Full-Scale Testing of Single and Parallel Highway Noise Barriers

LLOYD HERMAN

The results of research conducted by North Central Technical College and cosponsored by Ohio's Thomas Edison Program and Empire-Detroit Steel Division are reported. Laboratory and full-scale outdoor testing of both reflective and absorptive highway noise barriers are discussed. The phenomena of single-barrier insertion loss degradation caused by the addition of a second parallel barrier was confirmed. Further, absorptive barriers evidenced performance benefits over reflective barriers in parallel tests. Single-barrier insertion loss tests supported barrier attenuation theory for the configurations tested.

An important part of comprehensive noise abatement programs devised to alleviate adverse noise conditions involves the use of noise barriers. Highway noise abatement efforts, in particular, have been in effect in the United States for more than 15 years. To date, over 700 mi of highway noise barriers have been constructed along roadways, and another 700 mi are planned for construction over the next 10 to 15 years.

In 1988, Ohio's Thomas Edison Program accepted a proposal submitted by Cyclops Corporation, Empire-Detroit Steel Division, and North Central Technical College to provide funding for noise barrier research.

This paper is a report of the second phase of a three-part program to study highway noise barriers. The three parts are

1. Laboratory testing of acoustical panels.
2. Full-scale barrier tests at an isolated roadway.
3. Field tests at highway sites under traffic operations.

A summary of the first part of the program is included as background information. Part 2 of the program, the full-scale barrier tests at an isolated location, was completed in 1990. The goal of this phase was to produce a data base for both the third phase of the program and future research.

RESEARCH OBJECTIVES

The first objective for this phase of the project was to study in detail a variety of single-barrier configurations. Both a comparison of their performance with established barrier attenuation theory (which considers the path length increase for diffracted sound waves over a barrier), and observation of any differences between reflective and absorptive barriers, were to be made.

North Central Technical College, 2441 Kenwood Circle, Mansfield, Ohio 44901. Current affiliation: Vanderbilt University, Box 1625, Station B, Nashville, Tenn. 37235.

A second objective focused on the degradation effect occurring when a second barrier is installed parallel to the first barrier on the opposite side of a roadway. This phenomenon of barrier performance degradation, attributed to multiple reflections between barriers, has been studied by a number of researchers in recent years. Mathematical models have been developed to predict the effect of these multiple reflections in highway noise barrier applications. Test data, for the most part, have been the result of either acoustical scale model measurements or field data collected under operating conditions at highway sites. As Bowlby et al. (*1*) have observed:

> Full scale field data are limited and generally inconclusive because of the difficulty in isolating the phenomenon. There is a need for more carefully controlled, full-scale data collection to complement the scale modeling results and to confirm the insertion loss degradation phenomenon.

On the basis of this need of a larger data base, the objective to perform full-scale parallel barrier tests was chosen.

Absorptive barriers have been used in lieu of reflective barriers in applications where multiple reflections were predicted to be a problem. As a third objective, absorptive barriers were to be compared with reflective barriers to determine their effect on multiple reflections.

The primary project objectives are summarized as follows:

1. To compare single-barrier configurations with barrier attenuation theory, and to observe any performance benefits of single absorptive barriers compared to single reflective barriers;
2. To obtain full-scale test data to document any degradation of barrier performance resulting from parallel barrier installations; and
3. To determine the effect of absorptive barriers in parallel configurations compared to reflective barriers.

The overall goal was to provide a data base from a variety of barrier configurations with a minimum of outside variables. Highway test sites serving traffic operations were ruled out, because they contain many uncontrollable variables. This decision resulted in a trade-off. The data itself would not have direct application to a similar highway situation. However, the data would be indirectly applicable to a much broader range of highway situations. That is, the data, being foundational in nature, could serve both as a building block for future research, including Part 3 of this research program, and as a basis for formulating conclusions regarding specific highway applications.

NOISE BARRIER RESEARCH

Acoustical Panel Design

The absorptive panels tested were 2 in. thick and contained 1.5 in. of mineral rock wool with a solid steel back and a perforated steel front cover. The mineral rock wool had a density of 6 lb/ft^3. The perforated steel front cover contained a minimum perforation area of 15 percent. This amount of perforation area produced a cover that was essentially transparent to the sound striking the surface of the panels.

Laboratory Testing

Acoustical test panels were evaluated at Riverbank Acoustical Laboratories. The sound transmission properties of the test panels were evaluated using the ASTM standard test methods for sound transmission loss: E90-87 and E413-87. The sound transmission classification (STC) for the test panels was 33 when the seams between panels were sealed; however, in the unsealed condition, the STC rating was reduced to 26. Because an STC of 26 met the design goals for the test panels, it was decided that initial testing in the outdoor full-scale tests would not include sealed seams. Absorption testing was done according to the ASTM *Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method*: ASTM C423-87 and E795-83. The test panels with 1½-in.-thick mineral rock wool (6 lb/ft^3) produced a noise reduction coefficient of 0.95.

Full-Scale Outdoor Testing

Site Configuration

Test objectives called for an isolated outdoor test site where multiple barrier configurations could be evaluated under controlled conditions. The site chosen was an unused roadway in an open area at the Mansfield Lahm Airport in Mansfield, Ohio. A 16-ft-wide north-south roadway was located in a large grass-covered field. A wood support structure was erected on both sides of the roadway 50 ft from the centerline. The structure was designed to test barriers up to 250 ft long and 16 ft high in single or parallel arrangements.

Sound Source

The sound source used for the full-scale testing was a stationary, controlled, artificial point source. An artificial source was chosen to produce a high level of energy in all the frequency bands of interest. A point source was chosen because most of the data base from previous scale model research used a stationary point source. The type of tests scheduled were comparison tests requiring a high level of control and precision. There was no need to produce highway traffic conditions for these tests, but there was a need for repeatability with a minimum of variables. A moving point source was tested initially, but it proved more difficult to monitor random changes in background levels to determine the validity of a given sample. Also, sample time was limited with the moving source at any given position. Therefore, most of the tests were done with the point source held stationary. A Tracoustics Model NS-100 producing pink noise was selected. This source with its pink noise capability provided enough energy in a broad range of frequency bands to prevent masking caused by background levels in most cases. Dispersion testing was conducted to characterize the polar response of the speaker. Sound propagation from the speaker proved uniform and symmetrical. Barrier tests were made with the sound source in various positions; however, the most effective position proved to be with the speaker facing up. This position eliminated directionality effects that were especially important for the parallel barrier tests. The source heights used in the tests were 4, 8, and 12 ft.

Receivers

The receiver microphone was located, in all cases, on the opposite side of the barrier from the source, on the normal line with the source at 25, 50, 75, and 100 ft from the near barrier, at a height of 5 ft. A Larson-Davis Laboratories free-field ½-in. condenser microphone and preamp were used at the receiver positions.

Instrumentation

A Larson-Davis Laboratories dual-channel real time analyzer (Model 3100) was used to record ⅓-octave unweighted levels for a frequency range up to 10,000 Hz. In addition, all tests were recorded on a TEAC TASCAM dual-channel tape recorder.

Test Method

The test method used was taken from Methods for Determination of Insertion Loss of Outdoor Noise Barriers (*2*).

Test Environment

Testing began in August 1988 and ended in November 1989, a period much longer than had been originally anticipated. During this time, tests were run with few exceptions on all suitable days. However, moderate wind conditions prevail at this site, severely limiting the number of suitable days for testing. It was found that wind velocities greater than 7 mph distorted measurements and generally hindered data collection. In addition, adherence to test standards eliminated many days when temperatures, cloud cover, and humidity levels exceeded allowable variations. High levels of background noise because of the airport location further complicated the testing process. Nighttime testing was considered as a solution to the airport noise problem. It was rejected, however, out of concern for the effect on test microphones of the nighttime humidity levels (generally 100 percent at this location).

Test Procedures

All test equipment was set up for an individual test and taken down each day. Once equipment was in place, a checklist was used to review all settings for the instrumentation used. After settings were verified, a calibration procedure was begun using a Larson-Davis calibrator. Serial numbers of all equipment, including the calibrator, were recorded for each test and included in the test data file. All tests used the same receiver microphone. The microphone was calibrated as a first step, then the real time analyzer and microphone were used to record the output of the sound source. This procedure was a verification to ensure that the sound source would not vary in its output over time. This check was made at the beginning and the end of each test. In addition, the output voltage of the sound source was monitored with a voltage meter. This voltage was recorded at each change of the sound source height during a test. This procedure provided even further assurance that the sound source remained constant throughout the test. (Initially, and according to the specifications of the S12.8 test standards (*2*), a reference microphone located above the near barrier was used to monitor the sound source. However, the addition of a far barrier increased the sound level at the reference microphone position, thereby giving a false indication of sound source change. Therefore, the use of the reference microphone was abandoned in favor of using the procedure described to monitor the sound source output). Testing each barrier configuration then involved four microphone positions. The microphone was placed at 25, 50, 75, and 100 ft from the near barrier. These four microphone positions were used for sound source heights of 4, 8, and 12 ft. Therefore, 12 separate combinations were tested for each barrier configuration. Three samples, of 10 sec duration each, were taken at each microphone position. Microphone calibration checks were made at least three times throughout the test. Background levels were monitored before and after each sample and were recorded on the real time analyzer at least four times for each test.

Data Reduction

Raw test data produced by the real time analyzer was in the form of unweighted sound pressure levels for each of the $\frac{1}{3}$-octave frequency bands measured. These sound levels were keyed into a spreadsheet for each of the three samples taken, for each of the test runs completed. The sound levels for all three samples at each frequency band were then averaged. The average value was then adjusted for any calibration changes noted during the process of the measurements. Next, the averaged and adjusted values were corrected for any background interference that may have occurred. Finally, the insertion loss was determined by subtracting the adjusted and corrected average sound pressure levels with a barrier from the corresponding sound pressure levels without a barrier.

By preserving the insertion loss as expressed by frequency bands, the usefulness of the data has been maximized. For example, the insertion loss by frequency band, for a particular barrier configuration, can be imposed on any traffic spectrum. By modifying the spectrum according to the insertion loss produced by the barrier at each frequency, a new and different spectrum will result. If desired, the spectrum can then be weighted, added on an energy basis, and expressed as an overall level (i.e., dBA). This procedure has the effect of converting the performance of the barrier for pink noise to that for a selected traffic spectrum (considered as a point source).

Single Barrier Data Analysis

The sound reaching a receiver from a source some distance away is the result of that sound which travels in a straight line between the source and the receiver. By inserting a barrier between the source and the receiver, the sound propagation from that source to the receiver occurs in two major ways. Line-of-sight sound propagation, that is, from the source directly to the receiver, must go through the barrier itself. If the barrier characteristics produce a large transmission loss, then very little sound will actually be transmitted through the barrier itself. The second means of sound propagation from the source to the receiver is along a path in which the sound is diffracted or bent over the top edge of the barrier before it reaches the receiver.

As a general rule, if the transmission loss is at least 10 dB above the attenuation resulting from diffraction over the top of the barrier, the barrier noise reduction will not be significantly affected by transmission through the barrier (less than 0.5 dB) (*3*). The acoustical panels tested on this project produced sufficient transmission loss so that the transmitted sound can be neglected. Therefore, only the diffracted path of the sound needs to be considered when looking at the sound attenuation by the test barriers. To predict the barrier attenuation for a given barrier, the path length difference must first be calculated. The path length difference is the difference in the distance the sound must travel to go from the source to the top of the barrier and back to the receiver compared to the straight line distance between the source and the receiver. The greater the path length difference, the greater the barrier attenuation. The path length can be increased by increasing the height of the barrier or by moving the source or receiver closer to the barrier (*4*).

This simplified theory of barrier attenuation recognizes no difference between a reflective and an absorptive barrier. One of the research objectives was to set up a test in which any differences in performance between absorptive and reflective single barriers could be observed. The reflective barrier test used acoustical test panels in which the solid steel back faced the sound source. For the absorptive barrier test, the perforated front of the acoustical test panels faced the sound source. In this way the same panels were being tested to eliminate any differences from transmission loss, etc.

Before discussing the results of the analysis, it should be noted that the effect of an absorptive single barrier versus a reflective barrier has been addressed by other researchers. According to Simpson (*3*), for diffraction angles greater than 45 degrees, absorptive materials can influence the sound that is diffracted over the top of the barrier. However, in most highway situations it is rare to find a configuration in which the diffraction angle will approach that magnitude. For angles less than 45 degrees, use of absorptive materials is of little advantage in reducing noise levels.

L'Esperance has also studied the effect of single absorptive barriers compared to single reflective barriers. L'Esperance was consulted regarding the test barrier configurations for the possibility of increased attenuation caused by the absorption of the barriers. However, his analysis showed that absorption would have no effect at the small diffraction angles that were used for the test configurations on this project. It would appear then that absorptive barriers could exhibit a benefit over reflective barriers in single applications, when limited to situations where large diffraction angles occur.

The collected data was analyzed, as described earlier, and compared with the barrier attenuation theory described earlier. The graphs shown in Figures 1 and 2 are typical, and indicate the comparison between the calculated barrier attenuation and the experimental results. The solid line represents the calculated insertion loss caused by the barrier, for the particular geometry being considered. As indicated, this insertion loss for the barrier varies by frequency. Because the calculated values represent only the effect of path length difference and not other changes in the sound propagation, a relative comparison is in view here rather than an absolute comparison. Further, it is suspected that some of the scatter in the measured data may be the result of ground effects in which both constructive and destructive interference affect the receiver levels for different frequencies.

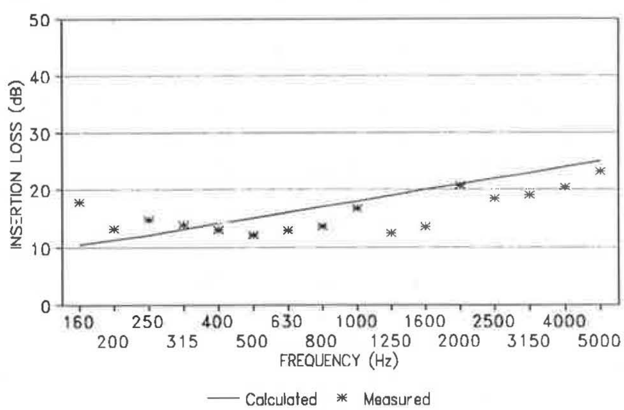

FIGURE 1 An example of single reflective barrier insertion loss test results (source 4 ft high, receiver at 50 ft).

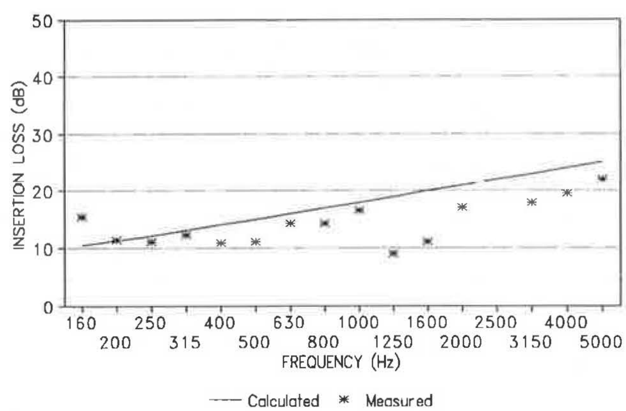

FIGURE 2 An example of single absorptive barrier insertion loss test results (source 4 ft high, receiver at 50 ft).

Several observations can be made from the data in its analyzed form. First, the experimental results generally followed the expectations calculated from theory. Second, there is no significant difference between the absorptive single barriers and the reflective single barriers as shown in the comparison of Figures 1 and 2. Overall, the measured data support rather than contradict barrier attenuation theory. Therefore, on the basis of the analysis of experimental data for this project, there is no basis for assuming that an absorptive single barrier performs better than a reflective single barrier for the range of geometries tested. However, other geometries, particularly those with large diffraction angles may indeed produce greater insertion losses for absorptive barriers. Such geometries may exist in some highway situations. As one example, though not typical, barriers installed close to the near lane may fall into this category. Further, multiple reflections between heavy trucks and such single barriers could be reduced by using absorptive barriers.

Parallel Barrier Data Analysis

As stated earlier, previous research has uncovered a potential problem when a second highway noise barrier is added in parallel to an existing single barrier. It is believed by many researchers that the addition of a second barrier degrades the performance of the first barrier because of an excess noise buildup caused by reflections between the walls of the parallel barriers. Objective 2 involved tests for the parallel barrier degradation phenomena. Parallel barrier tests were conducted for barrier heights of 10, 12, and 14 ft and barrier lengths of 250 ft. The same panels were used in both reflective and absorptive tests. This was done to eliminate any differences in the transmission loss and related areas caused by the use of a different type of panel. For the reflective parallel barrier test, the solid steel side of the panels was exposed to the sound source located in the middle of the roadway. For the absorptive parallel barrier test, the acoustical panels were reversed, allowing the perforated face to be exposed to the sound source located in the middle of the roadway. The performance of the parallel absorptive barriers was then compared with the performance of the corresponding single absorptive barrier, and the performance of the parallel reflective barriers was compared with the performance of the corresponding single reflective barrier.

Parallel barrier analysis involved a determination of performance degradation for the parallel arrangement. The sound pressure level at each frequency band tested for the parallel barriers was compared with the sound pressure level at the corresponding frequency band for a single barrier of the same configuration. Figure 3 shows an example of a graphical plot of the test results for a particular barrier configuration. Each individual data point indicates the actual barrier degradation measured for a particular frequency band. The solid line is a calculated degradation based on a simplified model and provided as a reference. Over 40 of these plots were produced for the degradation tests. Because there were too many to include in this paper, only a sample is shown. This particular plot was chosen as an example, because it was a midrange test, having an 8-ft source height. (Source heights, as mentioned before, were at 4, 8, and 12 ft.)

Figure 3 is typical of the other plots produced and confirms the presence of the barrier degradation effect. For this particular case, with the sound source used, an overall degradation of 1.5 dBA was realized. However, some configurations exhibited less degradation, whereas others produced an overall degradation as high as 4 dBA. A word of caution is given here—the overall levels, which are for the source spectrum used, are merely mentioned as a reference. They are not particularly relevant to the discussion, and provide no direct application to a given highway situation. As stated earlier, the degradation at each frequency band is of interest. It is this degradation that can be used to modify any number of spectra to predict degradation for the same configuration. It is intended that this data be used for further study to support mathematical models that will predict barrier degradation for any configuration.

Not only was the phenomenon of parallel barrier degradation confirmed by the test data, but several trends in the data were also observed. The degradation tended to increase for lower source heights, higher barriers, greater receiver distances, and higher frequencies. However, there were numerous exceptions to these general trends. In addition, as shown in Figure 3, scatter of the data points was observed in each test. One area for further study, as mentioned under single-barrier data analysis, is to consider the possibility of geometric interference caused by ground reflections. Such a phenomena, if it has occurred for the barrier geometry tested, could account for some of these variations, including large negative degradation values.

Figure 4 represents absorptive barriers of the same configuration as the reflective barriers shown in Figure 3. Again, the degradation is the difference between the parallel and single barrier values, and the solid line represents the calculated value, for reference. The absorption coefficients used in the calculations were the actual values measured in the laboratory for each frequency band. For the particular source spectrum and barrier configuration represented in Figure 4, the overall A-weighted degradation was zero.

As stated earlier, this overall degradation is not transferable to other situations, and is only mentioned as a reference. Absorptive barriers were seen to reshape the source spectrum

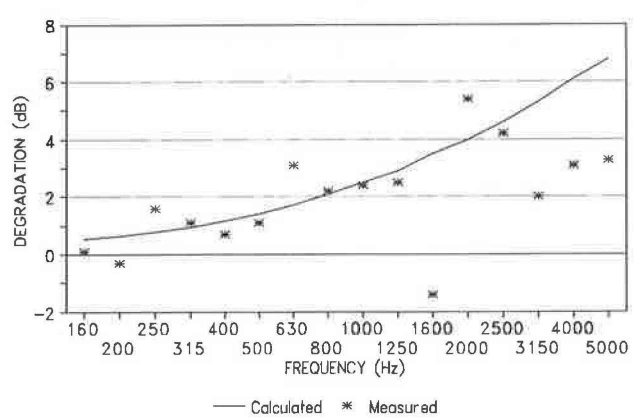

FIGURE 3 An example of parallel reflective barrier degradation test results (source 8 ft high, receiver at 25 ft).

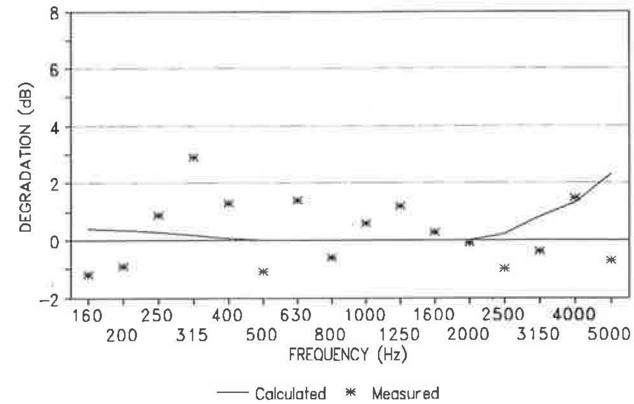

FIGURE 4 An example of parallel absorptive barrier degradation test results (source 8 ft high, receiver at 25 ft).

at the receiver by reducing the sound levels at those frequencies most affected by the absorptive material. By way of application, if a particular absorptive material proved effective at absorbing high-frequency sound but not low-frequency sound, little improvement would be realized by installing absorptive barriers of such material in parallel applications with predominately low-frequency noise. Following the same line of thought, an absorptive material, which provides very high absorption coefficients in the same frequency bands as the noise source, will eliminate the degradation problem. Most applications will fall in the middle of these extremes, with the results depending not only on the source spectrum and the absorptive characteristics of the barrier, but also on the source-barrier-receiver geometries.

In summary, parallel noise barrier testing on this project has demonstrated the performance degradation experienced with a parallel barrier arrangement. In addition, the absorptive barriers tested offer an effective means of reducing this degradation effect. The tests further expose the problem involved in any attempt to predict the degradation at one highway site on the basis of the amount of overall degradation experienced at another highway site. There is no single rule of thumb to be used, or typical degradation experienced. For highway applications, the amount of degradation experienced and the corresponding benefits of absorptive barriers depend on the many traffic, barrier, and geometrical parameters for a particular highway site. In order to predict the degradation for a particular site, a computer model that accounts for all these factors is required. As stated earlier, the test results are intended to serve as a data base to support further computer model development and refinement.

Combination Absorptive and Reflective Parallel Barrier Test

A test was made of a parallel barrier arrangement with one side reflective and one side absorptive. The sound source for this test was 8 ft high. Receiver positions were located on both the east and the west sides of the roadway. Analysis of the data indicated no significant difference in sound levels for the east and west receiver positions. Further, no significant reduction in sound level occurred as a result of one of the barriers being absorptive. Therefore, the case for reducing parallel barrier performance degradation by installing an absorptive barrier on one side of the roadway only, could not be substantiated from the test data. However, the relatively high source height of 8 ft reduced the number of reflections that could have contributed to barrier degradation. Testing with a lower source height may have demonstrated an advantage to having one of the barriers absorptive. A further consideration would be the receiver distances used for this test. Because barrier performance degradation with a parallel arrangement tends to be greater for greater receiver distances, a benefit of having one of the barriers absorptive may be realized but at the greater distances. Because relatively short distances were used in this test, this result could not be substantiated.

RESEARCH CONCLUSIONS

The following conclusions are based on the configurations tested. The results reported for this project are not intended for direct application to highway situations. However, they are intended to supplement existing data bases for future research and prediction model refinement.

1. The addition of a second reflective noise barrier installed parallel to an existing reflective barrier can degrade the performance of the existing barrier caused by multiple reflections between the barriers.
2. The expected performance degradation for various parallel barrier installations cannot be quantified by the same number. It is dependent on the source spectrum and source-barrier-receiver geometries, along with the absorptivity of the barrier itself. The many variables preclude a generalized answer for all cases. Models that account for these variables must be used to predict the results for individual cases.
3. The use of absorptive barriers instead of reflective barriers in parallel situations can significantly reduce and even eliminate the performance degradation effect caused by multiple sound reflections.
4. The use of one reflective barrier and one absorptive barrier in parallel situations does not significantly improve barrier performance compared to parallel reflective barriers. (This conclusion is based on limited testing.)
5. The experimental results for the single barriers tested were in good agreement with the single-barrier theory used, for the range of geometries tested.
6. The use of absorptive barriers instead of reflective barriers in single-barrier situations does not offer a performance advantage for the configurations tested. (This conclusion may not be valid for barriers close to the receiver or the source.)

RECOMMENDATIONS

Barrier Testing

1. A parallel barrier combination, with one barrier reflective and one barrier absorptive, should be tested using lower source heights as found with automobiles and medium trucks. This test may demonstrate a benefit for the combination, particularly at greater receiver distances.
2. Single absorptive and reflective barrier tests should be made for configurations with large diffraction angles to observe the potential performance benefit of absorptive barriers.

Further Study

The effect of ground reflections and their potential for producing both constructive and destructive interference patterns that may modify barrier insertion loss should be studied. This phenomena has the potential of giving explanation for some of the scatter observed in the measured data for the full-scale highway barrier tests.

ACKNOWLEDGMENT

The work performed by North Central Technical College and described in this paper was funded by the State of Ohio's Department of Development (Thomas Edison Program), and Empire-Detroit Steel Division of Cyclops Corporation. The support of both organizations is gratefully acknowledged. Empire-Detroit Steel, in addition, furnished all the acoustical panels for barrier tests along with the barrier structures, and installation.

REFERENCES

1. W. Bowlby, L. F. Cohn, and R. A. Harris. A Review of Studies of Insertion Loss Degradation for Parallel Highway Noise Barriers. *Noise Control Engineering Journal*, Vol. 28, No. 2, March–Apr. 1987, pp. 40–53.
2. *Methods for Determination of Insertion Loss of Outdoor Noise Barriers*. Report ANSI S12.8–1987, American National Standards Institute, New York, 1987.
3. M. A. Simpson. *Noise Barrier Design Handbook*. FHWA-RD-76-58. FHWA, U.S. Department of Transportation, 1976.
4. T. M. Barry and J. A. Reagan. *FHWA Highway Traffic Noise Prediction Model*. FHWA-RD-77-108. FHWA, U.S. Department of Transportation, 1978.

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