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 microweather 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.

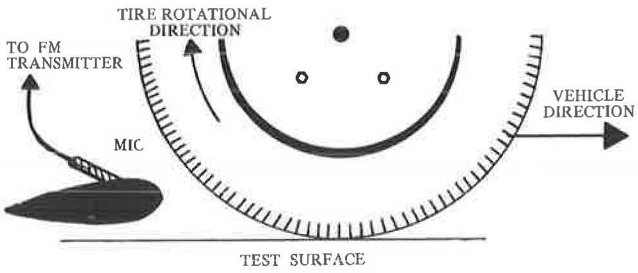
On-Board Measurements

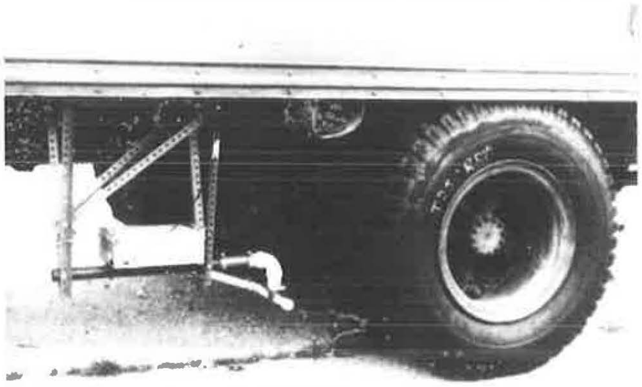
The third principal method of tire noise measurement is that achieved by attaching the microphone to the vehicle in the vicinity of one of the test tires. Figure 1 shows a typical microphone location (9) as used in recent studies (10,11). A variant of this procedure is the placement of the test tire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

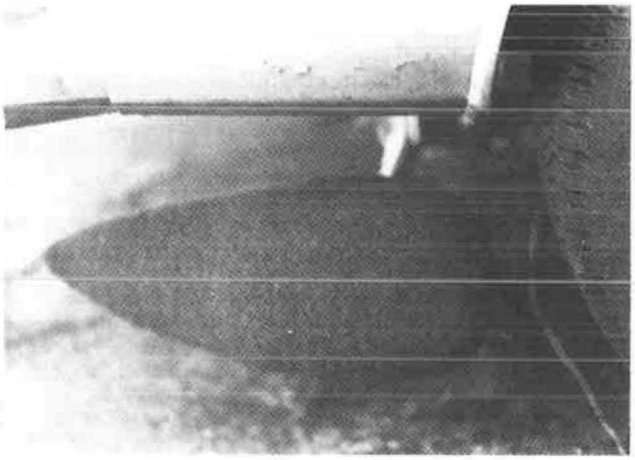


FIGURE 2 Windscreen used for on-board tire noise measurements.

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

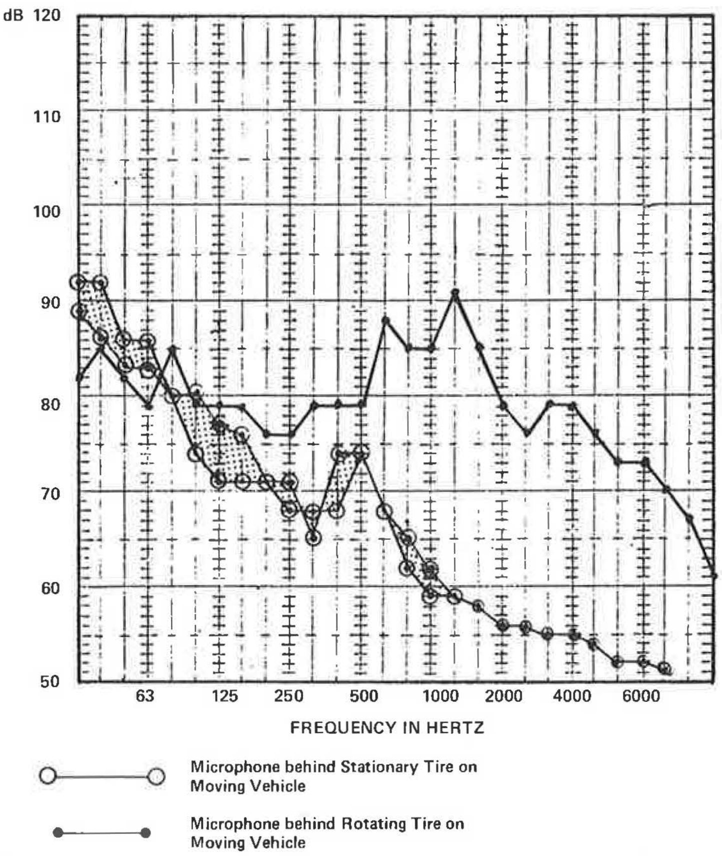


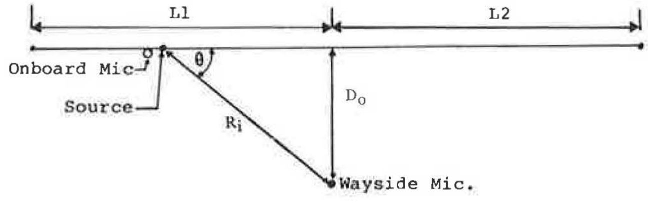
FIGURE 3 Third-octave data for teardrop-shaped windscreen.

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

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

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

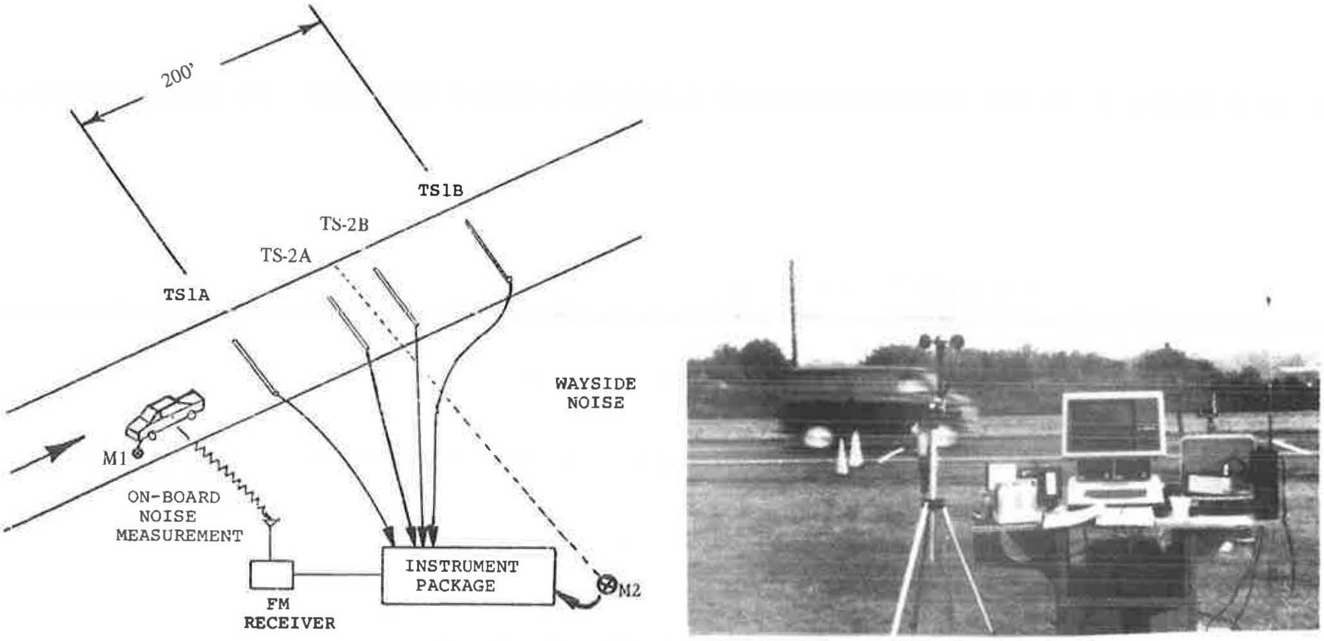


FIGURE 5 Equipment configuration for passby on-board/wayside noise measurements.

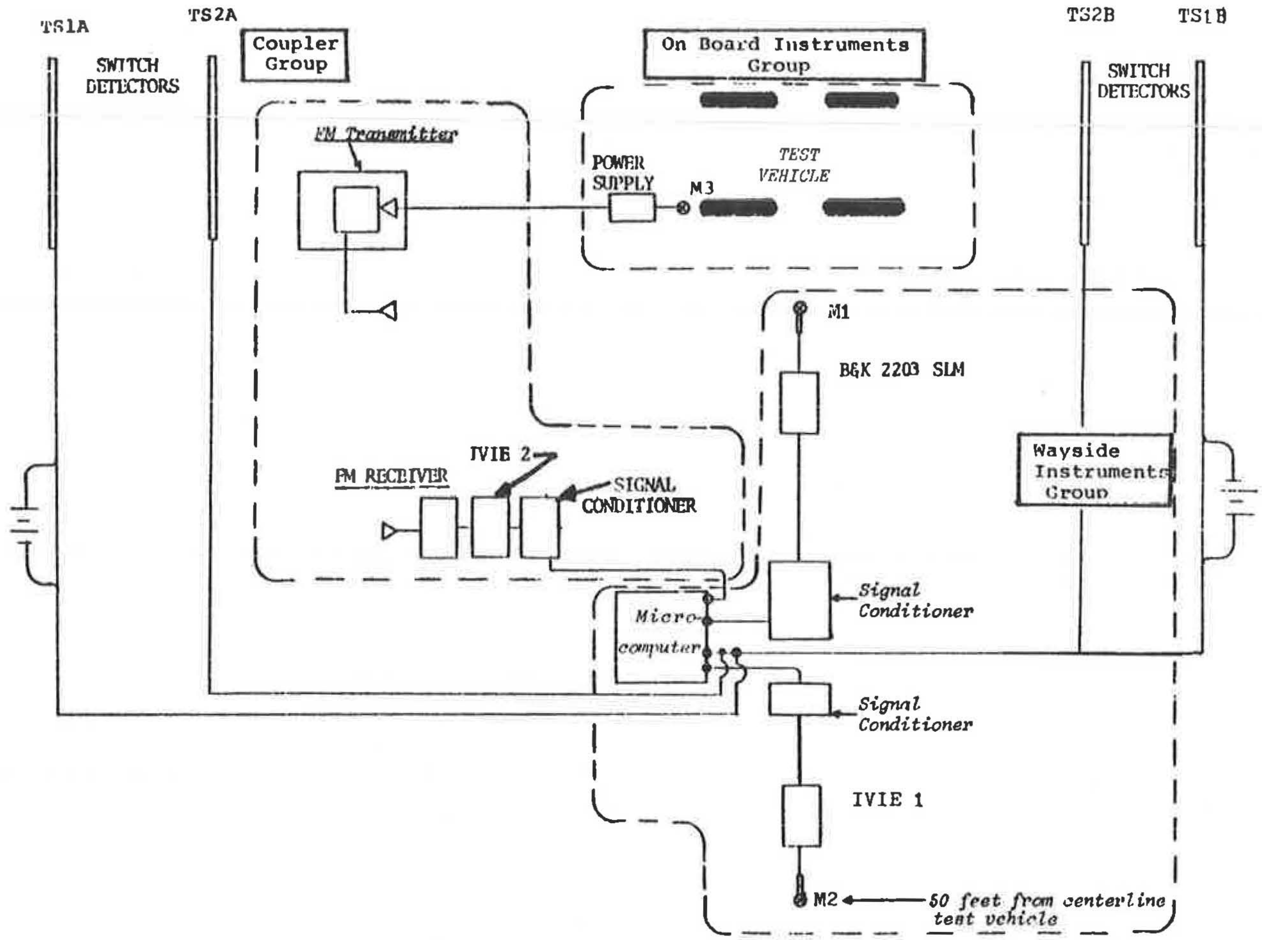


FIGURE 6 Block diagram of passby data acquisition instrumentation.

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

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

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

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

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

$$\begin{aligned} -10 \log 1/N \, \Sigma \, (D_o^2/R_i^2) \equiv \Delta = {} & 10 \log [\,|L_1/D_o| \\ & + |L_2/D_o|/\text{arc tan } |L_1/D_o| \\ & + \text{arc tan } |L_2/D_o|\,] \end{aligned} \qquad (4)$$

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:

$$\overline{TF} = 1/NR \sum_{r}^{NR} TF_r \qquad (5)$$

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

$$\overline{TF} = 10 \log 1/NR \sum_{r}^{NR} 10^{\overline{L_{OB}}/10}$$

$$- 10 \log 1/NR \sum_{r}^{NR} 10^{(EL50)/10} \qquad (7)$$

where

NR = total number of test runs,
TF_r = transfer function for test run r, with r varying from 1 to nr, and

$$EL50 = L_{eq} + \Delta \qquad (8)$$

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}:

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

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

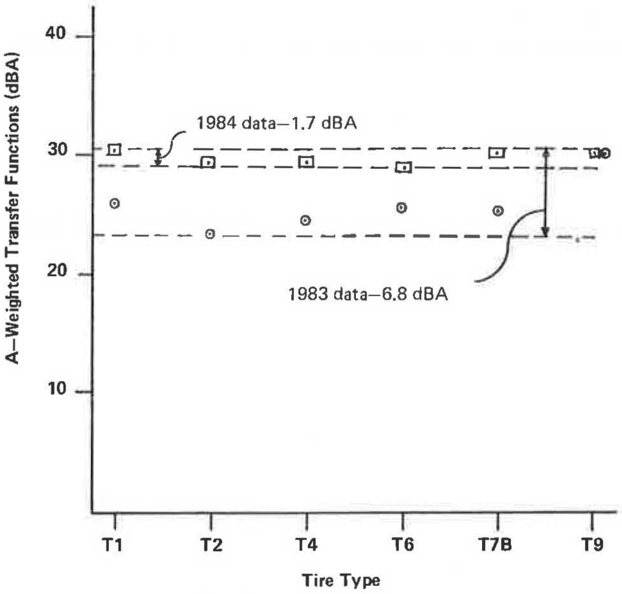
$$TF = 10 \log (1/K_i) \qquad (10)$$

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

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

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.

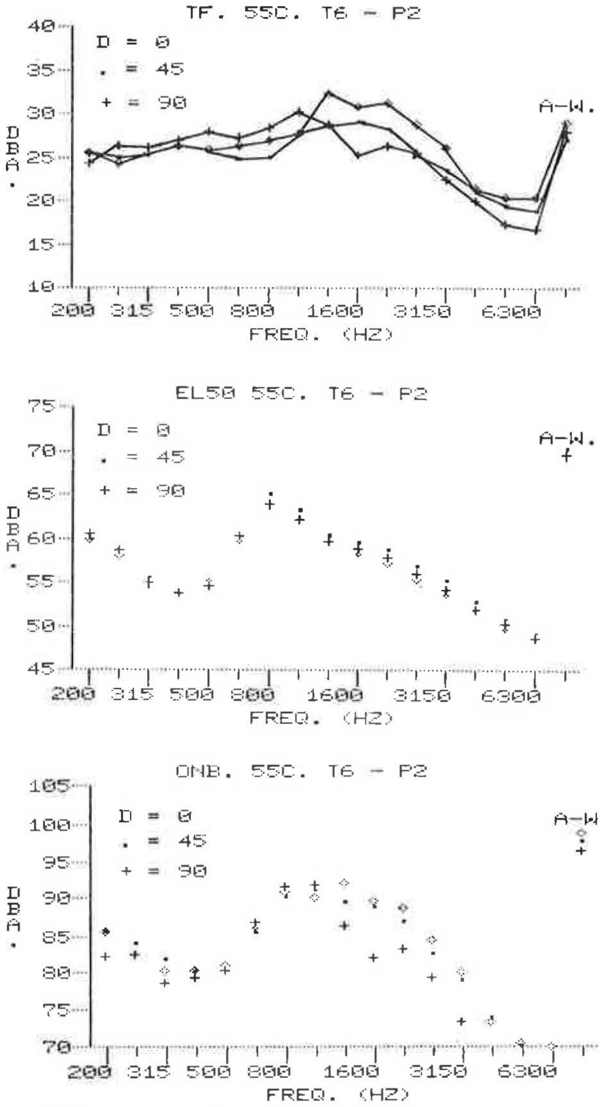
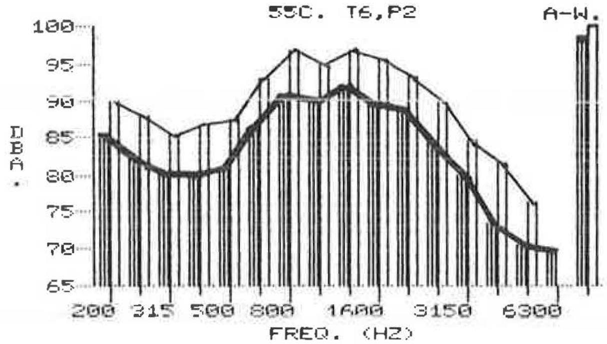


FIGURE 8 On-board/wayside measurements taken with on-board microphone at varying angles.

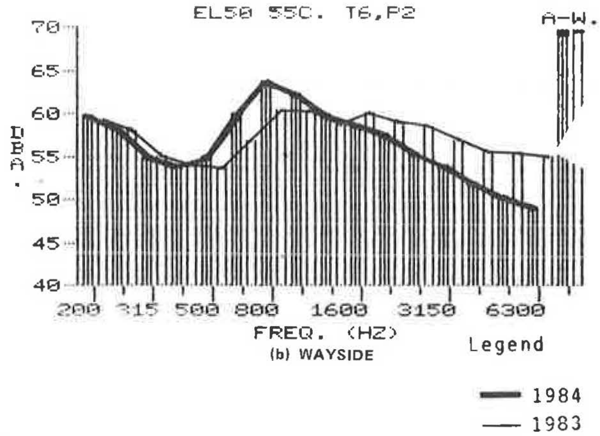
TABLE 1 Summary of Observed Wayside and On-Board Levels for 1983 Measurements versus 1984 Measurements at 55 mph Coastby

	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

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



(a) ON BOARD



(b) WAYSIDE

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.