measurements, as shown in Figure 1: Site 1 was selected as the direct-method location for the behind-the-wall study; at the same time, Site 2 was chosen as an equivalent site location. Selection of two sites would provide the working group with a comparison of two different field measurement techniques at one time.

Site 1, chosen because it was in the center of three vacant lots and had no activities, was monitored from two points: one was at a point equivalent to the edge of the future wall while the other was located behind the future barrier, 20 ft north of the first point and perpendicular to 54th Avenue South. The ground cover was grass and low weeds, typical of that found in this part of Florida, making Site 1 a soft site. This determination was borne out by comparison of the results of the field measurements and computer predictions. Several mature pines and other trees exist on the lots but were not located within the line of sight of the roadway. The measurement equipment was set up as a reference microphone (Microphone 1) and a receiver microphone (Microphone 2).

At Site 2, two microphones were set up in a backyard just east of the proposed barrier wall. This location was chosen for two reasons: the ground cover was also grass with no significant trees in the direct line of sight, and the traffic patterns were thought to be nearly identical to those found at Site 1, the direct measurement site. One variation between the sites was that the roadway narrowed from three lanes to two lanes between the two sites and that the Interstate off-ramp served as an earthen berm blocking traffic noise from the far lanes (east-

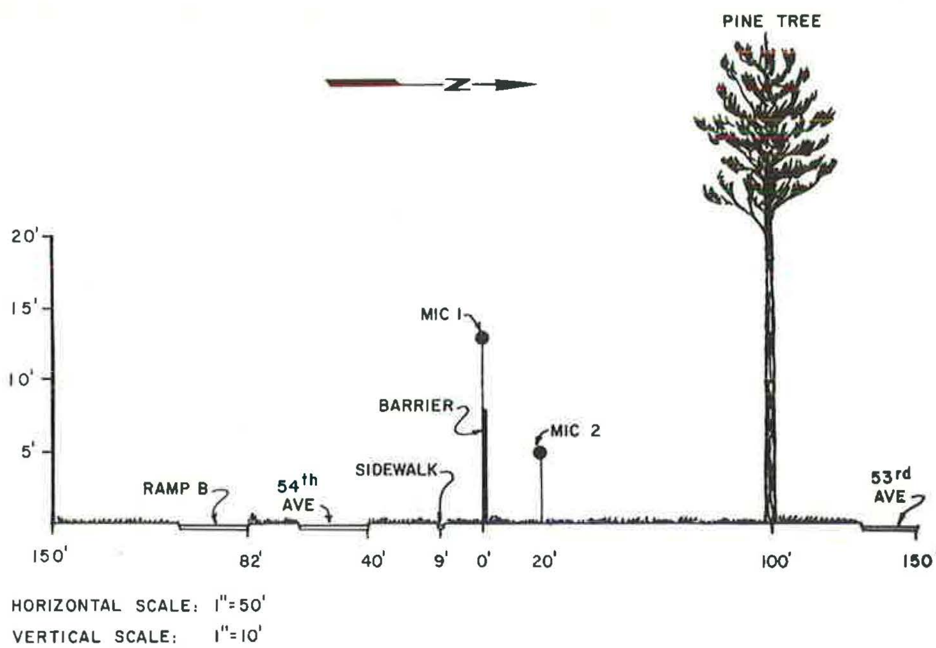


FIGURE 2 Profile of Site 1, showing location of Microphones 1 and 2.

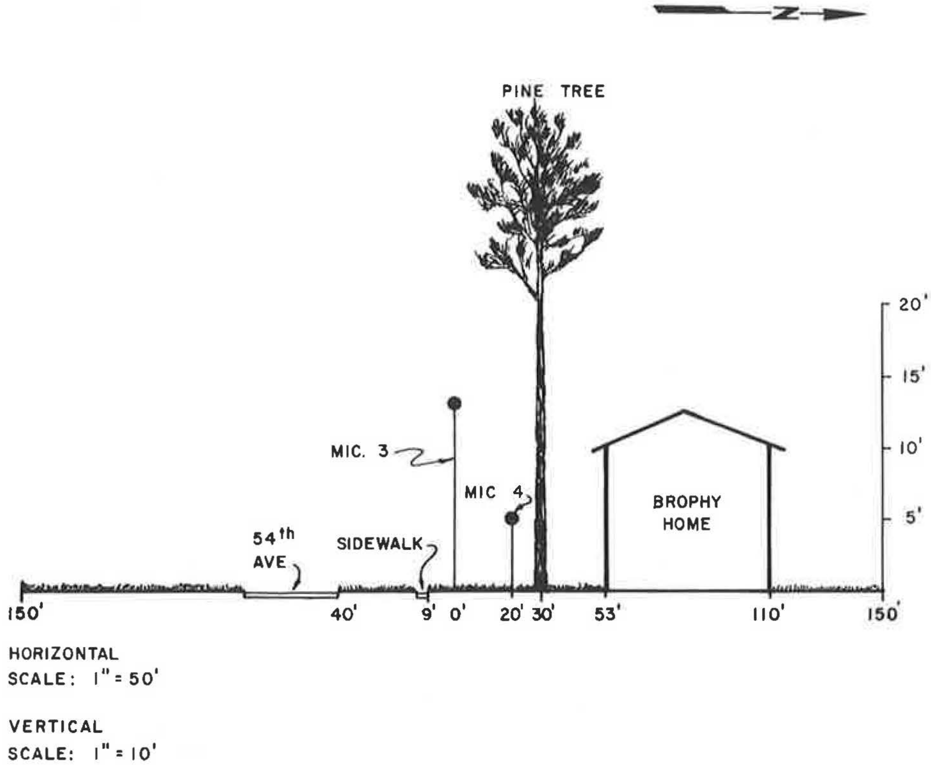


FIGURE 3 Profile of Site 2, showing location of Microphones 3 and 4.

bound). During field measurements, very little traffic was noted in the transition lane. The reference microphone, Microphone 3, was set up exactly in line with Microphone 1 at the same distance from the roadway.

Traffic counts were kept during each recording period, which lasted 20 min. The speeds were determined by using a radar gun that was calibrated before and after each study. The results of this effort are given in Table 1. Climatic conditions were automatically recorded. During the before studies, temperature varied from 60 to 68 °F while winds were steady at 5 mph out of the west-northwest to northwest direction; in the after study, temperature varied between 75 and 78 °F while winds were out of the west-northwest and northwest from 6 to 6 1/2 mph. The sky was clear during both studies.

At Microphones 2 and 3, the noise levels were recorded manually by the check-off method approved by FHWA, U.S. Department of Transportation (2). Each series of readings consisted of one reading taken every 10 sec until 100 readings were recorded. This produced an L10 level (within a 95 percent confidence level) that was converted to Leq, using all 100 readings, by a computer program developed for that purpose. Each sound level meter (SLM) was calibrated immediately before and after each run and the difference was noted.

At Microphones 1 and 4, the SLMs were set to record a continuous 20-min sample and then display

TABLE 1 Traffic Data for All Receivers on All Sites

	Westbound Traffic on 54th Avenue South					
	Cars		Medium Trucks		Heavy Trucks	
Run No.	No. of Vehicles	Speed (mph)	No. of Vehicles	Speed (mph)	No. of Vehicles	Speed (mph)
Before						
1	280	41	2	40	0	00
2	331	41	1	40	1	40
3	273	41	4	40	0	00
4	279	41	2	40	0	00
After						
1	342	39	11	35	3	35
2	264	40	4	30	7	32
3	250	39	5	38	5	32
4	253	41	9	36	5	35
5	224	40	8	37	7	37

Note: These data were recorded on Thursday, March 8, 1984, and Tuesday, April 24, 1984.

the Leq for the time period selected. It was the intention of the research team to conduct 4 runs at each location, but it soon became evident that this was not going to be feasible. On arrival at the measurement sites, which had been identified during the aborted February attempt, it was discovered that the contractor for the barrier wall installation was in the area and was preparing a base for the wall. This contractor was removing a small amount (generally less than 3 in.) of topsoil along the line of the wall by using a Gradall; this meant that the readings had to be delayed until the work was completed in the vicinity of the measurement locations. After completion of the base work in the vicinity of Site 1, a pair of noise measurements were taken. Site 2 could not be measured simultaneously because the Gradall had moved in front of that location and therefore dominated the noise levels at that point, even though it could no longer be detected at Site 1.

The ambient conditions for Runs 1 and 2 were determined to be the lowest actual reading during the monitoring period because this occurred in the absence of traffic in each case. (It is possible that the use of the L90 or an average of the lowest actual readings measured in the absence of traffic would make a more representative ambient determination.) By the time the first two runs had been made, the workers had completed their site preparation work and left the area. After their departure, another set of noise measurements was attempted at both sites and all four microphone locations. The results of the total effort can be found in Table 2.

Construction of the noise barrier wall was completed in March 1984 and the after condition measurements were scheduled to be made during the week of April 23. The precast concrete wall was 8 ft above ground level at most locations except at the far western end where a slight grade reduced the effective height to about 7 ft. The monitoring took place on a Tuesday with the sky completely free of clouds and a temperature of 78 °F. Because of man-power conditions and the experience of the previous measurement effort, the instrumentation was shifted around. Five runs were successfully completed on April 24, 1984, and the results are given in Table 3.

INSTRUMENTATION OF FOUR MICROPHONES

Throughout the studies, Microphone 1 instrumentation consisted of a General Radio (GR) Model 1988 Type 1 SLM with a 1/2-in. GR Model 1560-P42 microphone and preamplifier connected by a 30-ft cable. The microphone was mounted 13 ft in the air on a mast and topped with a windscreen. A GR Model 1562-A Sound Level Calibrator was used to calibrate the meter before and after each set of readings.

Microphone 2 instrumentation during the before study consisted of a GR Model 1933 Type 1 SLM with a 1-in. GR Model 1961 microphone connected by a 10-ft cable. The microphone was topped with a windscreen and mounted on a tripod 5 ft above ground level. An LK Systems 10 audio timer was used to indicate the passage of 10 sec through a set of headphones and a GR Model 1567 SLM Calibrator was used to calibrate the system. In the after study, this system was replaced with one similar to Microphone 1 except that no cable was used and the microphone was maintained at 5 ft. In addition to the noise monitoring equipment, traffic data were gathered using radar and traffic counters while meterological data were gathered using a portable weather station located 20 ft west of Microphone 2 on a mast 13 ft high.

The equipment used at Microphone 3 in the before study consisted of a Bruel & Kjaer (B&K) Model 2209 Type 1 SLM with a 1-in. B&K Model 4145 microphone attached by a 10-ft cable. The microphone was mounted to a mast 13 ft aboveground and topped with a windscreen and a B&K Model 4230 SLM Calibrator was used to calibrate the system. In the after study, the system consisted of a GR Model 1933 Type 1 SLM and a 1-in. GR Model 1961 microphone attached to a 30 ft cable. A windscreen topped the microphone and the system was calibrated using a GR Model 1567 SLM Calibrator.

Microphone 4 was set back 20 ft north of Microphone 3 and in line with Microphone 2, which was the equivalent site receiver position; the equipment used varied in the before and after studies. The system used in the before study was identical to the system used at Microphone 2 in the after condition. The system used in the after study was similar to that used at Microphone 3 in the before study except that no cable was used and the height was maintained at 5 ft aboveground.

TABLE 2 Results of Noise Readings at Microphones 1 to 4 on All Runs

Microphone No.	Run No.	Time of Readings	Measured Leq (dBA)	Measured Ambient Leq (dBA)
1	1	4:55-5:15 p.m.	64.2	49
2	1	4:55-5:15 p.m.	58.2	49
1	2	5:23-5:43 p.m.	64.5	50
2	2	5:23-5:43 p.m.	59.1	50
1	3	6:00-6:20 p.m.	63.1	48
2	3	6:00-6:20 p.m.	57.7	48
3	3	6:00-6:20 p,m.	62.6	50
4	3	6:00-6:20 p.m.	–[a]	50
1	4	6:30-6:50 p.m.	–[a]	48
2	4	6:30-6:50 p.m.	58.8	48
3	4	6:30-6:50 p.m.	64.0	49
4	4	6:30-6:50 p.m.	–[a]	49

Note: These data were collected on March 8, 1984, at both sites.
[a]Data not collected due to equipment failure.

TABLE 3 Results of Noise Readings at Microphones 1 to 4 on Runs 1 to 5

Microphone No.	Run No.	Time of Readings	Measured Leq (dBA)	Measured Ambient Leq (dBA)
1	1	12:30-12:50 p.m.	65.4	53
2	1	12:30-12:50 p.m.	54.0	47
3	1	12:30-12:50 p.m.	66.7	53
4	1	12:30-12:50 p.m.	61.2	47
1	2	12:55-1:15 p.m.	67.1	51
2	2	12:55-1:15 p.m.	54.6	48
3	2	12:55-1:15 p.m.	72.2	51
4	2	12:55-1:15 p.m.	65.3	48
1	3	1:27-1:47 p.m.	65.5	51
2	3	1:27-1:47 p.m.	53.2	49
3	3	1:27-1:47 p.m.	66.1	51
4	3	1:27-1:47 p.m.	60.2	49
1	4	1:51-2:11 p.m.	65.9	49
2	4	1:51-2:11 p.m.	55.2	46
3	4	1:51-2:11 p.m.	68.8	49
4	4	1:51-2:11 p.m.	61.1	49
1	5	2:26-2:46 p.m.	66.9	51
2	5	2:26-2.46 p.m.	54.4	49
3	5	2:26-2:46 p.m.	67.4	51
4	5	2:26-2:46 p.m.	62.4	49

Note: These data were collected on April 24, 1984, at both sites.

ACOUSTICAL DATA

Direct Method

The field measurements allowed for the analysis of the insertion loss by using the draft methodology developed by the working group. To compare the results effectively, each pair of appropriate receivers had to be matched to the proper data. Table 4 gives the adjusted source level information at the reference microphone (Microphone 1) at Site 1 in the before study. It should be noted that the source in Run 4 is not calculated; this resulted from battery failure midway through the run at this microphone. The results of the before study at Microphone 2, located 20 ft north of Microphone 1, are given in Table 5. This receiver (Microphone 2) was located in the behind-the-wall position for analysis by the direct measurement methodology. The after-barrier results at these two microphone locations are given in Tables 6 and 7. Table 8 gives the calculations for the insertion loss based on the direct method test. The mean adjusted insertion loss was determined to be 7.5 dBA.

Indirect Measured Method

The indirect measured method using an equivalent site was also employed to determine the mean insertion loss for the barrier. Table 9 gives the adjusted source level at the reference microphone (Microphone 3) during the before-wall condition. Table 10 shows that, because of a meter malfunction

TABLE 4 Adjusted Source Level Calculations at Site 1, Microphone 1—Before Study

Run	Measured Levels		Calibration Adjustment = (End-Start)/2	Levels Adjusted for Calibration		Source Level - Ambient Level	Ambient Adjustment	Adjusted Source Level at the Receiver
	Ambient	Source		Ambient	Source			
	(B1)	(B2)	(B3)	(B4)= (B1-B3)	(B5)= (B2-B3)	(B6)= (B5-B4)	(B7)	(B8)= (B5+B7)
1	49	64.2	114 - 114=0	49	64.2	15.2	0	64.2
2	50	64.5	114 - 114=0	50	64.5	14.5	0	64.5
3	48	63.1	114 - 114=0	48	63.1	15.1	0	63.1
4	48	-	-	48	-	-	-	-

Note: Standard deviation = 0.8. These data were collected on March 8, 1984; the source was traffic noise from 54th Avenue South.

TABLE 5 Adjusted Source Level Calculations at Site 1, Microphone 2—Before Study

Run	Measured Levels		Calibration Adjustment = (End-Start)/2	Levels Adjusted for Calibration		Source Level - Ambient Level	Ambient Adjustment	Adjusted Source Level at the Receiver
	Ambient	Source		Ambient	Source			
	(B1)	(B2)	(B3)	(B4)= (B1-B3)	(B5)= (B2-B3)	(B6)= (B5-B4)	(B7)	(B8)= (B5+B7)
1	49	58.2	114-114=0	49	58.2	9.2	-0.6	57.6
2	50	59.1	114-114=0	50	59.1	9.1	-0.6	58.5
3	48	57.7	114-114=0	48	57.7	9.7	-0.4	57.3
4	48	58.8	114-114=0	48	58.8	10.8	0.0	58.8

Note: Standard deviaton = 0.8. These data were collected on March 8, 1984; the source was traffic noise from 54th Avenue South.

TABLE 6 Adjusted Source Level Calculations at Site 1, Microphone 1—After Study

Run	Measured Levels Ambient	Measured Levels Source	Calibration Adjustment = (End-Start)/2	Levels Adjusted for Calibration Ambient	Levels Adjusted for Calibration Source	Source Level - Ambient Level	Ambient Adjustment	Adjusted Source Level at the Receiver
	(A1)	(A2)	(A3)	(A4)= (A1-A3)	(A5)= (A2-A3)	(A6)= (A5-A4)	(A7)	(A8)= (A5+A7)
1	53	65.4	114-114=0	53	65.4	12.4	0	65.4
2	51	67.1	114-114=0	51	67.1	16.1	0	67.1
3	51	65.5	114-114=0	51	65.5	14.5	0	65.5
4	49	65.9	114-114=0	49	65.9	16.9	0	65.9
5	51	66.9	114-114=0	51	66.9	15.9	0	66.9

Note: Standard deviation = 1.3. These data were collected on April 24, 1984; the source was traffic noise from 54th Avenue South.

TABLE 7 Adjusted Source Level Calculations at Site 1, Microphone 2—After Study

Run	Measured Levels Ambient	Measured Levels Source	Calibration Adjustment = (End-Start)/2	Levels Adjusted for Calibration Ambient	Levels Adjusted for Calibration Source	Source Level - Ambient Level	Ambient Adjustment	Adjusted Source Level at the Receiver
	(A1)	(A2)	(A3)	(A4)= (A1-A3)	(A5)= (A2-A3)	(A6)= (A5-A4)	(A7)	(A8)= (A5+A7)
1	47	54.0	114-114=0	47	54.0	7.0	-1.0	53.0
2	48	54.6	114-114=0	48	54.6	6.6	-1.0	53.6
3	49	53.2	114-114=0	49	53.2	4.2	-2.2	51.0
4	46	55.2	114-114=0	46	55.2	9.2	-0.6	54.6
5	49	54.4	114-114=0	49	54.4	5.5	-1.7	52.7

Note: Standard deviation = 1.2. These data were collected on April 24, 1984; the source was traffic noise from 54th Avenue South.

TABLE 8 Calculations for Insertion Loss Based on Direct Method Test at Site 1

	BEFORE 3/8/84			AFTER 4/24/84			
Run #	Adjusted Source Level at Reference (1) MIC 1	Adjusted Source Level at Receiver (2) MIC 2	Before Difference (3)=(1-2)	Adjusted Source Level at Reference (4) MIC 1	Adjusted Source Level at Receiver (5) MIC 2	After Difference (6)=(4-5)	Insertion Loss=Before Difference - After Difference (7)=(6-3)
1	64.2	57.6	6.6	65.4	53.0	12.4	6.2
2	64.5	58.5	6.0	67.1	53.6	13.5	7.5
3	63.1	57.3	5.8	65.5	51.0	14.5	8.7
4	-	58.8	-	65.9	54.6	11.3	-
5	-		-	66.9	52.7	14.2	-

Note: For before study, standard deviation = 0.2; for after study, standard deviation = 1.2; $\overline{IL}$ = 7.5.

TABLE 9 Adjusted Source Level Calculations at Site 2, Microphone 3—Before Study

Run	Measured Levels		Calibration Adjustment = (End-Start)/2	Levels Adjusted for Calibration		Source Level - Ambient Level	Ambient Adjustment	Adjusted Source Level at the Receiver
	Ambient	Source		Ambient	Source			
	(B1)	(B2)	(B3)	(B4)= (B1-B3)	(B5)= (B2-B3)	(B6)= (B5-B4)	(B7)	(B8)= (B5+B7)
1								
2								
3	50	62.6	94-94 = 0	50	62.6	12.6	0.0	62.6
4	49	64.0	94-94 = 0	49	64.0	15.0	0.0	64.0

Note: Standard deviation = 0.5. These data were collected on March 8, 1984; the source was traffic noise from 54th Avenue South.

TABLE 10 Adjusted Source Level Calculations at Site 2, Microphone 4—Before Study

Run	Measured Levels		Calibration Adjustment = (End-Start)/2	Levels Adjusted for Calibration		Source Level - Ambient Level	Ambient Adjustment	Adjusted Source Level at the Receiver
	Ambient	Source		Ambient	Source			
	(B1)	(B2)	(B3)	(B4)= (B1-B3)	(B5)= (B2-B3)	(B6)= (B5-B4)	(B7)	(B8)= (B5+B7)
1								
2								
3	50	a						
4	49	a						

Note: These data were collected on March 8, 1984; the source was traffic from 54th Avenue South.
[a]Data lost due to malfunction of the Leq Meter.

TABLE 11 Adjusted Source Level Calculations at Site 2, Microphone 3—After Study

Run	Measured Levels		Calibration Adjustment = (End-Start)/2	Levels Adjusted for Calibration		Source Level - Ambient Level	Ambient Adjustment	Adjusted Source Level at the Receiver
	Ambient	Source		Ambient	Source			
	(A1)	(A2)	(A3)	(A4)= (A1-A3)	(A5)= (A2-A3)	(A6)= (A5-A4)	(A7)	(A8)= (A5+A7)
1	53	66.7	114-114=0	53	66.7	13.7	0	66.7
2	51	72.2	114-114=0	51	72.2	21.2	0	72.2
3	51	66.1	114-114=0	51	66.1	15.1	0	66.1
4	49	68.8	114-114=0	49	68.8	19.8	0	68.8
5	51	67.4	114-114=0	51	67.4	16.4	0	67.4

Note: Standard deviation = 1.3. These data were collected on April 24, 1984; the source was traffic from 54th Avenue South.

that went undetected during the sampling periods, no data were obtained at the receiver position (Microphone 4) during the before-wall testing. After the wall was constructed, the site was once again studied at Microphones 3 and 4; the results of this study are given in Tables 11 and 12. To determine the mean insertion loss by the equivalent site method, a comparison of the after conditions at Microphones 3 and 4 must be made. At the same time, a comparison of Microphones 1 and 2 needs to be made to determine if anything unusual appears to have occurred between the two reference locations. Table 13 gives a comparison of results of Microphones 3 and 4 and also shows the mean insertion loss determination for the barrier based on the difference between Microphones 3 and 4 and Microphones 1 and 2. The mean insertion

TABLE 12 Adjusted Source Level Calculations at Site 2, Microphone 4—After Study

Run	Measured Levels		Calibration Adjustment = (End-Start)/2	Levels Adjusted for Calibration		Source Level - Ambient Level	Ambient Adjustment	Adjusted Source Level at the Receiver
	Ambient	Source		Ambient	Source			
	(A1)	(A2)	(A3)	(A4)= (A1-A3)	(A5)= (A2-A3)	(A6)= (A5-A4)	(A7)	(A8)= (A5+A7)
1	47	61.2	94-94 = 0	47	61.2	14.2	0	61.2
2	48	65.3	94-94 = 0	48	65.3	17.3	0	65.3
3	49	60.2	94-94 = 0	49	60.2	11.2	0	60.2
4	46	61.1	94-94 = 0	46	61.1	15.1	0	61.1
5	49	62.4	94-94 = 0	49	62.4	13.4	0	62.4

Note: Standard deviation = 1.2. These data were collected on April 24, 1984; the source was traffic from 54th Avenue South.

TABLE 13 Calculations Based on Indirect Measured Method

	AFTER 4/24/84			AFTER 4/24/84			
Run #	Adjusted Source Level at Reference ence	Adjusted Source Level at Receiver	Difference	Adjusted Source Level at Reference	Adjusted Source Level at Receiver	Difference	Insertion Loss
	(1) MIC 3	(2) MIC 4	(3)= (1-2)	(4) MIC 1	(5) MIC 2	(6)= (4-5)	(7)=(6-3)
1	66.7	61.2	5.5	65.4	53.0	12.4	6.9
2	72.2	65.3	6.9	67.1	53.6	13.5	6.6
3	66.1	60.2	5.9	65.5	51.0	14.5	8.6
4	68.8	60.2	7.7	65.9	54.6	11.3	3.6
5	67.4	62.4	5.0	66.9	52.7	14.2	9.2

Note: For columns (1), (2), and (3), standard deviation = 1.0; for columns (4), (5), and (6), standard deviation = 1.2; $\overline{IL}$ = 7.0.

loss determined by using this method was 7.0 dBA compared with 7.5 dBA determined by using the direct method.

Analysis of the data from Microphones 1 and 3 indicates that the traffic characteristics were not as similar as originally presumed, especially during the after-wall study. It is difficult to explain this difference except to note that in several instances at Site 2 heavy trucks passed by in an acceleration mode and set unusually high measured peaks that skewed the Leq at this location. By the time these trucks reached Site 1, some 650 ft down

TABLE 14 STAMINA 2.0 Prediction Results

	Before Leq			After Leq		
Run	Measured	Predicted	Difference	Measured	Predicted	Difference
Microphone 1						
1	64.2	63.9	0.3	65.4	65.8	0.4
2	64.5	65.0	0.5	67.1	65.6	1.5
3	63.1	64.1	1.0	65.5	65.1	0.4
4				65.9	65.9	0.0
5				66.9	66.2	0.7
Standard Deviation			0.3			0.4
Microphone 2						
1	58.2	61.9	3.7	54.0	56.9	2.9
2	59.1	62.9	3.8	54.6	57.4	2.8
3	57.7	62.1	4.4	53.2	56.6	3.4
4	58.8	61.8	3.0	55.2	57.4	2.2
5				54.4	58.1	3.7
Standard Deviation			0.5			0.5
Microphone 3						
1				66.7	65.8	0.9
2				72.2	65.6	6.6
3	62.6	64.1	1.5	66.1	65.1	1.0
4	64.0	63.8	0.2	68.8	65.9	2.9
5				67.4	66.2	1.2
Standard Deviation			0.7			2.2
Microphone 4						
1				61.2	63.4	2.2
2				65.3	63.3	2.0
3				60.2	62.7	2.5
4				61.1	63.6	2.5
5				62.4	63.9	1.5
Standard Deviation						0.4

Note: Blank space indicates lack of data.

the road, they apparently were not in this strong acceleration mode. A variation in the volume of trucks (heavy and medium) was also noted between the before study and the after study. It should be noted that the bias for the two methods was found to be identical.

Computer Prediction

For comparative purposes, the field data were loaded into the STAMINA 2.0 computer prediction program. A validation of the before-and-after field measurements was made at all four microphone locations. Computer prediction results are given in Table 14; these results were generated by using the traffic data given in Table 1. Table 15 gives the results of the insertion loss based on a computer prediction using the STAMINA 2.0 program. The mean insertion loss is shown to be 6.1 dBA.

TABLE 15 Results of Mean Insertion Loss Determined by Using STAMINA 2.0 Computer Prediction Program

Run No.	Without Barrier	With Barrier	Difference
1	63.4	56.9	6.5
2	63.3	57.4	5.9
3	62.7	56.6	6.1
4	63.6	57.4	6.2
5	63.9	58.1	5.8

Note: Without barrier, mean = 63.4; with barrier, mean = 57.3; mean insertion loss = 6.1.

RESULTS

A comparison of the mean insertion loss as determined by the computer prediction program was made with the results of the two draft methodologies. Based on the results, there appears to be a mean difference of 0.9 dBA between the results of using the indirect measured method and the computer predictions. As noted earlier, the difference between the direct and indirect measured methods could probably be explained based on the apparent difference in the source strength between the two points and the change in total truck volume; the acceleration of heavy trucks was isolated as the probable cause of this phenomenon. The difference between the computer predictions and the results of using the direct method is not easy to isolate. It would appear that the truck volume may be the cause of the difference, but it is difficult to conclude this with any degree of certainty.

SUMMARY AND RECOMMENDATIONS

In summation, the methodologies found in the draft standard (direct and indirect measured) are all usable; however, from the standpoint of traffic noise and highway agencies, use of computer predictions is recommended. This recommendation is based on manpower requirements, equipment needs, and relative accuracy of the various methods compared to the accuracy needs of the agency. Use of the indirect measured method is strongly discouraged because of the vast number of variables that can occur that are difficult to quantify. Although not employed during this research effort, the indirect predicted method would appear to be preferable to the indirect measured method. Using the direct method is suggested for those locations where public involvement has been high and the possibility of controversy has surfaced. This method would give greater credence to the ability of the barrier owner to accurately anticipate barrier effectiveness.

REFERENCES

1. W. Bowlby, chairman. Proposed American National Standard Methods for Determination of Insertion Loss of Outdoor Noise Barriers, ANSI S12.6-198X. Acoustical Society of America, New York, N.Y., Feb. 1984, 41 pp. (draft version).
2. W. Bowlby (ed.). Sound Procedures for Measuring Highway Traffic Noise. Final Report FHWA-DP-45-1R. FHWA, U.S. Department of Transportation, Aug. 1981.

Publication of this paper sponsored by Committee on Transportation-Related Noise and Vibration.

Airport Noise Monitoring Systems in North America

CLIFFORD R. BRAGDON

ABSTRACT

Airport noise is a recognized by-product of a transportation-based economy. Because the number of airports, aircraft, and flight operations over adjacent airport communities are essential to the economic base, noise monitoring systems are being installed by airport proprietors. Currently, there are 25 systems in operation at airports in North America (two additional airports are in the process of bidding on and installation of noise monitoring systems). They have been installed for a variety of reasons and purposes, including compliance with enacted regulations or standards. These airport noise systems consist of four basic components: remote monitoring station, central processing station, software, and accessories. It is anticipated that the number of such systems will increase more rapidly in the future, partially due to available federal funding under Federal Aviation Regulations (FAR) Part 150: Airport Noise and Land Use Planning.

Air transportation is a major component of the national transportation system. The Federal Aviation Administration (FAA), U.S. Department of Transportation, estimates that there are nearly 15,000 airports (towered and nontowered) in the United States. These airports operate civil air fleets of approximately 195,000 aircraft throughout the United States, generating nearly 8 million flight operations annually.

Although aircraft operations are beneficial to the economic base of the United States, there are certain impacts associated with such operations. Due to the rapid growth of airports and the adjacent airport communities, along with increasing numbers of jet-engined aircraft that operate during a 24-hr period, potential noise impact conditions often exist in residential areas near airports.

Many techniques are being used to address this potential problem through source controls (i.e., engine noise suppression, new generation aircraft) as well as receiver controls (i.e., building codes, land using planning) at the federal level, primarily through the FAA. Such noise-related FAA activities include Federal Aviation Regulations (FAR) Part 36: Noise Certification, FAR Part 91: General Operations and Flight Rules, and FAR Part 150: Airport Noise and Land Use Planning (1). Some state and municipal governments are also taking certain steps to control airport-related noise by using the regulatory and planning process (2-4). An increasingly common approach as part of the overall management of airport noise is the establishment of a permanent airport noise monitoring system.

HISTORY

The acoustical monitoring of airport noise on a permanent and continuous basis is a relatively new phenomenon in the United States. Historically, the first such system was installed by the Port Authority of New York in 1967, and was used initially at John F. Kennedy International Airport (5). Similar systems were subsequently installed at LaGuardia International Airport and Newark International Airport by the Port Authority of New York. The impetus for this instrumentation system was the establishment of a maximum peak noise-level requirement for aircraft operating in a takeoff mode. Such a noise standard was developed by the Port Authority of New York in part due to concerns about airport noise raised by neighboring municipalities. A peak noise-level threshold was established for aircraft takeoff purposes; it was equivalent to 104 dBA.

Inglewood, California, was the first municipality to have a permanent noise abatement program, beginning in 1969 (5). This city was specifically concerned about the problem of flyover noise associated with Los Angeles International Airport. In response to this problem, a series of three fixed monitoring stations was erected in Inglewood by using telephone poles with monitors connected by land lines to a central receiver system, located at City Hall. This noise abatement program also used a mobile van for observing aircraft flyover noise at locations throughout the community. The Noise Abatement Office developed both a fixed and mobile noise monitoring program.

Other than these efforts by New York Port Authority and Inglewood, California, there was little activity concerning noise abatement until the early 1970s when the California Department of Aeronautics established an Airport Noise Standard in their Administrative Code (6). These provisions, enacted in 1973, required a continuous monitoring system for noise when the composite noise exposure level (CNEL) exceeded a certain annual level along with a daily single event noise exposure level (SENEL). Beginning in 1975, several airports began to establish noise monitoring programs to determine compliance with this code.

CURRENT STATUS OF NOISE MONITORING SYSTEMS

Interest has grown steadily since the initial system for airport noise monitoring was installed in 1967. Currently, there are 25 airports in North America that operate permanent noise monitoring systems [two additional airports are in the process of bidding on and installation of noise monitoring systems (see Table 1)]. A large number of air carrier airports have been required by state law in California to install noise monitoring systems.

All existing airports that have monitoring systems are civilian based. These systems generally apply to air carriers, as opposed to general-aviation airports. The largest concentration of these airports (93 percent) are situated in the United States. Nearly one-half of these instrumented airports (42 percent) are located in California, while the remaining 58 percent are distributed throughout 10 states and the District of Columbia.

Within California, these monitoring systems are located primarily in the Los Angeles (7 systems) and the San Francisco (4 systems) metropolitan areas. New York, with four systems, and Washington, D.C., with two systems, are the only other metropolitan areas with multiple noise monitoring systems in place. The Port Authority of New York and New Jersey is in the process of replacing their original system installed during the 1960s. It should become totally operational before the end of 1986 (7).

Currently, there are three companies that manufacture equipment for measuring noise on a continuous basis at a fixed airport location: Tracor, Metrosonics, and Brael & Kjaer Instruments. Often the manufacturer will install a system after an independent acoustical study is prepared by a consultant for a specific airport proprietor.

TABLE 1 Airport Noise Monitoring Systems in North America

Geographic Location	Airport
California	
Burbank	Burbank Airport
Long Beach	Long Beach International Airport
Los Angeles	Los Angeles International Airport
Ontario	Ontario International Airport
Orange County	Orange County Airport
San Diego County	San Diego Airport
San Francisco	San Francisco International Airport
San Jose	San Jose International Airport
Santa Clara County	Reid-Hillview Airport
Santa Monica	Santa Monica Municipal Airport
Torrance	Torrance Municipal Airport
Florida	
West Palm Beach	Palm Beach International Airport[a]
Hawaii	
Honolulu	Honolulu International Airport
Massachusetts	
Boston	Boston Logan International Airport
Minnesota	
Minneapolis	Minneapolis-St. Paul International Airport
Missouri	
St. Louis	St. Louis Lambert International Airport
New Jersey	
Newark	Newark International Airport
New York	
New York	John F. Kennedy International Airport
New York	LaGuardia International Airport
White Plains	West Chester County Airport
Ohio	
Cleveland	Cleveland-Hopkins Airport
Virginia	
Hampton	NASA Langley Airport
Washington	
Seattle	Seattle-Tacoma International Airport
Washington, D.C.	Washington National Airport
	Dulles International Airport
Canada	
Edmunton, Alberta	Edmunton Airport[b]
Toronto, Ontario	Toronto International Airport

[a]As of December 1985, a specification document has been prepared for bidding on construction of an airport noise monitoring system in West Palm Beach.

[b]As of December 1985, bids have been received and a contract has been awarded for installation of a permanent airport noise monitoring system in Edmunton.

COMPONENTS OF A NOISE MONITORING SYSTEM

There are three basic equipment components of an airport noise monitoring system: the remote monitoring stations, central processing station, and associated software. Sometimes there is also a fourth component to a system, accessories. Each of these components will be discussed further.

Remote Monitoring Stations

Remote monitoring stations are fixed stations that physically measure airborne-generated noise. They consist of a microphone or hydrophone connected to a field equipment enclosure with microphone power, and single preprocessing and data transmission capability.

They are usually placed high above the ground, often roof-mounted. The total number of stations will vary according to three items: the specific airport, complexity of the airport layout, and associated impact on land use. The total number of noise monitoring stations per airport, based on the list of airports given in Table 1, ranges from 8 to 26. Currently, the maximum number of stations for a given airport is 26 because the printout area of the data printed is restricted. The average number of sites for all airport systems in place is 13.

Key factors to be considered in the performance characteristics of the field equipment include environmental protection from precipitation, wind turbulence, extreme temperature variation, dynamic range of equipment, transmission of signal for processing central and remote calibration, and constant power supply.

Central Processing Station

The central processing station receives all of the input data from the remote monitoring stations. The principal equipment at this location is a computer for central processing that receives, analyzes, and stores data transmitted from the field. In addition to the computer, there is accessory equipment that includes a visual display unit (CRT) and a high-speed printer.

Storage capacity will be essential for maintaining a data file; however, its size (capacity) is somewhat dependent on the intended use of the system, including the data desired to be displayed.

Consideration should be given to several factors in locating the central processing station:

- Accessibility
- Ambient temperature
- Storage of data tapes, diskettes, and discs
- Ergonomics of user or users
- Convenience of location
- Security and safety
- Ease of service and installation of equipment
- Protection against electrical interference (e.g., power surge)

Software

Software refers to the programming package designed to process, analyze, and graphically portray the monitored noise and related information. Several factors are important in selecting the software, including:

- Software language
- Program or user friendly
- Expandability of software programming
- Flexibility in the software
- Software to expedite report preparation, including data summaries and special studies
- Simultaneous processing without interruption
- All key noise metrics and descriptors, both current and future
- Ease of modification
- Software documentation

Several of the recently installed systems provide a graphic color display in real time of the monitoring locations on the CRT. This is used to assist the airport personnel responsible for the noise program, rather than the public-at-large.

Accessories

Certain accessory elements that can improve the potential noise monitoring system are often found at airports.

Map Display

Many airports maintain an electronic map at the installation, which gives a graphic display of the monitored noise levels, often in real time. At certain airports, these monitored aircraft operations are shown with colored lights indicating the degree of compliance. For example, a flashing red light indicates exceedance of level of permissible take-off noise and a flashing green light indicates compliance. Such maps are situated in various locations ranging from public access areas to worker or airport employee areas.

The San Jose Airport was one of the first airports to use a map display. Measuring approximately 4 x 4 ft, this display is located in the main terminal area to give maximum public exposure. Various maps are incorporated into each airport display. Some displays also incorporate an aerial mosiac of the airport community, while others rely on a land-use base map. The average cost for such a map display is $10,000 to $12,000.

ARTS Data (Aircraft Radar Tracking System IIIa)

Several airports have integrated flight operation data, available through ARTS (Aircraft Radar Tracking System), with the airport noise system; the purposes are to assist in identifying specific time, flight-track characteristics, as well as aircraft and airline operator. ARTS is needed for air traffic control. ARTS-IIIA provides a continuous surveillance of aircraft activity in their assigned airspace every 4 sec. Only two airports now directly use the radar system as part of a noise monitoring program, Washington National Airport and Dulles International Airport; both of these airports are operated by the FAA. Cleveland, Ohio, and the Port Authority of New York and New Jersey are in the process of installing the necessary electronics to provide the ARTS-IIIA information for their respective noise programs. However, recording of each aircraft operation will not occur in real time, but will be delayed for 15 to 30 days because the FAA must keep all ARTS data for 2 weeks in case there is an aircraft accident. The amount of data generated by this system is significant (e.g., up to 15 reels of tape per day). Therefore, to avoid excessive storage and handling requirements, a select sample would be the most desirable approach. Automatic aircraft detection, counting, and aircraft identification have been considered important noise management tools at several air carrier airports.

PURPOSE OF ESTABLISHING NOISE MONITORING PROGRAMS

Airport noise monitoring programs have been established for a variety of reasons. It is important that airports analyze the advantages and disadvantages of establishing a program of this type before proceeding.

Based on the purpose of systems already installed at airports throughout the United States, collective purposes of establishing a noise monitoring program are to:

- Assess alternative flight procedures for noise control
- Assist in the investigation of specific public inquiries and complaints
- Instill public confidence that airport-related noise is being monitored to protect the public's interest
- Validate noise modeling efforts at the airport over an extended period of time (e.g., 1 year)
- Assist in addressing land-use planning and noise-impact issues
- Indicate official concern for airport noise by the jurisdiction and its governing body
- Detect unusual flight events
- Educate airplane pilots, airlines, the air-

port proprietor, and the public about airport noise and its characteristics

- Obtain valid statistical data using an objective and scientific resource
- Apply research tools to assist the airport in performing certain tasks, as required or mandated
- Assess compliance with some voluntary or mandatory noise level, established by a governmental entity

CONCLUSION

Interest in establishing a noise monitoring system at airports is increasing. Today, there are 25 systems in place, primarily installed at commercial air carrier airports. Three such systems are operated by the federal government, including two in Washington, D.C., and one in Langley, Virginia (NASA). Three systems have been installed this past year (West Chester, New York; St. Louis, Missouri; and Cleveland, Ohio) for a variety of reasons and purposes. Some of the earlier systems are now being upgraded to reflect the state of the art (e.g., Port Authority of New York and New Jersey). Because of the growth of aviation and the proximity of communities to airports, which resulted in potential land-use incompatibility, and because of the FAA Part 150 Program (8), the demand for such systems is predicted to increase. Several airport operators are in the process of receiving or have already received federal support on a matching basis (80 to 20 percent) through the FAA to obtain an airport noise monitoring system. Such systems generally range in cost from $250,000 to $1,000,000, depending on equipment specifications.

REFERENCES

1. R.N. Tedrick and R.B. Hixson. Aircraft Noise and the Airport Community. Proc., AIAA, ASCE, TRB, ATRIF, CASI International Airport Noise Conference, Montreal, Canada, June 1983.
2. C.R. Bragdon. Municipal Noise Regulations. Fairmont Press, Atlanta, Ga., 1981.
3. C.R. Bragdon. The Control of Aircraft Noise in the United States: An Overview. Proc., Inter-Noise, Edinburgh, Scotland, May 1983.
4. P. Cline. Airport Noise Control Strategies. Advisory Circular, Federal Aviation Administration, U.S. Department of Transportation, May 1983.
5. C.R. Bragdon. Noise Pollution: The Unquiet Crisis. University of Pennsylvania Press, Philadelphia, 1972.
6. California Department of Aeronautics. Airport Noise Standards Administrative Code. Title 21, Chapter 2.5, Subchapter 6, 1973.
7. A.M. Attar. The Port Authority of New York and New Jersey Aviation Department. Presented at Airport Noise and Land Use Planning Conference, Georgia Tech and The Port Authority of Seattle, Seattle, Wash., May 1985.
8. U.S. Department of Transportation. Federal Aviation Administration. Airport Noise Compatibility Planning. In Federal Register, 14 CFR Parts II and 150, Dec. 1984.

Publication of this paper sponsored by Committee on Transportation-Related Noise and Vibration.

A Disaggregate Noise Interference Model for Estimating Airport Noise Impact

ALBERT T. STODDARD III and GORDON P. FISHER

ABSTRACT

Airport noise is a major problem facing the air transport industry. The noise intrusion on nearby communities not only leads to hard feelings but has also resulted in court action, forcing airport operators to pay large sums and to alter airport operations. To evaluate noise mitigation measures, a means of estimating the change in impact that will occur because of this mitigation measure is required. However, existing measures of airport noise impact are inadequate. Presented in this paper is a new, improved method of measuring noise impact and of estimating the changes that will result from noise mitigation efforts. Previous methods have been based on the notion of human annoyance. However, noise per se is not annoying; rather, it becomes annoying when it interferes with human activities. Therefore, this study bases the prediction of noise impact on activity interference. Because of the large random element in individual response to aircraft noise, residential interference is estimated by using a probabilistic model. A residential model is developed from the concept of household loss of utility due to increased noise. Comparisons of aggregate predictions show the model that was calibrated by using disaggregate data to be more reliable in predicting total impact than were other models.

One of the most important problems facing the air transport industry today is the disturbance of people by aircraft noise in the vicinity of airports. Several means of quantifying and predicting the impact of noise have been proposed; however, none have been shown to be highly reliable. In this study, the problem is approached from a new standpoint, which has been shown by Stoddard (1) to be an improvement over other possible means of predicting impact. A mathematical relationship between residential activity interference and noise is developed based on microeconomic theory. A binary logit model, estimated by using disaggregate data, is proposed for predicting the noise impact that results from aircraft operations.

BASIS FOR THE MODEL

The interference of aircraft noise with residential activities is approached from the standpoint of the economic utility derived from a residence by a household or family unit. Lancaster (2) viewed goods as having no utility themselves; rather, the attributes represented by the good provide utility. In this view, household utility can be defined as a function of the utility provided by each of the attributes. Microeconomic theory holds that a household may be expected to maximize its utility, subject to some budget constraint. In selecting a residence, the household maximizes utility by considering all of the attributes; it pays a market price reflecting that utility. The problem may be constrained by assuming that, after a residence is chosen, income and prices remain constant as an increase in noise exposure is introduced. This assumption may be expected to hold only in the short run, until market conditions begin to reflect this change in the attributes of a residence. In the short run, then, the impact of noise is a change in the utility experienced by the household. It is not necessary to know the total utility of the household; rather, it is sufficient to know only the amount of change in that utility.

It is necessary to identify those attributes that may be affected by noise exposure. Quiet is one attribute that is directly affected. Rylander et al. (3) found that there is a strong relationship between social class and noise impact, social class being a combination of income group, residential neighborhood, occupation, family relationships, and other characteristics. As in Rylander's work, social class is often represented by income group. Socioeconomic characteristics other than social class do not show as strong a relationship. Other attributes of residential choice are not expected to change as a result of the noise intrusion. Thus, the utility function of interest contains two independent variables: the change in quiet and the social class of the household. The change in quiet may be estimated by measuring the noise intrusion and assuming that ambient noise levels do not change. The noise characteristics that must be accounted for are noise level, frequency distribution, and number of events. The average of single-event sound exposure levels (SELs) is used to represent the noise because the measure incorporates noise level, frequency components, and duration. Social class is represented by household income relative to the mean household income in the standard metropolitan statistical area (SMSA).

If a relationship between activity interference is known and change in utility can be estimated, then residential impact may be measured. Activity interference must be determined from the subjective responses of individuals, for example as reported by Tracor (4) and Rylander et al. (3). In these surveys, respondents indicated on a semantic scale which activities are disturbed by noise and what level of disturbance they experience. Interference may be said to occur when the value reported by a respondent is above a given threshold, or interference level, on the sematic scale. Interference therefore may be represented as a binary variable, occurring for respondents who report values above the threshold and not below. Griffiths and DeLauzun (5) reported that the variance in response is due as much to randomness as to other factors; therefore the utility function must include a random term. The random element is included because of sampling errors and incorrect model specification. Factors that have a causal relationship to noise interference but that are not included in the model also appear as random errors when the individual variance is examined. The probability of there being residential interference is equal to the probability of the observed utility being reduced by the introduction of noise.

A mathematical relationship for activity interference in terms of the utility function is needed. The form of the relationship now depends on assumptions about the distributions of the error terms. Griffiths and DeLauzun (5) could not reject, on the basis of their data, the hypothesis that noise annoyance distributions are normal. If it is assumed that the distributions are multivariate normal, a probit model results; if the error terms are assumed to be independently and identically distributed in a Weibull distribution, the model takes the logit form (6-9). However, use of the logit model when the error terms are not Weibull distributed can give erroneous estimates of probabilities. Note that both Finney (7) and Daly (10) have found that there are not significant differences between the logit and probit models. Moreover, Daly states that a logit model is preferred, particularly because of convenience in estimation.

On the strength of these arguments, a logit model was used to represent the relationship between the change in utility due to noise and residential activity interference. The binary form of the model then is

$$P(I) = 1/(1 + e^{-U})$$

where $P(I)$ is the probability of interference and U is a function representing a change in utility.

Data for estimating this function were obtained from the Tracor study, which contains information on activity interference, socioeconomic characteristics, and noise levels (4). This study differs from others in that it addressed activity interference rather than general annoyance, an important distinction.

For this study, Boston was chosen as the source of data in developing a model of activity interference. It is a Phase II city in the Tracor data set, comprising 1,166 respondents. The Logan International Airport Office of Noise Abatement worked to decrease the noise impact during the period from 1976 to 1980 and kept records of those efforts. The intention to use the proposed model in a case study made it desirable to estimate the coefficients of the model for the city selected for the case study. Boston provided the best possibility because it was surveyed as part of the Tracor study and records were available about operational changes directed at noise impact reduction. Problems associated with the transferability of model parameters between cities are thus avoided and only the problems of temporal transferability need be accounted for.

DEVELOPMENT AND TESTING OF THE MODEL

Residential Activities

A review of the literature and the foregoing remarks on nonresidential activity interference make clear that some activities are much more likely to suffer interference from aircraft noise than are others. The more susceptible activities involve some form of auditory communication, for example, speech or audio transmission. The Tracor study identified 13 separate activities and asked respondents if they were ever disturbed by aircraft noise while engaged in these activities and, if so, how much they were bothered. The response to how much bother occurred was based on a semantic scale ranging from "not bothered at all" to "extremely bothered", represented numerically from 0 to 4.

The 13 activities addressed in the Tracor questionnaire were:

1. Relaxing or resting inside,
2. Relaxing or resting outside,
3. Young children sleeping,
4. Conversation,*
5. Telephone conversation,*
6. Going to sleep,
7. Listening to records or tapes,*
8. Listening to radio or television,*
9. Watching television,*
10. Reading or concentrating,
11. Late sleep,
12. Eating, and
13. Other activities.

Those activities denoted by * were considered to be those most susceptible to noise interference.

Statistical Tests

Four statistical tests were used to assess the quality of the mathematical relationship between activity interference and noise intrusion. The first test was the likelihood-ratio test evaluated for the prior probabilities, which gives an indication of the statistical significance of the model. The second test was the likelihood-ratio index suggested by McFadden (11), which indicates the goodness of fit of the model. The predictive success index, also suggested by McFadden, was used to show how well the model predicted the proper outcome. The final test was a t-test on the coefficient of each independent variable to determine the significance of that variable in the model.

Independent Variables

The explanatory variables used in the interference model initially were the average SEL per event, the number of noise events, and the social class of the respondents. It was necessary to estimate the values of each.

In the Tracor data set, noise is reported as the peak perceived noise level (PNL). However, this form was not suitable for the present purpose and had to be converted into SEL. SEL was calculated by converting peak PNL to peak dBA sound level and then estimating SEL. The average SEL value used as the variable in the model was obtained by taking the weighted average of the SEL values of all aircraft types for both arrivals and departures.

The numbers of flights for the major aircraft types are reported in the Tracor data. Flights, identified as arrivals or departures on different runways, are those that may be heard at the location of the residence. They are also broken down into day and night flights. The variable used in the model is the number of operations that would be discernible at the residence location during the time period being modeled.

It is now necessary to address the variable social class, which is represented here by income group of the respondent, as reported in the Tracor survey. The model was initially estimated by segmenting the data set by income groups and estimating separate models for each group. The income groups were determined by the ratio of income to the mean income of the community; mean annual household income for Boston in 1970 was $10,400 (12). Three groupings were selected for model development: 0 to $3,999, $4,000 to $10,000, and more than $10,000. These groupings were selected because they were combinations of the groupings in the data and could be related to the local mean income. The mean income for the neighborhoods surveyed was below that of the SMSA; approximately 30 percent of the respondents were above the $10,000 income level.

Other socioeconomic variables were investigated to determine their suitability for use in the model. Home ownership was considered because it has a relationship to social class and might have a relationship to noise interference. For example, those who own homes have a vested interest in the community and in their property and thus would be concerned if they perceived an intrusion by aircraft noise. Renters, however, are much more free to move to other locations if they are bothered and are less likely to be concerned than owners about possible decrease in property value resulting from noise.

It may also be important to consider air conditioning because the amount of externally generated noise that is perceived inside a house is masked by air conditioning noise and attenuated by closed windows. Households with air conditioning consequently could be expected to be less affected by noise than those without air conditioning.

Education level serves as another possible surrogate for social class and is highly correlated with income. Cost of housing also is a measure of social status and reflects the nature of the particular neighborhood. Those who are willing to pay more for housing would be expected to value a quiet neighborhood more than those who pay less. This variable includes rent payments and equivalent market rents for homeowners.

Age is another possible variable to use in the model. Although no other researchers have found a strong relationship between age and noise interference, it appeared useful to examine it. The shortcoming in using age as a variable is that, as people become more appreciative of quiet in older age, they also suffer the effects of hearing loss due to long-term noise exposure (13,14).

The final socioeconomic characteristic considered for inclusion in the model was duration of residence in the neighborhood. There is some suggestion that persons who have resided in a neighborhood with a high noise level for a long time are those who are least bothered. Some may learn to live with the noise, whereas others, who are more disturbed by the noise, tend to move away over extended periods of time. Independently, noise intrusion may not be sufficient to prompt people to move, but may be one factor that spurs the move.

To determine the best variable for inclusion in the model from among these possibilities, a stepwise estimation procedure was used that added the most significant variable at each step until all significant variables were included. Of the possible variables, the only ones significant at the 95 percent level were noise level, number of flights, and home ownership. The parameters were estimated for the three major income groups and the results are given in Table 1. Note that the model for the lowest income group does not meet even the weak likelihood-ratio test. The other two income-group models, while markedly better, are not satisfactory when tested by using the likelihood-ratio index and the success index. For those in the lowest income group, there apparently are significant factors other than the characteristics of the noise itself that influence the amount of interference that occurs.

TABLE 1 Statistical Tests of Parameter Estimation by Income Grouping

Income Group ($)	χ^2	ρ^2	σ
0 to 3,999	4.92	0.026	0.068
4,000 to 9,999	13.02	0.051	0.241
More than 10,000	39.89	0.088	0.347

Note: χ^2 (2,0.5) = 5.99.

Dependent Variable

A summation of the reported degrees of disturbance of various activities might be taken to give more weight to those extremely disturbed in many activities than to those only moderately disturbed in a few activities. Conversely, it is also possible to count persons who report any disturbance in any activity (for example, in specific activities such as conversing or watching television) more heavily than those who are highly disturbed in many activities. That is to say, small amounts of disturbance in a small number of activities may be more important. In selecting a dependent variable, therefore, several possibilities exist.

Rather than counting interference on the basis of representative activities, all responses to level of disturbance for all activities were summed. Different discrimination points were tested along with different activities variously weighted. It is realized that the selection of a discrimination point is arbitrary, so it was tested as part of the final estimation to determine the sensitivity of the point at which interference is defined to occur.

Utility Function

It was decided to test two different forms of the utility function in developing the model, a linear form and a log-linear form. The linear function was chosen because it is commonly used and is a simple form. The log-linear form was tested because previous researchers have used the logarithm of flights, as in the day-night average sound level (Ldn). The form exhibiting the strongest relationship to the data would be used in the final model.

Time-of-Day Weighting

An important issue related to noise impact is time-of-day weighting. It has been pointed out that weightings currently in use are based on some arbitrary assumptions and that research findings have since refuted the validity of those assumptions (15-19). The Tracor data on Boston show that people who report disturbance are most likely to report awareness of aircraft in the evening. It is possible that this evening disturbance occurs because more flights take place during this time period, or more people are at home then, or people are engaged in activities that are more likely to be disturbed by noise.

The operations at Logan International Airport were checked to determine the number of operations

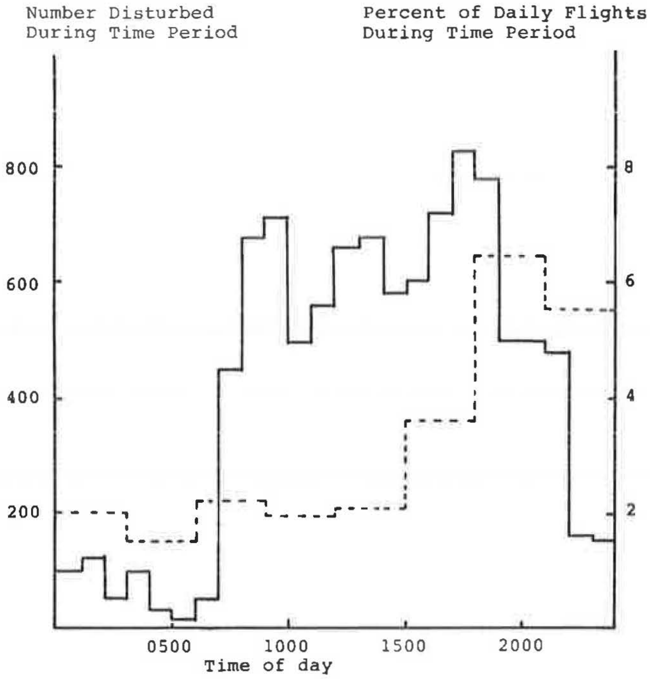


FIGURE 1 Comparison of number of flights and level of disturbance.

during the evening time period. Figure 1 shows the proportion of population disturbed each time period and the number of aircraft operations taking place during each hour of the day. Slightly more than one quarter of the daily flights occurred during the 6-hour period from 6:00 p.m. to midnight, the time period that differed significantly in the portion of the population disturbed. Approximately 80 percent reported some disturbance during the evening and only about 20 percent during other time periods. While the most aircraft activity occurred during the 3 hours preceding 6 p.m., the level of disturbance was only slightly higher than during other time periods. The evening period for many families generally is a time for more quiet activities that are sensitive to noise; it is the prime viewing period for television, the time for reading, and the time when families may gather for supper and conversation. It is also the time period when most people have returned home from their places of employment.

The principal reasons for the increased level of disturbance during the evening are the presence of more people and greater participation in noise-sensitive activities. It is important to note that level of disturbance during the night is no higher than level of disturbance during the day, contrary to night-weighting schemes such as Ldn. In view of these findings, two general models were adopted, one for the day and evening periods and another for the night period.

RESULTS

With the general forms of the models established, it was necessary to define more fully the dependent and independent variables and the associated utility functions.

The statistical weakness of the disaggregate models called for further testing. Although the logit formulation itself did not exhibit a strong statistical relationship, the models would be of value if it could be shown that the relationship was stronger than in previous formulations. The approach was to compare the model with a similar model that was estimated by using aggregated data and then to make comparisons of the total levels of interference predicted by various models with that interference reported in the survey data.

The two interference models that exhibited the best characteristics are shown in Table 2. The parameters are the coefficients for a linear utility function in the logit model. Because the statistical tests of the model were not definitive, the parameters were also estimated by using linear least-squares on the transformed function. The data were aggregated by noise level in SEL for the estimation. The model using the aggregate estimation procedure had an R-square value of 0.92 for the transformed function. The correlation between the predictive results of the disaggregate and the aggregate models was 0.92.

TABLE 2 Parameter Values for Estimation of Final Model

	Day-Evening		Night	
		t		t
Constant	-9.01917	-8.44	-8.69396	-6.22
SELAVG	0.07662	-6.48	0.05786	3.81
Flights	0.02605	4.91	0.16114	4.26
Owner	0.28929	2.42	0.28165	2.29

Note: $t_{\alpha} = 0.05 = 1.96$.

Aggregate predictions were made by using the disaggregate model; the results were compared with the aggregate impact reported in the data because although the disaggregate model did not meet all statistical tests, the predictions were highly correlated with those of a model that was estimated by using aggregated data. The model using aggregate data was able to meet relevant statistical tests. Moreover, the closeness with which the model was able to replicate the impact on the survey sample would indicate the usefulness of the model.

Two predictive tests were performed, the results of which are given in Table 3. The same approach was used for each test, although the first test used data only from Boston, whereas the second test used survey data from cities other than Boston. Two different cases were explored as part of each test; these cases differed in that the survey data was first considered as a population to be modeled and then as a representative sample of the population.

First Test

In the first case of the first test, the survey sample was assumed to be the affected population. The actual number of persons experiencing interference was compared with the number predicted by using the model with data for each census tract. The prediction was made by calculating the probability of interference for homeowners and renters and multiplying these figures by the number of each. The two groups were then added to determine the total number of people affected. During the evening period from 6:00 p.m. to midnight, the actual number of persons experiencing interference was 403 whereas the model predicted that 380 persons would be af-

TABLE 3 Comparison of Predictions Using the Model and Survey Data: Number of Persons Predicted To Be Disturbed

	Boston		New York		Miami	
	Survey	Model	Survey	Model	Survey	Model
Case 1 (Comparison to Number in Survey)						
Day	259	281	323	266	98	111
Evening	403	380	560	504	114	146
Night	145	126	202	165	135	88
Case 2 (Predictions for Population)						
Day	53,000	68,600	110,700	92,100	33,600	40,800
Evening	87,000	96,600	201,900	198,900	43,400	63,600
Night	27,700	34,600	64,300	69,900	53,600	35,800

fected, a difference of less than 6 percent. The number of persons experiencing interference during the day was estimated by taking the proportion of the residential population present during the day and the number of flights occurring during the period from 7:00 a.m. to 6:00 p.m., and by using the model that had been estimated for the evening period. Based on the data, 259 persons experienced interference whereas the model predicted that 281 persons would be affected, a difference of 8 percent. An attempt was made to make a similar prediction for the night period, but the model greatly overpredicted the number of people affected. As has been noted, Ollerhead (18) reported that people are less sensitive to noise when sleeping than when engaged in wakeful activities; therefore, a separate model was estimated for the entire population by using reported night interference. The prediction was that 126 persons would be disturbed during the night compared with the actual number reported, which was 145.

The second case of the first test considered the survey data as a sample of the population in the area; for each census tract the proportion of the sample experiencing interference was used to estimate the number of residents who were disturbed. The model was used to estimate the interference by using the same population figures; these population data were taken from the 1970 census for the census tracts included in the survey (20). In this case, the numbers of owners and renters were determined by using the average occupancy for owner-occupied housing units and the number of those units in each census tract.

The impact was estimated only for those tracts having survey data and not for the entire area around the airport. Based on the survey, the number of persons affected during the evening is 87,000 whereas the model predicted 96,600 persons, a difference of 11 percent. Although the difference is greater in this case than in the first case, one would expect a survey to contain sampling errors. The 95 percent confidence interval for the prediction based on the survey data is from 21,900 to 152,200. The sample of 1,166 persons is less than 0.5 percent of the total population of 335,524. The same tests were performed for the day and night periods. For the night period, the prediction based on the survey was 27,700 with a 95 percent confidence interval from 0 to 70,000 whereas the model predicted 34,600. By using the model, the number of persons disturbed during the day was estimated to be 68,600 whereas by using the survey data the number was 53,000, with a 95 percent confidence interval from 0 to 106,200. In every case, the model results were well within the confidence interval of the prediction based on the findings of the survey.

Second Test

A second test was made using the model and data from both New York City and Miami. As in the first case of the first test, the survey was treated as a complete population. Based on the data, the period impact during the evening in New York City was 560 persons whereas the model predicted that 504 persons would be affected, a difference of 10 percent. The other results of using New York City data were comparable to the findings obtained from using the Boston data. However, the results obtained by using the Miami data were not as good as those of the other two cities. In each time period, the difference between the survey results and the model prediction was greatest for Miami. Interestingly, the night period exhibited the highest reported level of impact for Miami, directly opposite from the results of the other two cities and not the results that one would expect. Thus, the noise sensitivity of residents around the Miami airport appears to be higher at night than during any other time period; this raises questions about the transferability of the model to all cities, although the model may be transferable in some cases, as exhibited by the New York results. However, even though the results are significantly worse for Miami, the model predictions are still within the 95 percent confidence interval of the survey predictions.

The sensitivity of the model to selecting a point on the summation of the semantic scale responses was tested. The definition of the occurrence of interference was adjusted up and down from the original point of 20 out of a possible 50. The model parameters were estimated by using the new definitions of interference and were tested. This alteration, however, did not change the model's statistical significance. The original definition was retained because it was based on a reasonable amount of interference being reported before an observation was counted as experiencing interference.

The model was also compared with some of the impact models that have been proposed by others. The models used for comparison were the one developed by Schultz (21), the one used in ALAMO (22), and the one developed by Hall (23). All three of these models are based on noise exposure measured in Ldn and are full-day models. Each predicts the percentage of the population that will be highly annoyed.

Schultz's model was published first and was developed by using both traffic and aircraft noise. It is estimated strictly on aggregate data by using the proportion of the population highly annoyed at each noise exposure level. Because this model is a function of Ldn, it is a full-day model incorporating a weighting for the night period. Using this model, one can derive the prediction for Boston:

53,700 persons. This function predicts a much lower figure than is obtained from the data or by using the estimated disaggregate model. A major reason for this difference is that Schultz considered only those persons who responded at the upper end of this scale when asked a question about how much they were annoyed by noise. The model and the Tracor survey address activity interference that is expected to occur before an individual becomes highly annoyed. Kryter's criticism of Schultz's work suggests that the function predicts values that are too low for aircraft noise (12).

The noise annoyance function used in the ALAMO model developed by NASA is a transformation of Schultz's function. The function is normalized to unity at 75 Ldn. However, the use of 75 Ldn to yield 100 percent of the population is arbitrary and may be expected to overpredict the number of people highly annoyed at all but the lowest levels of exposure. This is indeed the case when comparing the noise weighting function in ALAMO with the model that has been developed here. The prediction using the ALAMO function is that 145,900 persons will be highly annoyed. This prediction is substantially higher than the one based on activity interference, although activity interference generally occurs before someone becomes highly annoyed. Those persons exposed to levels higher than 75 Ldn are weighted by a factor greater than 1 when actually indications are that a certain proportion are not annoyed at high exposure levels.

The function developed by Hall is similar to the other two in that it predicts the percentage of the population that is highly annoyed as a function of exposure in Ldn. This function, like the ALAMO function, predicts numbers of persons highly annoyed well above the number predicted as experiencing activity interference. The value predicted in the Boston test case was 147,400 highly annoyed persons.

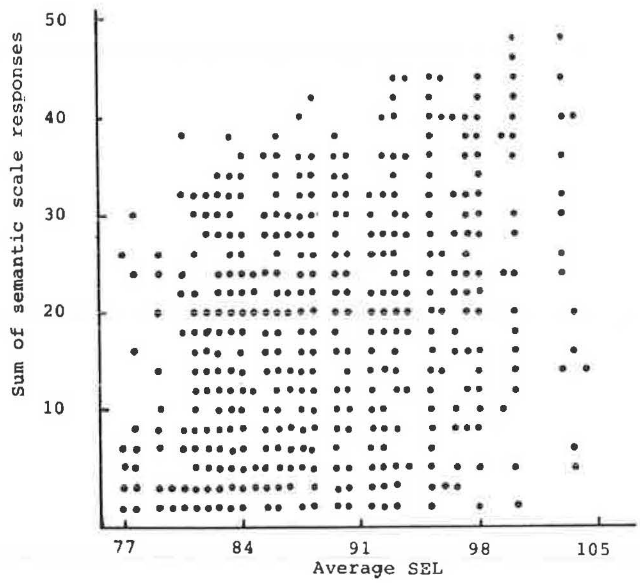
The large discrepancies between the models all purporting to predict the percentage of population highly annoyed indicates the poor basis for these models. Because substantial interference may take place before a person is highly annoyed, using a measure of persons highly annoyed as an indication of impact misses a large portion of the actual impact that occurs in the form of interference with home activities. On the other hand, it is argued by some that the number of persons annoyed that are not included in the prediction (which is based on the number highly annoyed) is proportional to the share included, so that the models are of value in estimating impact. The rationale for this argument is the relative stability of aggregate proportions of respondents reporting annoyance at the various levels. A better argument can be made for a negative correlation between the various degrees of annoyance because each respondent is limited to a single response. The theoretical basis for the functions is weak in that impact occurs with interference and annoyance is a reaction to or manifestation of that interference.

The disaggregate model was selected for use in predicting residential impact. This model meets several statistical tests and the results are highly correlated with those of the aggregate model. The disaggregate model prediction compares favorably both to the data as a population and to the prediction based on the data as a sample.

Individual Variance

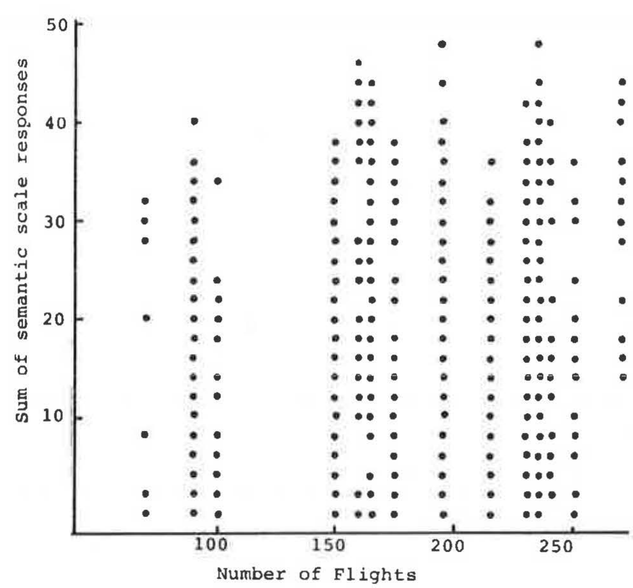
The difficulty in obtaining a good model fit is best explained by observing plots of the summed responses to degree of disturbance against the independent variables of noise level and number of flights. Figures 2 and 3 show individual responses. Although a trend is present and meets statistical tests for significant variables, it is clear that the individual variance in response is too large to be accounted for in the model. Griffiths and DeLauzun (5) reported the apparent randomness in response, noting that the individual variance was due as much to randomness as to any characteristics of the individuals.

It was this randomness that led to the use of a logit model in this research, but it is apparent that the random element is of such magnitude that a logit formulation is unable to account for all of it. It is likely that this randomness could be reduced by the use of independent variables similar to



Note: Each point may represent more than one observation.

FIGURE 2 Sum of semantic scale response versus average sound exposure level (SEL), excluding supersensitive respondents.

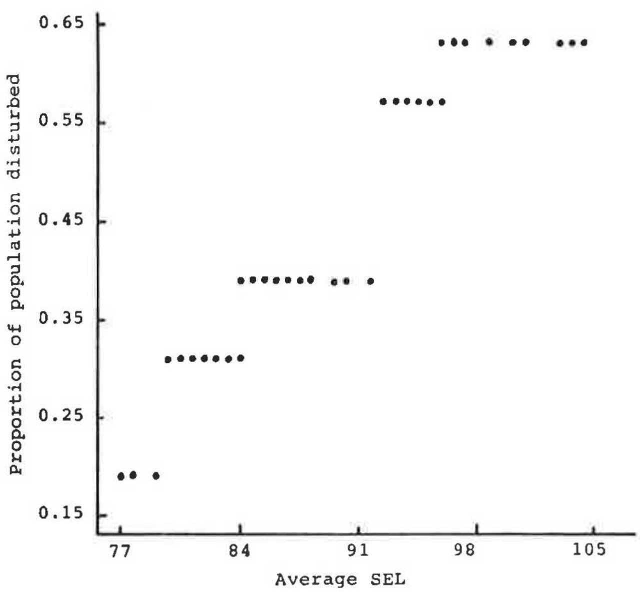


Note: Each point may represent more than one observation.

FIGURE 3 Sum of semantic scale responses versus number of flights, excluding supersensitive respondents.

those used in the Tracor report. These variables included personality traits such as fear of aircraft crashing, susceptibility to noise, noise adaptability, and belief in misfeasance on the part of the airport operator. Because these variables are combinations of subjective responses, it is impossible to estimate these variables for any population without conducting a survey. There is no advantage in using a model if a new survey is required for every use.

It was initially hypothesized that the incorporation of socioeconomic characteristics would allow the development of a model that would reduce the random element to an acceptable level. This hypothesis was rejected, but it was found that the random effects are significantly reduced during aggregation; for that reason the aggregate predictions are reasonably good. The effects of aggregating the data are shown in Figure 4, and a trend is evident after the loss of most individual variance. It is significant to note that a disaggregate model by itself will not provide a good fit, but some aggregation must take place to reduce the individual variance. This finding holds with that of Hall and Taylor (24), who reported that reliability for individuals being resurveyed about noise annoyance was very poor, but that the aggregate percentages of persons annoyed were very reliable.



Note: Each point represents multiple observations.

FIGURE 4 Proportion of population disturbed by aircraft noise at various sound levels (SEL).

Residential Impact Prediction

The model that has been developed predicts the probability of interference occurring for a particular average SEL and number of flights based on home ownership. The probability of interference occurring is multiplied by the number of people in the same situation to determine the number of people affected. To estimate the actual impact, the amount of time that this interference occurs must be incorporated. This calculation is made by taking the TA75--the amount of time that the level 75 dBA is exceeded during each time period (day, evening, and night)--and multiplying it by the number of people affected during each period. The basis for selecting the TA75 has been described elsewhere (1). In the Boston test case mentioned previously, the impact was estimated to be 39,800 person-hours/day. The same calculation using the survey data as a population sample estimates the impact to be 44,500 person-hours/day. The total number of person-hours for all impacted census tracts and time periods is the measure of the residential impact from the airport noise.

SUMMARY

The methodology for developing a model of residential activity impact due to aircraft noise has been described. The model is based on the concept of the loss of utility to a household as a result of a change in the attributes of the residential location. The primary residential attribute affected by aircraft noise is quiet in the neighborhood.

Based on economic theory, a mathematical relationship for activity interference in terms of the utility function was developed. The form of that relationship was a logit model that includes a random element, an important consideration in modeling airport noise impact. The data used for calibration of the model were described and the procedures used in developing the model were explained. Socioeconomic characteristics of the survey sample were explored to determine significant relationships between these characteristics and noise interference; the only characteristic that was found to be significant was home ownership.

Because the individual variance in response to aircraft noise was so high, a disaggregate model that met all statistical tests could not be developed. A similar model estimated by using aggregate data was found to be statistically significant.

Total impact predictions were used to determine the usefulness of the model in predicting impact. The model was able to provide predictions within 10 percent of that reported in survey data. The interference model predictions were also compared with the predictions of other impact models based on annoyance and were found to be more reliable. The procedure for calculating the residential impact using the interference model was described and an example provided. The model of residential noise interference is more reliable than other procedures that have been developed in the past. It cannot, however, be used in any location without consideration of the characteristics of the community being analyzed and the possible need for recalibrating the model parameters.

REFERENCES

1. A. Stoddard. Airport Noise Impact Prediction and Measurement. Ph.D. dissertation. Cornell University, Ithaca, N.Y., 1984.
2. K. Lancaster. A New Approach to Consumer Theory. Journal of Political Economy, 74, 1966, pp. 132-157.
3. R. Rylander et al. Annoyance Reactions from Aircraft Noise Exposure. Journal of Sound and Vibration, 24, 1972, pp. 419-444.
4. Tracor, Inc. Community Response to Aircraft Noise. Report NASA CR-1769. National Aeronautics and Space Administration, Washington, D.C., 1971.
5. I. Griffiths and F. DeLauzun. Individual Differences in Sensitivity to Traffic Noise: An Empirical Study. Journal of Sound and Vibration, 55, 1977, pp. 93-107.
6. C. Daganzo. Multinomial Probit. Academic Press, New York, 1979.
7. D. Finney. Probit Analysis. University Press, Cambridge, Mass., 1971.

8. P. Stopher and A. Meyburg. Behavioral Travel-Demand Models. In Behavioral Travel-Demand Models (P. Stopher and A. Meyburg, eds.), Lexington Books, Lexington, Mass., 1976, pp. 3-53.
9. Survey Sampling and Multivariate Analysis for Social Scientists and Engineers. Lexington Books, Lexington, Mass., 1979.
10. A. Daly. Some Issues in the Application of Disaggregate Choice Models. In New Horizons in Travel-Behavior Research (P. Stopher, A. Meyburg, and W. Brog, eds.), Lexington Books, Lexington, Mass., 1981, pp. 55-72.
11. D. McFadden. Quantitative Methods for Analysing Travel Behavior of Individuals: Some Recent Developments. In Behavioral Travel Modelling (D. Hensher and P. Stopher, eds.), Croom Helm, London, 1979.
12. U.S. Bureau of the Census. 1970 Census of Population and Housing. Washington, D.C., 1972.
13. A. Harris et al. A Guidance Document on Airport Noise Control. Report FAA-EE-80-37. Federal Aviation Administration, U.S. Department of Transportation, 1980.
14. K. Kryter. The Effects of Noise on Man. Academic Press, New York, 1970.
15. R. Bullen and A. Hede. Time-of-Day Corrections in Measures of Aircraft Noise Exposure. Journal of the Acoustical Society of America, 73, 1983, pp. 1624-1630.
16. S. Fidell and G. Jones. Effects of Cessation of Late-Night Flights on an Airport Community. Journal of Sound and Vibration, 42, 1975, pp. 411-427.
17. S. Fidell et al. Community Sensitivity to Changes in Aircraft Noise Exposure. NASA CR-3490, National Aeronautics and Space Administration, Washington, D.C., 1981.
18. J. Ollerhead. Variation of Community Response to Aircraft Noise with Time of Day. Noise Control Engineering, 11, 1978, p. 68.
19. P. Schomer. Time of Day Noise Adjustments or "Penalties". Journal of the Acoustical Society of America, 73, 1983, pp. 546-555.
20. U.S. Bureau of the Census. 1980 Census of Population and Housing. Washington, D.C., 1983.
21. T. Schultz. Synthesis of Social Surveys on Noise Annoyance. Journal of the Acoustical Society of America, 64, 1978, pp. 377-405.
22. R. DeLoach. An Airport Community Noise-Impact Assessment Model. NASA TM-80198. National Aeronautics and Space Administration, Washington, D.C., 1980.
23. F. Hall et al. Direct Comparison of Community Response to Road Traffic Noise and Aircraft Noise. Journal of the Acoustical Society of America, 70, 1981, pp. 1690-1698.
24. F. Hall and S. Taylor. Reliability of Social Survey Data on Noise Effects. Journal of the Acoustical Society of America, 72, 1982, pp. 1212-1221.

Publication of this paper sponsored by Committee on Transportation-Related Noise and Vibration.

Design of Acoustical Insulation for Existing Residences in the Vicinity of San Jose Municipal Airport

C. MICHAEL HOGAN and JORGEN RAVNKILDE

ABSTRACT

The vicinity of the San Jose Municipal Airport includes a large number of residences that lie in land-use zones that are acoustically incompatible with California state requirements. Analyzed in the current study was a sample of 10 residences of various ages, locations, and structure types within this incompatible residential class. Retrofit designs were developed for each structure to reduce interior sound levels, based on simultaneous indoor-outdoor sound level measurements and on architectural acoustical analysis of the structure. Follow-up sound level measurements were conducted to establish the success of original acoustical predictions for interior sound levels.

The location of the San Jose Airport has many advantages for providing commercial and general aviation services to the San Jose metropolitan area. In the midst of the urban area, the airport is convenient to major economic and employment centers in Santa Clara County and industrial areas in San Jose, Santa Clara, and Sunnyvale as well as the San Jose downtown core area, and is a significant attraction to private investment and development in these centers. The airport is also centrally located for the population in the south San Francisco Bay area, the area that provides the bulk of the airport's users.

However, the central location of the airport, surrounded by urban development, also involves impacts that extend beyond its boundaries. The noise produced by aircraft affects the living environment close to the airport.

STATEMENT OF PURPOSE OF THE AIRPORT VICINITY PLAN

The purpose of the Airport Vicinity Plan of July 15, 1980, is the achievement and maintenance of compatibility between the airport and its environs through 1997, the planning horizon of the Airport Development Plan. Specifically, the objective of the plan is to establish a realistic program that

- Permits persons who live, work, and own property near the airport to enjoy a maximum amount of freedom from noise and other impacts generated by the operation of the airport
- Recognizes the vital service provided by the airport and the need to maintain the level of operations necessary to satisfy existing and future aviation requirements of the community
- Protects the public investment in the airport, a facility for which there is no feasible replacement
- Complies with airport noise standards mandated by the state of California
- Complies with the operational and safety requirements of the Federal Aviation Administration (FAA), U.S. Department of Transportation regulations

BACKGROUND

Study Area

The boundaries of the study area for the purposes of noise compatibility planning are an approximation of the projected 65 community noise equivalent level (CNEL) contour for the year 1997, developed as part of the Airport Master Plan Study. The projected contours are based on the following:

- A projected aircraft mix, and levels and hours of operations for air carrier aircraft
- Typical flight paths and aircraft departure profiles (i.e., gross takeoff weight) in current operations and assumed arrival profiles, each of which varies by type of aircraft
- The assumption that all air carrier aircraft will be new models or will be retrofitted to comply with the noise emission requirements of Federal Aviation Regulations (FAR) Part 36: Noise Certification

The study area is characterized by a diversity of land uses. Commercial uses include neighborhood retail outlets and major regional centers, including downtown San Jose and the Great America Theme Park. Industrial land uses include small, older establishments such as machine and welding shops as well as large, modern facilities devoted to electronics manufacture and research and development. Public and quasi-public uses include neighborhood schools and churches as well as regional facilities such as Agnews State Hospital and the City of San Jose, County of Santa Clara Civic Center. Residential land uses include single family, duplex, townhouse, and multifamily dwellings, ranging in age from recently constructed to over 50 years old.

Noise

A substantial body of scientific evidence documents the effects of very high levels of noise on human health and well being, both physical and psychological. There is also documentation of the effects of noise on level of annoyance and interference with daily living. The problem is particularly serious in urban areas surrounding major metropolitan airports, such as San Jose Airport, where the arrival and departure of jet aircraft cause noise impacts in the airport environs.

The response to the problem of airport-related noise is twofold: (a) reduction of noise at its source and (b) resolving or preventing land-use incompatibilities around the airport. It is the latter approach that is addressed in the Santa Clara County Airport Land Use Commission's Land Use Plan for Area Surrounding Santa Clara County Airports (1).

California State Noise Law

The choice of 65 CNEL as the boundary for the vicinity is based primarily on the provisions of the California Airport Noise Standards. These noise standards require that by January 1, 1986, all land uses around airports that are subject to noise levels of 65 CNEL or above be compatible with the noise environment generated by airport operations. Schools and residential land uses are defined as usually incompatible with airport noise above 65 CNEL. However, these uses are compatible under the following circumstances:

- Subject to an avigation easement for noise
- Highrise apartments with acoustical treatment to achieve maximum interior noise level of 45 CNEL
- Any existing residential unit subject to noise levels of 65 to 80 CNEL as long as acoustical treatment of the structure provides an interior noise level that does not exceed 45 CNEL

Commercial, industrial, agricultural, and other open-space uses are deemed compatible with airport noise.

Federal and California Sound Level Standards

The California Airport Noise Standards form the basis of the noise standards in this Vicinity Plan, in which the primary focus is on schools and residences. In the vicinity of San Jose Airport, the following noise compatibility standards will apply.

- Exterior noise levels below 65 CNEL are acceptable for any land use.
- Existing and new schools and residences are compatible with exterior noise levels of 65 to 76 CNEL if a maximum interior noise level of 45 CNEL is achieved through acoustical treatment.
- Schools and residences are not compatible with exterior noise levels in excess of 76 CNEL, regardless of interior noise levels.
- Existing commercial, industrial, and open space uses are compatible with noise levels in excess of 65 CNEL.

• New industrial and commercial uses are compatible with exterior noise levels in excess of 65 CNEL if a maximum interior noise level of 55 CNEL is achieved through acoustical treatment. A higher interior noise level is acceptable if it is demonstrated that the inherent noise characteristics of the particular use being proposed would exceed 55 CNEL irrespective of exterior noise levels.

The maximum exterior noise level for schools and residences is 76 CNEL because General Plan noise standards in both San Jose and Santa Clara identify this level as the maximum noise level in conformance with the U.S. Environmental Protection Agency hearing loss criteria. The allowance in the California Airport Noise Standards for exclusive reliance on avigation easements was not incorporated in the noise standards of this plan. While they may eliminate an airport's legal liability for noise resulting from aircraft overflight and may also serve as a consumer protection device for prospective purchasers of noise-impacted properties, avigation easements clearly do not provide actual relief from noise.

The noise criteria for interior spaces are based solely on a CNEL measurement rather than on a single-event criteria as has been adopted by the Land Use Commission of the Santa Clara County Airport. There are several reasons why single-event criteria were not used in this plan. First, the most restrictive single-event criteria are to protect the sleeping environment; yet current and projected aircraft operations during the time period from 11 p.m. to 7 a.m., the hours typically devoted to sleep, constitute a negligible portion of the total operations in a 24-hour day at San Jose Municipal Airport. Second, achieving compliance with single-event criteria is not at all practical. For remedial sound attenuation of existing school and residential structures, single-event criteria are virtually impossible to meet. For sound attenuation in new construction, single-event criteria can be achieved, but only with considerable additional expense. The intent of this plan was that standardized construction methods and materials could be identified to meet noise criteria rather than having to rely on sound meter testing in each project. Third, the air carrier aircraft of the future will be quieter than those presently in operation at San Jose Airport. With the likelihood that aircraft noise emissions will be reduced even below the requirements of FAR Part 36, it makes little practical sense to rely on the noise characteristics of aircraft from the period before FAR Part 36 to develop land-use compatibility criteria.

Finally, it should be noted that the noise standards in the Airport Vicinity Plan have been developed with practicality and other goals in mind rather than in an abstract, theoretical way. The choice of interior noise standards using CNEL rather than single-event ratings is one example of keeping noise in context, balancing protection from noise against other considerations. A second such example is using the 65-CNEL contour as the boundary of the vicinity. Aircraft noise does not cease to be a concern outside the 65-CNEL contour; rather, this noise contour defines the extent of the most critical impact area. The noise standards do not appear to take into account impacts on outdoor activities, often an integral component of the residential environment. Although the effects of noise on outdoor activities were not ignored, it was judged that the disadvantages in the vicinity for outdoor activities typically associated with residences are outweighed by the advantages of housing in the vicinity, including proximity to employment centers and the housing price advantage of some older neighborhoods.

NOISE INSULATION STUDY

Ten residences were selected so that diverse situations in the airport vicinity could be sampled. The final selection of the 10 residences for the pilot Noise Insulation Study reported in this paper was evaluated by using the following criteria:

• Spatial distribution around the San Jose Airport
• Location within the 1997 noise contours
• Location according to the main aircraft approach and take-off pattern
• Variety of building structures

The 10 residences selected, including a brief description of the structures, are presented in Table 1.

Five of the 10 homes are located northwest of the airport, 3 of the homes are located east of the airport, and 2 of the homes are located southwest of the airport. Five of the 10 homes are exposed to

TABLE 1 Final Selection of Residences in the Pilot Program

Residence No.	Subarea	City	Brief Description of Structure Before Soundproofing
1	2C	Santa Clara	Bitumen shingle roof; shingle-stucco exterior walls; double-hung and side-hung wood windows; single glass; wood paneled doors; no weather stripping; sheetrock ceilings; no insulation
2	2C	Santa Clara	Wood shake roof; stucco exterior walls; double-hung wood and aluminum slide windows; single glass; wood doors; no weather stripping; plasterboard ceilings; no insulation
3	3A	Santa Clara	Wood shake roof; stucco exterior walls; aluminum sliding windows and doors; single glass; main door—solid wood; weather stripping; sheetrock ceilings; 6 in. of insulation in attic
4	3B	Santa Clara	Asbestos shingle roof; stucco exterior walls, one wall wood siding; aluminum sliding windows; single glazing; entrance door—1.25-in. wood with ornament glass; no weather stripping; plasterboard ceiling; 1-in. insulation in attic
5	3B	Santa Clara	Wood shingle roof; stucco exterior walls; aluminum sliding windows and doors; single glazing; wood entrance door with glass; weather stripping; plasterboard ceiling; insulation in attic
6	4D	San Jose	Tarpaper roof; wood siding exterior walls; aluminum sliding windows and doors; single glass; wood door; no weather stripping; exposed beams on ceiling
7	4D	San Jose	Bitumen shingle roof; stucco exterior walls; aluminum double-hung windows; aluminum sliding door with single glazing; paneled wood doors; no weather stripping; plasterboard ceiling; 9-in. insulation in attic
8	4B	San Jose	Bitumen shingle roof; stucco exterior walls; double-hung wood windows; aluminum sliding door; wood exterior doors; minor weather stripping; plasterboard ceiling; no insulation
9	6B	San Jose	Wood shingle roof; stucco exterior walls; side-hung wood windows; single glass; paneled wood door; no weather stripping; plastered ceilings; 2- to 3-in. insulation in attic
10	6B	San Jose	Wood shingle roof; stucco exterior walls; double-hung wood, wood-framed-fixed and aluminum-framed-sliding windows; single glazing; paneled wood door; no weather stripping; plastered sheetrock ceilings; 6-in. insulation in attic

operational aircraft noise levels from 65 to 70 CNEL, and the remaining 5 homes are exposed to noise levels from 70 to 75 CNEL. The 10 homes represent a variety of common building structures, which are typical of residential structures in the vicinity of San Jose Airport.

Sound Reduction Measurements

The initial sound measuring program was performed during the week of January 19-23, 1982. The measurements were performed simultaneously indoors and outdoors for each residence, during a minimum time of 1 hr. The outdoor microphone was placed in front of that side of the residence facing the airport or the typical flight path. The microphone was located 6 ft above the ground and 6 ft from any object. The indoor microphone was located in a room (preferably a bedroom) with an exterior wall and a window facing the airport or the typical flight path. In two cases, the kitchen was selected as the interior microphone position because the bedrooms were located on the opposite side of the house.

Care was taken to ensure that all doors and windows were closed during the period of measurement, and that household appliances, ventilation, and heating systems were inoperable and would not affect the interior sound level. During the sound measurements, the dimensions of the house, doors, windows, and so forth were measured, and a description related to existing weather stripping, caulking, and insulation in exterior walls and attic was prepared. The sound insulation performances for each of the 10 structures were calculated and compared with the actual measured sound insulation. Table 2 presents the results of the measured and calculated sound insulation of the residences.

TABLE 2 Summary of Sound Measurements and Calculations

Residence No.	Measured Difference of Outdoor-to-Indoor dBA a (L10)	b (Leq)	Existing (calculated) STC c	d
1	17.2	17.5	11.7	17.7
2	16.5	17.0	15.0	17.0
3	17.5	17.3	18.2	20.3
4	18.0	14.7	17.0	19.5
5	16.8	16.2	17.0	19.5
6	14.0	14.1	11.7	15.4
7	19.0	19.2	16.5	19.0
8	13.2	13.2	13.0	12.6
9	19.0	23.3	14.0	20.0
10	16.7	13.8	15.0	17.0

Note: In Column a, L10 is the A-weighted sound level, which is exceeded 10 percent over the duration of the monitoring. In Column b, Leq is the A-weighted average sound level, which represents the average energy content of the sound rather than the average sound pressure level. In Column c, STC, sound transmission class, is the calculated average sound reduction of the house, including roof-ceiling, exterior walls, windows, and doors. In Column d, STC is the calculated sound reduction of the wall facing the airport or the flight pattern.

Two sets of calculations were performed for each residence. The first calculation considered the sound insulation of the total building envelope, (Table 2, Column c), and the second calculation took only the exterior wall facing the airport or the flight path, into consideration (Table 2, Column d). A relatively low calculated value of the building envelope indicates low insulation of the roof-ceiling assembly.

Recommendations of Proposed Improvements

As discussed previously, the purpose of the Noise Insulation Study was to demonstrate a cost-effective solution for reducing the interior noise level in residences. Therefore, the candidate improvements included accessible components, materials, and methods normally available on the market. Improvements that were acceptable to the homeowners and the building authorities and at the same time represented a reduction in energy consumption for house heating were installed.

Each residence was evaluated in a nondestructive way. Information about the design of exterior walls and the amount of thermal insulation was, in many cases, estimated based on information from the homeowner and possible visual inspection because detailed building plans did not exist. The current homeowner was often not the first owner of the residence, and thus the information was approximate. The attic space was not always accessible; therefore, the amount of insulation in the attic, in many cases, was estimated based on homeowner information. The quality of the residence, the maintenance condition, and possible air leaks around window and door frames were evaluated carefully.

Based on the above information and estimates, the sound insulation performance of each building component was adjusted according to the actual conditions in the residence. This adjustment required experience and knowledge of the sound insulation performance of the wide range of building materials and components, as well as of the changes in the characteristics of the sound reduction frequency range due to varying amounts of insulation in exterior walls and attics, air leaks around windows and doors, and the possibilities of other sound transmission paths.

The basic data for a wide range of building components are generated as laboratory measurements, which are available in reference literature. Many of these measurements are rated according to the sound transmission class (STC) reference contour, which yields a single number rating for the building component. There are, however, significant differences in the results of the sound insulation measurements between the laboratory measurements, which are performed under carefully controlled conditions, and the field measurements, which include all possible sound transmission paths. Differences of 3 to 5 dB for building components from the laboratory measurement to the field measurement are not uncommon, and additional differences due to other (multiple) transmission paths in the actual building structure are almost always present and must also be considered.

The adjusted STC values for the various building components were used for computing the existing sound insulation of each residence. The computations were performed as the composite transmission loss of the building structure or the partial building structure. Based on the sound reduction measurements of each residence, a correction factor for the calculation program was derived for each individual residence. This correction factor would take the following into consideration:

- Varying angles of incidence of the sound from the noise source (aircraft)
- The whole building envelope not being exposed to an equal level of sound energy because of directional characteristics of the sound
- Sound transmission paths that can not be corrected without major reconstruction of the residence

The correction factor for each individual residence was applied during the computations of the proposed improvements.

In most cases, it will be found that the windows in older residential structures often represent the highest transmission loss in the building structure. The exterior doors will often be the second-ranking components, closely followed by uninsulated attics. When energy-conserving aspects are included, the improvements of the insulation of the attic should initially be considered in the computations.

In one case, the residence featured a peaked open-beam ceiling and no insulation. An additional and insulated roof (constructed over the existing roof) was recommended. In the remaining cases, additional insulation to a minimum thickness of 5 in. was recommended. Standard, solid core doors with a perimeter seal and without a mail slot would provide a reduction in sound equivalent to 20 STC. All door and window frames should be sealed between the frame and exterior wall to prevent air leaks. The modifications for each home are described in Appendix B of Architectural Specifications for the Representative Residences (2). A summary of the proposed improvements is given in Table 3.

At this point it should be stressed that the Noise Insulation Study intends to include accessible standard components, materials, and methods, and to avoid recommendations of sophisticated and expensive measures. Acceptable recommendations include thermal insulation of a minimum thickness that can satisfy energy conservation requirements, and a maximum thickness limited by the space in the building component. Replacement of existing exterior windows, doors, and glazed areas with new doors, windows, and glazing each with a standard STC rating are also acceptable recommendations.

Sound Reduction Measurements After Improvements

The sound reduction measuring program of the 10 homes was performed during the week of July 11-15, 1983. The microphone positions used were exactly the same as initially installed in each residence. The results of the sound reduction measurements are presented in Table 4.

As stated previously, the goal of the Noise Insulation Study was to demonstrate that interior noise in residential structures can be reduced to or below 45 CNEL as required by the state of California by using cost-effective and energy-effective methods. In addition, the technical objective was to demonstrate that predictions of the interior sound level after improvements could be achieved by meeting a desired goal.

CONSTRUCTION PROBLEMS

The improvements of the residences were carried out by a contractor and craftsmen without previous special acoustical training and with commercially available materials and components. The improvements, however, demanded good craftsmanship and attention to details so that the improvements would be acoustically effective. The improvements were carried out in inhabitated residences.

The improvements of the homes were considered almost as remodeling of homes. Two major areas of concern were found during this project. First, planning of the work by one contractor in a small number of distinctively different homes distributed over a

TABLE 3 Summary of Proposed Improvements

Residence No.	Exterior CNEL in 1997	Roof Alterations	Windows Replaced	Doors Replaced (STC)	Predicted Sound Reduction (STC)	Predicted Indoor CNEL (dB)
1	71	More than 5-in. insulation	26	20	27	44
2	72	More than 6-in. insulation	26	20	27	45
3	67	None	26	20	25	42
4	73	More than 5-in. insulation	26	20	28	45
5	74	More than 5-in. insulation	26	20	28	46
6	69	Additional roof (insulated)	26	20	23	46
7	71	None	26	20	26	45
8	68	More than 4-in. insulation	26	20	23	45
9	67	More than 4-in. insulation	26	20	26	41
10	68	None	26	20	25	43

Note: Data are from Earth Metrics (1983).

TABLE 4 Results of Sound Reduction Measurements Related to 1997 CNEL

Residence No.	Exterior CNEL in 1997	Sound Calculated (dB)	Reduction Measured (dB)	Deviation from Calculated CNEL[a]	Interior CNEL in 1997
1	71	27	25	−2	46
2	72	27	29	+2	43
3	67	25	26	+1	41
4	73	28	29	+1	44
5	74	28	28	0	46
6	69	23	25	+2	44
7	71	26	27	+1	44
8	68	23	19	−4	49[b]
9	67	26	26	0	41
10	68	25	22	−3	46[c]

Note: Data are from Earth Metrics (1983).

[a]+ = more attenuation than designed; − = less attenuation than designed.

[b]Estimated 45 CNEL in bedroom.

[c]Estimated 43 CNEL in bedroom.

relatively large area appears to be very difficult. In inhabited residences, it is necessary to minimize the inconvenience to the homeowner by compressing the time of construction in each home. The work ideally should be executed continuously or should be executed by appointment to minimize disruptions to the family's routine. The second area of concern was that acoustical modifications involve unusual craftsmanship requirements and attention to details. Several of the homeowners had complained about planning procedures, failure to set up work appointments with homeowners, and failure to keep work appointments. For the continuation of the Noise Insulation Study, the following two measures are recommended.

• Each neighborhood should be subdivided into groups of residences of similar design and structures to aid in planning work and ordering materials.
• The acoustical modifications of residences should be performed on a large enough scale to utilize the services of a large contracting organization.

EVALUATION OF RESULTS

From a technical point of view, the Noise Insulation Study was very successful. A deviation of plus or minus 2 dB from the design goal is acceptable, given state-of-the-art data for acoustical performance of building components, realistic craftsmanship standards, and round-off effects. From this point of view, eight of the ten residences met the technical objective prediction range but two residences did not meet the design goal. From the standpoint of sound level standards, six of the residences achieved 45 CNEL or below, three residences achieved 46 CNEL, and one residence achieved 49 CNEL. The four residences that did not meet the 45 CNEL are discussed next.

In Residence No. 1, the interior sound level resulted in 46 CNEL. An examination of the windows revealed that the recommended weather stripping had not been installed, leaving airgaps around window sashes. The installation of the recommended weather stripping would have increased the sound insulation by 2 to 3 dB, thereby reducing CNEL to below 45.

In Residence No. 5, the interior sound level resulted in 46 CNEL, 1 dB above the design goal, but meeting the designed CNEL. A comparison was performed between Residence No. 5 and Residence No. 4. The two residences are almost identical acoustically, and the STC recommendations for the two residences are identical. Two different window types were installed. In Residence No. 4, the existing windows remained in place and additional interior storm windows, which according to Earth Metrics recommendations should provide 26 STC, were installed. In Residence No. 5, the existing windows were replaced by new aluminum sliding windows, which according to Earth Metrics recommendations should also provide 26 STC. The results of the sound measurements indicated that the installation of additional interior storm windows was a better solution than the replacement of the windows. Therefore, it appears that the windows installed in residence No. 5 did not provide the required 26 STC. Based on the comparison of these two residences, it is emphasized that only window and glass sliding-door components with documented sound reduction data should be used.

Moreover, the installation of additional storm windows in Residence No. 4 resulted in less expense than replacement of existing windows in Residence No. 5. This indicates that in the continuation of the Noise Simulation Study, actions to be considered are (a) selecting groups of residences of similar house type, (b) developing a noise remedy package that will meet the desired goal, and (c) offering this package to the homeowner.

In Residence No. 8, the interior sound level resulted in 49 CNEL, 4 dB above the design goal and 4 dB above the designed CNEL; the major cause was as follows. The outdoor patio is located along the exterior wall facing the airport. The roof over this patio is supported by posts along the outside edge and attached to a 2 x 4-in. wood plate, which is mounted to the exterior wall; this roof contains approximately 100 ft^2 of fiberglass material. Aircraft-generated vibrations of the patio roof are transmitted to the interior through the building structure, representing the major sound transmission path and limiting the installed sound insulation features. (The sound transmission path from the patio roof to the interior of the residence could be eliminated by detaching the patio roof from the building structure and supporting the roof on separate posts along the exterior wall.) Furthermore, the interior microphone was located in the kitchen, where the reverberation time normally is somewhat longer; this results in a slightly lower sound reduction because calculations of the interior sound level generated by exterior noise sources indicate variations in the interior sound level, depending on the reverberation time in the receiving room. Within a range from 0.8 sec (typical for kitchens) to 0.3 sec (typical for bedrooms), the sound level will vary 4 dB.

The location and orientation of Residence No. 10 did not leave many options for the positions of the exterior and interior microphones. To avoid the shielding effect of the adjacent residence, the exterior microphone was located outside the kitchen (Windows 6 and 7). Because all bedrooms were located on the opposite side of the residence (away from the flight path), only the kitchen could be used for the location of the interior microphone. As noted previously, reverberation time in kitchens is normally somewhat higher than in living rooms and bedrooms, which contain more absorbent materials such as carpeting and upholstered furniture. As a result, the interior sound level generated by exterior noise sources is 2 to 4 dB higher in kitchens than in living rooms and bedrooms. This matter has been discussed for Residence No. 8.

REFERENCES

1. Land Use Plan for Area Surrounding Santa Clara County, Santa Clara County Airport Land Use Commission, California.
2. Architectural Specifications for the Representative Residences. Earth Metrics, Inc., Burlingame, Calif., 1984, Appendix B.

Publication of this paper sponsored by Committee on Transportation-Related Noise and Vibration.

California Vehicle Noise Emission Levels

RUDOLF W. HENDRIKS

ABSTRACT

The Federal Aid Highway Program Manual (FHPM) 7-7-3 directs state highway agencies to analyze traffic noise impacts and abatement measures for federal and federal-aid highways. The directive requires noise prediction methods to be consistent with Federal Highway Administration (FHWA) RD-77-108 procedures, using either national reference energy mean emission levels as a function of speed or reference energy mean emission levels determined by methodologies described in the FHWA report Sound Procedures for Measuring Highway Noise (FHWA-DP-45-1R). The California Department of Transportation recognized the need for developing California vehicle noise reference energy mean emission levels. Criteria, methods, and analyses used to develop these emission levels are presented in this paper. More than 3,000 noise measurements were made of automobiles, medium trucks, and heavy trucks as defined in the FHWA report FHWA Highway Traffic Noise Prediction Model (FHWA-RD-77-108). The measurements, taken at 16 sites in California, included vehicles traveling at constant speeds from less than 25 mph to greater than 65 mph on level roads. Microphones were set up at 25-, 50-, and 100-ft distances and at heights of 5 and 10 ft. The results show automobile levels 0.8 to 1.0 dBA higher than national levels at 31 and 62 mph respectively (the current range of speeds for national levels). Medium and heavy trucks were less than 0.5 to about 3 dBA lower than national levels at 31 and 62 mph. Further analyses indicated that at 50 ft the effects of terrain type, wind speeds of 12 mph or less, and wind direction could be ignored without introducing errors of more than 1 dBA. The study also indicated that the three vehicle groups adequately represented the California vehicle population and that geographical differences could be ignored.

The noise abatement procedures for federal and federal-aid highway projects are governed by the Federal Aid Highway Program Manual (FHPM) 7-7-3 (1). This directive requires state highway agencies to determine and analyze expected traffic noise impacts and alternative noise abatement measures for mitigating these impacts.

As part of the traffic noise impact analysis under FHPM 7-7-3, prediction of future traffic noise is required. Any prediction method may be used to satisfy this requirement if it generally meets the following two conditions:

1. Consistency with the FHWA highway traffic noise prediction model [FHWA RD-77-108 (2)].
2. The prediction method uses either the national reference energy mean emission levels as a function of speed (1,2) or reference energy mean emission levels determined by the methodology described in the FHWA report Sound Procedures for Measuring Highway Noise [FHWA-DP-45-1R (3)].

Since 1978, the California Department of Transportation (Caltrans) has used the national reference energy mean emission levels as a function of speed. These noise emission levels were based on FHWA's Update of TSC Highway Traffic Noise Prediction Code [FHWA RD-77-19 (4)] (automobiles), and Statistical Analysis of FHWA Traffic Noise Data [RD-78-64 (5)], which presented statistical analyses on truck data gathered in the 1975 four-state noise inventory (6). Aside from California not being among the four states, it is reasonable to assume that vehicle noise emission levels may have changed since 1975. New truck noise emissions regulations have changed and compact energy-efficient automobiles have become more popular since the first energy crisis in 1973-1974. The need for a California vehicle noise emission study was therefore recognized.

A 1981 barrier evaluations study by the Office of Transportation Laboratory at Caltrans (7), which compared before-and-after barrier measured noise levels with those predicted by FHWA methods [FHWA-RD-77-108 (2)], concluded that the latter methods tended to predict values that were an average of 3 to 4 dBA higher than those measured at 11 barrier sites throughout California. The study recommended further investigation to examine the validity of using the national emission levels in California. The recommendation was followed up, and the results are presented in this paper.

The primary objective of this study was to develop California vehicle noise reference energy mean emission levels within a speed range of 25 to 65 mph for use in California highway noise studies complying with the FHPM 7-7-3 requirements. The methods and criteria used to accomplish the primary objective are consistent with FHWA-DP-45-1R (3) and FHWA-OEP/HEV-78-1 (8).

There were also some secondary objectives in this study:

- Verification of the inference from the four-state study that vehicles in California can be categorized into three acoustic source groups to represent the state's entire vehicle population without introducing significant errors in noise predictions.
- Examination of the effects of hard and soft site characteristics on noise emission levels measured at the reference distance of 50 ft.
- Examination of geographical differences in vehicle emission levels for two regions in California, designated as Northern California and Southern California.

• Examination of the effect of wind on emission level measurements.

A total of 16 sites were selected for this study, 8 in Northern California and 8 in Southern California. Each vehicle group was about equally represented in the northern and southern portions of the state.

The number of vehicles measured was 3,045. Because of stringent contamination control and other rejection criteria, 2,734 events were actually used to determine emission levels. Of these, 46.2 percent were automobiles, 11.6 percent were medium trucks, and 42.2 percent were heavy trucks [as defined in FHWA-RD-77-108 (2)]. Reference energy mean emission levels that were speed dependent were developed for each of the three vehicle groups for constant speeds from 25 mph to 65 mph on level roads.

The secondary objectives were attained by measurements using up to 5 microphones at distances ranging from 25 to 100 ft from the centerline of vehicle travel and at heights of 5 ft and 10 ft.

No frequency spectra were measured, nor was any attempt made to verify vehicle noise centroid heights as reported in FHWA-RD-77-108 (2). Also, no comparisons of effects of pavement types were made; rather, such comparisons should be the subject of a separate research project. Pavements at all sites conformed to requirements set by FHWA-DP-45-1R (3) and FHWA-OEP/HEV-78-1 (8).

INSTRUMENTATION

All sound level meters (SLMs) used in this study met the requirements of Type I precision SLM per the 1983 Specification for Sound Level Meters (S1.4) of the American National Standards Institute. The SLMs were connected to a data logger specifically designed for the California Transportation Laboratory.

The data logger has 16 channels that may be selectively activated to receive up to 16 D.C. output signals from SLMs. These signals are then converted by the data logger's microprocessor into continuous, time-varying noise signals that are digitally displayed and updated at short time intervals depending on the slow or fast response settings. The data logger has two mode settings: standby and sampling. In the sampling mode, the data logger stores one sample per activated channel per second in the microprocessor. The stored values are used at the end of each sampling period to derive noise descriptors and statistical values. At the end of each noise measurement period, the data logger prints out the channel number, date, site number, time sampling began, time sampling ended, number of samples lost (due to editing during measurement), L_{eq}, L_{10}, L_{50}, a histogram of noise levels versus percent frequency, standard deviations, skewness, and kurtosis, for each channel.

The data logger also has the capability of measuring maximum noise levels in either the standby or sampling mode while a peak button is pressed. When the button is released, the maximum noise level received by each channel while the peak button was depressed is printed with the date, site number, time, and elapsed time of a single event. The data logger was used in this mode during the California vehicle noise emission levels study.

Figure 1 shows the noise instrumentation, typical setup, and site cross-section criteria. All instruments were field calibrated as a system before and after each measuring period in addition to the semi-annual calibrations by the Transportation Laboratory, which has facilities and instruments for performing SLM calibrations using two laboratory standard microphones calibrated every 6 months by the National Bureau of Standards in Washington, D.C. Wind speeds and directions were measured with a portable anemometer mounted on a 7-ft high standard. Vehicle speeds were measured with a radar gun.

SITES

The physical criteria for sites used in this study were in conformance with emission level site criteria set forth by FHWA OEP/HEV-78-1 (8) and FHWA-DP-45-1R (3). Cross-sectional and layout criteria are shown

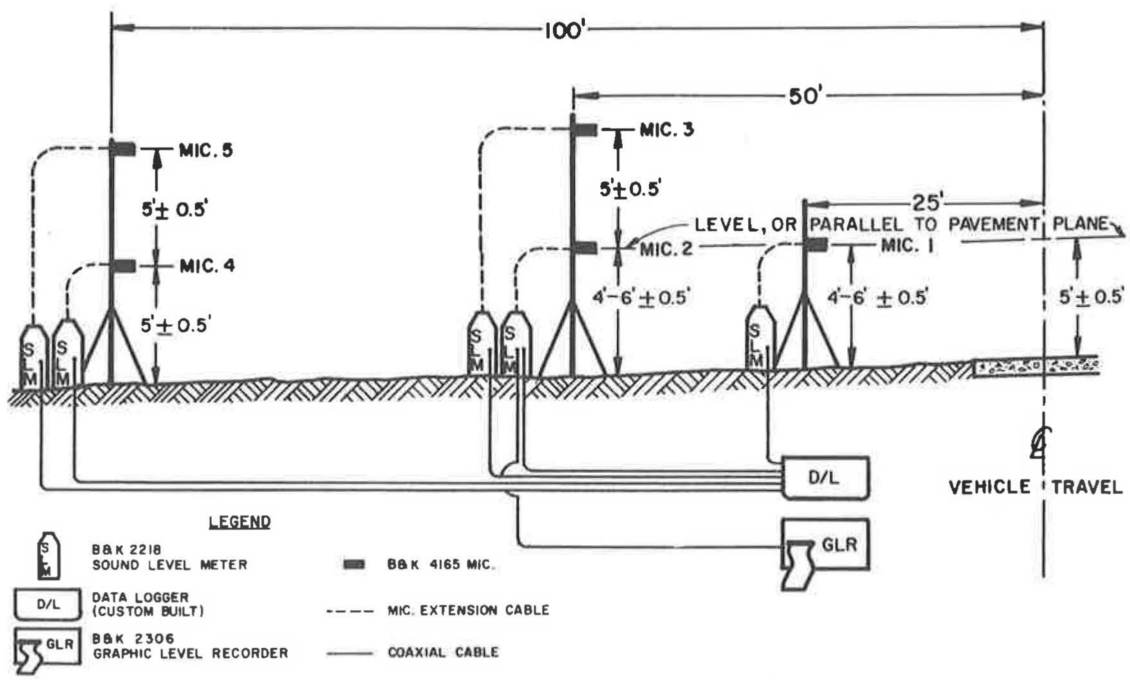


FIGURE 1 Noise instrumentation, typical setup, and site cross-section criteria.

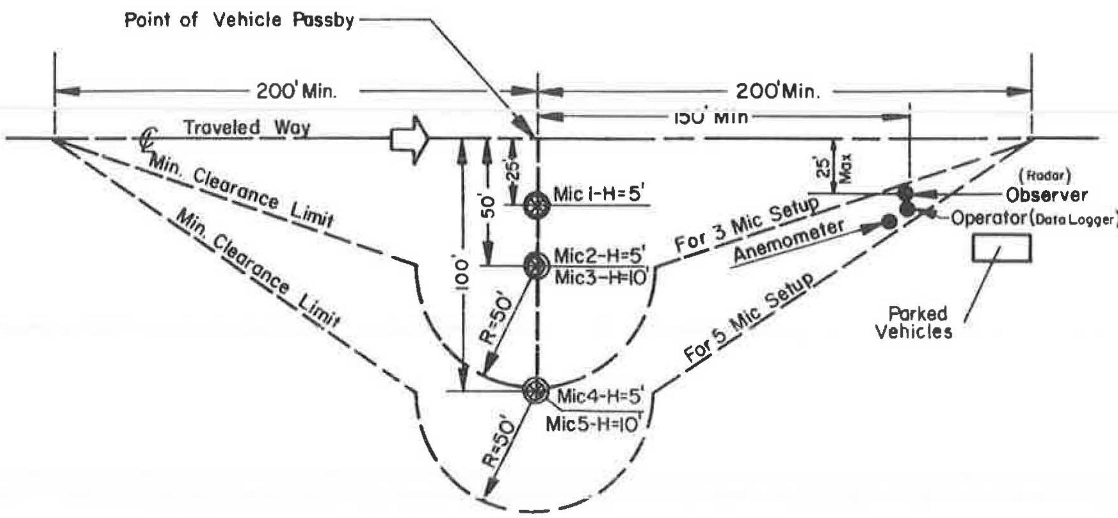


FIGURE 2 Typical site layout and microphone locations.

in Figures 1 and 2. In addition to these criteria, the following two general requirements were strived for during the site selection process:

1. Adequate representation of hard and soft sites as defined in FHWA RD-77-108 (2). Of the 16 sites used in this study, 5 were considered hard sites and 11 were considered soft.
2. Adequate geographical and speed representations. Because of California's diversity in traffic, it was opted to take fewer samples at many sites rather than many samples at few sites. In California, the FHWA highway traffic noise prediction model is used predominantly with higher speed traffic in urban and suburban regions. Adequate high-speed representation of automobiles and heavy trucks was obtained by sampling near high-population densities of the state as well as near Interstate highways (Figure 3).

FIGURE 3 Site locations.

Nineteen sites (Nos. 1-19) were selected originally. For various reasons, two sites (Nos. 4 and 13) were later rejected and one (No. 8) was never measured due to adverse weather conditions. To avoid confusion and maintain correlation with the original data, the remaining sites were not renumbered.

FIELD MEASUREMENTS

General Approach

Field measurements consisted of three operations: (a) vehicle identification and speed measurements, (b) A-weighted noise measurements, and (c) meteorological measurements. The first operation was performed by a vehicle observer, and the last two operations by an instrument operator. All measurement procedures and criteria reported in this section were consistent with FHWA-OEP/HEV-78-1 (8) and FHWA-DP-45-1R (3).

Where space and other conditions permitted the use of five microphones and SLMs, the typical microphone setup shown in Figure 1 was used to measure highest noise levels of individual vehicles. These were assumed to occur when vehicles crossed the point closest to the microphones.

Nine sites (Nos. 1, 2, 5, 7, 11, 12, 15, 16, 17) had the typical setup, shown in Figure 1, although site 5 had an exception. At this site, Microphones 4 and 5 were located 75 ft from the centerline of traveled way instead of the typical 100 ft. At each of the seven remaining sites, the terrain did not allow a setup of five microphones, so a setup of three microphones was used. Except for the elimination of Microphones 4 and 5, the microphone location criteria and numbering convention for three microphone setups were identical to those shown in Figure 1. Sites 3, 6, 9, 10, 14, 18, and 19 had a three-microphone configuration.

Quality Control Criteria for Events

An event was defined as the set of noise, vehicle, and meteorological measurements during a vehicle passby. Each of the measured components comprising an event was evaluated for acceptance or rejection according to five objective and subjective criteria: noise measurements, vehicles, meteorological criteria, number of events accepted and rejected, and sample size. Each of these criteria will be discussed further.

Noise Measurements

Significant contamination of noise measurements by extraneous noise sources was avoided by using three contamination control strategies: (a) selecting vehicles that were adequately separated from other vehicles, (b) analyzing the graphic level recorder (GLR) trace for compliance with valid-peak criteria, and (c) audiovisual observation by the radar observer and instrument operator.

Vehicle separation criteria were developed from two common scenarios, which are shown in Figures 4 and 5. Figure 4 shows two vehicles with equal noise strengths and a background noise level (L_B) of 10 dBA below the vehicles' noise emission levels (L_O) measured 50 ft from the point of passby. The two vehicles are separated by a minimum distance so that the highest observed noise level includes no more than 0.5 dBA contamination when Vehicle 1 crosses the point of passby. Because of the symmetrical relationship between the two noise sources, the same contamination is present when Vehicle 2 crosses the point of passby. A GLR documenting the events would produce a trace similar to the solid line in Figure 4, depicting the sum of L_i Vehicle 1 + L_i Vehicle 2 + L_B. This scenario approximates the passing of two automobiles without the presence of trucks and may also be applied conservatively to the passing of two trucks. The minimum distance of 308 ft between the vehicles provides a criterion of separation when two vehicles of equal noise source are involved.

Because of uncertainties in actual background levels and because there were usually more than two vehicles in the vicinity, the minimum distance criterion between the measured vehicle and any other vehicle of approximately equal source was set at 400 ft. A traffic cone placed 400 ft ahead of the point of passby aided the observer in estimating the minimum distance criterion in the field.

The second scenario, shown in Figure 5, involves two vehicles of unequal source strength. In this scenario, the noise source of one vehicle is 10 dBA higher than that of the other vehicle. The background noise is assumed to be 10 dBA below the lower noise source. This scenario approximates that of measuring the noise emission level of an automobile while a truck is approaching. In this case, the minimum vehicle separation should be 985 ft, or approximately 1,000 ft, to avoid contamination of more than 0.5 dBA.

The observer in the field had to estimate the 1,000-ft distance when the second scenario applied. Usually, this did not present a problem. Most automobile measurements were taken when there were not trucks in sight. In the cases when trucks were pres-

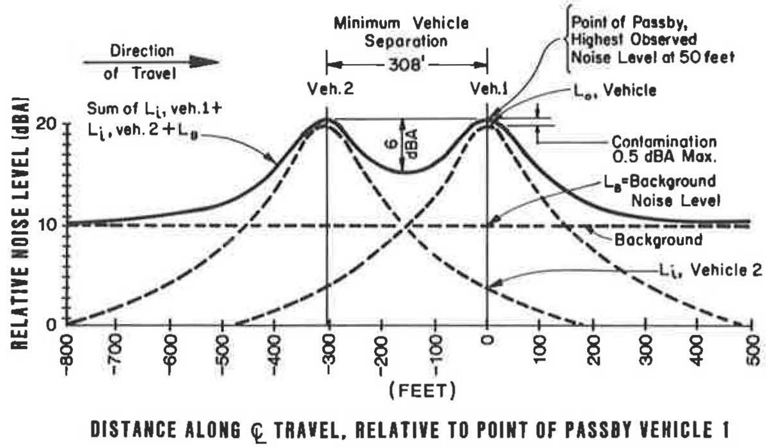


FIGURE 4 Minimum separation between two vehicles—equal noise sources.

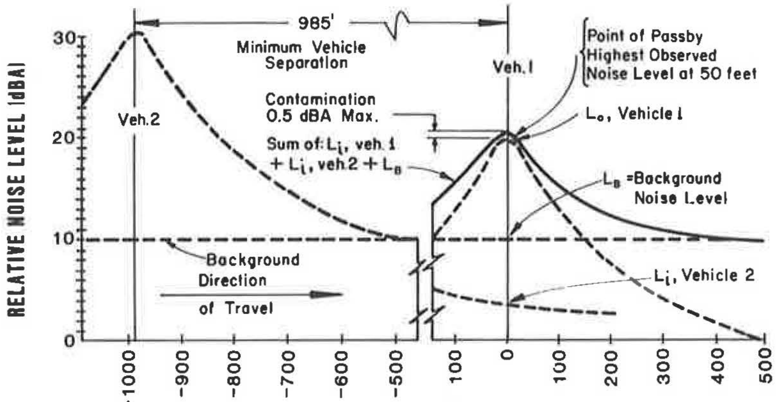


FIGURE 5 Minimum separation between two vehicles—unequal noise sources.

ent, the observer and instrument operators made independent judgments about the measurement quality. Because of probable presence of considerable ground attenuation and some atmospheric attenuation over a 1,000-ft distance (not included in the criterion calculation), this criterion was probably conservative.

Finally, a short discussion about the reverse of Scenario 2 (Figure 5) should be included. In this scenario, the louder vehicle is measured and the quieter vehicle is in the vicinity. If the difference between the sources is 10 dBA or greater, no separation should be necessary when 2 vehicles are involved. However, when the louder source is surrounded by several quieter sources, contamination may still occur. No criteria were set to cover this situation, but in general, trucks were not measured when surrounded by more than two or three automobiles in the immediate vicinity. In most cases, trucks selected for measurement were adequately separated from automobiles so that few judgments were necessary.

Valid-peak criteria were developed to help determine whether background noise contributed to the highest observed noise level of each event (vehicle passby). These criteria were based on a GLR trace of the event, recorded 50 ft from the centerline of vehicle travel at a microphone height of 5 ft (Reference Microphone 2 location).

To limit contamination to less than 0.5 dBA, the background noise levels should be at least 10 dBA lower than the highest observed value, which would have been a convenient criterion to use. However, a previous study by the New Jersey Department of Transportation (9) suggests that accepting only peaks of 10 dBA or greater would introduce a bias toward noisier vehicles. This would be true especially if background noise were relatively high. The New Jersey study used a rise-and-fall criterion of 6 dBA to prevent this bias, at the risk of slightly contaminating the measurement. For this reason, the California study used the same 6-dBA rise-and-fall criterion for acceptance. In this study, a rise and fall of 6 to 9 dBA was coded as an event of Quality 1; a rise and fall of 10 dBA or greater was coded as an event of Quality 2. Figure 6 shows the relationships between valid-peak criteria, event quality codes, and resulting maximum contamination.

The final audiovisual contamination control strategy consisted of an on-the-spot judgment by the vehicle observer or instrument operator, or both, to determine the quality of an event. In these instances, judgments were made using ears and eyes. Common examples included: sudden rises in background noise during measurements due to aircraft, nearby construction, or sporadic traffic on nearby frontage roads or ramps. When these rapid background noise increases coincided with vehicle passby measurements, they sometimes blended in with GLR traces, showing a valid peak. Contamination would have gone undetected except for the alertness of the observers during measurements.

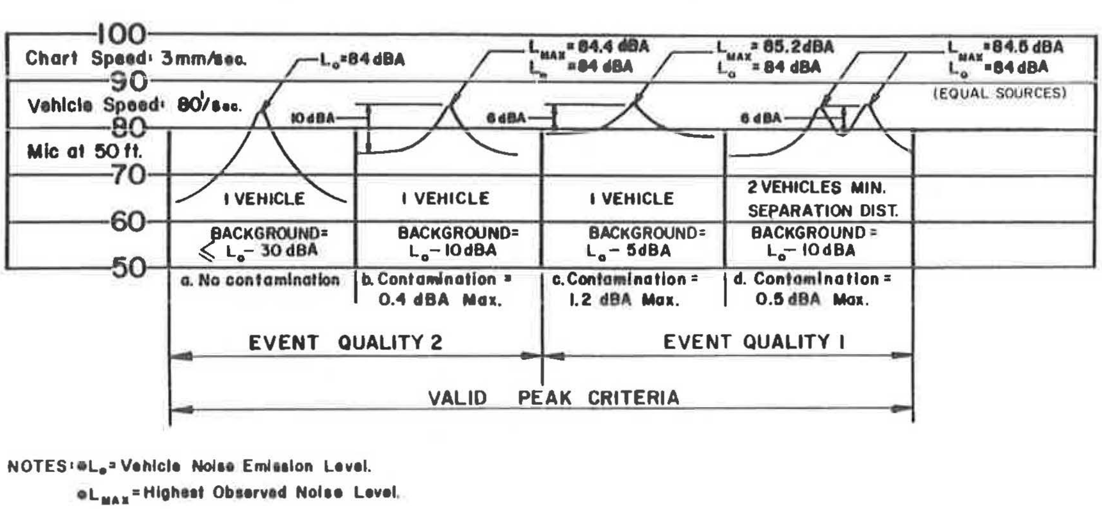
Vehicles

The three vehicle groups discussed in FHWA-RD-77-108 (2)--automobiles, medium trucks, and heavy trucks--were also used throughout this study. However, to confirm that vehicles can be placed in these three acoustic source groups, vehicles were identified in greater detail than were the FHWA groups. Automobiles were divided into compact and standard categories, a division that was made subjectively in the field by the observer. Heavy trucks were categorized by number of axles. The subdivisions resulted in eight vehicle types, which are given in Table 1.

All events were identified in the field and recorded with the passby speeds in mph. The speeds were measured with a radar gun by the observer, beginning at a point approximately 400 ft ahead of the point of passby and ending just beyond the point of passby. The speed at the point of passby was recorded. If the speed changed more than 3 mph in the 400-ft distance, the vehicle was assumed to be accelerating or decelerating and the event was rejected. Because of its position, the radar gun was usually not noticed by the drivers until after the point of passby, and thus few let up on the throttle.

Meteorological Criteria

One of the secondary objectives of this project was to attempt to isolate the effects of wind on vehicle noise emission measurements and noise measurements in general. FHWA-OEP/HEV-78-1 (8) and FHWA-DP-45-1R (3) do not recommend taking noise measurements when



NOTES: • L_o = Vehicle Noise Emission Level.

• L_{MAX} = Highest Observed Noise Level.

• Contamination = $L_{MAX} - L_o$

• When L_{MAX} - Background Level <6 dBA, Event Was Rejected. (Event Quality 0)

FIGURE 6 Valid-peak criteria, event quality codes, and maximum contamination.

TABLE 1 Vehicle Types

Vehicle Type	Designation	Definition-Description	FHWA-RD-77-108 Designation *(2)*
0	Compact automobile	Four cylinders; otherwise same as FHWA automobiles	Automobile
1	Standard automobile	Six or eight cylinders; otherwise same as FHWA automobiles	Automobile
2	Medium truck	Same as FHWA medium trucks; includes two-axle, six-tire buses	Medium truck
3	Three-axle truck	Three axles; otherwise same as FHWA heavy trucks	Heavy truck
4	Four-axle truck	Four axles; otherwise same as FHWA heavy trucks	Heavy truck
5	Five-axle truck	Five axles; otherwise same as FHWA heavy trucks	Heavy truck
6	Trucks with more than five axles	More than five axles; otherwise same as FHWA heavy trucks	Heavy truck
7	Miscellaneous	Vehicles not covered under Types 0-6; example: motorcycles	NA

wind speeds exceed 12 mph. All measurements in this study were made at wind speeds below 10 knots (11.5 mph).

Wind speeds and direction were measured with a Belfort anemometer set on top of a standard at a height of 7 ft near the instrument operator and observer at a distance of approximately 25 ft from the centerline of the nearest roadway. The measurements were taken between measured events and during gaps in traffic to avoid turbulence from passing vehicles. Wind speeds were measured to the nearest 1 knot and then grouped into three wind speed classes, as follows:

Wind Speed Class	Range (knots)	Range (mph)	Center Speed (mph)
0	0-2.5	0-3	0
3	2.5-5.5	3-6	4.5
6	5.5-10	6-12	9

The center speed was later used to compute cross-wind components 90 degrees to the roadway. These were then categorized as follows: 6 to 12 mph, 3 to 6 mph, -3 to +3 mph, -6 to -3 mph, and -12 to -6 mph. A positive wind blew from source to receiver, and a negative wind from receiver to source. Other important environment criteria were the 90 percent or greater relative humidity and wet pavement. No measurements were attempted under either condition.

Number of Events Accepted and Rejected

The event data were recorded on four different types of charts and sheets: (a) GLR chart (vehicle trace at reference distance), (b) vehicle observation sheet (vehicle identification and speed), (c) data-logger printout (maximum observed noise levels at each microphone), and (d) environmental and site data sheet (meteorological data). Data from each of these sources were coded with either an event Quality 1 (accepted) or 0 (rejected). GLR data was coded either 2, 1 (accepted), or 0 (rejected), as discussed previously. Thus, each event had four quality codes. Events with at least one 0 code were called Quality 0 events and were rejected, for example, 1011. Events with all quality 1 (1111) were designated Quality 1 events and accepted for emission levels only. Events with a GLR quality 2 (2111) were designated Quality 2 events. Of the 3,045 events measured at the reference microphone (Microphone 2), 2,426 (79.7 percent) were Quality 2, 308 (10.1 percent) were Quality 1, and 311 (10.2 percent) were Quality 0 (rejected).

Sample Size

The minimum required sample size for each vehicle group was first estimated from methods described in FHWA-OEP/HEV-78-1 (8) for a 95 percent confidence interval of ±1 dBA around the mean of each speed class. Table 2 gives the speed classes that were designed for this purpose.

TABLE 2 Ranges of Speed Classes

Speed Class	Speed Range (mph)	Speeds to Nearest 1 mph
0	<24.50	<25
1	24.50-28.49	25-28
2	28.50-32.49	29-32
3	32.50-36.49	33-36
4	36.50-40.49	37-40
5	40.50-44.49	41-44
6	44.50-48.49	45-48
7	48.50-52.49	49-52
8	52.50-56.49	53-56
9	56.50-60.49	57-60
10	60.50-64.49	61-64
11	>64.49	>64

After data had been collected in each speed class, the minimum required data for the confidence interval of ±1 dBA was calculated from

$$n = \left\{[(t_{\alpha/2;n-1}) \cdot (S)]/d\right\}^2 \tag{1}$$

where

$t_{\alpha/2;n-1}$ = the amount of sample standard deviations associated with (1.00 - α) $\cdot$ 100 percent confidence level and n - 1 degrees of freedom,
α = significance level (= 0.05),
S = the sample standard deviation,
d = (1. 00 - α) x 100 percent confidence interval (= ±1 dBA).

Tables 3 and 4 give the number of points sampled, minimum number of points required, mean speed, mean energy noise levels, mean noise levels, and standard deviations for each speed class. The statistics are shown for the 50-ft reference microphone (Microphone 2) only. The total number of events sampled and accepted was 2,734, and consisted of the following

TABLE 3 Low-Speed Data by Vehicle Group

Data by Speed Class	Automobiles	Medium Trucks	Heavy Trucks
Class 0 (less than 25 mph)			
No. of points sampled	3	1	3
Minimum number of points required	535	0	345
Mean speed (mph)	23.00	22.00	21.00
Mean energy noise level (dBA)	60.55	63.30	76.68
Mean noise level (dBA)	58.20	63.30	75.57
Standard deviation mean dBA	5.37	0.00	4.32
Class 1 (25 to 28 mph)			
No. of points sampled	6	7	18
Minimum number of points required	113	178	50
Mean speed (mph)	27.33	27.43	27.11
Mean energy noise level (dBA)	63.90	74.37	79.45
Mean noise level (dBA)	62.25	72.03	78.20
Standard deviation mean dBA	4.13	5.46	3.35
Class 2 (29 to 32 mph)			
No. of points sampled	21	8	37
Minimum number of points required	25	45	49
Mean speed (mph)	30.57	30.50	30.54
Mean energy noise level (dBA)	63.44	74.48	80.55
Mean noise level (dBA)	62.75	73.61	78.59
Standard deviation mean dBA	2.40	2.85	3.49
Class 3 (33 to 36 mph)			
No. of points sampled	46	20	40
Minimum number of points required	37	50	32
Mean speed (mph)	34.59	34.10	34.80
Mean energy noise level (dBA)	64.95	76.02	79.49
Mean noise level (dBA)	63.69	74.63	78.57
Standard deviation mean dBA	3.03	3.38	2.83
Class 4 (37 to 40 mph)			
No. of points sampled	33	15	34
Minimum number of points required	39	48	22
Mean speed (mph)	38.45	38.67	38.53
Mean energy noise level (dBA)	66.86	76.73	80.89
Mean noise level (dBA)	65.68	75.58	80.22
Standard deviation mean dBA	3.11	3.23	2.33
Class 5 (41 to 44 mph)			
No. of points sampled	88	16	48
Minimum number of points required	34	31	20
Mean speed (mph)	42.65	42.38	43.06
Mean energy noise level (dBA)	68.00	76.25	81.74
Mean noise level (dBA)	66.70	75.50	81.17
Standard deviation mean dBA	2.93	2.62	2.26

vehicles: 1,263 automobiles, 317 medium trucks, and 1,154 heavy trucks. For automobiles and heavy trucks, sufficient amounts of data were gathered in all speed classes from 32 to 64 mph (except for automobiles in the 37 to 40 mph range, of which there were slightly fewer than the minimum number required). For medium trucks, the minimum amount of samples required was reached for all speed classes above 48 mph. Because of the deficiency in data at lower speeds and to cover the desired range of 25 to 65 mph, curve-fitting methods were employed with 95 percent confidence intervals for the prediction equation.

Use of this curve-fitting method should be restricted to normally (Gaussian) distributed data in each speed class for each vehicle group. Although this constraint was never tested on the data in this project, previous unpublished Caltrans studies suggest that at constant speeds, vehicle noise approaches a normal distribution.

ANALYSES AND RESULTS

Emission Levels by Vehicle Types

Reference energy mean emission curves as a function of speed were developed for all vehicle types shown in Table 1 except for Types 6 and 7. Type 6 was not included because only one event was observed; Type 7 vehicles (motorcycles and miscellaneous) were also very scarce.

The energy mean emission curves were expressed as

$$LOE_{(i)} = A + 0.115(Sy)^2 + B \log(\text{speed,mph}) \qquad (2)$$

where

$LOE_{(i)}$ = energy mean emission level for vehicle type i,
A = constant in the regression equation,
Sy = standard error of y(dBA) on log X (speed, mph), and
B = slope in the regression equation.

Figure 7 shows a comparison of compact versus standard automobile mean emission curves. The curves indicate that compact automobile (four-cylinder) emission levels are between 1.2 dBA (at 25 mph) and 1.5 dBA (at 65 mph) lower than standard automobiles (six or eight cylinders). The reasons for this difference are unclear, but it is suspected that the compact car fleet consists of later model cars with better mufflers than the standard car fleet. The difference, however, is not significant enough to warrant separate emission curves. Instead, compact and standard curves were combined.

Figure 8 shows comparisons of curves for three-, four-, and five-axled trucks. Because of close agreement between the curves for heavy trucks, one combined curve was used to represent them. [This study therefore concurs with the original FHWA findings that all vehicles can be categorized in three acoustic source groups (2).]

TABLE 4 High-Speed Data by Vehicle Group

Data by Speed Class	Automobiles	Medium Trucks	Heavy Trucks
Class 6 (45 to 48 mph)			
No. of points sampled	92	19	77
Minimum number of points required	34	59	25
Mean speed (mph)	46.66	46.32	46.22
Mean energy noise level (dBA)	69.34	75.96	82.10
Mean noise level (dBA)	68.36	74.95	81.26
Standard deviation mean dBA	2.90	3.66	2.50
Class 7 (49 to 52 mph)			
No. of points sampled	117	32	106
Minimum number of points required	36	23	27
Mean speed (mph)	50.73	50.69	50.97
Mean energy noise level (dBA)	72.68	78.48	82.64
Mean noise level (dBA)	71.21	77.85	81.74
Standard deviation mean dBA	3.01	2.42	2.62
Class 8 (53 to 56 mph)			
No. of points sampled	258	69	233
Minimum number of points required	28	29	31
Mean speed (mph)	54.57	54.58	54.60
Mean energy noise level (dBA)	72.99	78.98	83.49
Mean noise level (dBA)	72.09	78.11	82.51
Standard deviation mean dBA	2.64	2.71	2.79
Class 9 (57 to 60 mph)			
No. of points sampled	272	78	300
Minimum number of points required	31	23	21
Mean speed (mph)	58.53	58.45	58.60
Mean energy noise level (dBA)	74.03	80.78	83.99
Mean noise level (dBA)	73.04	80.11	83.34
Standard deviation mean dBA	2.79	2.37	2.27
Class 10 (61 to 64 mph)			
No. of points sampled	220	44	212
Minimum number of points required	27	24	23
Mean speed (mph)	62.35	62.07	62.12
Mean energy noise level (dBA)	74.85	81.74	85.21
Mean noise level (dBA)	73.91	81.02	84.44
Standard deviation mean dBA	2.62	2.46	2.40
Class 11 (more than 64 mph)			
No. of points sampled	107	8	46
Minimum number of points required	35	8	85
Mean speed (mph)	67.79	67.38	66.76
Mean energy noise level (dBA)	76.07	81.24	87.20
Mean noise level (dBA)	74.91	81.10	85.39
Standard deviation mean dBA	2.94	1.21	4.60

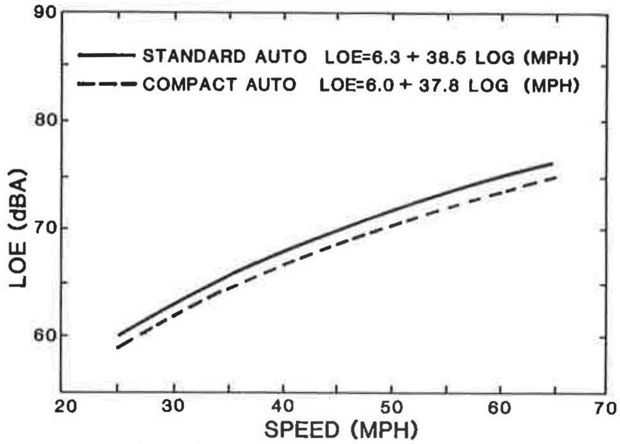


FIGURE 7 Comparison of compact versus standard energy mean regression lines.

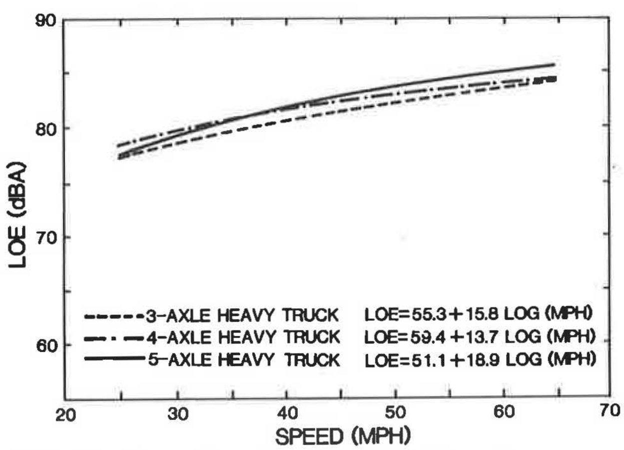


FIGURE 8 Comparison of three-, four-, and five-axle energy mean regression lines.

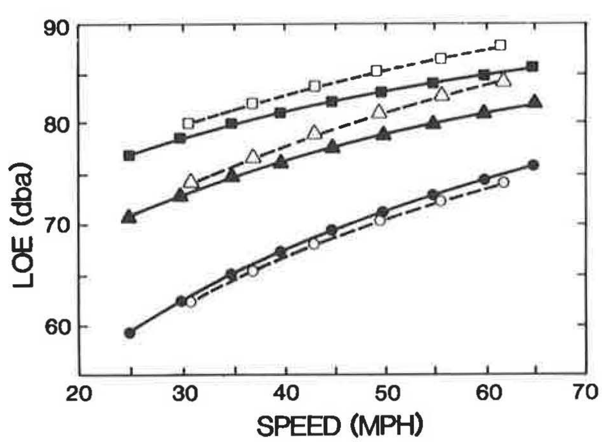
Figure 9 shows a comparison of energy mean emission levels for automobiles, medium trucks, and heavy trucks in the California study with the same three vehicle groups reported in FHWA-RD-77-108 (2). The California automobile curve is from 0.7 dBA (at 25 mph) to 1.0 dBA (at 65 mph) higher than the FHWA automobile curve (projected up to 65 mph and down to 25 mph). The California medium-truck curve is from 0.3 dBA higher (at 25 mph) to 3.2 dBA lower (at 65 mph) than the FHWA medium-truck curve. Approximately the same is true for the California heavy-truck curve, which is from 0.7 dBA lower (at 25 mph) to 3.1 dBA lower (at 65 mph) than the projected FHWA heavy-truck curve.

The emission levels for the three vehicle groups were also plotted by energy mean noise levels for each speed class at 50 ft. Although these plots deviated up to about 3 dBA from the regression lines for automobiles and medium trucks, the differences were not statistically significant (Student's t-test, $\alpha = 0.05$). The heavy-truck plot, however, showed statistically significant deviations of 1.4 and 1.7 dBA above the regression line for speed classes 25 to 28 mph and 29 to 32 mph, respectively (see Figure 10), deviations that may have been caused by increased noise levels in lower gears. Because of the importance of heavy-truck noise emission levels in predicting highway noise and designing noise barriers, further refinements in the curve appeared justified.

Figure 11 shows the California vehicle noise reference energy mean emission levels, including the modified curve for heavy trucks. These curves are recommended for use with traffic noise prediction models in California.

Hard Versus Soft Sites

There are several problems in comparing emission levels measured at one group of sites with those from another group: (a) vehicle populations may be different, (b) meteorological conditions are probably not the same, and (c) the speed distributions are likely to be different. These problems were reduced, if not eliminated, by normalizing the 50-ft



	○ ● AUTOS	△▲ MEDIUM TRUCKS	□■ HEAVY TRUCKS
---○--- FHWA	LOE=5.5+38.1 LOG(MPH)	LOE=23.4+33.9 LOG (MPH)	LOE=43.6+24.6 LOG(MPH)
—●— CALIFORNIA	LOE=5.2+38.8 LOG(MPH) No. of observations: 1263 Std.error y on LOGx: 2.81 r^2=0.56; r=0.75	LOE=35.3+25.6 LOG (MPH) No. of observations: 317 Std. error y on LOGx: 2.83 r^2=0.42; r=0.65	LOE=50.4+19.2 LOG (MPH) No. of observations: 1154 Std. error y on LOGx: 2.68 r^2=0.29; r=0.53

FIGURE 9 Comparison of California versus FHWA energy mean regression lines.

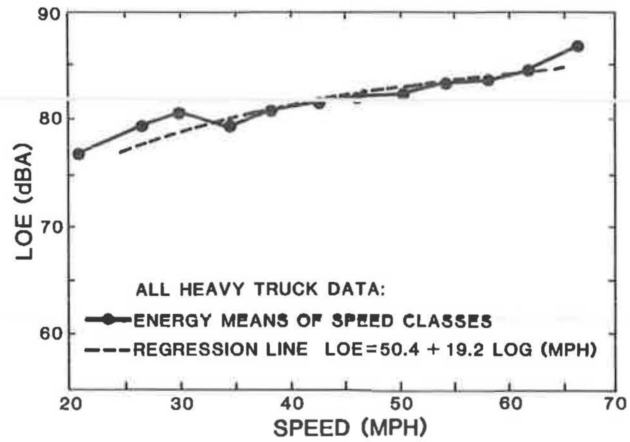


FIGURE 10 Comparison by energy means of speed classes and energy mean regression line for heavy-truck data plots.

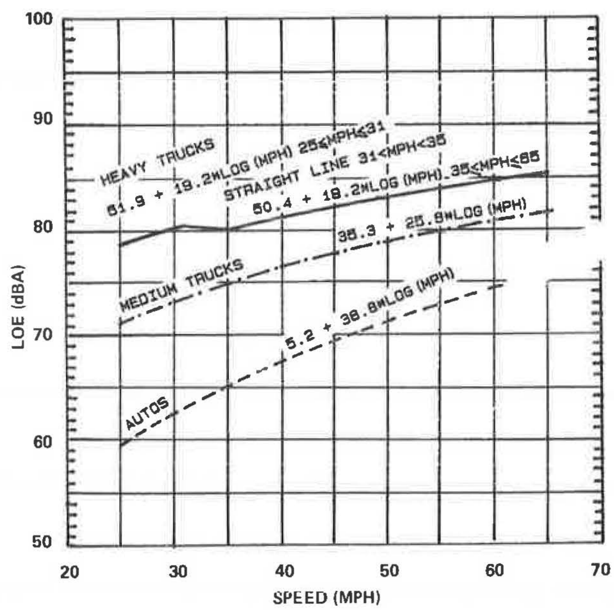


FIGURE 11 California reference energy mean emission levels.

microphones of soft sites to those of hard sites. This was accomplished by setting the 25-ft microphones equal and correcting up the 50-ft microphones. The underlying assumptions were that site and meteorological effects were negligible near the source. Remaining differences could then be attributed to differences in vehicle populations. The normalizing process eliminated these differences. Variations in speed distributions were eliminated by comparing only those speed classes with sufficient data to assure 95 percent confidence intervals of ±1 dBA around the means.

Table 5 shows that for all vehicle groups and speed classes tested with a statistical t-test (10), the effects on measured noise levels caused by hard or soft site characteristics were significant at the 50-ft reference distance at a height of 5 ft. These differences (maximum 2 dBA) appeared to decrease with increasing source heights, but appeared to be insensitive to speed.

In reality, there are few true hard sites, whereas variations in soft sites are almost endless. It is therefore impractical to have separate emission levels for hard sites and soft sites. It appears that site characteristics will, in most cases, affect noise predictions by no more than 0.8 dBA when using the California emission curves.

Geographical Differences

Table 6 shows a comparison of emission levels measured at 25 ft for Northern California and Southern California by vehicle group and speed classes with sufficient data to ensure a 95 percent confidence interval of ±1 dBA. As was discussed previously, at 25 ft the site and environmental effects could be eliminated. In general, automobiles and medium trucks did not appear to be significantly different. In the heavy-truck group, however, Northern California trucks were up to about 2 dBA noisier. The differences were statistically significant (t-test, α = 0.05). Between 49 and 64 mph, the average difference was slightly greater than 1 dBA. Using the California heavy-truck emission curve would probably result in maximum errors of 0.5 dBA due to geographic differences. Separate curves for Northern California and Southern California would therefore not be justified or practical.

Effects of Wind

The effects of wind on measured noise levels were examined at 50 ft and 100 ft. After crosswind com-

TABLE 5 Comparison of Vehicle Emission Levels for Hard Sites Versus Soft Sites

	Energy Mean (dBA)								
Vehicle Type	Speed Class (mph)	Hard Sites– 50 ft ($\bar{X}$)	Normalized[a] Soft Sites– 50 ft ($\bar{Y}$)	Difference in dBA ($\bar{X}$-$\bar{Y}$)	Standard Deviation (S_x)	No. of Observations (N_x)	Standard Deviation (S_y)	No. of Observations (N_y)	t-test (α = 0.05 significant)
Automobiles	53-56	74.2	72.2	2.0	2.9	84	2.3	174	Yes
	57-60	74.8	72.8	2.0	3.3	96	2.4	176	Yes
	61-64	76.1	74.1	2.0	3.5	71	2.0	149	Yes
Medium trucks	57-60	82.1	80.2	1.9	2.0	23	2.2	55	Yes
Heavy trucks	49-52	82.9	81.3	1.6	2.5	46	2.7	60	Yes
	53-56	83.9	82.5	1.4	2.9	101	2.7	132	Yes
	57-60	84.8	83.1	1.7	2.4	123	2.1	177	Yes
	61-64	85.7	84.1	1.6	2.3	81	2.4	131	Yes

Note: Speed classes with sufficient data only.

[a]Normalized: 25-ft microphone of soft sites was set equal to 25-ft microphone of hard sites and 50-ft microphone was corrected with same correction.

TABLE 6 Comparison of Vehicle Emission Levels for Northern California and Southern California

Vehicle Type	Speed Class (mph)	Energy Mean (dBA) Northern California Sites—25 ft ($\bar{X}$)	Southern California Sites—25 ft ($\bar{Y}$)	Difference in dBA ($\bar{X}$-$\bar{Y}$)	Standard Deviation (S_x)	No. of Observations (N_x)	Standard Deviation (S_y)	No. of Observations (N_y)	t-test (α = 0.05 significant)
Automobiles	45-48	76.7	75.4	1.3	2.2	2.9	45	47	Yes
	53-56	79.5	79.5	0	2.3	2.7	160	90	No
	57-60	80.5	80.7	−0.2	2.4	3.2	129	134	No
	61-64	81.5	81.2	0.3	2.3	3.1	96	119	No
	>64	83.4	82.3	1.1	2.8	3.2	41	62	No
Medium trucks	53-56	85.6	84.7	0.9	2.1	3.1	33	34	No
	57-60	87.6	86.9	0.7	2.5	2.2	31	46	No
Heavy trucks	49-52	89.5	87.4	2.1	2.7	2.4	63	41	Yes
	53-56	90.1	88.9	1.2	2.5	2.7	111	114	Yes
	57-60	90.8	89.7	1.1	2.3	2.1	119	178	Yes
	61-64	91.4	91.5	−0.1	2.1	2.6	68	142	No

Note: Speed classes with sufficient data only.

ponents (90 degrees to the roadway) had been calculated and categorized as previously discussed, associated noise data at 50 ft and 100 ft were normalized using the 25-ft microphone data. Wind effects at 25 ft were judged to be small and therefore neglected. Tables 7 and 8 give comparisons of opposite crosswinds at 50 ft, first using all sites (Table 7), then using soft sites only (Table 8). Table 9 shows the comparison using data from all five microphone sites at 100 ft.

Wind effects were expected to be greatest for soft sites, longer distances, and lower noise sources. As the tables indicate, however, no significant changes could be detected at 50 ft. At 100 ft, there was a significant difference in the automobile data when opposite winds between negative and positive wind speeds of 6 to 12 mph were compared.

SUMMARY

The California vehicle noise reference energy emission levels are 0.7 to 1.0 dBA higher for automobiles, 0.3 higher to 3.2 dBA lower for medium trucks, and from 0.8 dBA higher (at 25 mph, after refinement) to 3.1 dBA lower (at 65 mph) than FHWA (2) emission levels (projected down to 25 mph and up to 65 mph). For average traffic mixes and at-grade highways, noise predictions made with California emission levels will be about 2 dBA lower than those made with the FHWA levels. The FHWA categorization of vehicle noise sources into three groups appears to also be valid for use in California. Although there are significant differences of up to 2 dBA in noise levels at 50 ft for hard sites and soft sites, the California curve will cause maximum errors of no more than about 0.8 dBA due to site characteristics. Similarly, geographic differences will cause maximum deviations of 0.5 dBA. The effects of wind speed and direction on noise measurements at 50 ft may be ignored if wind speeds are 12 mph or less. The current practice of increasing truck emission levels to 87 dBA for speeds below 31 mph (2) is contradicted by the data in this study for constant speeds from 25 mph to 31 mph.

TABLE 7 Comparison of Wind: +6 mph to +12 mph Versus -6 mph to -12 mph at All Sites, 50 ft (Microphone 2)

Vehicle Type	Speed Class (mph)	Energy Mean (dBA) Wind: +6 mph to +12 mph ($\bar{X}$)	Wind: -12 mph to -6 mph[a] ($\bar{Y}$)	Difference in dBA ($\bar{X}$-$\bar{Y}$)	Standard Deviation (S_x)	No. of Observations (N_x)	Standard Deviation (S_y)	No. of Observations (N_y)	t-test (α = 0.05 significant)
Automobiles	All	74.1	73.9	0.2	4.4	24	4.7	124	No
Medium trucks	All	83.3	84.7	−1.4	1.3	3	4.0	26	No
Heavy trucks	All	83.9	84.3	−0.4	2.3	48	3.5	52	No

[a]25-ft microphone for -6 mph to -12 mph was set equal to 25-ft microphone for +6 mph to +12 mph and 50 ft microphone was corrected with same correction.

TABLE 8 Comparison of Wind: +6 mph to +12 mph Versus -6 mph to -12 mph at Soft Sites, 50 ft (Microphone 2)

Vehicle Type	Speed Class (mph)	Energy Mean (dBA) Wind: +6 mph to +12 mph ($\bar{X}$)	Wind: -12 mph to -6 mph[a] ($\bar{Y}$)	Difference in dBA ($\bar{X}$-$\bar{Y}$)	Standard Deviation (S_x)	No. of Observations (N_x)	Standard Deviation (S_y)	No. of Observations (N_y)	t-test (α = 0.05 significant)
Automobiles	All	69.3	69.6	-0.3	1.1	7	2.5	48	No
Medium trucks[b]	All	76.5	77.0	-0.5	3.7	29	3.1	7	No
Heavy trucks	All	81.1	81.4	-0.3	2.5	7	4.4	7	No

[a]25-ft microphone for -6 mph to -12 mph was set equal to 25-ft microphone for +6 mph to +12 mph and 50-ft microphone was corrected with same correction.

[b]Because of insufficient data, +3 mph to +6 mph was used for medium trucks.

TABLE 9 Comparison of Wind: +6 mph to +12 mph Versus -6 mph to -12 mph at Sites with Five Microphones, 100 ft (Microphone 4)

		Energy Mean (dBA)							
Vehicle Type	Speed Class (mph)	Wind: +6 mph to +12 mph ($\bar{X}$)	Wind: -12 mph to -6 mph[a] ($\bar{Y}$)	Difference in dBA ($\bar{X}$-$\bar{Y}$)	Standard Deviation (S_x)	No. of Observations (N_x)	Standard Deviation (S_y)	No. of Observations (N_y)	t-test (α = 0.05 significant)
Automobiles	All	68.4	65.0	3.4	3.5	17	2.5	48	Yes
Medium trucks	All	76.7	75.4	1.3	1.2	3	3.6	7	No
Heavy trucks	All	77.9	77.8	0.1	2.1	41	4.7	7	No

[a]Set 25-ft microphone for -6 mph to -12 mph equal to 25-ft microphone for +6 mph to +12 mph and corrected 100-ft microphone with same correction.

ACKNOWLEDGMENT

This study was performed in cooperation with FHWA, U.S. Department of Transportation.

REFERENCES

1. Federal-Aid Highway Program Manual. FHWA, U.S. Department of Transportation, Aug. 9, 1982, Vol. 7, Ch. 7, Sec. 3.
2. T.M. Barry and J.A. Reagan. FHWA Highway Traffic Noise Prediction Model. Report FHWA-RD-77-108. FHWA, U.S. Department of Transportation, Dec. 1978.
3. W. Bowlby. Sound Procedures for Measuring Highway Noise: Final Report. Report FHWA-DP-45-1R. FHWA, U.S. Department of Transportation, Aug. 1981.
4. F.F. Rudder, Jr., and P. Lam. Update of TSC Highway Traffic Noise Prediction Code (1974). Report FHWA-RD-77-19. FHWA, U.S. Department of Transportation, Jan. 1977.
5. Y.Y. Ma and F.F. Rudder, Jr. Statistical Analysis of FHWA Traffic Noise Data. Report FHWA-RD-78-64. FHWA, U.S. Department of Transportation, July 1978.
6. E.J. Rickley, D.W. Ford, and R.W. Quinn. Highway Noise Measurements For Verification of Prediction Models. Report DOT-TSC-FHWA-78-1, FHWA, U.S. Department of Transportation, April 1976.
7. R.W. Hendriks and M.M. Hatano. Evaluation of Noise Barriers. Office of Transportation Laboratory, California Department of Transportation, Sacramento, June 1981.
8. J.A. Reagan. Determination of Reference Energy Mean Emission Levels. Report FHWA-OEP/HEV-78-1. FHWA, U.S. Department of Transportation, July 1978.
9. S.R. Sasor. Determination of Truck Noise Levels for New Jersey. Division of Research and Development, New Jersey Department of Transportation, Trenton, July 1980.
10. A.H. Bowker and G.J. Lieberman. Engineering Statistics. Prentice-Hall, Inc., Englewood, Cliffs, N.J., 1972, second edition.

The contents of this paper reflect the views of the author, who is also responsible for the accuracy of the data. The contents do not necessarily reflect official views or FHWA or Caltrans policies and do not constitute a standard or regulation. A copy of the detailed report for this study is available from Caltrans.

Publication of this paper sponsored by Committee on Transportation-Related Noise and Vibration.

Are Stringent Emission Standards for Heavy-Duty Trucks Worth the Cost?

C. L. SARICKS and M. K. SINGH

ABSTRACT

A study sponsored at Argonne National Laboratory (ANL) by the U.S. Department of Energy's Office of Environmental Analysis investigated the costs, benefits, and cost-effectiveness of requiring heavy-duty trucks to meet gaseous and particulate emission standards suggested or proposed by the U.S. Environmental Protection Agency (EPA) in 1981. The EPA and engine and truck manufacturers disagree over the feasibility of achieving these standards and the expenditure required. Moreover, EPA apparently did not include explicit computation of fuel economy losses in its draft regulatory analyses. The resulting incremental costs, presumably passed on to truck buyers both at time of sale and during the vehicle's lifetime, could be considerable. The greatest variation in cost estimates is related to trap oxidizer technology for heavy-duty diesel particulate control. Although the ANL study arrived at a quantitative estimate of cost-effectiveness in $/ton of pollutant removed, the values are distributed over a wide range that reflects the continuing unresolved disagreements in control costs. The study also focused more specifically on the likely air quality benefits of the suggested standards in a case-study urban area with a history of nonattainment. While the proposed NO_x standard would result in a 45 percent reduction in total NO_x loading from the current standard, the corresponding reduction of short-term NO_x exposure in prototypical urban corridors of high heavy-truck vehicle-miles traveled would not exceed 35 percent. The resulting health benefits are unknown.

Section 202(a)(3)(A)(ii)-(iii) of the Clean Air Act as Amended 1977 stands as one of the signal manifestations of the egalitarian philosophy of the framers of the mobile-source-related facets of this historic legislation: what applies to cars will also apply (albeit with some delay) to trucks. Mandated in Subsection 202(a)(3)(A)(ii) were exhaust emission standards for the so-called Set II pollutants that

> . . . in the case of hydrocarbons and carbon monoxide . . . require a reduction of at least 90 percent, and . . . in the case of oxides of nitrogen . . . require a reduction of at least 75 percent, from the average of the actually measured emissions from heavy-duty gasoline-fueled vehicles or engines . . . manufactured during the baseline model year (of 1973).

These reduction targets, for trucks rated at gross weights of 8,500 lb and above, were to be met no later than the 1983 and 1985 model years, respectively. Moreover, the potential hazard posed by the particulate emissions from diesel-fueled vehicles did not escape the notice of the Congress, which in 202(a)(3)(A)(iii) called for exhaust particulate standards after model year 1981 that reflect

> . . . the greatest degree of emission reduction achievable through the application of technology which the Administrator determines will be available for the model year to which such standards apply, giving appropriate consideration to the cost . . .

Thus the percentage reduction requirements for exhaust pollutants from heavy-duty trucks were brought into line with those for automobiles. The basis for particulate reduction was to be the best control technology reasonably available.

That the NO_x and particulate requirements in particular might turn out to be irreconcilable did not at that time occur to or influence the Congress--it was still the era of technology forcing. Nevertheless, the issue did not attain much prominence until EPA issued a Notice of Proposed Rulemaking (NPRM) for the heavy-duty engine particulate emission standard on January 7, 1981, and an Advance Notice of Proposed Rulemaking (ANPRM) for the NO_x exhaust emission limitation on January 19 of that same year (1,2). Each of these notices assigned numerical values to emission reductions previously expressed as a percentage difference from a baseline. The actual proposed value for NO_x in the ANPRM did not represent a 75 percent reduction from the calculated baseline of 6.8 grams per brake-horsepower hour (g/bhph) on the EPA steady-state test (a value that would have been 1.7 g/bhph), but rather a compromise value of 4.0 g/bhph. EPA considered this to be the lowest exhaust rate achievable by trucks using either (a) heavy-duty gasoline engines (HDGEs) without the requirement of control through unproven catalyst devices, or (b) heavy-duty diesel engines (HDDEs) without significant losses in fuel economy. The particulate standard of 0.25 g/bhph, applicable to all heavy-duty trucks but requiring control equipment only for HDDEs, was believed to reflect the best achievable performance of trap oxidizers (the apparent control technology of choice).

Despite this somewhat more lenient interpretation by EPA of the intent of the Congress, vehicle and engine manufacturers expressed dismay. In public testimony and comments submitted to the public docket on these proposals, the manufacturers indicated that

- Trap oxidizer technology for diesel vehicles was not near the degree of durability and reliability necessary for HDDE application.
- Even under an HDDE particulate standard of 0.6 to 0.7 g/bhph, roughly the average level then being achieved by new HDDEs, the lowest controlled noncatalyst (certifiable) emission level for NO_x that is achievable without significant fuel economy and other emission trade-offs was not below about 6.0 g/bhph.
- Any requirement for NO_x control to a level of 4.0 g/bhph or below would result in both substantial fuel consumption penalties in all heavy-duty trucks and, for HDGE, a substantial increase in emissions of HC, which were also to be the subject of rulemaking (3-10).

Thus, the battle lines were drawn.

In an effort to clarify many of the salient issues associated with these standards, the Center for Transportation Research at Argonne National Laboratory (ANL) (Argonne, Illinois) conducted independent analyses of (a) the technological issues associated with achieving the standards, (b) the cost and cost-effectiveness of the standards, and (c) the potential benefits of a 0.25-g/bhph particulate standard at the national level and a 4.0-g/bhph NO_x standard at both the national and local (site-specific) level. The standards were assumed to be in effect with the 1988 model year. Results of these analyses are presented in this paper; for a more detailed discussion, see Singh and Saricks (11).

TECHNOLOGICAL ISSUES

Heavy-Duty Diesel Engines

To meet the proposed NO_x and particulate standards, significant changes in HDDE emission control technology will be required. HDDEs generally do not employ emission control systems to comply with existing federal emission standards, although emission requirements are taken into consideration in HDDE design (12 and July 1983 letter and comments from D.C. Dowdall of Caterpillar Tractor Co. to M.K. Singh). The range of NO_x emissions from current production HDDEs outside California is 6 to 10 g/bhph on the steady-state cycle (13). The range of particulate emissions from national current production engines is 0.3 to 0.8 g/bhph, but the rate generally averages about 0.6 g/bhph.

Technologies under consideration to control HDDE NO_x to 4.0 g/bhph include injection timing retardation, aftercooling, exhaust gas recirculation (EGR), electronic engine control, turbocompounding, and modification of engine design (e.g., modifications to the compression ratio, combustion chamber shape, and spray tip design). Not all of these technologies work equally well on all diesel engines and therefore a variety of emission control systems is likely. Further, some of these technologies require additional development before they can be employed. While injection timing retardation, aftercooling, and turbocharging are essentially developed technologies, development is still under way on EGR and electronic engine controls. Many manufacturers anticipate that electronic engine controls (e.g., to provide more flexible and precise timing of fuel injection) will be available later in this decade (14). In contrast, considerable debate exists within the industry concerning the feasibility of using EGR to reduce NO_x substantially. However, the National Research Council (NRC), in an assessment of technologies available for NO_x control, estimated that EGR would be available by 1990, assuming use of electronic controls (13).

TABLE 1 Trade-Offs Between NO_x Emissions and Particulate Emissions, Hydrocarbon Emissions, and Fuel Consumption *(13)*

Emissions (g/bhph)			Fuel Consumption Penalty (%)
NO_x	Particulates[a]	Hydrocarbons	
8	0.4-0.5	0.6-0.8	0
6	0.5-0.7	0.7-1.4	2.5-4
4	0.6-1.0	0.8-1.7	7-12
2	-[b]	-[b]	15-20

Note: Data are for low-mileage emission levels, as measured by the transient test procedures. Data on NO_x emissions and fuel consumption are from the steady state test procedures for this purpose, the two tests are assumed equivalent.

[a]Particulate trap not included.

[b]Unknown; too few data are available to permit realistic estimates.

Associated with many of these NO_x control technologies are trade-offs in fuel economy and hydrocarbon emissions. Table 1 gives hydrocarbon and particulate emission levels and fuel consumption penalties that should be achievable in the mid-1980s at various NO_x emission levels. These estimates were developed in the NRC study (13) and are generally supported by the manufacturers (3-6). Only low-mileage targets are given in the table, and thus the estimates do not account for deterioration in emissions control with increasing use. Insufficient information is available for determining the appropriate standard. If appropriate deterioration factors and margins to accommodate engine-to-engine variability (based on data from current production engines) are assumed, the standards that could be met would be 1.2 to 1.4 times the low-mileage values given in the table. Only modest additional NO_x control can be achieved without fuel economy penalties or HC and particulate emission levels higher than those currently being achieved (13). In other words, a 4.0-g/bhph NO_x standard could not be achieved for HDDEs without (a) particulate traps to meet the 0.25-g/bhph particulate standard, (b) risking exceedence of the 1/3-g/bhph HC standard, and (c) a substantial fuel economy penalty. Finally, there are no data that show the technical feasibility of achieving the 1.7-g/bhph NO_x standard (13).

Unlike the case for NO_x control, only one major technology is anticipated for particulate control: a trap to intercept particulates in the exhaust. Traps are undergoing intensive development for light-duty diesel engines (LDDEs), and EPA assumed that a trap oxidizer with an efficiency of 60 percent would be available for HDDEs to meet the 0.25-g/bhph standard. The NRC study indicated that HDDE traps could be ready by 1990 (13). However, the feasibility of such HDDE traps in the near future is seriously questioned by the manufacturers. Because many HDDEs are turbocharged and are designed (for durability reasons) to have a lower exhaust temperature than that of LDDEs, the exhaust does not reach the temperatures required by the traps for self-cleaning (3,8). Furthermore, the maximum exhaust flow of an HDDE is much greater than that of an LDDE; the traps for HDDEs therefore must be much larger than those for LDDEs to ensure that undue increases in back pressure do not occur (3,8). Use of auxiliary heating for regeneration of large traps is considered very difficult for HDDEs; it is complicated by the need to apply heat evenly over a large surface (3,8).

Heavy-Duty Gasoline Engines

The major control problems for HDGEs are related to HC and CO emissions. However, some changes in emission controls in these engines can also be anticipated to meet the NO_x standard. (Control of particulates is not a concern with HDGEs.) NO_x levels from current HDGEs are above the 4.0-g/bhph standard on the EPA transient test cycle. Engine modifications and EGR will probably be used for NO_x control in all HDGEs. However, these technologies have also been suggested for HC and CO control in HDGEs, and trade-offs in control of the three pollutants exist. Furthermore, some of these technologies will affect fuel economy. For example, in several tests by manufacturers, EGR led to HC levels at or above 3.0 g/bhph (the standard for HDGEs is currently 1.9 g/bhph on the Motor Vehicle Manufacturers Association test cycle) and fuel economy losses of 6 to 8 percent as low-mileage NO_x targets of 3.0 and 3.3 g/bhph were approached or achieved, or both (6,8). The NRC study concluded that with both EGR and engine calibration, NO_x levels of 3.0 g/bhph could be achieved in vehicles with new engines, but with a 3 to 6 percent loss in fuel economy (13).

Comments

The manufacturers of HDDEs and HDGEs perceive greater difficulty in achieving the proposed NO_x and particulate standards than does EPA. EPA has been more optimistic than the manufacturers about development of emission control technologies, particularly particulate traps; EPA did not consider in its regulatory analysis the potential for increased HC emissions associated with NO_x control, and did not estimate the fuel economy loss associated with NO_x control. The manufacturers, concerned with fuel economy and emissions trade-offs and developmental problems, have proposed that the NO_x and particulate standards for HDGEs be substantially higher than EPA has proposed, that is, 6 to 10.7 g/bhph for NO_x and 0.6 to 0.8 g/bhph for particulates (3,4,6, 9,10 and letter with comments from J. Feiten of G.M. to M.K. Singh).

BENEFITS, COSTS, AND COST-EFFECTIVENESS OF STRINGENT NO_x AND PARTICULATE CONTROL

Emissions Reduction

Estimated total NO_x and particulate emissions attributable to heavy-duty trucks in 1980 (baseline), 1988 (first year of stringent standard), and 1995 (majority of fleet covered) under alternative NO_x standards are given in Table 2. Implementation of the 4.0-g/bhph NO_x standard would result in a 45 percent reduction in NO_x emissions in 1995 from those that would occur under the current 10.7-g/bhph standard. If this 10.7-g/bhph standard remains in effect, NO_x emissions attributable to heavy-duty trucks will increase by more than 50 percent between 1980 and 1995. If the lower standard is implemented, NO_x emissions from trucks will be reduced by 16 percent. Implementation of the 0.25-g/bhph particulate standard would similarly lead to a substantial reduction in particulate emissions from what would otherwise occur by 1995. Even with the standard, particulate emissions from HDDEs will increase slightly by 1995.

Emission factors for NO_x in g/mi used to develop these totals are given in Table 3. They are based on EPA's MOBILE2.5 emission factors (15,16), which take into account assumptions about the age distribution of the fleet, mileage driven per year, ambient atmospheric conditions, speed of operation, and changes in emission control performance over time. Emission factors for particulates used to develop Table 2 are 2.0 g/mi (no control) and 0.7 g/mi (controlled to 0.25 g/bhph) (17). Truck VMT used in the derivation of Table 2 values are given Table 4. Manufacturer weightclass sizes progress from Class IIB (Trucks of 8,501 to 10,000 lb gross vehicle weight) to Class VIII (all trucks of 33,000 lb gross vehicle weight and above). The VMT figures are derived from freight projections developed by ANL (M. Millar, unpublished information, 1983). Further documentation of the derivation of Tables 2-4 is provided by Singh and Saricks (11).

Cost and Cost-Effectiveness of NO_x Control

Estimates of per-vehicle capital costs and lifetime costs per mile increase in fuel consumption associated with NO_x control are given in Tables 5 and 6. The estimates are basically from EPA and NRC reports; manufacturers' cost estimates for NO_x control systems are generally not available (13,22). Within the HDD and HDG truck categories, capital costs and fuel penalties are not expected to vary with vehicle size (weight). Variation does occur in the lifetime cost estimates for increases in fuel consumption because of differences in lifetime vehicle-miles traveled (VMT) and vehicle fuel economy.

ANL, in its study of the cost and benefits of stringent NO_x control, independently evaluated the lifetime costs (both capital and operating) for heavy-duty trucks produced under a 4.0-g/bhph NO_x standard beginning in 1988. EPA's capital cost estimate for NO_x control in HDD trucks was assumed, although modified to assign 50 percent instead of 100 percent of the cost of electronic engine controls to emission controls; in addition, General Motor's (GM's) capital and maintenance cost estimate for HDG trucks was assumed at face value. A range of lifetime fuel penalties was assumed for HDD and HDG trucks to reflect the greatest ranges shown in these tables. Lifetime costs per 1%/mi increase in fuel consumption were determined to be lower than those in the NRC study due to lower lifetime mileage assumptions in the ANL study and differences in as-

TABLE 2 Estimated Total NO_x and Particulate Emissions from Heavy-Duty Trucks Under Alternative Standards for 1980, 1988, and 1995

	Particulates					NO_x				
	No Standard			0.25 g/bhph		10.7 g/bhph			4.0 g/bhph	
Vehicle Type	1980	1988	1995	1988	1995	1980	1988	1995	1988	1995
HDD	0.142	0.186	0.233	0.171	0.148	1.606	2.115	2.644	1.658	1.499
HDG	–[a]	–	–	–	–	0.537	0.545	0.616	0.453	0.302
Total	0.142	0.186	0.233	0.171	0.148	2.143	2.660	3.260	2.111	1.801

Note: Date are in 10^6 short tons.

[a]Virtually no particulates are emitted from HDGEs.

TABLE 3 Fleet Average NO_x Emission Factors for HDD and HDG Trucks by Year Under Alternative Standards *(11,15,16)*

Vehicle Type	Emission Factors (g/mi) by Year 1980	1988	1995
Standard: 10.7 g/bhph			
All HDD	22.70	22.70	22.70
All HDG	9.78	9.82	11.31
Standard: 4.0 g/bhph			
All HDD	22.70	17.79	12.87
All HDG	9.78	8.15	5.54

TABLE 4 Heavy-Duty Truck VMT by Class Size, Fuel Type, and Year *(11,18-20)*

Manufacturer Weight Class	VMT (10^9) by Year 1980	1988	1995
Vehicle Type: HDD			
IIB	0	0.923	2.135
III-V	0.248	1.039	2.495
VI	3.067	10.016	16.546
VII	4.042	4.816	5.609
VIII	56.841	67.737	78.888
Total	64.198	84.531	105.673
Vehicle Type: HDG			
IIB	19.861	25.105	27.608
III	3.729	5.565	6.676
IV-V	3.202	1.719	0.352
VI	19.701	16.537	14.101
VII	1.793	0.777	0.353
VIII	1.557	0.675	0.307
Total	49.843	50.378	49.397

Note: Data are also from M. Millar, ANL, 1983 unpublished information.

TABLE 5 Estimated Cost per HDD Truck to Meet 4.0-g/bhph NO_x Standard

Manufacturer Weight Class	Capital/ Maintenance Cost[a] ($)	Lifetime Fuel Penalty (%)	Lifetime Cost of a 1%/mi Increase in Fuel Consumption ($)	Total Lifetime Cost ($)
IIB	NA	NA	NA	NA
III-V	NA	NA	306[b]	NA
VI	NA	NA	342[b]	NA
VII-VIII	NA	NA	1,151[b]	NA
All	733[c]; 1,000[d]	7-12[b]; 9-14[e]	754[c]	NA

Note: Assumes 1.3-g/bhph HC standard and 15.5-g/bhph CO standard.
[a]Where applicable and available.
[b]NRC *(13)*; year of cost data is unknown.
[c]Ford Motor Co. *(22)*; cost data are given in $1980.
[d]Energy and Environmental Analysis *(12)*; cost data are given in $1981.
[e]Ford Motor Co. *(21)*.

sumed fuel economies and price of fuel. The results of this analysis on a lifetime cost increase (¢/mi) basis are given in Table 7. Lifetime cost increases, which are largely due to fuel consumption increases, are higher on a per-mile basis for larger trucks in both HDD and HDG categories. Lifetime cost increases are larger for HDD trucks than for HDG trucks.

ANL estimated the overall cost-effectiveness of the 4.0-g/bhph NO_x standard by using these lifetime cost increases, estimates for VMT by trucks

TABLE 6 Estimated Cost per HDG Truck to Meet 4.0-g/bhph NO_x Standard

Manufacturer Weight Class	Capital/ Maintenance Cost[a] ($)	Lifetime Fuel Penalty (%)	Lifetime Cost of a 1%/mi Increase in Fuel Consumption ($)	Total Lifetime Cost ($)
IIB	NA	NA	NA	NA
III	NA	NA	258[b]	NA
IV-V	NA	NA	258[b]	NA
VI	NA	NA	293[b]	NA
VII	NA	NA	550[b]	NA
VIII	NA	NA	550[b]	NA
All	70[c]; substantially less than 279[d]	3-7[b]; 8[e]	150[d]	1,220[c]

Note: Assumes (a) for Class IIB-III, 1.3-g/bhph HC and 15.5-g/bhph CO standard, and (b) for Class IV-VIII, 2.5-g/bhph HC standard and 40.0-g/bhph CO standard.
[a]Where applicable and available.
[b]NRC *(13)*; year of cost data is unknown.
[c]General Motors *(8)*.
[d]EPA *(22)*; cost data are given in $1980.
[e]Ford Motor Co. *(21)*.

TABLE 7 Lifetime Cost Increases Because of NO_x Control to 4.0 g/bhph

Manufacturer Weight Class	Cost Increases (¢/mi) by Vehicle Type HDD	HDG
IIB	1.2-1.9	0.4-1.1
III-V	1.7-2.8	0.6-1.5
VI	1.7-3.0	0.8-1.9
VII	1.7-3.1	0.9-2.4
VIII	1.8-3.4	1.0-2.5

meeting the 4.0-g/bhph NO_x standard in 1988 and 1995, and the ANL estimates of total NO_x removal that were due to this standard; these results are given in Table 8. The total cost of NO_x control, total NO_x reduction, and cost/ton reduced is greater for HDD trucks than for HDG trucks. However, if the higher lifetime cost estimates for HDG trucks and the lower lifetime cost estimates for HDD trucks were the more accurate estimates, respectively, cost/ton removed could be higher for HDG trucks in both years.

Cost and Cost-Effectiveness of Particulate Control

Considerable difference exists between EPA and some manufacturers over the costs of particulate traps. EPA estimated that the retail price of each HDD truck would increase by $527 to $650 ($ 1980) because of the particulate trap (17). Alternatively, Caterpillar Tractor Company estimated the cost of the trap to be at least $2,000, and GM from $2,000 to $3,500 ($ 1982) (3,8). This wide variation is not easy to explain, but may in part reflect different assumptions regarding research and development costs. Further, EPA expects maintenance costs to be reduced with use of a trap, while Caterpillar does not (3,22). Finally, EPA does not project fuel economy loss with traps, while the manufacturers project at least a 1 percent loss.

Because of this wide variation in cost estimates, ANL assumed in its study a range of costs reflecting EPA's estimates at the low end and Caterpillar's and GM's at the high end. Table 9 gives these assumptions and the resulting cost/mile. By using these results, together with estimates of VMT driven by

TABLE 8 Cost-Effectiveness of NO_x Control to 4.0 g/bhph

Vehicle Type	NO_x Benefit (10^6 tons) 1988	1995	Total Cost for NO_x Removal ($\$10^6$) 1988	1995	Cost/Ton ($1982) 1988	1995
HDD	0.457	1.145	188-352	1,047-1,945	411-470	914-1,699
HDG	0.092	0.314	27-69	197-505	293-750	627-1,608
Total	0.549	1.459	215-421	1,245-2,450	392-767	853-1,679

TABLE 9 ANL Cost Estimates per HDD Truck to Achieve 0.25-g/bhph Particulate Standard

Manufacturer Weight Class	Capital Cost ($)	Lifetime Fuel Cost ($)	Maintenance Savings ($)	Net Cost[a] ($)	Lifetime Cost Increase (¢/mi)
IIB	539-645	0-104	0-308	231-749	0.21-0.68
III	539-645	0-175	0-308	231-820	0.21-0.74
IV	539-2,000	0-175	0-308	231-2,175	0.21-1.98
V	617-2,000	0-175	0-402	215-2,175	0.20-1.98
VI	617-3,500	0-355	0-402	215-3,855	0.12-2.08
VII	663-3,500	0-370	0-438	225-3,870	0.12-2.09
VIII	655-3,500	0-662	0-519	136-4,162	0.05-1.44

Note: Costs are expressed in $1982.
[a]Capital cost + lifetime fuel cost - maintenance savings.

trucks meeting the 0.25-g/bhph standard and the ANL estimates of total particulate removed because of the standard, ANL also estimated the overall cost-effectiveness of the proposed particulate standard. The estimated cost/ton of particulate removed ranges from $427-$1,059 in 1988 to $461-$10,778 in 1995. The high estimates are 6 to 14 times as high as the corresponding estimates for NO_x control presented previously.

Summary: Cost of NO_x and Particulate Control

Estimates of the cost-effectiveness of total potential additional emission control (particulates and NO_x combined) for both HDD trucks and HDG trucks are given in Table 10. Emission-control costs for HDD trucks are significantly higher than those for HDG trucks, although additional costs will be associated with HC and CO control from HDG trucks. Over the life of a Class IIB or Class III HDG truck, EPA estimates that these costs will range from $400 to $900/ton (23). Although these figures are not directly additive to those in Table 10, it is clear that when all control costs are combined, the cost/ton of emission removal from the HDD fleet is greater than that from the HDG fleet.

TRUCKS AND AIR QUALITY IN CITIES: A CASE STUDY

Raw estimates of total emissions reduction, as presented previously, have little to do with the primary purpose of air quality standards, that is, the protection of public health. To focus more selectively on the effectiveness of emission controls on heavy-duty trucks in reducing the threat to public health represented by ambient pollutants, the impact of these controls on reducing ambient NO_x in two high-volume traffic corridors was evaluated. Dispersion of NO_x in these corridors was simulated and potential exposure to NO_x was evaluated.

Traffic Corridors

The choice of prototypical truck traffic corridors for a comparative air quality analysis was governed by availability of data and proximity of the research team to candidate sites. On both counts, locations in the Chicago standard metropolitan statistical area proved superior to other alternatives. Chicago has long been a hub of national freight movement, with extensive inter- and intramodal cargo transfer occurring around the clock. According to D.A. Zavattero, baseline (1975) data on heavy-duty truck movements in the Chicago area had been obtained from the Chicago Area Transportation Study (CATS) (personal communication, September 1983), together with forecasts of local heavy freight activity that included identification and targeting of roadway corridors where extensive movement of commercial goods is expected in the future (24). The researchers' location in relation to these corridors facilitated field surveillance of candidate locations and final selection of those that appeared to be both representative and of interest because of the presence of sensitive receptors. An expressway corridor and an

TABLE 10 Cost-Effectiveness of Particulate Control to 0.25 g/bhph and NO_x Control to 4.0 g/bhph

Vehicle Type	Particulate Control 1988	1995	NO_x Control 1988	1995	Total 1988	1995
HDD	427-10,592	461-10,778	411-770	914-1,699	838-11,362	1,375-12,477
HDG	NA	NA	293-750	627-1,608	293-750	627-1,608

Note: Costs are expressed in $/ton removed; NA = not applicable.

arterial corridor that contains a major intersection were chosen for microscale air quality simulation.

The central feature of the expressway corridor is an elevated, mile long segment of urban freeway constructed to Interstate system standards. (The segment is actually a link of the Interstate network.) Three lanes of traffic in each direction are separated by a median at least 15 ft wide; alignment is roughly west-southwest to east-northeast. The corridor itself is largely industrial, but the freeway passes over surface streets along which commercial and industrial premises house employees throughout the workday; the closest establishment is 88 lateral meters from the edge of the freeway (25). Numerous heavy-truck trips originate and terminate in this corridor daily.

The arterial corridor is functionally linked to the expressway corridor with respect to the origin-destination points for much of the heavy-duty truck traffic; many of Chicago's intercity truck freight terminals (important break-in-bulk points) are north of this corridor. Considerable truck traffic is channeled along the corridor between these terminals and the heavy-industry districts of western and southeastern Chicago. A key intersection in this corridor is heavily used by commercial traffic turning east toward destinations in southern and southeastern Chicago and north toward the truck terminals and expressway system. This intersection historically has experienced high volumes of heavy-truck movement, and these are expected to continue.

Dispersion Analysis

The CALINE-3 model, developed by the California Department of Transportation and endorsed by EPA for microscale simulation, was used in the dispersion analysis. Because NO_x dispersion was to be simulated, the molecular weight of the pollutant species (hard-coded for CO) was changed from 28 to 46 (NO_x as NO_2) before source compilation. The result did not take into account the reactivity of NO_x species, but carried the assumption that chemical reduction of NO_2 has a negligible effect in the estimation of short-term (<1 hr) concentrations from local emission sources.

The baseline truck network assignment performed by CATS (for which link and turn volumes were graciously provided to the ANL researchers) had generated heavy-truck flow volumes for the study corridors; these were converted to percentages of average daily traffic based on total traffic data (25). The results were used to weight the heavy-duty portion of the 1987 and 1992 time-of-day VMT fractions used by the Illinois EPA in its 1982 NO_2 analysis (26). It was assumed that 1987 splits would reasonably approximate the 1988 simulated distribution and that 1992 splits would serve as a reasonable surrogate for 1995. The sum of the relevant VMT fractions for arterials or freeways in each year (for both HDG and HDD trucks) was multiplied by a factor that made it equivalent to the appropriate value above; all fractions were then renormalized to reflect the revised heavy truck share. Off-peak splits were used because of the higher truck share of off-peak volume. Table 11 presents a summary of the simulation inputs used by MOBILE2.5 and CALINE-3.

Results: Hourly Exposures for Worst-Case Conditions

For the case in which current heavy-duty emission standards are retained through 1995, short-term (hourly average) NO_x exposures undergo no significant reduction throughout the period in the arterial corridor. Exposures to total NO_x species in the roadway itself in 1988 range from about 220 $\mu g/m^3$ (250 ft from the intersection) to 425 $\mu g/m^3$ (in a vehicle actually stopped at the intersection), while exposure at the sensitive-receptor distance from the roadway can reach as high as 400 $\mu g/m^3$ near the interection. By 1995, the corresponding roadway concentration range is 225 to 440 $\mu g/m^3$, and sensitive-receptor exposure is up to 415 $\mu g/m^3$. (Note that NO_2 accounts for 30 to 70 percent of total NO_x.)

Under the same set of heavy-duty standards, the expressway corridor experiences a modest improvement

TABLE 11 Emission and Dispersion Model Inputs

Input	Freeway Corridor	Arterial Corridor
Road azimuth (degrees)	70	Link A: 180 Link B: 90
Link length (m)	1700	Link A: 600 Link B: 300
Wind azimuth (degrees)	185	120
Wind speed (m/s)	1.5	1.5
Stability class	D (urban)	D (urban)
Mixing height (m)	1500	1500
Mixing-cell width (m)	42	31
Background NO_x (ppm)	0.04 (75 $\mu g/m^3$)	0.03 (66 $\mu g/m^3$)
Surface roughness, settling velocity, deposition velocity	0,0,0	0,0,0
Source height (m)		
Above roadway	0.6	0.6
Above datum	9.8	0.6
Receptor heights (m) (above datum)	1.8 (on surface street) 11.0 (on expressway)	1.8
Ambient temperature (°F)	54	54
Altitude (ft)	1,000	1,000
Region	49 states	49 states
Cold-start percentage	38.5	18.5
Composite emission factor (g/mi) from MOBILE2.5		
1988 current	5.6	3.8
1988 stringent	5.1	3.3
1995 current	5.4	2.8
1995 stringent	3.4	1.9
Heavy-duty truck traffic as percentage of average daily traffic	10.6	Link A: 11.7 Link B: 21.3
Bidirectional daytime off-peak average hourly traffic volume	7,800	Link A: 2,500 Link B: 2,200

in worst-case NO_x from 1988 to 1995, but this is due primarily to reduction in NO_x emissions from automobiles. In 1988, conditions appear to be potentially serious: exposures to total NO_x species of more than 930 μg/m³ in the roadway itself (a vehicle occupant could be caught in this situation for 15 to 30 min, depending on traffic), with the sensitive-receptor location on the surface street experiencing up to 415 μg/m³ as the 1-hr average. By 1995, peak exposure has declined to 900 μg/m³ in the roadway and 405 μg/m³ at the receptor. It appears in both cases that the relatively high truck emissions are neutralizing the gains in air quality that otherwise would be achieved in these corridors by the current (or impending) tighter controls on light-duty cars and trucks.

Under the stringent (4.0-g/bhph) NO_x standard for heavy trucks commencing with the 1988 model year, significant reductions are seen in both the arterial and expressway corridor. By 1995, hourly NO_x exposures in excess of 280 μg/m³ in the arterial corridor are confined to the roadway itself, in the immediate vicinity of the intersection. Peak exposures on the expressway have fallen to about 600 μg/m³ and to 280 μg/m³ at the sensitive receptor. Exposure levels under this stringent standard represent a 21 to 35 percent reduction in these corridors by 1995 from exposure levels experienced under the 10.7-g/bhph standard. If high NO_x exposure risks exist today in these corridors, they should diminish significantly or (in the case of the arterial) vanish by 1995 under stringent NO_x control for heavy trucks.

Table 12 presents the modeled concentrations at representative receptor points in each corridor for each year and each emission control stringency case.

Case-Study Conclusions

Two general conclusions can reasonably be drawn from the corridor analysis:

1. The current standard (10.7 g/bhph) would, if left in place, produce an apparent retention of status quo conditions in each of the corridors. That is, the reduced NO_x emissions of the light-duty fleet will, over time, only balance the increased NO_x emissions from heavy-duty trucks because of increased numbers of trucks and (possibly) deterioration of emission control equipment. It should therefore be concluded that, if there is a problem today, it will persist into the future.

2. Stringent NO_x control standards (4.0 g/bhph) for heavy-duty trucks result in a significant net improvement in the arterial corridor. Potential peak NO_x exposures in the expressway corridor are reduced but remain very high.

In addition, although NO_x emissions from heavy-duty vehicles have been shown to be substantial, it has not been established how or whether this gaseous effluent is borne aloft to the upper troposphere. Because these emissions cannot be traced (with current modeling processes) to a substantial distance from their point of origin without considerable conjecture about their buoyancy, it is not yet clear what beneficial effect the stringent NO_x control standards for heavy-duty trucks would actually have in reducing acid precipitation precursor emissions, or if such standards would even constitute an effective ozone control strategy.

CONCLUSIONS

The case for stringent emission controls for heavy-duty trucks is not well grounded in the argument of improved air quality. There are few areas today exceeding the ambient NO_2 standard; retention of the current heavy-duty truck emission standard alone would apparently lead to no net degradation of NO_2. Furthermore, any other grounds, such as reduction of acid rain precursors, are only tenuous if heavy-duty vehicles are considered in isolation. The costs of stringent control are high; whatever justification--beyond the letter of the law--is finally put forward, the ultimate attributable costs of such controls are far from being a bargain.

ACKNOWLEDGMENTS

The study on which this paper is based benefited from the participation of many individuals, and we would like to thank all those who provided information and reviewed our analysis. In particular we

TABLE 12 Modeled Hourly Average NO_2 Concentration at Selected Receptors

	NO_2 Concentration (μg/m³)			
	1988		1995	
Corridor	Current Standard	4.0-g/bhph Standard for Model-Year 1988	Current Standard	4.0-g/bhph Standard for Model-Year 1988 and Later
Expressway				
Median	811	698	787	527
Downwind lanes	938	806	910	605
Upwind lanes	734	633	713	480
Northeast terminus of link (street level)	523	455	509	351
Sensitive receptor	415	363	404	284
Roadway edge (street level)	465	405	453	315
365 m from roadway (street level)	226	203	221	168
Arterial[a]				
Link A; southbound vehicle stopped for left turn	421	374	438	309
Link A; southbound vehicle 75 m north of intersection	302	274	311	228
Link A; northbound vehicle 75 m north of intersection	268	243	277	206
30 m west of intersection	196	179	200	153
Link B; 30 m east of intersection on north side of street: sensitive receptor	302	268	315	223
30 m east of A, 100 m north of B	132	121	136	108

[a] A is the north-south link; B is the east-west link.

would like to thank D.O. Moses, U.S. Department of Energy, Project Officer, whose continuing support has been invaluable.

REFERENCES

1. U.S. Environmental Protection Agency. Control of Air Pollution from New Motor Vehicles and New Motor Vehicle Engines: Particulate Regulation for Heavy-Duty Diesel Engines (Notice of Proposed Rulemaking). 46 Fed. Reg. 1910, Jan. 7, 1981.
2. U.S. Environmental Protection Agency. Control of Air Pollution from New Motor Vehicle Engines: Gaseous Emission Regulations for 1985 and Later Model Year Light-Duty Trucks and 1986 and Later Model Year Heavy-Duty Engines (Advance Notice of Proposed Rulemaking). 46 Fed. Reg. 5838, Jan. 19. 1981.
3. Caterpillar Tractor Co. Response to EPA Advance Notice of Proposed Rulemaking for Gaseous Emission Regulations for 1985 and Later Year Light-Duty Trucks and 1986 and Later Model Year Heavy-Duty Engines and EPA Notice of Proposed Rulemaking for Particulate Regulation for Heavy-Duty Diesel Engines. Public Dockets A-80-31 and A-80-18. U.S. Environmental Protection Agency, Washington, D.C., Sept. 9, 1982.
4. International Harvester. Final Response to the Environmental Protection Agency's Notice of Proposed Rulemaking for Particulate Regulations for Heavy-Duty Diesel Engines and Advance Notice of Proposed Rulemaking for Gaesous Emission Regulations for 1985 and Later Year Light-Duty Trucks and 1986 and Later Model Year Heavy-Duty Engines. Public Dockets A-80-31 and A-80-18. U.S. Environmental Protection Agency, Washington, D.C., 1982.
5. Motor Vehicle Manufacturers Association. Submittal to Public Dockets A-80-31 and A-80-18. U.S. Environmental Protection Agency, Washington, D.C., 1982.
6. Ford Motor Co. Response to the Environmental Protection Agency on the Control of Particulate Emissions from Heavy-Duty Diesel Engines and NO_x Emissions from Light-Duty Trucks and Heavy-Duty Engines. Public Dockets A-80-31 and A-80-18. U.S. Environmental Protection Agency, Washington, D.C., Sept. 13, 1982.
7. Engine Manufacturers Association. Submittal to Public Dockets A-80-31 and A-80-18. U.S. Environmental Protection Agency, Washington, D.C., Sept. 19, 1982.
8. General Motors. Submittal to Public Dockets A-80-31 and A-80-18. U.S. Environmental Protection Agency, Washington, D.C., Sept. 13, 1982.
9. Cummins. Submittal to Public Docket A-80-31. U.S. Environmental Protection Agency, Washington, D.C., Sept. 16, 1982.
10. Mack Trucks, Inc. Response to the Environmental Protection Agency's Notice of Proposed Rulemaking for Particulate Regulations for Heavy-Duty Diesel Engines and the Advance Notice of Proposed Rulemaking for Gaseous Emissions Regulations for Heavy-Duty Diesel Engines. Public Dockets A-80-31 and A-80-18. U.S. Environmental Protection Agency, Washington, D.C., Nov. 10, 1982.
11. M.K. Singh and C.L. Saricks. Effectiveness, Benefits, and Costs of More-Stringent Nitrogen Oxide and Particulate Emission Controls for Heavy-Duty Trucks. Report ANL/EES-TM-273. Argonne National Laboratory, Argonne, Ill., Nov. 1984.
12. Auto Industry Response to Alternative Environmental Standards (Automobile and Truck Efficiency) Final Report. Energy and Environmental Analysis, Inc., Arlington, Va., March 1982.
13. NO_x Emission Controls for Heavy-Duty Vehicles: Toward Meeting a 1986 Standard. Motor Vehicle Nitrogen Oxides Standard Committee, Assembly of Engineering, National Research Council, Washington, D.C., 1981.
14. U.S. Environmental Protection Agency. Control of Air Pollution from New Motor Vehicles and New Motor Vehicle Engines: Gaseous Emission Regulations for 1984 and Later Model Year Heavy-Duty Engines. Final Rule. 45 FT 4136, Jan. 21, 1980.
15. User's Guide to Mobile2 (Mobile Source Emissions Model). Report EPA-460/3-81-006. U.S. Environmental Protection Agency, Ann Arbor, Mich., Feb. 1981.
16. Motor Vehicle Emission Standards for Carbon Monoxide and Nitrogen Oxides. Office of Mobile Source Air Pollution Control, U.S. Environmental Protection Agency, Washington, D.C., June 1981.
17. Draft Regulatory Analysis, Heavy-Duty Diesel Particulate Regulations. Office of Mobile Source Air Pollution Control, U.S. Environmental Protection Agency, Washington, D.C., Dec. 23, 1980.
18. Truck Inventory and Use Survey. Report TC77-T-52. U.S. Department of Commerce, May 1980.
19. Energy and Environmental Analysis, Inc. The Highway Fuel Consumption Model: Ninth Quarterly Report. Report DOE/PE/70045-1. U.S. Department of Energy, Feb. 1983.
20. MVMA Facts and Figures. Motor Vehicle Manufacturers Association of the United States, Inc., Detroit, Mich., 1983.
21. Ford Motor Co. Response to Revised Gaseous Emission Regulations for 1984 and Later Model Year Light-Duty Trucks and Heavy-Duty Engines. Public Dockets A-80-31 and A-80-18. U.S. Environmental Protection Agency, Washington, D.C., 1982.
22. Draft Regulatory Analysis, Environmental Impact Statement and NO_x Pollutant Specific Study for Proposed Gaseous Emission Regulations for 1985 and Later Model Year Light-Duty Trucks and 1986 and Later Model Year Heavy-Duty Engines. Office of Mobile Source Air Pollution Control, U.S. Environmental Protection Agency, Washington, D.C., Nov. 5, 1980.
23. Issue Analysis--Final Heavy-Duty Engine HC and CO Standards. Office of Mobile Source Air Pollution Control, U.S. Environmental Protection Agency, Washington, D.C., March 1983.
24. J.W. Behrens et al. Recommendations for the Chicago Area Freight System for 1995. Chicago Area Transportation Study Report No. 364-08. Illinois Department of Transportation, Chicago, Feb. 1974.
25. State Implementation Plan for Air Pollution Control: 1982 Plan Revision for Ozone and Carbon Monoxide. Illinois Environmental Protection Agency, Springfield, June 1982, pp. V-45 to V-54.
26. A Reanalysis of the Effect of U.S. EPA Proposals to Relax Vehicle Emission Standards on Chicago Air Quality: Three Studies and a Summary. Illinois Environmental Protection Agency, Springfield, April 1982, p. B-20.

Publication of this paper sponsored by Committee on Transportation and Air Quality.

Effect of a Noise Wall on Snow Accumulation and Air Quality

J. KIRBY LIDMAN

ABSTRACT

A noise wall was investigated to assess its effect on snow accumulation and air quality. Wind tunnel studies were undertaken to evaluate (a) possible snow accumulations and (b) the dispersion of particulate concentrations (dust, smoke, and lead particles) and carbon monoxide. Full-scale monitoring of particulate concentrations and carbon monoxide was performed both before and after the noise wall was constructed. The wind tunnel experiments for snow accumulation were conducted on a model wall located in a flat, unobstructed area. A separated flow zone existed upwind of the wall and snow immediately began to accumulate over most of the separated zone. Having the noise wall in an aerodynamically rough area, such as in an urban area as this one was, substantially decreased the amount of snow collected, compared with in the wind tunnel studies, because of turbulence reducing the separation zone. The snow accumulation has not been significantly greater with the noise wall in place than it was before construction and has proven to be of no concern to date. Monitoring for particulate concentrations has shown that the noise wall has had a beneficial effect because the amount of material collected was reduced. With the noise wall in place, monitoring for carbon monoxide has indicated that (a) for equivalent emissions under conditions of high atmospheric stability and low wind speeds, the carbon monoxide levels would be lower; and (b) under conditions of low atmospheric stability and high wind speeds, the carbon monoxide levels would be higher than expected without the wall in place.

Iowa's first Type II (retrofit) noise wall has been effective as a traffic noise screen. However, at an initial public information meeting before construction had taken place, some concern was expressed about the effect that the proposed noise wall would have on snow accumulation and air quality (1). An assessment of the effect of the noise wall on snow accumulation and air quality in the vicinity of the wall is given in this paper.

Figure 1 is a map showing the location of the project in relation to the Des Moines metropolitan area. A steel wall was constructed on the east side of the I-235 Freeway on a general north-south alignment between Easton Boulevard and Guthrie Avenue in Des Moines. The wall consists of steel H beams placed at 16-ft intervals with 16-in. by 16-ft corrugated interlocking steel panels attached to the steel beams by self-tapping screws. These steel panels are coated with a polyvinylflouride film to make the wall corrosion resistant. The wall is 1,055 m long and varies in height 4 to 5 m along the major portion of its length. At its nearest locations, the wall is 1 to 2 m from the shoulder of the highway; therefore, a guardrail is required on the highway side of the wall. The backyards of numerous residences are adjacent to the wall.

Aerodynamics of a Wall

According to aerodynamic theory, air flow near an exposed wall on the downwind side is said to separate and form aerodynamic eddies and cavities that may concentrate airborne material such as snow or pollutants in localized regions, as shown in Figure 2. On the upwind side, a separated zone also exists, and material will tend to settle in this region. The extent to which separation occurs depends principally on wind speed, wind direction, and turbulence. On the highway side of a wall, moving vehicles create air turbulence, thoroughly mixing pollutants or snow, or both, with flowing air and greatly reducing the separation zones. On the residential side of the wall, buildings, vegetation, and other obstructions to smoothly flowing air create turbulence, again mixing any pollutants or snow, or both, with air flow and reducing the separation zones.

METHODOLOGY: WIND TUNNEL

A wind tunnel is a useful and convenient experimental facility for providing any wind speed and wind direction by rotating a model of the object under investigation within the tunnel. The Iowa Department of Transportation constructed a model wall approximately 6.35 cm high, placed it on a turntable 76 cm in diameter, and installed it in an Iowa State University wind tunnel. Material representing snow or smoke as pollutants was introduced near the model wall to permit visualization of the air flow and the patterns of drifting snow. A schematic of the wind tunnel and model for the experiments is shown in Figure 3.

WIND TUNNEL STUDIES OF THE EFFECT OF A SOLID WALL ON ACCUMULATING SNOW

The model of the wall, as previously described, spanned the entire wind tunnel floor and thus the experiments represented a two-dimensional flow, that

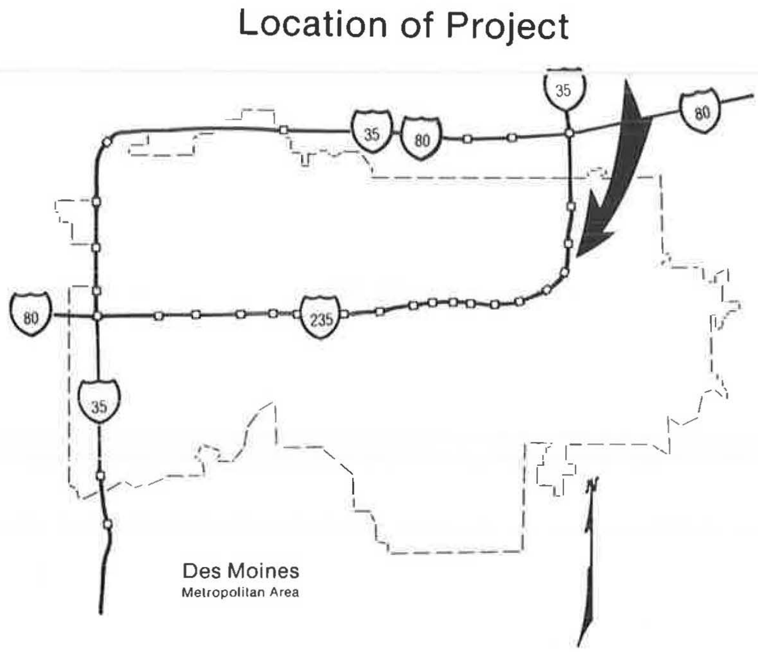


FIGURE 1 Location of the noise wall project.

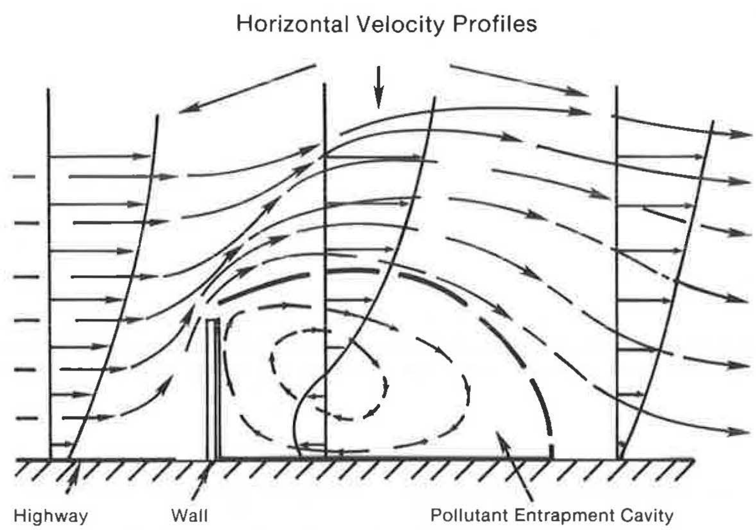


FIGURE 2 Velocity profiles. Note: Upwind of wall, a favorable pressure gradient exists and flow accelerates. Downwind, an adverse pressure gradient exists during deceleration, flow separates at top of wall, flow reverses, and aerodynamic eddies are formed. Size of cavity is dependent on wind speed and wind direction.

is, the results were similar to the snow accumulations resulting from the central portion of a very long wall. The model city was not used for these experiments. The wind direction was normal to the wall and wind speeds for Experiment 1 was 4.9 m/sec and for Experiment 2 was 3.9 m/sec. Full-scale wind speeds would be three times those values and correspond to 33 mph and 24 mph, respectively.

Nearly all of the snow accumulations were deposited on the windward (upwind) side of the wall, which is typical of a tall solid wall without a bottom gap. Eventually, the space to windward will drift full to a windward drift length (normal to wall) of approximately 10 times the wall height and then the leeward (downwind) side will start to collect drifted material, again eventually to a drift length of 10 times the wall height (James D. Iverson, unpublished data, 10/2/79). However, the experiments were not continued long enough to accumulate much leeward drift. Figures 4 and 5 show the timewise accumulation of drift area in plan. A separated flow exists upwind of the wall and immediately material starts to accumulate over most of the separated zone, demonstrated by the sharp increase in plan area for early time in Figure 4. As shown in Figure 4, material accumulates more rapidly for the higher wind speeds.

Figure 5 shows the accumulated upwind drift area as a function of dimensionless time. Note that the data from the two different wind speeds effectively

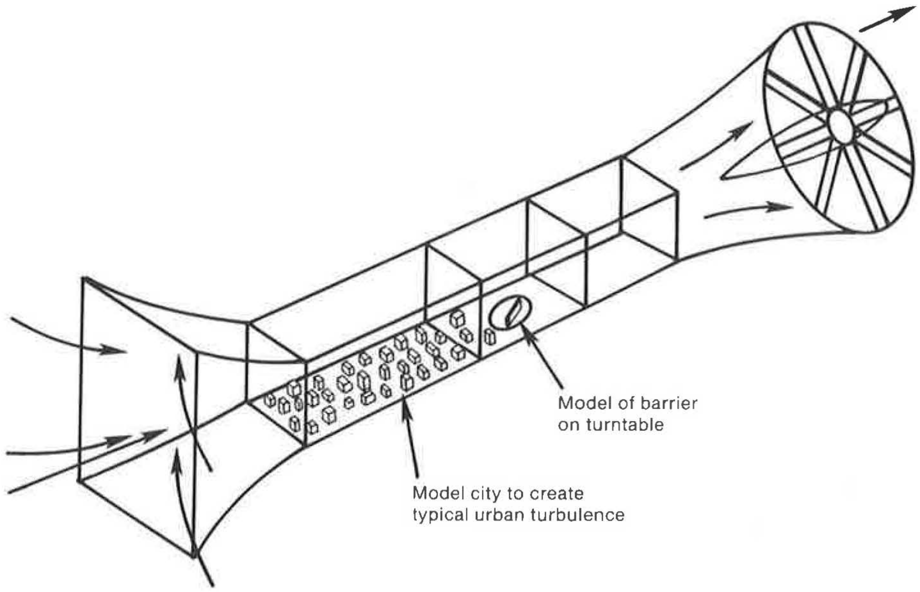


FIGURE 3 Schematic of wind tunnel and model for experiments.

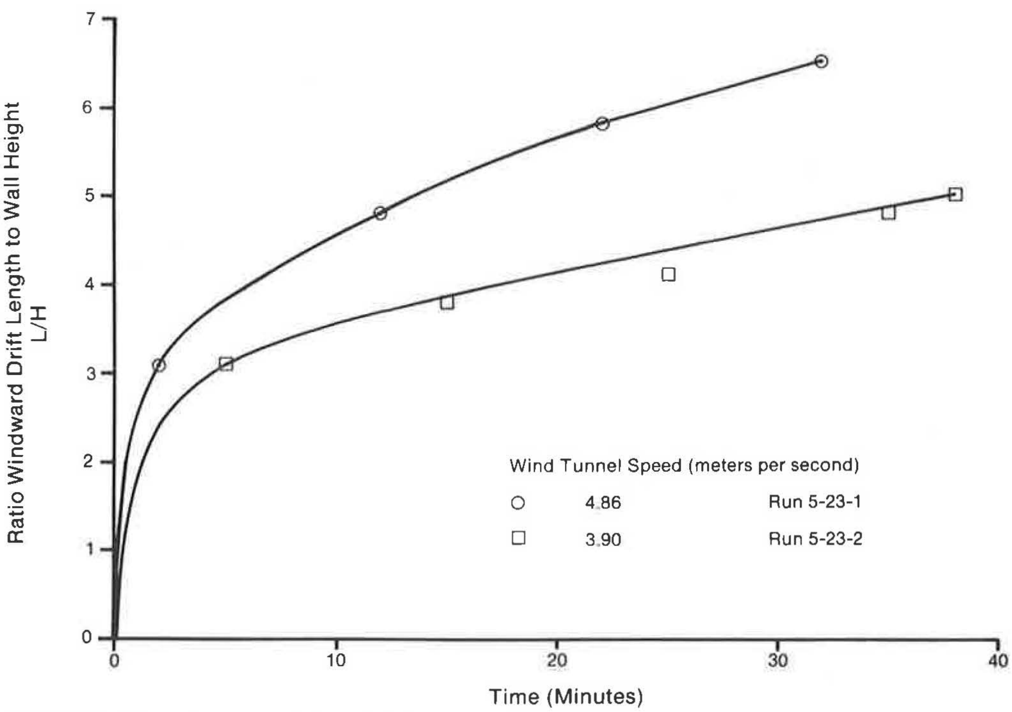


FIGURE 4 Timewise accumulation of drift area in plan.

collapse into one curve. The ratios of full-scale to model time for the two experiments are predicted to be 9.93 for Run 5-23-1 and 10.04 for Run 5-23-2. Thus, Run 5-23-1 corresponds to a full-scale storm with wind speeds of 32 mph lasting 5 hr, 18 min and Run 5-23-2 corresponds to a storm with wind speeds of 24 mph lasting 6 hr, 22 min.

Although the experiments were not continued until equilibrium drift capacity, a significant amount of drifted material was accumulated upwind of the wall, as shown in Figure 6. The experiments correspond to a wall located in a flat unobstructed area. Placing the wall in the middle of an aerodynamically rough area would decrease the amount of material accumulated.

CONCLUSIONS OF THE EFFECT OF A SOLID WALL ON ACCUMULATING SNOW

The wall is located in a relatively flat urban area consisting of many buildings and a significant amount of vegetation, including many trees of substantial size. Snow accumulations have not been a concern in the 4 years since construction of the wall. Apparently, the turbulence created by the aerodynamic roughness of the area and the moving vehicles on the freeway have prevented any substantial drifting, as might be expected from the results obtained from the wind tunnel experiments. A number of snow storms have occurred in the Des Moines area since construction of the wall, although probably not of the in-

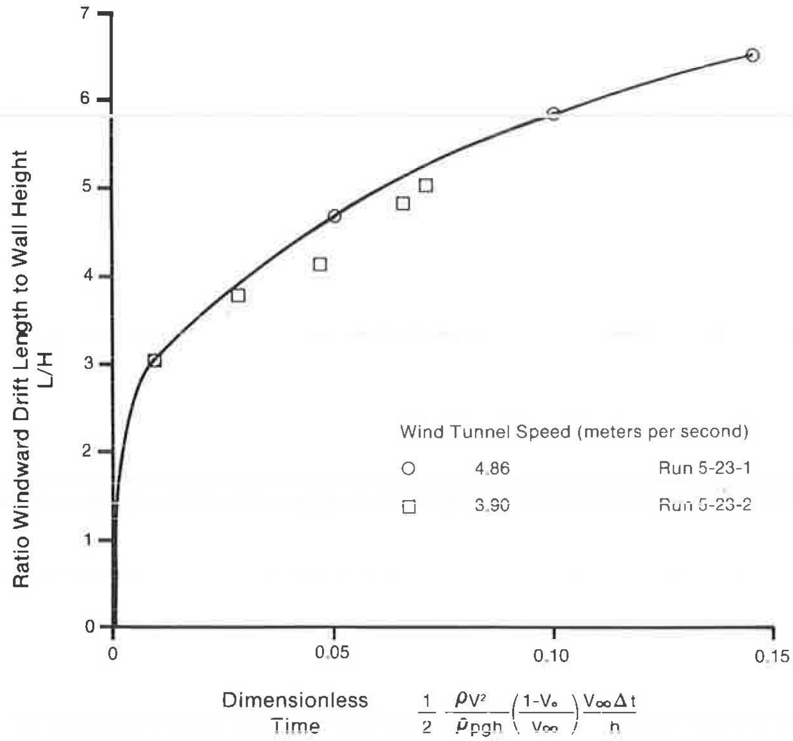


FIGURE 5 Accumulated upwind drift area as a function of dimensionless time.

tensity modeled in the wind tunnel. The wind tunnel results should probably be considered a conservative baseline estimate of what could be possible under extreme conditions.

WIND TUNNEL STUDIES OF THE EFFECT OF A SOLID WALL ON AIR QUALITY

The model of the wall was placed in the wind tunnel, as shown in Figure 3. Smoke was introduced into the tunnel near the model to permit visualization of the flow; qualitative testing was then performed at various speeds and wind directions. (Models of buildings were located within the tunnel upwind of the wall to create turbulence that is found in a typical urban situation.) A number of photographs were taken; examples are shown in Figures 7-10. In general, the flow patterns as depicted in Figure 2 were confirmed, that is, aerodynamic eddies or vortices and cavities are present downwind of a wall under certain conditions; therefore, entrapment and concentration of pollutants near walls are a distinct possibility, especially for certain wind speeds and wind directions.

AIR-QUALITY MONITORING

Because the wind tunnel studies indicated a possibility of increased air pollutant concentrations when the wall was in place and because of the concern brought out at the initial public information meeting that the wall would have an adverse effect on general air movements and dispersion of exhaust emissions from the I-235 Freeway, a small-scale research project was proposed to monitor the air quality before and after construction and to evaluate the results.

The primary air pollutants from the internal combustion engine are carbon monoxide, hydrocarbons, oxide of nitrogen, lead, and other particulates--primarily dust and smoke. A steady stream of moving vehicles on a highway constitute a line source of these pollutants. The air turbulence created by the moving vehicles thoroughly mixes the pollutants with air. The region where this occurs is called the mixing cell, the limits of which are defined and confirmed by studies to be approximately twice the height of the average vehicle in the vehicle mix (approximately 4 m), the width of the highway, including medians up to 9 m wide, and 3 m on each side of the highway to account for horizontal turbulence; the ambient pollutant level is excluded. The uniform well-mixed pollutant source contained in the mixing cell is then dispersed downwind. This definition of the mixing cell is shown in Figure 11 for a typical carbon monoxide concentration level pattern.

Monitoring for carbon monoxide entailed the use of four portable carbon monoxide monitors calibrated using the Des Moines nondispersive infrared monitoring unit. A meteorological bivane was used for wind speed and wind direction. Strip-chart recording instruments were interfaced with the monitors and a climate-controlled trailer was used to house the instrumentation.

Preconstruction monitoring for carbon monoxide began on July 1, 1979. The climate-controlled trailer was positioned near the midpoint of the proposed noise wall location. The intakes, connected to the monitoring units with polyvinyl tubing, were located at the right-of-way fence--the proposed location of the wall--and at distances of 5, 15, and 23 m from the fence at a height of 2 m.

In addition to carbon monoxide dispersion, particulate (dust, smoke, and lead particles) concentrations arising from the freeway were also of concern in relation to the effects of the noise wall. This type of pollutant was measured by two high-volume samplers, an instrument that draws a 24-hr sample of known volume through a filter of predetermined weight. The amount of particulates retained on this

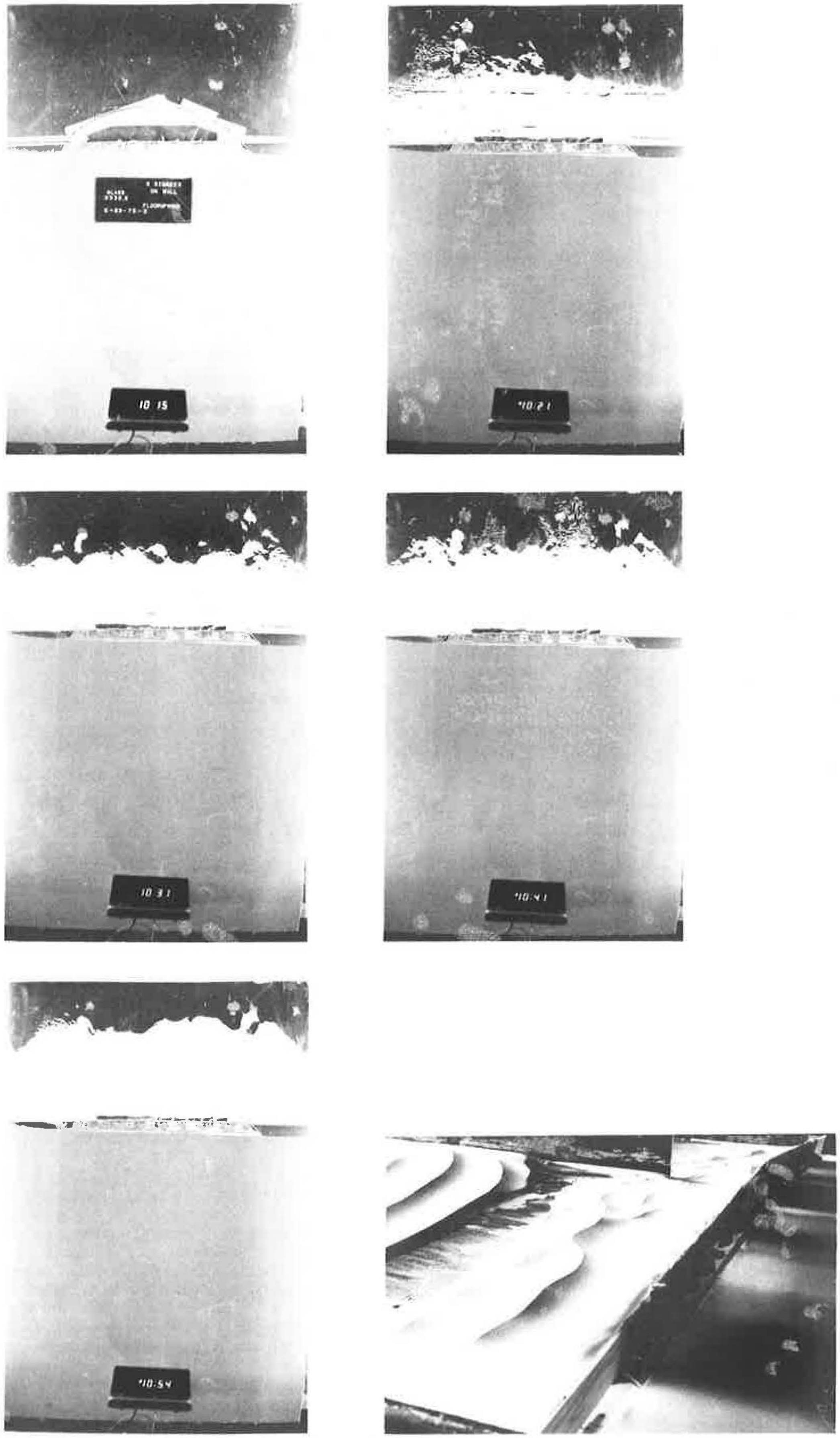


FIGURE 6 Significant amount of drifted material accumulated upwind of wall.

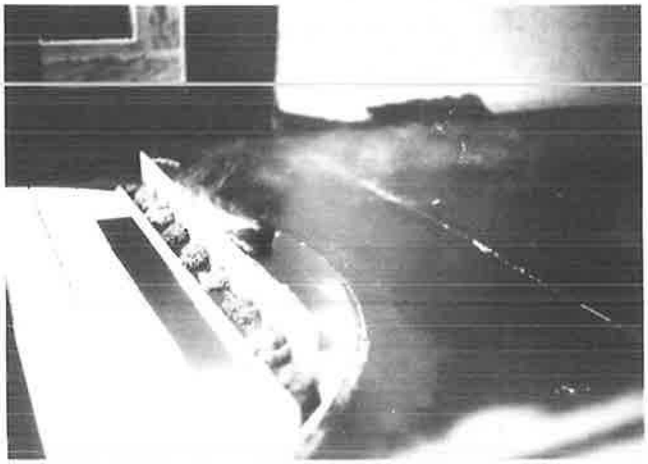


FIGURE 7 Plate No. 1: General view of model wall on turntable. Note: Shrubbery can be seen in front (upwind) of wall and flow is 90 degrees with respect to wall. Black strips in front of and behind wall were placed on turntable to enhance flow visualization after it was found that it was difficult to see smoke over the white turntable.

FIGURE 9 Plate No. 3: General view of model wall, showing tufts of yarn attached to top of wall with tape to further enhance flow visualization. Note: Part of model city can be seen in the upper left corner.

FIGURE 8 Plate No. 2: View of model wall and turntable from top viewing window. Note: Flow is from lower right corner to upper left corner and is approximately 45 degrees with respect to wall. Blocks in lower right corner are part of model city. A side viewing window can be seen in the upper right.

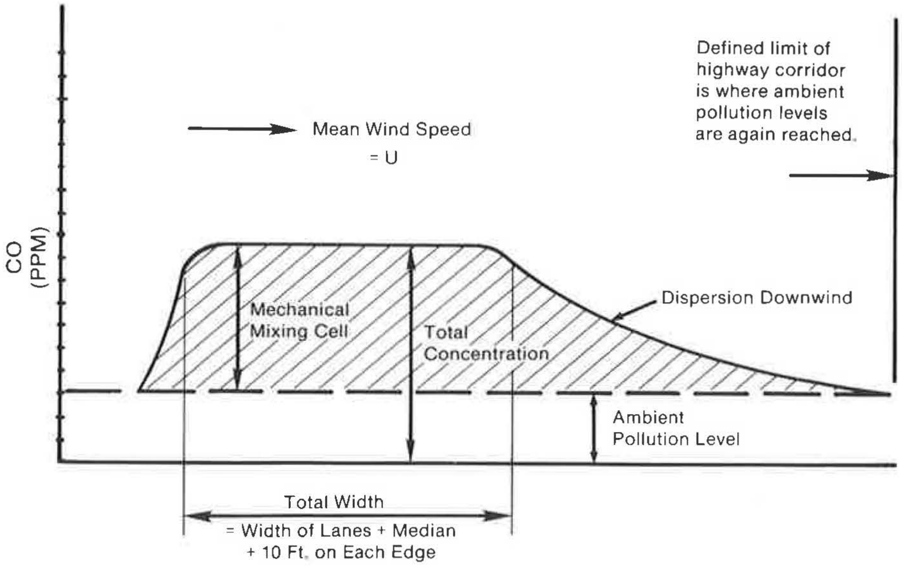
FIGURE 10 Plate No. 4: General view of model wall showing pollutant entrapment cavity. Note: Flow is left to right at approximately 45 degrees with respect to wall. Pollutant entrapment cavity can be seen as a white cloud near center of photograph and just downwind of wall. Random motion, vortices, aerodynamic eddies, and flow reversal are indicated by the wisps of smoke in cavity. Above and downwind of cavity, smoke (seen as less dense than in cavity) is moving uniformly.

filter was converted to the concentration per cubic meter of air. One sampler was located 5 m from the right-of-way fence and a second one 15 m from the right-of-way fence.

The meteorological bivane to measure wind speed and wind direction was calibrated and interfaced with a strip chart recorder for continuous monitoring. Hourly meteorological data for the monitoring period were also obtained from the National Weather Service located at the Des Moines Municipal Airport. This latter information was to be used as a check on the study-site wind data and a backup source for these data if the study-site data instrumentation failed. These data were used to determine the degree of correlation between the measured traffic-related pollutant levels and the wind parameters at the study site. Traffic data were obtained for I-235 during the monitoring period.

The monitoring units were in continuous operation from July 1 to October 1, 1979. Construction of the noise wall began in May 1980 and was completed in July 1980. Air quality monitoring was resumed in July 1980 and continued through September with the noise wall in place. Intakes for the carbon monoxide monitoring system were located on the highway side of the noise wall and at distances of 5, 15, and 23 m from the residential side of the wall at a height of 2 m, similar to the preconstruction layout. Meteorological instrumentation was again put in service, and a new series of particulate samples was integrated with the national total suspended particulate (TSP) monitoring schedules.

It soon became apparent that both the 15-m carbon monoxide monitor and the 23-m monitor were measuring identical and very low concentrations. Consequently, the 15-m intake was eliminated and the 23-m unit



Note: Total concentration = ambient level plus pollutants from the highway line sources.

FIGURE 11 Typical pattern of carbon monoxide concentration level.

continued to measure what were considered background carbon monoxide levels for the study area. Traffic data for I-235 and hourly meterological data for the monitoring period were obtained from the National Weather Service as they were for the preconstruction period.

STATISTICAL ANALYSIS OF AIR-QUALITY DATA

Table 1 gives the TSP monitoring data for the preconstruction and postconstruction study periods. As shown, the mean TSP at 5 m from the wall was found to be 82 micrograms/m^3 before construction and 79 micrograms/m^3 after construction, which is not a significant difference. However, at 15 m from the wall the mean TSP was 78 micrograms/m^3 before construction and 65 micrograms/m^3 after construction. A statistical analysis of the data indicates a significant difference for the ratios of the 5-m values over the 15-m values for TSP before construction and after construction. The average ratio of the 5-m values over the 15-m values for the 1979 preconstruction monitoring period was found to be 1.07, and the average ratio of the 5-m values over the 15-m values for 1980 (or the postconstruction period) was found to be 1.22. Thus, the difference in the average ratios for the two years is 0.15. At the 95 percent confidence level, the range is 0.13, and the upper-level difference is 0.28 and the lower-level difference is 0.02. This implies a beneficial effect of the wall in retarding the dispersion of particulates from the highway to the east-side residential area. The monitor farthest from the wall, the high-volume sampler 15 m from the wall and nearest the residences, shows a somewhat lower seasonal average concentration with the wall in place. The indications are that a portion of the transportation-related particulate matter from the I-235 Freeway quickly settles near the residential side of the wall, its further transport being limited to a degree by the effect of the wall on air movements.

A summary of the observations for carbon monoxide by wind direction is given in Tables 2-5. A statistical matrix is given for 1979 and Monitor 2, the monitor 5 m from the right-of-way fence or the wall (Table 2); for 1979 and Monitor 4, the monitor 23 m from the right-of-way fence or the wall (Table 3); for 1980 and Monitor 2 (Table 4); and for 1980 and Monitor 4 (Table 5). The frequency and the overall percent of the specific occurrence for wind direction and a given carbon monoxide range of values are given. The intake for Monitor 1, located at the right-of-way fence in 1979 and at the top of the wall on the highway side in 1980, does not provide useful information for comparison because of the

TABLE 1 TSP Monitoring Data for Preconstruction and Postconstruction Study Periods

	TSP Concentration (micrograms/m^3)	
Date Collected	5 m from Right-of-Way/Wall	15 m from Right-of-Way/Wall
07-08-79	76	77
07-14-79	59	49
07-20-79	118	121
07-26-79	87	85
08-01-79	69	67
08-07-79	113	102
08-13-79	102	67
08-19-79	42	51
08-23-79	92	70
08-25-79	65	63
08-31-79	68	68
09-06-79	79	66
09-12-79	83	94
09-18-79	128	124
09-24-79	68	72
09-30-79	87	91
10-04-79	67	57
(Wall constructed June 1980)	Mean = 82	Mean = 78
07-26-80	44	35
08-01-80	76	67
08-07-80	80	67
08-13-80	59	51
08-19-80	76	62
08-25-80	96	83
08-31-80	29	26
09-06-80	68	57
09-12-80	96	71
09-18-80	99	57
09-24-80	89	71
09-30-80	76	85
10-06-80	135	112
10-12-80	85	72
	Mean = 79	Mean = 65

TABLE 2 Average Carbon Monoxide at Monitor 2 (ppm) and Average Wind Direction per Hour

Avg at Monitor 2	Wind Direction East	West	Calm	Total[a]
0 to 1 ppm				
Frequency	892	360	146	1,398
Percent	32.98	13.31	5.40	51.68
Row percent	63.81	25.75	10.44	
Column percent	57.03	43.01	48.03	
2 ppm				
Frequency	568	381	106	1,055
Percent	21.00	14.09	3.92	39.00
Row percent	53.84	36.11	10.05	
Column percent	36.32	45.52	34.87	
3 ppm				
Frequency	89	87	40	216
Percent	3.29	3.22	1.48	7.99
Row percent	41.20	40.28	18.52	
Column percent	5.69	10.39	13.16	
4 to 5 ppm				
Frequency	15	9	12	36
Percent	0.55	0.33	0.44	1.33
Row percent	41.67	25.00	33.33	
Column percent	0.96	1.08	3.95	
Total[a]				
Frequency	1,564	837	304	2,705
Percent	57.82	30.94	11.24	100.00

Note: 1979 data.
[a]Some totals off by 0.01 due to rounding.

TABLE 3 Average Carbon Monoxide at Monitor 4 (ppm) and Average Wind Direction per Hour

Avg at Monitor 4	Wind Direction East	West	Calm	Total[a]
0 to 1 ppm				
Frequency	1,308	620	201	2,129
Percent	48.70	23.08	7.48	79.26
Row percent	61.44	29.12	9.44	
Column percent	84.50	74.34	66.12	
2 ppm				
Frequency	214	195	73	482
Percent	7.97	7.26	2.72	17.94
Row percent	44.40	40.46	15.15	
Column percent	13.82	23.38	24.01	
3 ppm				
Frequency	20	16	28	64
Percent	0.74	0.60	1.04	2.38
Row percent	31.25	25.00	43.75	
Column percent	1.29	1.92	9.21	
4 to 5 ppm				
Frequency	6	3	2	11
Percent	0.22	0.11	0.07	0.41
Row percent	54.55	27.27	18.18	
Column percent	0.39	0.36	0.66	
Total[a]				
Frequency	1,548	834	304	2,686
Percent	57.63	31.05	11.32	100.00

Note: 1979 data.
[a]Some totals off by 0.01 due to rounding.

change in position of the intake. Therefore, Monitor 2 information, where the intake is located 5 m from the wall or 5 m from the right-of-way fence in the preconstruction phase, is the one chosen for the comparison study. Also, the intakes of the monitors are downwind from the I-235 Freeway only for west winds. Therefore, only west winds are considered in the following analyses.

In comparing 1979 and 1980 data for Monitor 2 (Tables 2 and 4) for west winds, it can be seen that the percentages tend to be lower for the lower carbon monoxide ranges in 1979 compared with those in 1980,

TABLE 4 Average Carbon Monoxide at Monitor 2 (ppm) and Average Wind Direction per Hour

Avg at Monitor 2	Wind Direction East	West	Calm	Total[a]
0 to 1 ppm				
Frequency	822	198	36	1,056
Percent	50.96	12.28	2.23	65.47
Row percent	77.84	18.75	3.41	
Column percent	71.92	52.38	39.13	
2 ppm				
Frequency	237	133	24	394
Percent	14.69	8.25	1.49	24.43
Row percent	60.15	33.76	6.09	
Column percent	20.73	35.19	26.09	
3 ppm				
Frequency	70	35	12	117
Percent	4.34	2.17	0.74	7.25
Row percent	59.83	29.91	10.26	
Column percent	6.12	9.26	13.04	
4 to 5 ppm				
Frequency	13	7	15	35
Percent	0.81	0.43	0.93	2.17
Row percent	37.14	20.00	42.86	
Column percent	1.14	1.85	16.30	
>6 ppm				
Frequency	1	5	5	11
Percent	0.06	0.31	0.31	0.68
Row percent	9.09	45.45	45.45	
Column percent	0.09	1.32	5.43	
Total[a]				
Frequency	1,143	378	92	1,613
Percent	70.86	23.43	5.70	100.00

Note: 1980 data.
[a]Some totals off by 0.01 due to rounding.

TABLE 5 Average Carbon Monoxide at Monitor 4 (ppm) and Average Wind Direction per Hour

Avg at Monitor 4	Wind Direction East	West	Calm	Total[a]
0 to 1 ppm				
Frequency	995	329	54	1,378
Percent	61.69	20.40	3.35	85.43
Row percent	72.21	23.88	3.92	
Column percent	87.05	87.04	58.70	
2 ppm				
Frequency	123	23	22	168
Percent	7.63	1.43	1.36	10.42
Row percent	73.21	13.69	13.10	
Column percent	10.76	6.08	23.91	
3 ppm				
Frequency	18	8	12	38
Percent	1.12	0.50	0.74	2.36
Row percent	47.37	21.05	31.58	
Column percent	1.57	2.12	13.04	
4 to 5 ppm				
Frequency	7	13	4	24
Percent	0.43	0.81	0.25	1.49
Row percent	29.17	54.17	16.67	
Column percent	0.61	3.44	4.35	
>6 ppm				
Frequency	0	5	0	5
Percent	0.00	0.31	0.00	0.31
Row percent	0.00	100.00	0.00	
Column percent	0.00	1.32	0.00	
Total[a]				
Frequency	1,143	378	92	1,613
Percent	70.86	23.43	5.70	100.00

Note: 1980 data.
[a]Some totals off by 0.01 due to rounding.

and higher for the higher carbon monoxide ranges. For example, in 1979 43.01 percent of the west winds are in the 0 to 1 parts per million (ppm) range, and in 1980 52.38 percent of the west winds are in the 0 to 1 ppm range. However, in 1979 45.52 percent of the west winds are in the 2 ppm range, whereas in

1980 only 35.19 percent of the west winds are in the 2 ppm range. This tends to indicate that the wall may have a beneficial effect and may lower the carbon monoxide levels. Monitor 4 levels (Tables 3 and 5) are all somewhat lower than Monitor 2 levels, which is to be expected. Also, east winds for both monitors in both years tend to result in higher percentages for the lower carbon monoxide levels, which again is to be expected.

Data collected from the National Weather Service and data from the meteorological bivane were used to calculate the stability class for each hour of carbon monoxide levels obtained from Monitor 2, and the data on wind speed and wind direction obtained from the meteorological bivane were combined with the determined stability class in a statistical analysis. It was assumed that the following is true:

$$CO = \text{function}\ (T, E.F., U\sin\phi, S.C.)$$

where

- CO = carbon monoxide (ppm),
- T = traffic (vehicles/hr),
- E.F. = emission factor (g/vehicle-mile),
- ϕ = angle (degrees between wind direction and highway alignment),
- $U\sin\phi$ = crosswind speed (mph), and
- S.C. = stability class.

The emission factors for 1979 and 1980 were computed; by using the data obtained from this study, the following were obtained for west winds only. For the preconstruction year of 1979,

$$CO = 1.03 + .000015(E.F.)(T)(U\sin\phi)^{.033}\ S.C.^{.174} \quad (1)$$

and for the postconstruction year of 1980,

$$CO = 1.14 + .0000297(E.F.)(T)(U\sin\phi)^{.67}/S.C.^{.99} \quad (2)$$

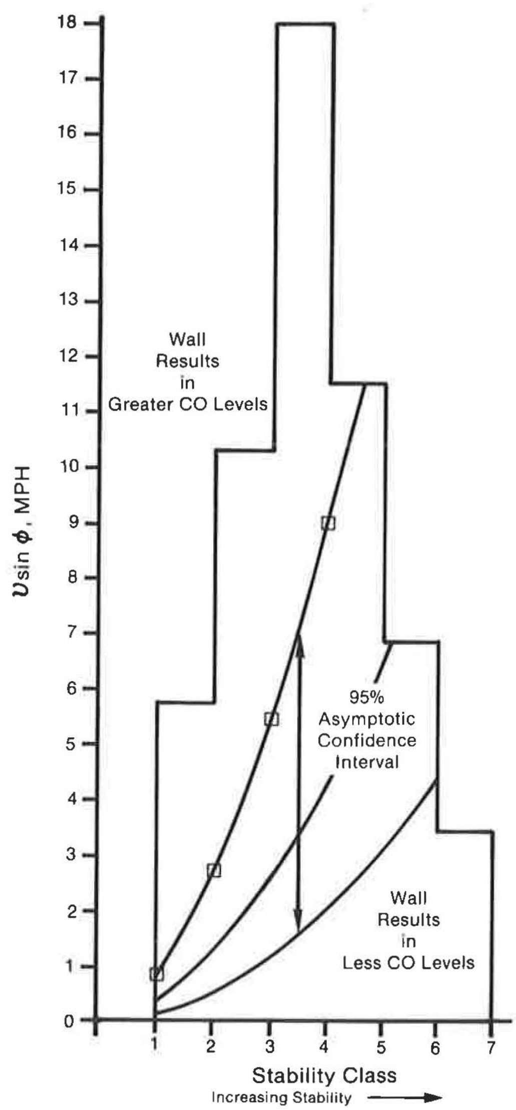
It is observed that in 1979 carbon monoxide levels were largely dependent on emission factors and traffic. In 1980, with the wall in place, carbon monoxide levels were significantly affected by stability class and the crosswind speed as well. It is interesting to note that the lower the wind speed and the higher the stability class (more stable conditions), the lower are the carbon monoxide levels. This is contrary to the usual carbon monoxide line source models, which suggests that for low wind speeds and stable meteorological conditions, the wall contains the mixing cell on the highway side. With higher wind speeds and unstable conditions, the wall is not as effective in containing the pollutants on the highway side.

Assuming the first term in each of the equations is a background of ambient carbon monoxide level and equating the second terms, the intersections of the 1979 and 1980 carbon monoxide level plots can be found for a given stability class or a given $U\sin\phi$. For comparison, equivalent emissions are assumed for 1979 and 1980, making the product of E.F. and T for 1979 equal to the product of E.F. and T for 1980, and the effect of only the wall is thus obtained. The result of the intersections can then be plotted as shown in Figure 12.

CONCLUSIONS OF THE EFFECT OF A SOLID WALL ON AIR QUALITY

The total suspended particulate monitoring data has suggested that the wall has had a beneficial effect in retarding the transportation-related particulate matter from the I-235 Freeway. The extent to which this may occur cannot be quantified for a solid wall in general. The statistical sample was small, and it was not possible to correlate pertinent meteorological data on a continuous basis. Nevertheless, sufficient data is available for a qualitative assessment, and it appears that a benefit is realized from presence of a wall.

Figure 12, developed from the carbon monoxide monitoring data, clearly indicates that as the atmospheric stability is increased or the crosswind speed is reduced beyond a certain level for west winds and equivalent emissions, or both, the carbon monoxide levels are lower when the noise wall is in place. This would indicate that the wall is contain-



Note: Critical crosswind components versus stability class of CO levels obtained at Monitor 2; west winds; equivalent emissions.

FIGURE 12 Effect of noise wall on air quality.

ing the mixing cell on the highway side under the conditions of low wind speed and high atmospheric stability. Conversely, as the atmospheric stability is decreased or the crosswind speed is increased beyond a certain level for west winds and equivalent emissions, or both, the carbon monoxide levels are higher when the noise wall is in place. This suggests that a higher-than-expected concentration of carbon monoxide is occurring near the wall because of aerodynamic entrapment.

REFERENCE

1. An Iowa Noise Barrier: Sound Levels, Air Quality and Public Acceptance. Iowa Department of Transportation, Ames, Feb. 1983, pp. 4-6.

Publication of this paper sponsored by Committee on Transportation and Air Quality.

Caltrans Experiences with Earthborne Vibration

MAS HATANO and RUDOLF W. HENDRIKS

ABSTRACT

An overview of vibration investigations performed by the California Department of Transportation since 1958 is presented. These investigations involved measurement of earthborne vibrations induced by highway vehicles, construction equipment, and train passbys. All of the investigations indicated vibration levels below the criterion established for architectural damage (plaster cracking). However, pile driving and pavement breaking were potential problems and monitoring was suggested for these situations. Two case studies are also presented, one on a train passing near a machine shop and a second on a new freeway alignment near a manufacturing plant.

Since 1958, the California Department of Transportation (Caltrans) has conducted more than 40 investigations of earthborne vibrations induced by construction equipment, highway vehicles, and train passbys. All of these investigations were performed because of complaints or concerns about adverse impacts on activities inside buildings or damage to buildings. Earthborne vibrations are caused by construction activities from pile driving, pavement breaking, and moving construction equipment. Vibrations generated by highway truck traffic become a problem when the pavement is rough (potholes) or because of stepped joints. Train passbys also create earthborne vibrations.

Presented in this paper are some of the fundamentals of earthborne vibrations, guidelines for assessing their impact, Caltrans experiences over 26 years, and some case histories.

FUNDAMENTALS OF EARTHBORNE VIBRATIONS

Earthborne vibrations are mainly from P-waves (compression), S-waves (shear), and Raleigh waves (surface). The Raleigh waves are generally the problem and are used by Caltrans in its studies.

Peak particle velocity within the range of normal earthborne vibrations correlates best with architectural damage and intrusion, whereas acceleration and displacement do not. Therefore, the peak particle velocity (in in./sec) is used as the descriptor for Caltrans studies. Particle velocity is further defined to mean the vertical velocity at which the soil particles or other materials vibrate locally as opposed to the propagation velocity of vibrations. The latter is the speed at which vibrations travel through the ground away from the source.

GUIDELINES FOR ASSESSING IMPACT OF EARTHBORNE VIBRATIONS

No single standard exists for assessing the level at which earthborne vibrations will cause annoyance to people, cause architectural damage (plaster cracking), or be disruptive to precision operations. However, Table 1 shows guideline velocities (in in./sec) from various sources. Caltrans uses the guidelines established by Whiffin and Leonard of the Road Research Laboratory in England (1).

Instrumentation

The following instruments were used to collect vibration data:

4 seismometers (Kinematrics Ranger SS-1)
1 signal conditioner (Kinematrics SC-1)
1 graphic level recorder (Clevite Brush 16-2300-00), oscillograph

TABLE 1 Selected Vibration Criteria

Reference or Authority	Threshold of Perception	Annoyance	Architectural Damage Risk Level	Minor Architectural Damage Likely, Structural Damage Risk Level	Remarks
Whiffen and Leonard *(1)* (used by Caltrans)	.0059-.0188 (peak)	.0984 (peak)	.1968 (peak)	.3937-.5905 (peak)	For continuous vibrations
FHWA-RD-78-166 *(2)*	.0054 (RMS) (.0077 peak)	.0306 (RMS) (.0433 peak)		.0967 (RMS) (.1368 peak)	8 to 80 Hz for continuous vibrations
Committee on Hearing, Bioacoustics, and Biomechanics Assembly for Behavioral and Social Sciences *(3)*	.0040-.0051 (RMS) (.0057-.0721 peak)	.0056-.0110 (RMS) (.0079-.0156 peak) Depending on time of day			8 to 80 Hz for continuous vibrations
Bureau of Mines *(4)*			2.0 (peak) Single blast	5.4 (peak) Single blast	Single events
ANSI S 3.29 (1983) S 3.18 (1979)	.0039 RMS (.0055 peak) For sensitive persons .0078 RMS (.0110 peak) For average persons	.0039-.0156 (RMS) (.0055-.0221 peak)			8 to 80 Hz for continuous vibrations

Note: Velocities given in parentheses were converted from other descriptors.

The equipment is calibrated using a shake table as shown in the schematic in Figure 1.

CALTRANS EXPERIENCES

The Caltrans Transportation Laboratory (TransLab) has performed investigations throughout California involving the following situations:

- Private residences
- Manufacturing plants
- Aerospace companies
- Machine shops
- Art gallery
- Movie studio
- Computer company
- Historic site
- Pile driving
- Pavement breaking

Of the more than 40 investigations, all have been resolved. Two cases went to trial with no monetary award in one case and a $25,000 judgment against Caltrans in the second. The second involved highway vibrations that affected a machine shop.

Measurements of Vibrations Induced by Highway Vehicles

Highway vehicles that induced earthborne vibrations were trucks, buses, and a Caltrans lowboy. The weight of the lowboy was 9,560 lb (front axle 1), 24,380 lb (tractor axle 2 and 3), and 35,160 lb (trailer axle 4 and 5); the total weight was 69,100 lb. On occasion, a loaded dump truck (50,000 lb) was run over 2 x 6-in. boards placed on the pavement and spaced at 25-ft intervals to simulate a worst-case situation. Measurements were taken over a broad spectrum of highway structures, cuts, fills, and level sections of highway. The soil type covered a wide range of geologic formations.

Figure 2 shows the data from the measurements, all of which were all below the architectural damage level of .1968 in./sec.

Measurements of Vibration Induced by Construction Equipment

Figure 3 shows a plot of earthborne vibrations induced by highway construction equipment versus various distances from that equipment. The largest vibrations were caused by an EMSCO pavement-breaking machine. Velocities of 2.88 and .275 in./sec were recorded at distances of 10 and 38 ft; these were the highest velocities measured in the more than 40 studies to date. Vibrations from a Caterpillar D8 and D9, Caterpillar earthmover, Euclid earthmover, and drilling piles were all below the architectural damage level of .1968 in./sec. In general, it appears that the earthborne vibrations from construction equipment were not high enough to cause architectural

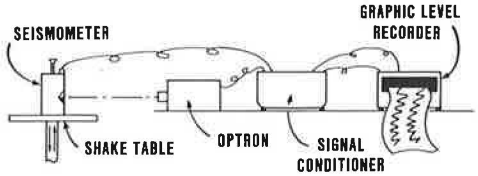


FIGURE 1 Schematic of calibration setup.

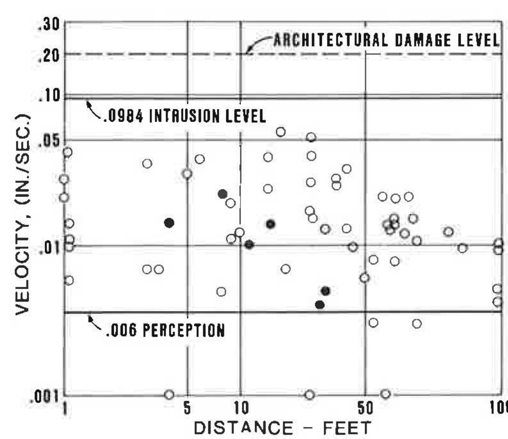


FIGURE 2 Measurements of vibrations induced by highway traffic.

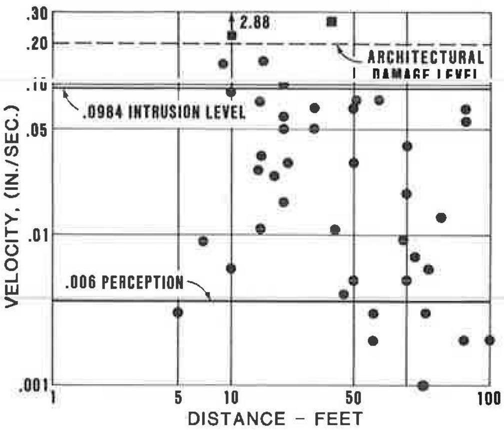


FIGURE 3 Measurements of vibrations induced by construction equipment.

damage. However, vibrations from pavement-breaking and pile-driving machines are potentially damaging and should be carefully monitored when working close to sensitive receptors.

Measurements of Vibrations Induced by Trains

Figure 4 shows a plot of earthborne vibrations induced by train passbys versus various distances from those passbys. All of the vibration levels were below the architectural damage level of .1968 in./sec.

In-House Vibrations

Normal activities associated with living in and maintaining a home give rise to vibrations that are, in some instances, capable of causing minor damage to plaster walls and ceilings in localized sections of the building. Vibration levels of various activities measured in residences are shown in the following table.

Activity	Velocity (in./sec)
Washer and dryer	.004 to .005
Walking	.008 to .187
Door closing	.010 to .056
Jumping	.219 to 5.000

All of the vibration levels except jumping are

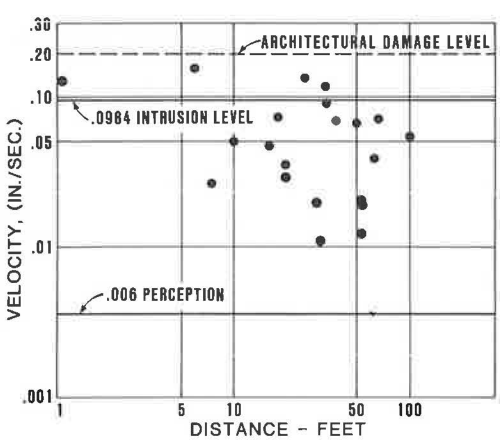


FIGURE 4 Measurements of vibrations induced by trains.

within the range of measurements of earthborne vibrations induced by transportation vehicles. Jumping in a room generates vibrations that are potentially damaging; however, the large amplitude vibrations resulting from jumping are localized and generally do not affect the entire building as earthborne vibrations do. Thus, although the potential for causing vibrations is present, it is confined to a small specific area and the probability of damage is therefore reduced.

Earthborne vibrations appear to be an improbable cause of architectural damage. For residential construction, the cracking of plaster walls, ceilings, and exterior stucco is generally caused by foundation settlement, alternate shrinking, expansion due to moisture and temperature, and earthquakes.

CASE STUDY 1: VIBRATION STUDY AT KAISER

On December 23, 1980, vibration measurements were made at the Kaiser Aerospace and Electronics Company, located in San Leandro, California (Figure 5). A railroad drill track was to be relocated close to the Kaiser Aerospace Building. The initial study in 1978 indicated that earthborne vibrations from trains running on the proposed railroad track would be insufficient to adversely affect Kaiser's precision machining operations for the aerospace industry. The railroad track was constructed late in 1980.

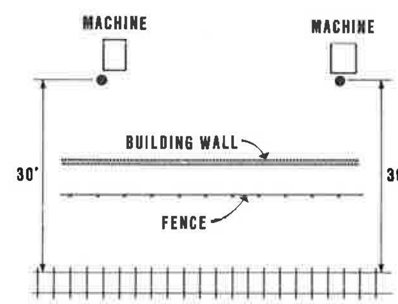


FIGURE 5 Plan of Kaiser plant.

On November 14, 1980, Kaiser Aerospace approved the Specifications for Machine Vibration Study, an in-house plan for evaluating effects of trains operating on the adjacent railroad tracks. This plan included things such as instrumentation, machining specifications, and actual cuts on materials while the train was operating on the tracks. Follow-up measurements of vibrations were made on December 23, 1980, to evaluate whether Kaiser's concern about earthborne vibrations induced by trains running on this track was valid.

Caltrans personnel observed Kaiser's operations but could not detect any adverse effects from train operation. Figure 1 shows the distances and locations of the TransLab seismometers that were used to measure earthborne vibrations from the train to Machine 386 and Machine 553. Measurements were made while the machines were making cuts without the trains, with the trains running 5 to 10 mph, and during a coupling operation (Table 2). The train consisted of one locomotive and five fully loaded cars.

Analysis of the data indicated that earthborne vibrations from the train to Machine 386 and Machine 553 were slightly lower than reported during the first study. The conclusions during the first and current study indicate that earthborne vibrations

TABLE 2 Kaiser Aerotech Summary of Vibrations

	Peak Vertical Velocity (in./sec)			
	Machine 553		Machine 386	
	Inside	Outside	Inside	Outside
Machine cut only	.0028	.0026	.0054	.0045
Train and machine cut, steady speed	.0106	.0455	.0195	.0717
Train and machine cut, coupling	.0138	.0569	.0170	.0372
Ambient, no train machine idling, no cut	.0011	.0015	.0011	.0012

Note: Measurements were made on December 23, 1980.

from the train are insufficient to adversely affect Kaiser's machining operation.

CASE STUDY 2: VIBRATION STUDY AT WESTERN GEAR CORPORATION

Case Study 2 was performed in response to concerns expressed by officials at Western Gear Corporation, Lynwood, Calfiornia, that vibrations originating from equipment and traffic during and after construction of Route 105 might disrupt the plant's precision machining operations (Figure 6).

On March 28, 1984, vibration measurements were taken inside the operations building of Western Gear Corporation and at an outside test area approximately 0.4 mile south of Imperial Highway along Alameda Street. At the outside test site, vibrations were generated by a fully loaded water truck (approximately 25 ton gross vehicle weight) driving at 35 mph across five wooden 2 x 4-in. boards spaced 25 ft apart to simulate construction activity. During the runs, vibrations were measured at seven locations to a distance of 300 ft from the test truck. Figure 7 shows a plan of the measurement site and Figure 8 gives the vibration field test data. Attenuation ratios were calculated from the measurements and combined with freeway and construction data measured in previous Caltrans studies (Figure 9). This information was used to estimate maximum expected vibrations at Western Gear Corporation during and after construction of Route 105. These vibrations were compared with measured existing vibrations made on the Western Gear Premises (Figure 10).

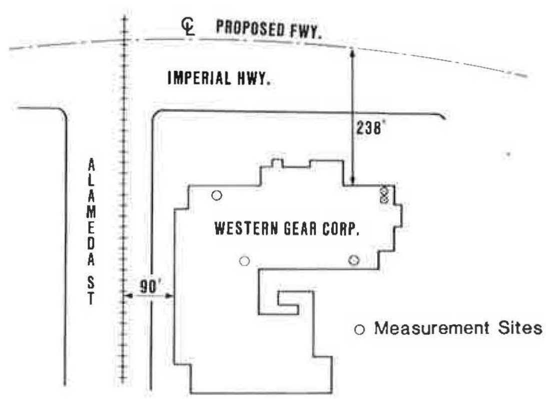


FIGURE 6 Plan of Western Gear Corporation.

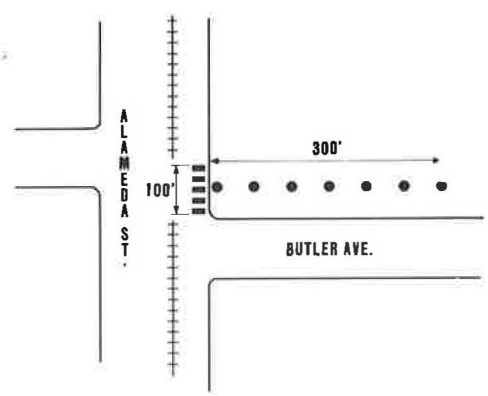


FIGURE 7 Plan of measurement site.

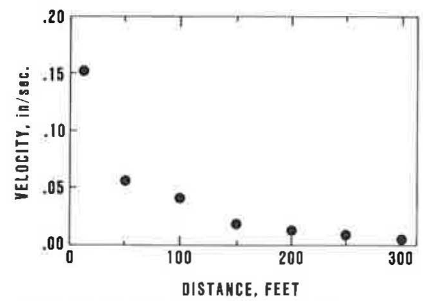


FIGURE 8 Vibration field test data.

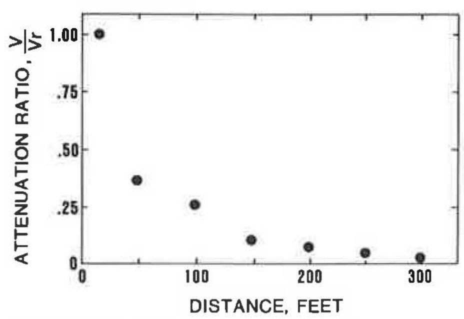


FIGURE 9 Vibration test data ratios.

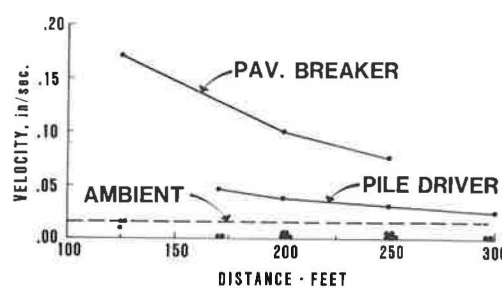


FIGURE 10 Estimated vibration levels.

From the measurements, it can be concluded:

• Vibrations induced by traffic on Route 105 will be far below vibrations currently experienced inside the machine operations building.
• Vibrations induced by construction equipment also will generally be lower than the existing vibrations inside the building. However, if pile drivers or pavement breakers are going to be used near Western Gear Corporation, vibration monitoring at less sensitive locations first is recommended for determining if the vibration levels will be acceptable for Western Gear operations.

CONCLUSIONS

1. Earthborne vibrations induced by highway traffic, construction equipment, and train passbys are below the architectural damage level of .1968 in./sec.
2. Earthborne vibrations cause annoyance to occupants of residences. This generally occurs when occupants are sleeping or engaged in a quiet activity such as reading with nothing else going on (washer, dryer, etc.)
3. Pavement-breaking machines produce vibrations exceeding the architectural damage level of .1968 in./sec. Discretion needs to be applied when used close to sensitive receptors. Although data on pile driving were not collected in sufficient numbers, it is believed that this can also be a problem.
4. In-house activities often create larger building vibrations than those caused by earthborne vibrations.

REFERENCES

1. D.R. Leonard and A.C. Whiffin. A Survey of Traffic-Induced Vibrations. TRRL, RRL Report LR418. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1971.
2. F.F. Rudder, Jr. Engineering Guidelines for the Analysis of Traffic-Induced Vibration. Report FHWA-RD-78-166. FHWA, U.S. Department of Transportation, Feb. 1978.
3. J.T. Nelson and H.J. Saurenman. State-of-the-Art Review: Prediction and Control of Groundborne Noise and Vibration from Rail Transit. Report UMTA-MA-06-0049-83-4. UMTA, U.S. Department of Transportation, May 1983.
4. D.E. Siskind, V.J. Stachura, M.S. Stagg, and J.W. Kobb. Structure Response and Damage Produced by Airblast from Surface Mining. Report of Investigations 8485. Bureau of Mines, U.S. Department of the Interior, 1980.

Publication of this paper sponsored by Committee on Transportation-Related Noise and Vibration.

Making the Environmental Process Work: The Trenton Complex

THOMAS L. WECK, JOHN A. HOTOPP, A. BROOK CROSSAN, and HOWARD ZAHN

ABSTRACT

The Environmental Impact Statement on the Trenton Complex Highway System is a classic example of how, through extensive and meaningful coordination, a highly complex and controversial highway project can move through the process of the National Environmental Policy Act (NEPA) to implementation with the full support of all review agencies as well as those that issue permits. Throughout the NEPA process, the Trenton Complex received broad-based public support while simultaneously being shadowed by well-defined and intricately interrelated environmental concerns--mainly those related to cultural resources and wetlands. The challenge was to minimize or eliminate these and other environmental problems while simultaneously maintaining public support, keeping construction cost down, minimizing delays, and refraining from creating new environmental problems as a result of resolving existing ones. What finally evolved during the coordination process was an ingenious compromise, carefully integrated with the design efforts, which resulted in substantial cost savings while simultaneously protecting otherwise adversely impacted archaeological resources and wetlands areas. Many review agencies such as the Advisory Council on Historic Preservation have referred to the Trenton Complex project as a textbook case of how environmental studies on transportation and other development projects should be carried out. This praise illustrates that the team concept used for this project, with all participants pulling together toward a common goal, can succeed even in projects as environmentally challenging as the Trenton Complex.

Completion of the final links of the I-195/I-295, NJ 29, NJ 129 system near Trenton, New Jersey (commonly referred to as the Trenton Complex project), has long been a top-priority item for the New Jersey Department of Transportation (NJDOT) and FHWA. Without the Trenton Complex project, the partially completed Interstate highway and freeway system in and around Trenton could not meet the Interstate and regional transportation needs for which it was designed (Figure 1). Without the Trenton Complex project, local roads would have to continue serving Interstate and regional traffic movements and, as a result, would continue experiencing severe congestion and high numbers of traffic accidents. Clogged roads in the Trenton area would continue to act as an impediment to the economic revitalization plans of the city.

PROJECT DEVELOPMENT

Planning for the highway project proposed for Trenton began in the late 1950s. During the ensuing years, numerous configurations of roadway links were considered with several different proposals reaching advanced levels of planning and design. Public hearings were held in the early 1960s and alignment approvals were obtained in the mid-1960s. Final design was completed and certain property acquisitions, relocations, and clearings were accomplished in the late 1960s, before enactment of the National Environmental Policy Act (NEPA) in 1969.

With the enactment of NEPA, the proposed project underwent review to check for compliance with the new law. Comprehensive environmental studies began in 1974, leading to a Draft Environmental Impact Statement (EIS) issued in 1976. After extensive consultation and coordination with review agencies and affected communities, the Final EIS was approved in 1981. This document included commitments for new final design for almost the entire project. In accordance with the Final EIS, comprehensive mitigation programs have been or will be implemented, and the entire project is currently in various stages of final design, construction, or both.

OVERVIEW OF ENVIRONMENTAL ISSUES

The Trenton Complex project was characterized by a large number of potentially severe adverse impacts for which creative solutions and mitigation measures had to be developed before approval for proceeding with construction. These potential impacts included:

- Infringement of the highway on major portions of the Abbott Farm National Historic Landmark, one of the most significant and valuable archaeological resources in the eastern part of the United States, and loss of portions of other archaeological districts and sites.
- Infringement on significant portions of the Crosswicks Creek Wetlands system, considered one of the most valuable wetlands in the Upper Delaware Estuarine System.
- The taking of 7 park and recreational facilities in Trenton.
- Significant aesthetic impact through loss of more than 75 mature shade trees along a principal urban street.
- Significant noise impacts to residential areas adjacent to the roadway.

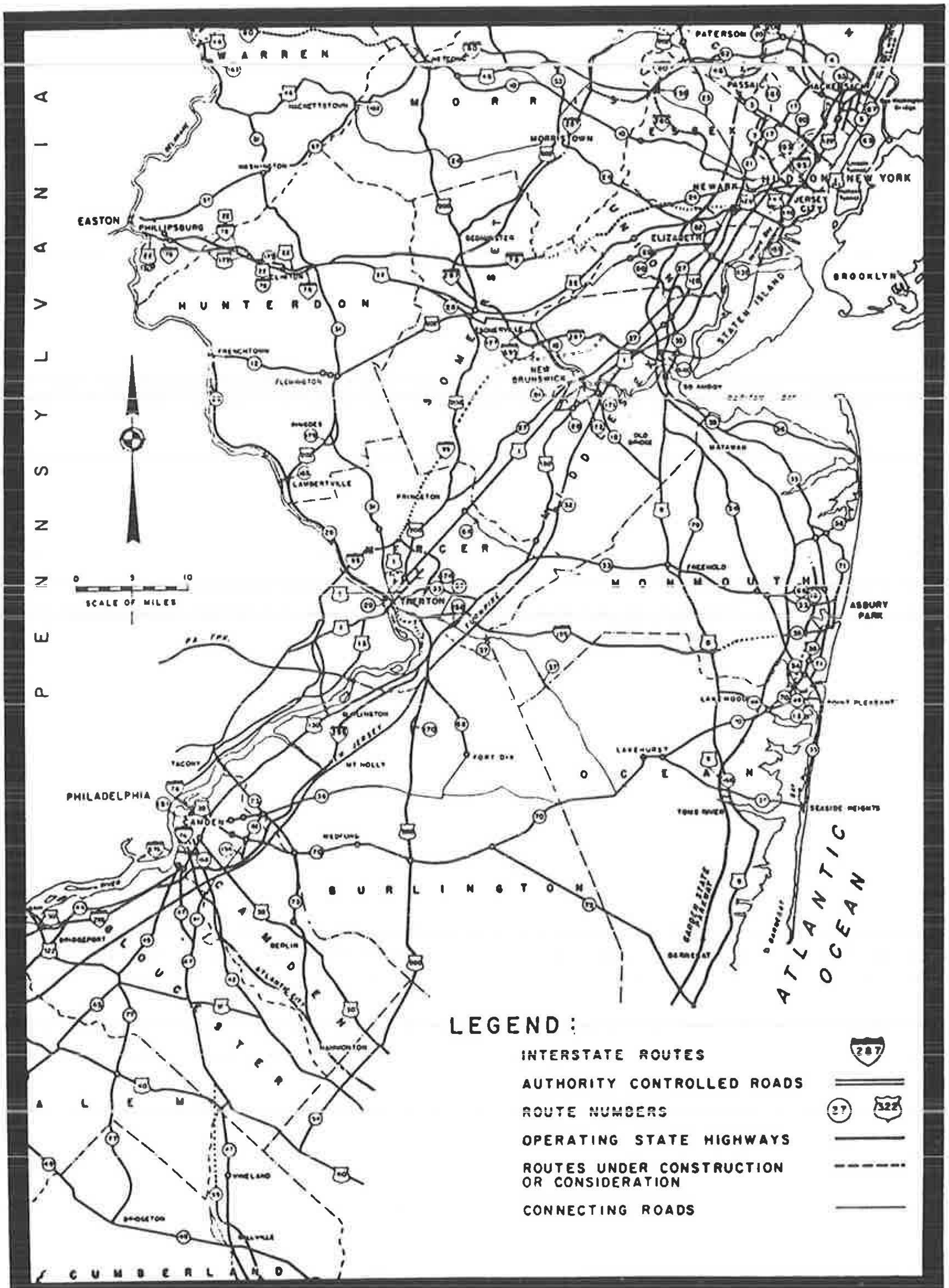


FIGURE 1 Regional highway systems.

Because the project involved construction of relatively short links (each between 1 and 6 miles long) to an otherwise completed Interstate highway and freeway system, there were no easy solutions to these environmental problems, such as might have been entailed in a major shift or roadway alignment (Figure 2). Moreover, potential mitigation measures to address one environmental issue had to be considered in terms of their own possible adverse effect on other environmental issues. For example, in the major interchange area between the I-195 and I-295 links, a shift of the alignment away from

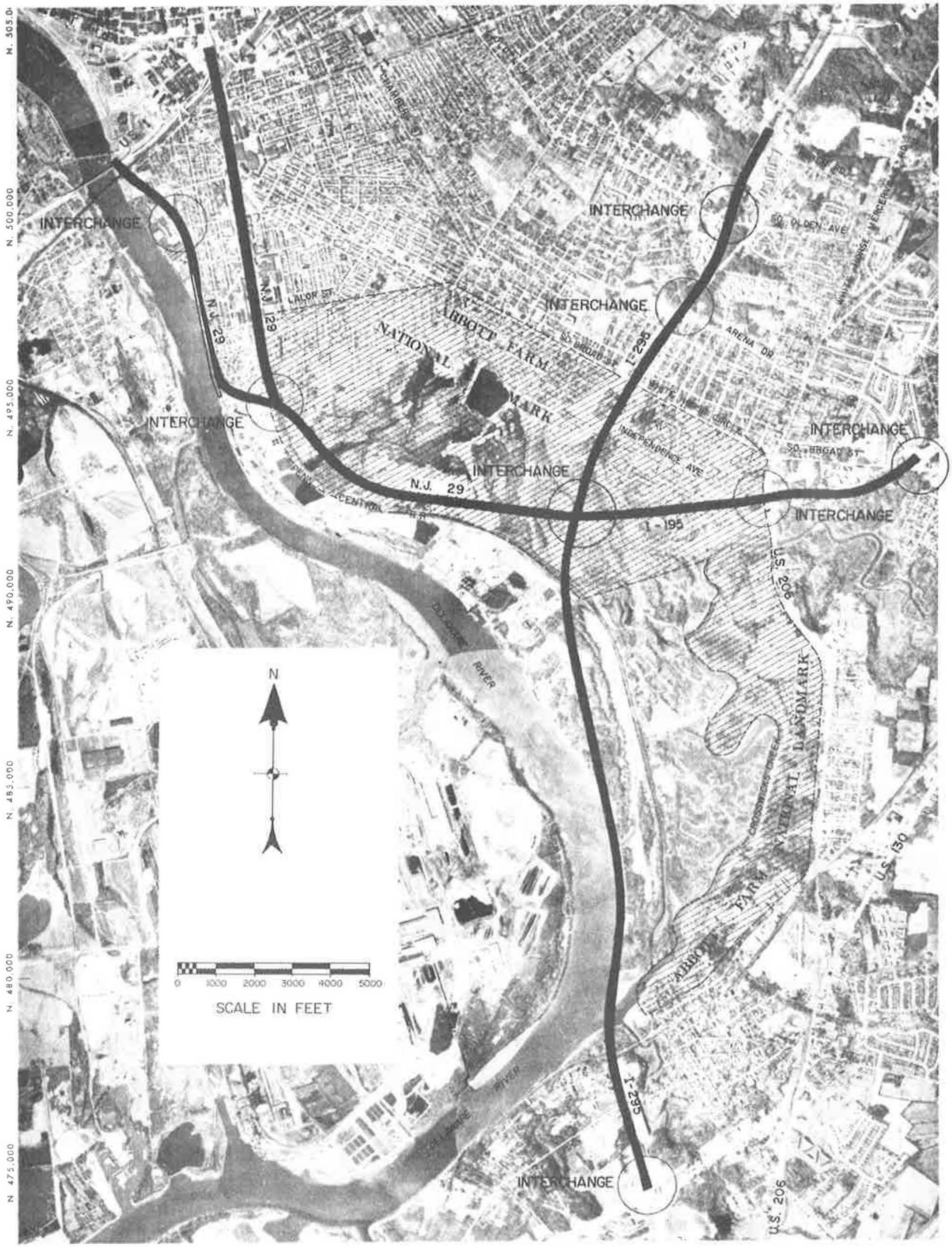


FIGURE 2 Recommended alternatives for I-195/I-295, N.J. 29, N.J. 129.

prime archaeological resources within the Abbott Farm National Historic Landmark could result in the taking of more wetlands and vice versa.

As a result of the complexity of interrelationships among environmental issues, a wide range of alternatives were posited and examined in the preparation of the Draft EIS. These alternatives included 11 system configurations for the 6 major links of the project, 5 location alternatives for 1 link, and a total of 13 design alternatives for 2 links and the major I-195/I-295 interchange. In combination, this array of alternatives resulted in 125 separate and discrete design-location alternatives for the entire project. It was only through continual coordination and consultation with federal, regional, state, county, and municipal agencies--both during the environmental studies and throughout the subsequent mitigation programs--that consensus was reached that both satisfied the regional transportation needs and protected and preserved to the maximum extent possible important environmental features and resources in the project area.

The extensive coordination for the Trenton Complex project can be conveniently divided into two basic stages:

Stage I: Consultation during the preparation of the Draft EIS and Final EIS

Stage II: Consultation after approval of the Final EIS in 1981 on the major mitigation programs for the Abbott Farm National Historic Landmark and the Crosswicks Creek Wetlands system

A summary of Stages I and II and a more detailed description of Stage II are presented in the following sections. This focus has been selected because

- The archaeological impacts and the wetlands impacts presented the greatest obstacles to the implementation of the highway project.
- Archaeological features and wetlands resources were spatially fused, thereby creating additional impediments to developing an environmentally acceptable mitigation program.
- The archaeological and wetlands mitigation program developed was one of the most comprehensive ever undertaken for a highway project.
- The success of the archaeological and wetlands mitigation program has been hailed as a classic example of how the needs for both transportation improvement and environmental protection can be met despite formidable challenges and constraints.

STAGE I: CONSULTATION DURING PREPARATION OF DRAFT AND FINAL EISs

Abbott Farm National Historic Landmark

Background

The Abbott Farm National Historic Landmark is a 2,000-acre site located generally southeast of Trenton and includes both wetlands and upland terrace areas. The Abbott Farm area was first brought to prominence through the work of Dr. C.C. Abbott in the late nineteenth century. His theories about the antiquity of man in the New World, based on research in the Trenton area, subsequently inspired a number of professional excavations in and around Abbott Farm during the past 100 years.

Abbott's pioneering efforts and subsequent excavations have made the Abbott Farm site one of the best known areas of prehistoric habitation along the eastern seaboard of the United States. Archaeological evidence has been underscored for the entire known span of human occupation in the New World ranging from Paleo-Indian (about 10,000 B.C.) through late Woodland (about 1400 A.D.). In addition, Abbott Farm contained important historic sites from the eighteenth and nineteenth centuries. Ironically, despite its national prominence, the cultural resources within the Abbott Farm National Historic Landmark had never been definitely determined before the Trenton Complex project.

Impacts

The original design of the Trenton Complex project during the 1960s was completed before Abbott Farm was declared a national historic landmark. The original design would have resulted in loss of approximately 400 acres of the landmark and an indeterminate loss of cultural resources. As part of the Draft EIS, in consultation with the State Historic Preservation Officer (SHPO), the Advisory Council on Historic Preservation (Advisory Council) and the U.S. Department of the Interior, it was agreed that extensive archaeological investigations would be performed to identify the degree of potential impact of the proposed roadway project on Abbott Farm and other nearby cultural resource sites. As a result, a Phase I Archaeological Investigation, consisting primarily of a surface reconnaissance with minimal subsurface testing, was carried out for the potentially affected portions of the landmark. These studies were sufficient for determining a reasonable and prudent alternative that achieved a 33 percent reduction in areal loss compared with that of the original alternative; however, many questions about the full impact of encroachment on buried archaeological resources in the Abbott Farm district and adjacent historic areas were still left unanswered.

During negotiations with the SHPO, the Advisory Council, and the U.S. Department of the Interior, a compromise was reached whereby it was agreed that:

1. Based on the Phase I studies of the Draft EIS, NJDOT and FHWA would be allowed to proceed to a decision on alignment approval.
2. In return, NJDOT firmly committed to pursue more detailed Phase II studies, and based on those further studies, to prepare a comprehensive mitigation plan before construction in the areas in which cultural resources would be affected.

Within the scope of this comprehensive mitigation plan, NJDOT also committed to conducting specific archaeological studies in the I-195/I-295 interchange area and surrounding areas of alignment to determine if access to significant cultural resources would be preserved by placing additional portions of the highway system or interchange on structures rather than embankment. This compromise was put in the form of a Process Memorandum of Agreement among the Advisory Council, the SHPO, NJDOT, and FHWA. This agreement essentially allowed the project to proceed to approval and final design without further delay while at the same time it provided for necessary protection of Abbott Farm.

The Crosswick Creek Wetlands

Background

All but a small amount of the tidal marshland once present along the Delaware River Estuary north of Philadelphia has been replaced by development. Of the marshland remaining, the Crosswicks Creek Wetlands is the largest single tract, covering approximately 2,900 acres of tidal and nontidal areas. Although not an undisturbed area, the Crosswicks Creek Wetlands is still an extremely valuable component of the Upper Delaware Estuarine System. It functions as a source of food organisms for its own food web and for those of the estuary and beyond, as a breeding and nursery area for resident and migratory fish, and as a habitat for a variety of birds, including some that are considered threatened or endangered (chiefly the Ospry and the Bald Eagle).

Impacts

The impacts of the proposed roadway project on the tidal portions of the Crosswicks Creek Wetlands were analyzed by using two criteria: the first criterion was a measure of actual areal loss resulting from the project and the second criterion was a determination of functional value loss associated with actual areal loss. A grid structure was superimposed over the wetlands and each cell (approximately 50 acres) of the grid was evaluated on the basis of characteristics such as the actual amount of tidal wetland it contained, the type and condition of vegetation, and the extent of tidal circulation (Figure 3). This grid system was designed to provide a rapid means of assessing the impact of construction on the single most important attribute of the Crosswicks Creek Wetlands--its ability to continue functioning as a productive tidal wetlands. Impacts on tidal portions and on terrestrial habitat were analyzed separately to avoid undue complication of the grid-system analysis.

Under the design concept prepared in the early 1960s for the highway project, construction of the Trenton Complex project would have resulted in a loss of 40 acres of tidal wetlands and a functional value loss of 11 percent. Working in close coordination with the New Jersey Department of Environmental Protection (NJDEP) and the U.S. Department of the Interior, a proposed mitigation scheme was developed that reduced the areal loss to only 1 acre of tidal wetlands and the functional loss to only 1 percent. This mitigation program included the following three major steps:

1. Alignment of one of the I-295 links was shifted out of the Crosswicks Creek Wetlands on an upland area known as Duck Island. In the original design in the 1960s, the wetlands alignment had been selected for construction to preserve the Duck Island area for future industrial development. The shift in alignment to the Duck Island alternative resulted in an estimated savings of $20 million in construction cost of the highway. Extensive multidisciplinary coordination was necessary in assessing this alignment shift to ensure that intact cultural resources would not be adversely affected by this action.
2. A commitment was made to construct the major I-195/I-295 interchange on a structure over the 24 acres of tidal wetlands in the interchange area. This would result in only 1 acre of designated wetlands being lost, with 23 acres of designated wetlands spanned by structure. In the Final EIS, this design was estimated to cost an additional $60 million more than the original design concept of embankment construction for the entire interchange.
3. The I-195 route link crosses a wetland or tidal flat at the confluence of Crosswicks Creek and the Delaware River. If the roadway link were built on an embankment over the tidal flat, 8.8 acres of wetlands would be filled. A commitment was made by NJDOT to undertake a study of the feasibility of creating compensatory wetlands in the project area to replace the 8.8 acres that would be lost if the road link were built on an embankment over the tidal flat. Based on the results of this study, a decision would be made to build either the extended bridge alternative or the short bridge alternative with compensatory wetland replacement. The cost of the first alternative would add at least an additional $7.0 million to the construction cost of the project.

Park and Recreational Facility Impacts

Background

The northern and western corridors of the Trenton Complex project pass through a section of the urban core of Trenton. The land use mix in this section of the city consists of densely settled neighborhoods; a key industrial employment center; and municipal facilities such as parks, recreational facilities, and a large cemetery. Most of the neighborhoods are ethnic communities, some with a long history of community cohesion and stability.

Impacts

Because of existing dense development patterns, it was impossible to locate the new highway links without affecting existing park and recreational facilities. Extensive design and location studies were undertaken to minimize the level of impact. Some of these studies were undertaken in the 1960s, before the beginning of the studies for the Draft EIS. Where impacts were unavoidable, extensive consulting and negotiations were undertaken with the municipalities of Trenton, Hamilton, and Bordentown as well as the Mercer County Parks Commission and NJDEP to reach mutually agreeable resolutions concerning mitigation. As a result of these extensive efforts, agreement was reached on the mitigation program, which included the following:

- Construction of new ball parks and playgrounds in the same neighborhood areas as the five such facilities lost as a result of the project.
- The building of an additional playground in the project area.
- The upgrading of a ball field slightly affected by the project.
- Modification of the alignment adjacent to the proposed Delaware Raritan Canal State Park to allow for towpath activity, a scenic overlook, and increased pedestrian access to the proposed new park.

Through these extensive mitigation commitments, agreement was reached with all of the municipalities and agencies concerned and the Section 4(f) plan (Department of Transportation Act of 1966) was approved.

Aesthetic Impact

Background

Lamberton Field is a 6-acre linear walkway that is tree-lined and unpaved, located in Trenton along the eastern bank of the Delaware River. The most important characteristic of the field is the large number of mature sycamore trees. There are 118 such trees, most of them forming two parallel rows along the field. These trees contribute significantly to the aesthetic setting of the area and to the scenic view of the Delaware River from residences along Lamberton Street.

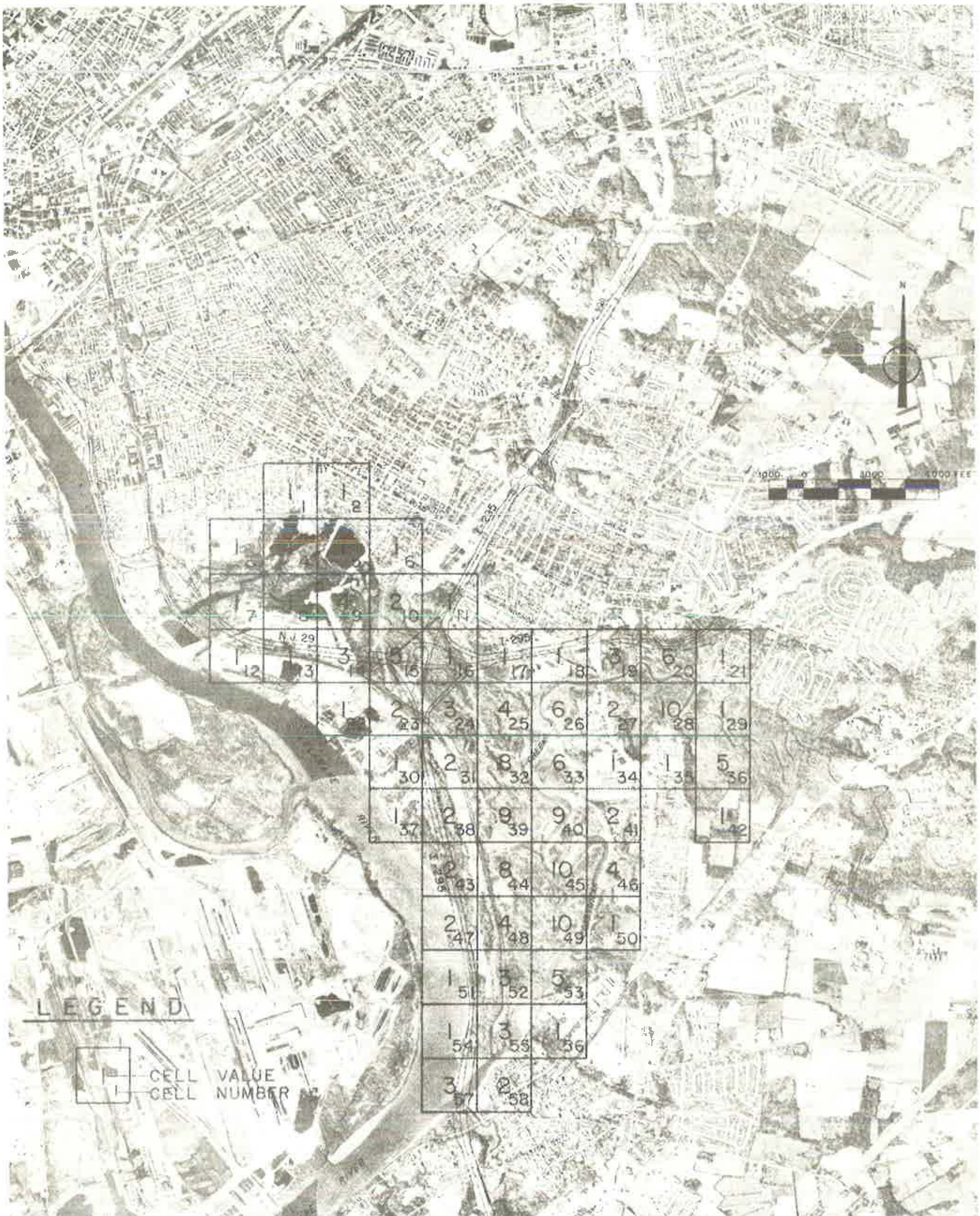


FIGURE 3 Grid analysis map of Crosswicks Creek Wetlands.

Impacts

The original design of the NJ 29 link of the Trenton Complex project would have necessitated the removal of more than 75 of the 118 sycamore trees in Lamberton Field. Moreover, the profile of the roadway would also have acted as an aesthetic barrier to viewsheds along the Delaware River. As part of the studies undertaken for the Draft EIS, extensive consultations were held with the city of Trenton and NJDEP to develop an alternative scheme for mitigating this potentially significant adverse impact. As a result of these consultations, a new alignment was developed that required the removal of less than 50 trees, and the roadway immediately adjacent to the river was redesigned with a depressed profile thereby making it barely visible from the Lamberton Street residences. Coupled with elimination of the severe traffic congestion along Lamberton Street that would result from the construction of the Trenton Complex project, this new scheme--developed through the consultation process--ensured that the aesthetic setting for the residents of Lamberton Street would, on balance, be improved by the project.

Noise Impacts

Background

The existing noise levels in the area of the Trenton Complex project were those characteristic of urban-suburban settings. As is true with most such settings, the predominant background noise was created by vehicular traffic. The L10 noise level in the project area averaged 65 dB except in those areas of high traffic volume and traffic congestion, where levels in excess of 70 dB, and in some instances 80 dB, occurred.

Impacts

As a result of the Trenton Complex project, it was determined that noise levels would be substantially reduced along existing roadways from which traffic would be diverted. There would, however, be significant noise impacts to about 200 dwelling units along the new alignment. In accordance with FHWA procedures, noise abatement measures were investigated as part of the Draft EIS. Aesthetically pleasing noise barriers were found to be feasible along all noise-impacted sections of the roadway with the exception of the NJ 29 link where, because of engineering constraints, the noise barrier would have also resulted in an unattractive visual obstruction of the Delaware River viewsheds currently afforded the neighborhoods along the proposed NJ 29 route. Adverse noise impacts would occur to 40 residences along NJ 29 and would result in an increase in noise level from 3 to 5 dBA higher than current levels. Because existing noise levels were already at or above the 70-dBA design noise level, this 3- to 5-dBA increase in noise due to the building of the new alignment was determined to be an adverse impact; however, in reality this level of increase is only slightly higher than the threshold of noise increase perceptible by the human ear.

NJDOT consulted with residents along Route 29 and with the city of Trenton to determine their preferences with respect to the noise barrier. Because of the visual obstruction that would have resulted from the barrier and because actual noise levels would only rise slightly above current levels, both the affected neighborhoods and the city of Trenton opposed construction of any noise barriers. As a result, NJDOT obtained approval from FHWA for an exception to the design noise levels in this area. In all other areas where adverse noise impacts would occur, aesthetically pleasing noise barriers were designed as part of the project.

STAGE II: CONSULTATION AFTER APPROVAL OF THE FINAL EIS IN 1981: ARCHAEOLOGICAL AND CULTURAL RESOURCES

Mitigation of Abbott Farm National Historic Landmark

With the publication of the Final EIS in 1981 and approval of the proposed Interstate complex the same year by FHWA, the question of the archaeological resources within the alignments assumed critical importance. Archaeological studies in support of the Draft EIS (1976) indicated that the right-of-way purchased by NJDOT for the project would significantly affect the Abbott Farm National Historic Landmark. The historic archaeological studies also located a number of historic properties comprising a mill, early residences, industrial remains, and portions of the Delaware River and Raritan Canal that appeared to be in the impact areas (Figure 4).

A substantial number of the sites initially reviewed by the Keeper of the National Register were located within portions of the right-of-way that lay outside of the boundaries of Abbott Farm National Historic Landmark. Responding to questions raised by the keeper of the National Register for these sites was seen as crucially important for the planning of Phase II testing to be coordinated with engineering design, and was structured to collect the necessary information in the same sequence as in the planned construction schedule. By providing archaeological information early in the final design phase, it was anticipated that cultural resource concerns could be incorporated into the final designs, thereby reducing the adverse impact to archaeological sites and minimizing the requirements for data recovery. Concomitant with Phase II testing for Determination of Eligibility was the requirement to conduct archaeological testing to develop mitigation plans for sites already determined eligible for the National Register.

With construction planned to begin in 1983, there was enormous pressure to complete the Phase II studies, mitigation plans, and the actual archaeological mitigation. Assembling the required documentation, securing the reviews, responding to questions, and obtaining the necessary state and federal approvals within the compressed time frame required extremely close and continual coordination of the consultant team, NJDOT, FHWA, the SHPO, the National Register, and the Advisory Council.

Phase II Testing and Mitigation Planning: 1981 to 1982

The proposed highway complex was divided into 7 sections for archaeological testing and mitigation planning. Three closely related prehistoric archaeological sites (the Shady Brook Complex) were located on the northernmost section of I-295. This section was scheduled for construction in fall 1983. From an archaeological perspective, the Shady Brook Complex was considered to be an outlier site because it was located more than 1 mile northeast of the main

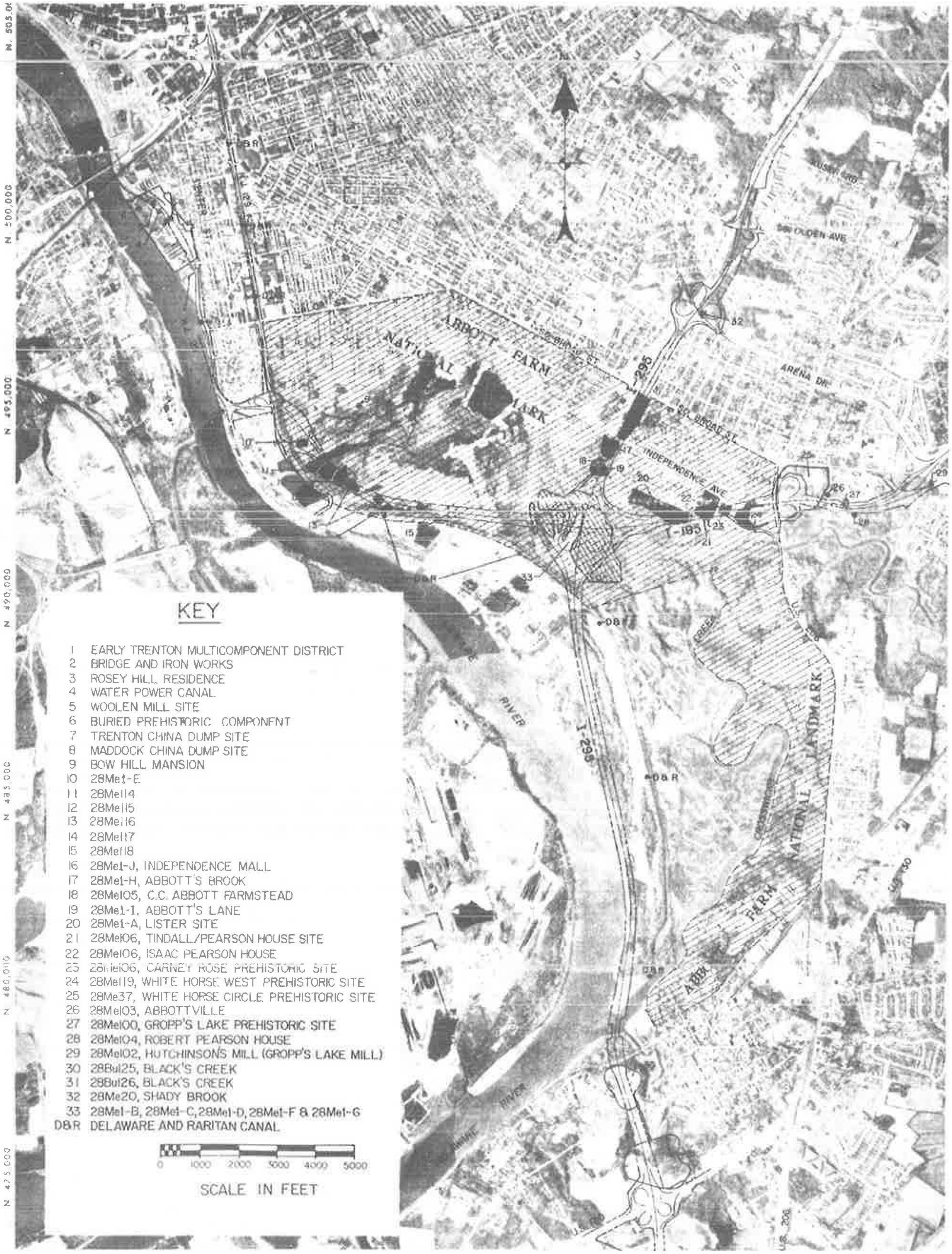


FIGURE 4 Archaeological sites of the Trenton Complex.

complex of sites in the Abbott Farm National Historic Landmark.

Consultations with the SHPO and representatives of the Advisory Council resulted in the decision to break out this section of the project as a separate compliance action. Allowing the Phase II research, report, Determination of Eligibility, and mitigation to proceed independently of the remainder of the project provided the necessary lead time for the Shady Brook Complex to be mitigated within the tight design and construction schedule while the remainder of the Phase II studies were being conducted. Phase II testing of this site began in June 1981; the report of the testing, Determination of Eligibility, and mitigation plan were prepared during the winter and all necessary approvals were in place by May 1982; mitigation fieldwork was conducted and the site released for construction on schedule in August 1982.

Successful completion of all requirements for the Shady Brook Complex in advance provided an invaluable preview of the challenges and requirements for the remainder of the project. Moreover, the data recovered provided an advance look at the types and quantities of artifacts that could be expected from the remainder of the sites in the corridors and provided an opportunity to test the pre-field hypotheses being developed for the large-scale mitigation. The Shady Brook Complex also allowed a complete run-through, on a manageable scale, of all phases of analysis, laboratory work, graphics, and report production.

Immediately following the conclusion of Phase II testing at the Shady Brook Complex, two additional field crews were brought in to begin testing sites along the rights-of-way on the remainder of the Trenton Complex. At the peak of Phase II testing, crew size numbered more than 50 persons working on three sites simultaneously. The work involved close coordination among prehistoric and historic archaeologists, informant interviewers, an architectural historian, a historian, and museum researchers working with the collections from the Works Progress Administration excavations on Abbott Farm.

As testing progressed, however, it became clear that the majority of the prehistoric cultural materials scattered throughout the corridors lacked integrity, having been disturbed by more than 100 years of plowing, erosion, and land modifications associated with residential construction. Results of the extensive testing revealed 5 prehistoric sites within the I-195 corridor that would require mitigation before construction (Figure 5). Prehistoric archaeological materials from the remainder of this 6,000-ft segment were determined to be in a context too disturbed to provide data useful for understanding the prehistory of the area.

The Black's Creek Prehistoric Archeological District was initially viewed as a manageable problem because the two sites had been determined eligible for the National Register and testing was designed only to establish the basis for mitigation. As testing progressed, however, it became apparent that both sites were badly disturbed and that no intact site areas had survived within the proposed right-of-way (Figure 6)--the only site fragment that was intact was located on a bluff edge well outside of the right-of-way. Therefore, NJDOT, in consultation with FHWA, the SHPO, and the Advisory Council, modified the original evaluation of the significance of the Black's Creek District, and recommended no mitigation and a reevaluation of its National Register status. This obviated the need for what would have been a major archaeological excavation effort.

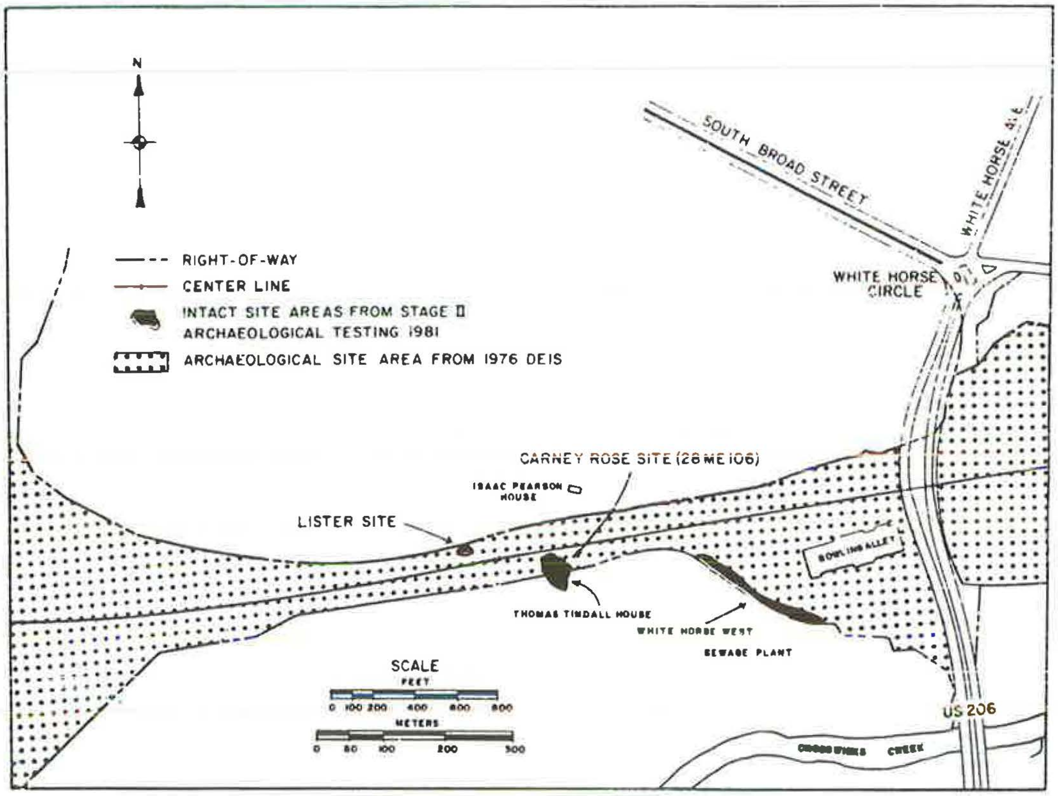
Work in the Wetlands Interchange began during late fall 1982. This interchange, comprising approximately 80 acres, was initially thought to consist of a single major prehistoric site partially bifurcated by the wetlands. Intensive testing throughout the 80-acre area located two major archaeological concentrations (Figure 7): one site consisted of a linear configuration more than 2,000 ft long and was narrow, averaging less than 100 ft wide; the second site was located on a major wetland finger immediately adjacent to an area excavated in the late 1800s. Both of these sites, although of immense scientific importance, were clearly definable and were much more limited in area than postulated in the 1976 report. A number of smaller disturbed sites were investigated on the remaining wetlands fingers.

While testing the water power canal and industrial foundations on the Route 29 segment, the crew encountered an intact prehistoric component deeply buried beneath the terrace. The survival of prehistoric materials in a heavily used industrial and residential area was considered so significant that the Advisory Council and the SHPO met with FHWA and NJDOT representatives to evaluate options for the site. This discovery of a prehistoric component demonstrated that extensive testing would be required to determine the extent of the prehistoric materials present and to develop a mitigation plan sensitive to the needs of both prehistoric and historic resources. However, the duration of testing for prehistoric resources would require significantly more time than was available if construction delays on other sections were to be avoided. Consultation resulted in the decision to break out the New Jersey Route 29 segment of the project as a separate compliance action to allow the remainder of the project to move ahead; this segment is scheduled to be completed last (about 1990), allowing adequate time for testing and mitigation planning without jeopardizing the remainder of the project.

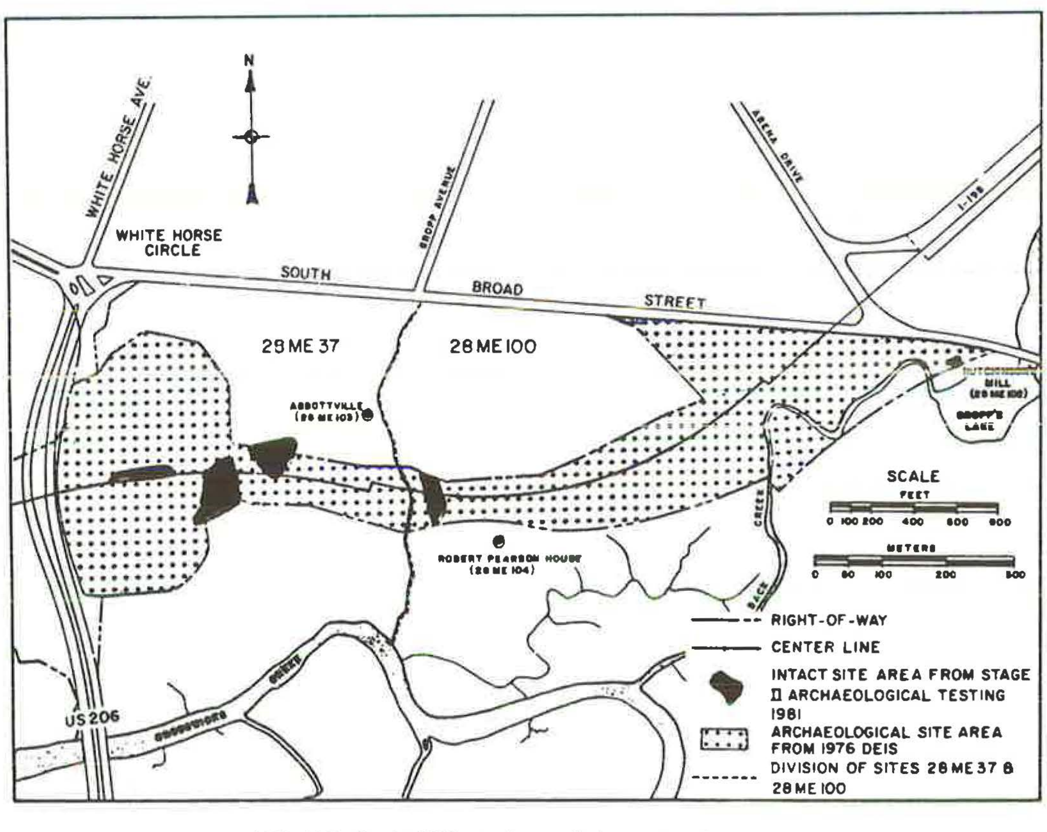
A review of the fieldwork results demonstrated that designing a workable mitigation of prehistoric resources in the Trenton Complex could be accomplished in an archaeologically sound and cost-effective manner. To collect the necessary site data, slightly more than 3,000 posthole-size windows and 200 2.5 x 2.5-m units and 13 backhoe trenches had been excavated within the 13 miles of highway corridor. For the first time, NJDOT, FHWA, the SHPO, and the Advisory Council had an accurate assessment of the size, depth, and nature of the cultural resources located throughout the highway corridors in the Trenton Complex. These data and reports clearly revealed that the impact on cultural resources, although substantial, could be mitigated by careful excavation planning and through coordination with engineering design.

Review and Mitigation Planning: 1983

During development of the reports, constant coordination was maintained with NJDOT archaeologists, FHWA, the SHPO, and the Advisory Council archaeologists. Their interaction was beneficial because it kept all parties working at a good pace as the analysis proceeded. Advance reviews also provided valuable feedback and removed the element of potential surprises in the documents as they were being developed. By maintaining complete familiarity with the



I - 195 Wetlands Interchange to U.S. Route 206



I- 195 U.S. Route 206 to Arena Drive Interchange

FIGURE 5 Estimated and actual intact archaeological site areas.

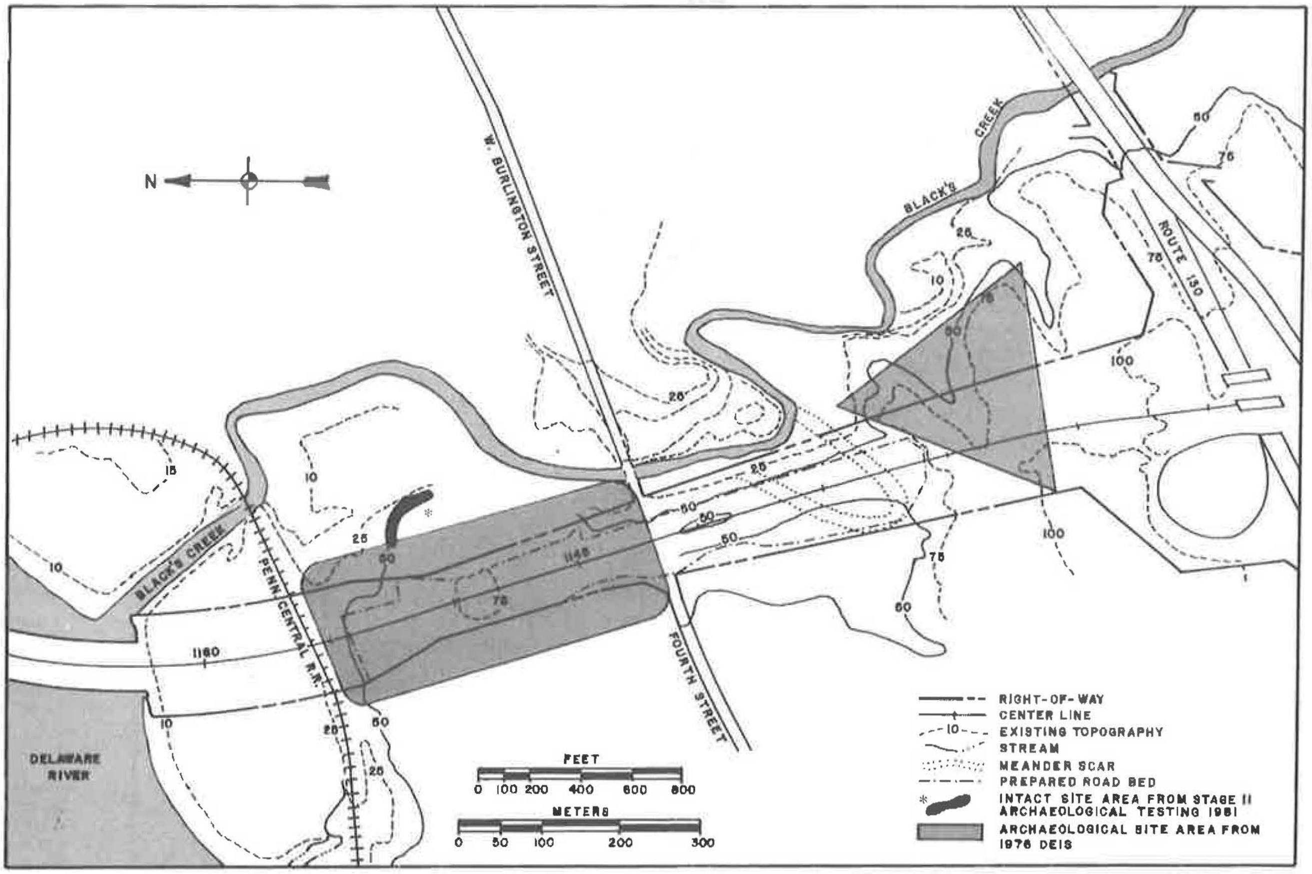


FIGURE 6 Black's Creek prehistoric archaeological district.

study throughout, review time for the massive quantity of documents was minimized, which allowed for a quick turnaround time after they were submitted.

After the determination was made of those sites eligible for the National Register, all proposed mitigation plans were submitted to the Advisory Council for review. The formal review required less than 2 months because of the continuing coordination throughout the project. A Memorandum of Agreement (MOA) was coordinated among all parties (the Advisory Council, FHWA, NJDOT, the SHPO), with every recommendation in the mitigation plan being evaluated before it was included in the MOA.

During the review and development of the MOA, mitigation planning for the I-195 segment was initiated. This segment was designated for letting of the construction contract in late fall 1983 and for construction in spring 1984. To complete the excavation of 4 prehistoric and 1 multicomponent (prehistoric and historic) site within the time frame remaining, 3 of the sites had to be under excavation simultaneously. This level of excavation required a large number of archaeologists to be in the field and an increase in laboratory staff. By beginning planning for this segment during the review, start-up time was reduced to less than 1 week.

After completion of the MOA, it was decided that an official signing ceremony would be held at the Advisory Council in Washington, D.C., with representation from the SHPO, FHWA, NJDOT, the consulting firm, and the Advisory Council. On September 28, 1983, the MOA was signed with all parties present, an unprecedented cooperative effort that saved 2 to 3 months over the normal process of routing, review, and signature by each agency.

Mitigation: 1983 to 1984

Within 1 week of the signing of the MOA, fieldwork began on the I-195 segment. Approximately 40 archaeologists and support personnel were involved in this work. Excavation of the Gropps Lake prehistoric site was the most complex, involving construction of a half-mile access road and removal of 3 to 5 ft of overburden with a dragline. Preservation in this site was excellent because of the overburden placed in the early 1800s. Hearths, projectile points, tools, lithic debitage, and a large pottery collection were recovered from the site. Most important, the site contained datable organic remains, a rarity in upland archaeological sites.

The historic house foundation at the Carney Rose site yielded a major ceramic collection that will contribute to the understanding of early historic settlement and trade patterns throughout the Delaware Valley. The prehistoric component also provided a major collection of materials that are undergoing analysis and interpretation.

Fieldwork continued until January 1984. In the last months, work was conducted in heated shelters because of bitter winter conditions. Completion of the fieldwork on the I-195 segment ahead of construction removed the last potential impediment to

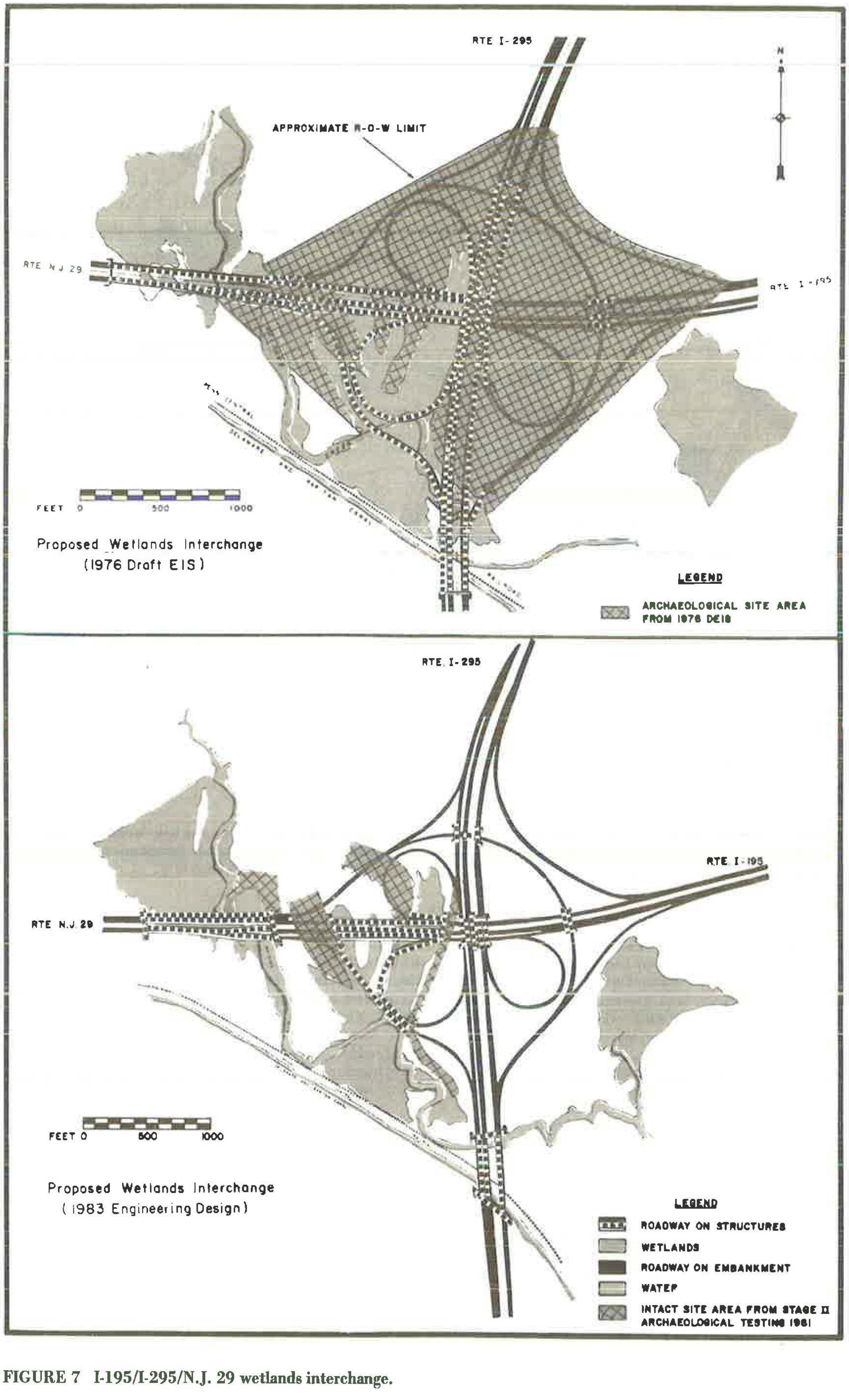


FIGURE 7 I-195/I-295/N.J. 29 wetlands interchange.

completion of the entire Trenton Complex within the original schedule. The design and letting sequence for the remaining sections is such that excavations will be completed a minimum of 1 to 4 years ahead of construction.

STAGE II: CONSULTATION AFTER APPROVAL OF THE FINAL EIS IN 1981--WETLANDS AND ECOLOGY

The Mudflat

The purposes of the special studies of the Crosswicks Creek crossing (Figure 8) were fourfold.

First, the functional characteristics, both ecological and hydrologic, and the uniqueness of the wetland area at the mouth of the Creek (known as the Mudflat) were documented so that the feasibility of replacing the affected area could be determined for both land area and functional value.

Second, an assessment was undertaken for two proposed bridge schemes: constructing the short bridge and embankment and constructing the extended bridge. Implicit in the comparison of these two schemes was the understanding that implementing the short-bridge-and-embankment alternative would result in the loss of a greater percentage of the Mudflat area than would implementing the extended-bridge alternative. Of additional concern with this short-bridge-and-embankment alternative was the effect it would have on the physical tidal flow regimes in Crosswicks Creek; that is, whether the additional constriction at the mouth of the Creek, due to an extension of the embankment into the channel, would cause significant adverse backwater impacts.

Third, having determined the functional characteristics and physical acreage of the Mudflat, other areas in the Crosswicks Creek study area were evaluated to determine their potential as replacement wetland areas. A plan was then proposed to create suitable wetland acreage.

Fourth, preliminary engineering was conducted on the two bridge schemes for cost comparison. In addition, information was generated on location of the embankment for the hydraulic modeling, construction methods (to assess the length of construction), and the associated impacts to the wetland area.

Both quantitative and qualitative studies of the biological and ecological values of the Mudflat were undertaken. Officials from NJDOT, FHWA, NJDEP, U.S. Fish and Wildlife Service, U.S. Army Corps of Engineers, U.S. Environmental Protection Agency, Delaware River Basin Commission, and the U.S. Coast Guard participated from the outset with the consultant in these field studies in review and advisory capacities. This participation facilitated the formal review process later in assessing the feasibility of replacement alternatives. In the field studies, the flora and fauna present (macrophytes, algae, invertebrates, and fish) were documented. The importance of the habitat and food chain production were studied, as well as the Mudflat's role in erosion control, flood moderation, recreation, and aesthetics.

Based on the various investigations and studies performed, NJDOT, FHWA, U.S. Fish and Wildlife Service, and U.S. Army Corps of Engineers concurred in the finding that the Mudflat functions as:

- An active, healthy, and productive wetland component of the Crosswicks Creek estuarine system.
- A buffer between the waters of the Delaware River and Crosswicks Creek, attenuating both wave energy and tidal currents.
- A nourishment center for fish because of its rich macroinvertebrate fauna and planktonic flora.
- An important habitat area for fish, especially as a nursery area for immature species (bass, pickerel, herring) and as a feeding area for adults (including the shortnosed sturgeon, an endangered species).
- A feeding and resting site for many species of waterfowl and seabirds.
- A significant area in primary productivity and nutrient cycling; however, because of its size, this area is not a crucial component of the overall capacity of the Crosswicks Creek wetlands system for these biological activities.
- A moderating force against adverse effects of flooding.

The key element of the hydrologic studies was to document whether the Mudflat could be partially filled without causing backwater effects upstream from the embankment. The first phase of the determination of the Crosswicks Creek hydrologic characteristics involved data collection and review. All available models and supporting data describing the hydraulic and hydrologic characteristics of Crosswick Creek were sought. Direct contact was made with the appropriate technical and management personnel at the National Oceanic and Atmospheric Administration, the U.S. Geological Survey, the Federal Emergency Management Administration, NJDEP, and the Delaware River Basin Commission.

Information existed on the nontidal portion of Crosswicks Creek and on tides in the Delaware River 9 miles downstream from the mouth of Crosswicks Creek. Unfortunately, no information about the cyclical nature of the tides at the confluence of Crosswicks Creek and the Delaware River was available.

Because of the influence of wetlands and nontidal inflow in the Crosswicks Creek basin, hourly elevations at the mouth of the Creek could not be interpolated from other Delaware River stations. To augment the information available, it was necessary to collect field data concerning floodplain and river profiles, stream flows, and velocities. The location and extent of this supplemental data collection was closely coordinated with NJDOT.

Based on a review of the ecological and hydrological values and characteristics of the Mudflat, it was decided--in consultation with NJDOT, NJDEP, FHWA, and the U.S. Fish and Wildlife Service--that any proposed replacement acreage had to satisfy two general criteria:

1. The acreage had to be located, to the extent possible, either within or adjacent to the area of the Crosswicks Creek mouth.
2. Replacement of the acreage had to at least maintain and, at best, enhance and improve the overall ecological function of the Crosswicks Creek estuarine system.

The short-bridge-and-embankment alternative required 7.4 acres of the Mudflat, 0.2 acres of the sandbar, and 1.7 acres of open water, totaling 9.3 acres of wetlands. It was determined, in consultation with the resource agencies, that the recommended replacement acreage should be in this same general range, depending on the site. This amount of acreage, suitably located and properly vegetated, would result in replacement of the habitat elements lost in the Mudflat, and with the adoption of certain schemes, would increase the nutrient cycling and primary productivity of the overall system.

Based on a review of aerial and topographic mapping and on-site field investigations, various sites were primarily screened as potential areas for wetland replacement activities in coordination with

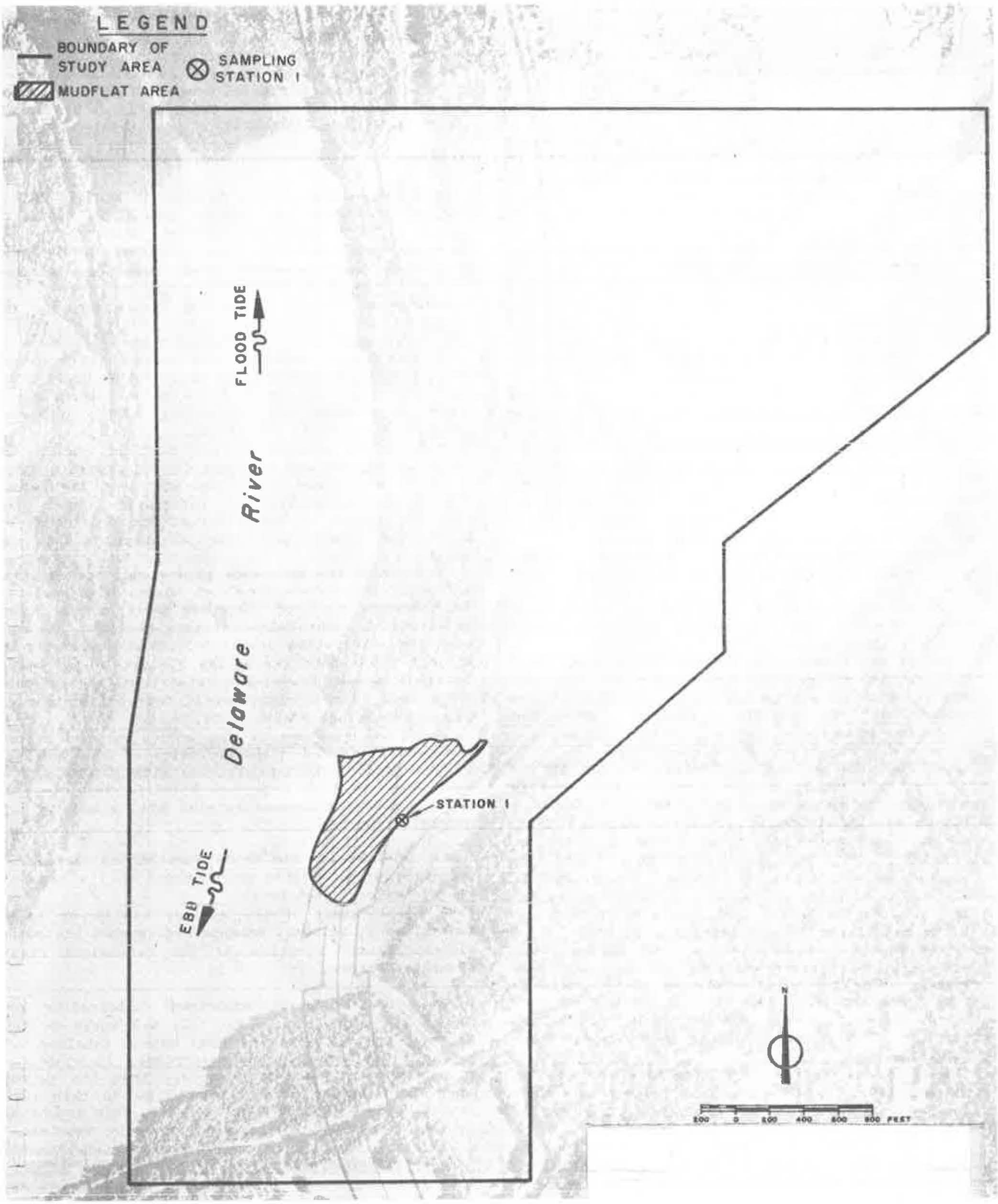


FIGURE 8 Study area of Crosswicks Creek Wetlands replacement.

NJDOT. Although the Crosswicks Creek estuarine system is large, the focus for replacement sites was localized within an approximately 4,000-ft radius of the Mudflat. The major purpose of this focus was the desire to position the replacement site as near as possible to the Crosswicks Creek and Delaware River confluence. In this manner, it became more feasible for a replacement site to function as a buffer between the two water bodies, thus duplicating a significant functional characteristic of the Mudflat.

The following guidelines, jointly developed in consultation with NJDOT, FHWA, and the U.S. Fish and Wildlife Service, were considered in determining the overall suitability of the replacement sites:

- The site selected would, optimally, have a low current ecological value that would clearly benefit from conversion to wetlands. Currently developed areas were excluded.
- It was necessary that the site be subject to tidal action and not require additional periodic maintenance to provide adequate water circulation. However, it was recognized that initial excavation or fill might be required to render a site acceptable for emergent wetland vegetation to thrive.
- Sites located within the boundaries of the Abbott Farm National Historic district would be avoided. The location of potential sites was coordinated with the archaeological team performing the ongoing investigations, and the probability of impacts on cultural resources was noted.

Four potential sites were identified. After coordination with NJDOT, one site was selected and a wetlands replacement scheme developed, which included a grading plan showing the final elevation in the site, number of plants, amount of fertilizer, and estimated cost of planting the vegetation.

Preliminary engineering was performed to estimate construction costs of the two Crosswicks Creek crossings alternatives. It was estimated that the extended-bridge alternative would cost $24 million. The short-bridge-and-embankment alternative was estimated to cost $17 million, including the $3 million estimated cost of wetland creation, making a $7 million cost difference between the two alternatives. The ultimate decision about which alternative will be selected for construction is recognized to be one requiring high-level consultation and coordination among concerned agencies, with consideration given to the cited technical background.

Wetlands Interchange

Further studies in the I-195/I-295 interchange area were more straightforward, but no less important in minimizing the cost of construction. There had been a commitment in the EIS not to fill any tidal wetlands in the interchange; that is, any tidal wetlands would be spanned by structure (Figure 9). As the project proceeded further into design, two things became clear: one, the amount of the interchange to be built on a structure was significant; and two, the mapping of the tidal wetlands was not of sufficient detail and accuracy to propose and evaluate design modifications.

Thus, a substantial amount of supplemental field work was conducted by the consultant and NJDOT biologists to stake the boundaries of tidal and nontidal wetlands. Slopes throughout the wetlands area were slight; therefore, it was important to be in the field at high tide to observe the areas of inundation and correlate the type and density of vegetation in the tidal areas. Survey crews then followed to map the boundaries exactly. After this information had been mapped, the consultant's engineers were able to make slight shifts in the location and shape of the Wetlands Interchange that obviated the need for most of the construction on structure originally anticipated.

SUMMARY AND CONCLUSION

A mitigation program of the magnitude of the Trenton Complex--which involves adhering to tight deadlines, coordinating multidisciplinary studies of ecology, cultural resources, and engineering, and working in harmony with the funding and review agencies--created a series of challenging management problems. From the viewpoint of the cultural resources and wetlands, four key problems existed: ensuring the quality of work, coordinating with the review agencies, incorporating study findings into the engineering design in a cost-effective manner, and keeping the project on schedule.

Modification of engineering design to preserve priceless cultural resources and critically important wetlands proved difficult on the Trenton Complex project because the right-of-way had been purchased almost 20 years previously and engineering was locked in. Nevertheless, through extensive coordination of the wetlands and archaeological investigations with engineering design considerations, creative mitigation programs were developed to protect these environmental resources without compromising engineering design requirements; an example of this was the Wetlands Interchange. At the time the Final EIS was approved in 1981, NJDOT and FHWA had agreed to build the entire interchange on a structure to minimize impacts on cultural resources and wetlands. Tight definition of wetlands, combined with accurate mapping of the archaeological sites, allowed the engineers to slightly rotate the interchange configuration to avoid or minimize the impact on cultural resources and wetlands. Through this modification in alignment--a direct result of coordination of the disciplines--80 percent of the structure could be built on fill, resulting in a savings of $40 million compared with the original EIS design concept.

Many review agencies, such as the Advisory Council, referred to the Trenton Complex project as a textbook case of how environmental studies on transportation and other development projects should be carried out. This praise illustrates that the team concept used for this project, in which all participants pulled together toward a common goal, can succeed, even in the case of projects as challenging as the Trenton Complex.

The Trenton Complex Interstate highway project might easily have gone uncompleted, had it not been for the enormous public need that otherwise might have gone unsatisfied and the perseverance of project sponsors to see this need fulfilled. Throughout the NEPA process, this project enjoyed broad-based public support while simultaneously being shadowed by well-defined and intricately interrelated environmental concerns--mainly those related to cultural resources and wetlands.

Faced with a range of comments from governmental agencies, comments that covered the spectrum from general acceptance and support for the project to disbelief that it would ever be approved and expression of unalterable opposition, NJDOT and FHWA had to separate the legitimate issues from the rhetoric. This was accomplished by dividing the concerns into logical categories, including impacts on cultural resources, ecological impacts, as well as other environmental impacts; coordinating as appropriate on a continuing basis; and seeking solutions for valid concerns. Extensive alternative locations and

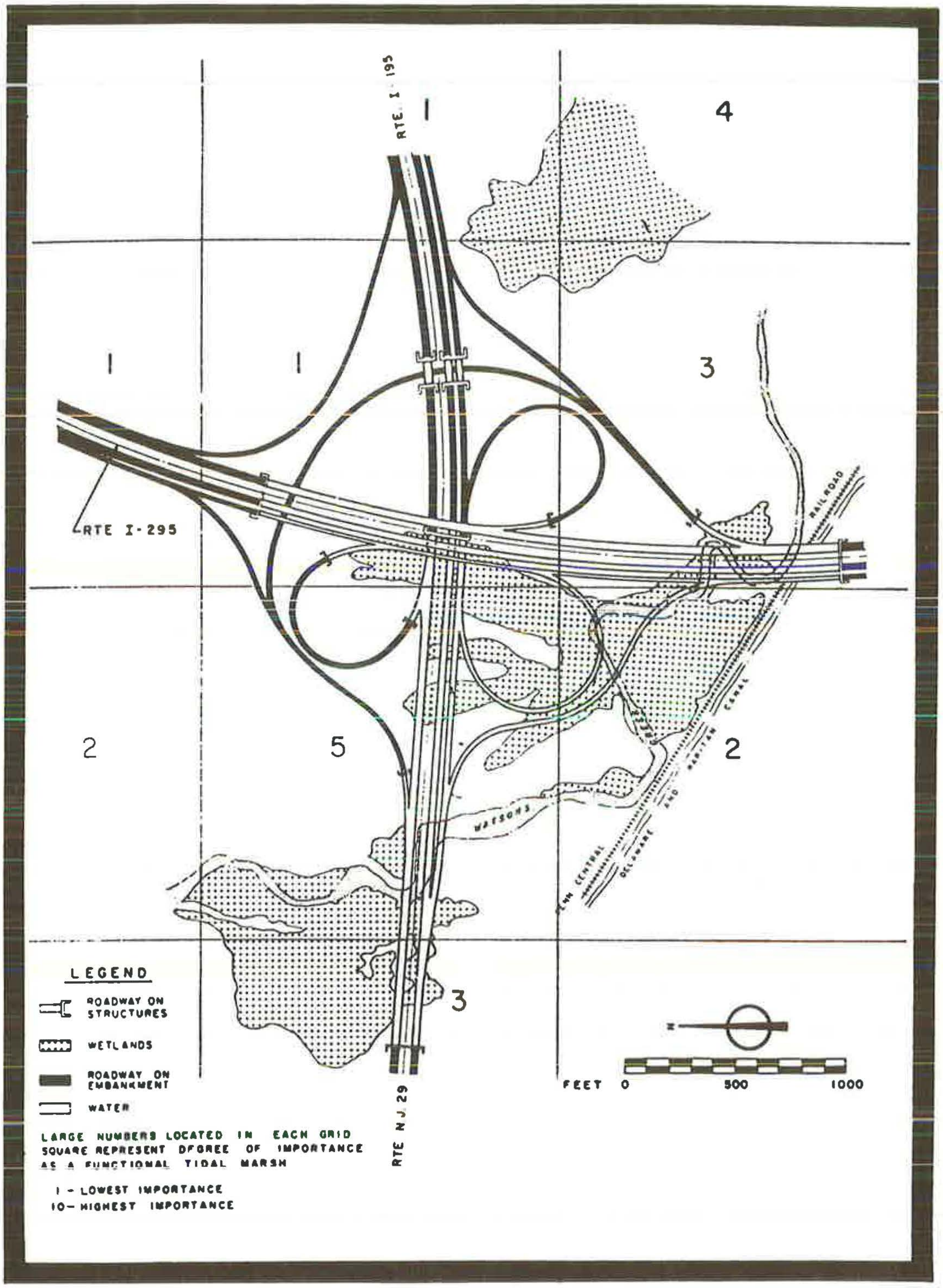


FIGURE 9 Proposed I-195/I-295/N.J. 29 interchange.

design treatments, and combinations thereof, were studied as means to this end. The challenge was to minimize or eliminate problems while simultaneously maintaining public support, keeping construction costs down, minimizing delay, and refraining from creating new environmental problems as a result of resolving existing ones.

In the final analysis, the cultural resources and ecological issues would be the most challenging to resolve, not only because of their individual significance but also because of the potential for the solutions related to one adversely affecting the other, thereby increasing costs. Through the process of coordination an ingenious compromise evolved, carefully integrated with the design efforts, which resulted in substantial cost savings while simultaneously protecting archaeological and wetland areas that were otherwise adversely affected.

Portions of the Trenton Complex are now under construction, another contract is soon to be let, and several other portions are in the advanced stages of design. Even though the Final EIS has been approved, the MOA signed, and several construction permits granted, the environmental work continues and will continue into the future. In the early 1970s, approval of a Final EIS was viewed as the end of the NEPA process. However, the Trenton Complex project, perhaps more than any other, has demonstrated that although approval of the Final EIS yields the decision about location, environmental work must continue during the design process to meet specific environmental needs such as fulfilling the requirements of the MOA, and to provide solutions to environmental problems that arise during the process of securing construction permits. The realization that approval of a Final EIS is not the end of the NEPA process and that environmental work must continue during the final design phase has developed over an extended period of time and has not come without some frustrations. Ahead lie substantial amounts of work in completing archaeological investigations to gain ultimate acceptance; additional work has to be completed on wetlands mitigation, including major decisions about project design and methods of construction to secure needed construction permits. Even now, almost 15 years after NEPA and almost 5 years after Final EIS approval, expenditures of time and cost for environmental mitigation and coordination are substantial. Although much of this was unforeseen in the beginning, it has become clearer over time--particularly as new and unforeseen issues arose and new regulations were introduced during the approval process--that Final EIS approval is not the end of environmental involvement for the project, but rather the beginning of a new and more issue-related environmental phase demanding more and better coordination than previously.

The Trenton Complex has evolved dramatically during the years since enactment of NEPA in 1969. In many ways and by nearly any standard, the Trenton Complex project has been improved for those who will live within its proximity and for mankind in general, as a result of the environmental coordination process. It must be remembered, however, that it did not come without substantial costs in manpower and money invested in studies and that it did not come without postponing other needed transportation improvements for the many years during the process.

Perhaps one of the greatest benefits of the environmental coordination carried out on the Trenton Complex project is that it has been a learning experience for all those who have been associated with it during the past 15 years. During those years, as the NEPA process itself matured, so did those who worked with it and served it. Many who originally thought the Trenton Complex should not and could not be built have, through the extensive coordination efforts, come to believe this project is beneficial not only to regional and local needs, but also to environmental preservation and enhancement. Staff members from NJDOT and FHWA who once sat across the table from representatives of environmental agencies opposed to the project have long since reconciled their differences and cemented relationships that will serve to expedite future projects. This reconciliation resulted from considerable discussion and coordination among the interested communities and agencies, leading to a mutual understanding and respect for the various positions taken on the many sensitive environmental issues involved in the Trenton Complex project. The Trenton Complex being built in a manner more environmentally compatible than some ever believed possible is perhaps reward enough for the years of effort spent. For some of those who worked on the project, however, the learning experience with respect to coordination and reconciliation of differences among those who hold different views is perhaps even more satisfying.

Publication of this paper sponsored by Committee on Environmental Analysis in Transportation.