Placement of Sound-Absorbing Materials To Control Traffic Noise Reflections at a Highway Underpass

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The effectiveness of the installation of sound-absorbing material on the vertical retaining walls of a highway underpass was evaluated. A multifaceted experimental approach, involving both the actual traffic noise source and an artificial source, was used. The experimental results indicated that only a minor reduction in noise levels had been achieved from the sound-absorbing material. A theoretical analysis of sound propagation near highway underpasses was made and implemented in a computer simulation model. The application of the model to the highway underpass supported the experimental results. In addition, the modeling results indicated that reflections from the bridge understructure were more significant than reflections from the vertical walls.

Interstate 675 passes under Alexanderville-Bellbrook, a local street in Dayton, Ohio. Residents living in the vicinity of the underpass have complained of excessive traffic noise, which they perceived to be originating from the underpass area. Ohio Department of Transportation (ODOT) analysts suspected that multiple sound reflections from the retaining walls of the underpass were contributing to the annoyance experienced by the residents. The noise levels at the residences were not high enough to warrant abatement by current criteria due to large source-to-receiver distances. However, this underpass provided an opportunity to evaluate the use of sound-absorbing materials to control multiple reflections in such situations while addressing complaints made by local residents. Therefore ODOT designed a system of sound-absorbing panels to be installed on the vertical retaining walls of the underpass and funded a study to evaluate the effectiveness of the abatement measure. A schematic of the site is shown in Figure 1.

A conventional evaluation of noise abatement measures such as this would be based on the difference in the noise levels at affected receivers measured before and after the implementation of the abatement. In this case, however, residents were located more than 300 m from the underpass. At such distances, the effect of differing atmospheric conditions on sound levels for before and after measurements could be greater than the effect of the sound-absorbing material. Therefore, a multifaceted measurement approach (which included, but did not rely on, measurements at residences) was developed for the study. This approach included sound level measurements of traffic noise near the I-675 right-of-way line and in the median, along with a number of other measurements that used an artificial noise source. Assuming that one or more of the methods might prove to be unsuccessful, the use of multiple methods was an experiment to determine which method might be useful in similar situations in the future. Further, any conclusions drawn from the multiple approach might be based on more than one measurement method, which would provide greater confidence than if conclusions rested on only one approach.

The primary objective of this study was to evaluate the effectiveness of the sound-absorbing material installed on the vertical walls of the underpass by conducting before and after field measurements. However, the results of the field measurements raised additional questions that fostered a secondary objective—to develop a computer simulation to model traffic noise near highway underpasses. An overview of the entire study is given.

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EXPERIMENTAL APPROACH

All the measurements were performed both before and after the installation of the sound-absorbing material on the vertical walls of the underpass. Measurement procedures conformed to American National Standards Institute S12.8 (*1*) where applicable, with regard to instrumentation setup, atmospheric conditions, and so on. Unless indicated otherwise, all sound level measurements were the equivalent continuous, A-frequency-weighted sound pressure levels for the period of measurement, in units of dB. The purpose, procedure, and results for each measurement method are given in the following subsections.

Right-of-Way Measurements

Sound level measurements within the highway right-of-way were made to evaluate the effectiveness of the sound-absorbing material. The receiver locations were chosen arbitrarily to provide a relatively short propagation path from the traffic noise source to the receivers in order to minimize atmospheric effects.

The results of the before and after measurements are presented in Table 1. The reduction in noise levels for the after case compared to the before case varies from 0 dB to 1.3 dB. Although some reduction in noise levels was measured, the results do not indicate that the installation of sound-absorbing material significantly reduced the noise level.

Measurements at the Residences

Measurements were carried out at several residences in the vicinity of I-675 to directly measure the sound levels at the residences before and after the installation of sound-absorbing material. The potential error due to atmospheric effects for sound propagation over the long distances from the I-675 traffic noise source to the residences

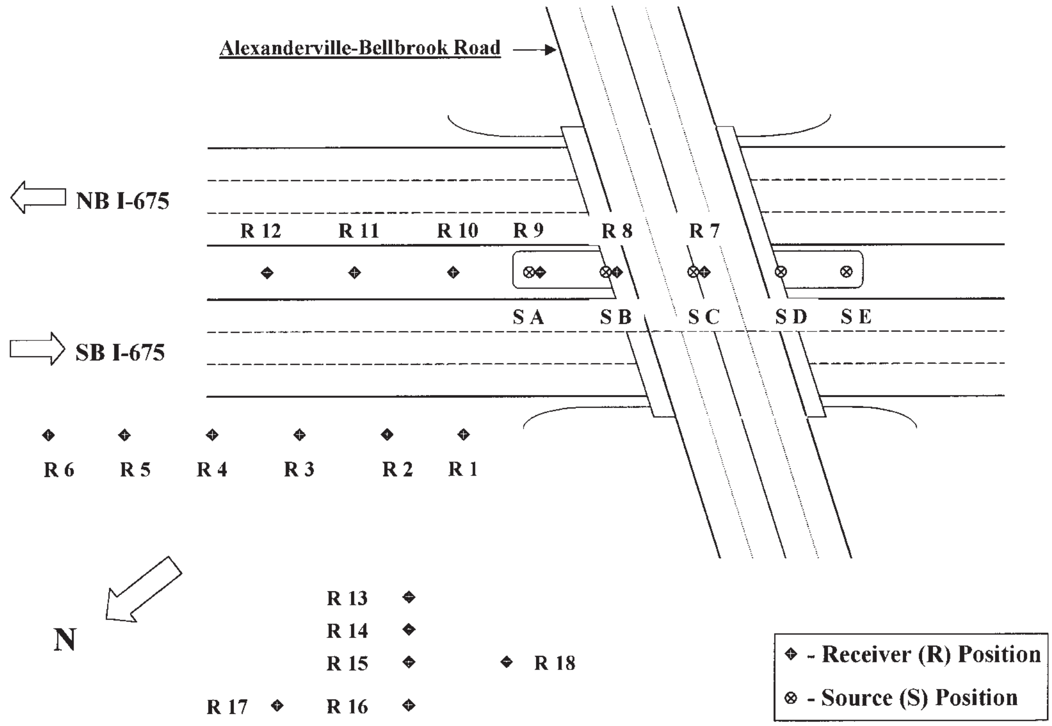

FIGURE 1 Representation of the underpass study site.

precluded an evaluation based solely on the results of these measurements. They were made primarily in deference to the residents, and secondarily to provide data that might complement other results. A reference microphone was placed along I-675 where the microphone would not be affected by the underpass. The reference microphone was used to normalize the data collected at the residences before and after the abatement measure to account for any differences in the traffic noise source between before and after measurements.

During the before measurement, sound level meters were placed at three residences, and another sound level meter was placed midway between the underpass and the residences at the right-of-way fence. However, during the time period between the before and after measurements, unanticipated construction activity involving earthwork for a development altered the terrain between the I-675 right-of-way fence and the residences. As a result, two of the residences were eliminated from the after measurements because they were shielded by mounds of topsoil. The third residence received little, if any, shielding by the earth berm. Therefore, an after measurement was made, although true terrain equivalence could not be assured.

TABLE 1 Equivalent Continuous Sound Levels, A-Weighted, Measured at Positions Within I-675 Right-of-Way

SLM Positions	BEFORE (dB)	AFTER (dB)	Abatement due to sound absorbing material on walls (dB)
1	72.2	72.2	0.0
2	69.0	68.9	0.1
3	65.5	64.6	0.9
4	63.0	62.5	0.5
5	64.6	63.3	1.3

NOTE: SLM = sound level meter.

The normalized results of the measurements at the residences are presented in Table 2.

The small reduction in noise levels measured at the residences and the right-of-way fence must be viewed cautiously in light of the measurement conditions. Taken at face value, the measured levels do not indicate a significant change due to the installation of the sound-absorbing materials.

Centerline Measurements

For a typical highway section (with the median width, the number of lanes, the roadway grades, and other geometrical conditions remaining constant), measurements carried out with sound level meters located at intervals along the highway in the center of the median will result in constant average noise levels along the highway. The noise level will be nearly equal at each location because the levels are measured for the same traffic over time.

When reflections occur at an underpass, sound paths that undergo single or multiple reflections create an area of reverberation that can result in higher measured levels. It was hypothesized that the levels would be highest at the center of the underpass and then gradually drop off as the distance from the underpass increased. To verify the effect of reflections in the area of the underpass, simultaneous measurements were carried out with six sound level meters located in the median at 15-m increments from the center of the underpass.

The main objective of this measurement was to establish the pattern of noise levels with respect to distance from the center of the overpass. The last receiver was located at a distance from the center of the underpass where the time-averaged noise levels were expected to be affected little, if any, by the underpass. The installation of sound-absorbing material on the underpass walls was expected to affect the change in levels from one sound level meter to the next for

TABLE 2 Normalized Average Levels Measured at Residences

	BEFORE (dB)	AFTER (dB)	Change in levels after installation of sound absorbing material (dB).
Reference Microphone	77.2	77.2	0
ROW Fence	64.3	64.2	-0.1
234 Estates Drive	55.4	54.0	-1.4

the after case compared to the before case. The actual levels of the before and after traffic noise were not important because the drop-off rate, and not the absolute values, was being measured.

A plot of noise levels versus distance from the center of the underpass is shown in Figure 2. The levels are not normalized for differences in traffic conditions for the before and after conditions because only the shape of the curve was of interest. From Figure 2, it is evident that the noise levels both before and after the installation of the sound-absorbing material follow a similar pattern. Therefore, the results of the centerline measurements provide no indication that the sound-absorbing material was effective in reducing the drop-off rate or changing the noise level pattern in the vicinity of the underpass. The results do indicate, however, that the traffic noise within the underpass represents a source with a level of at least 5 dB above the source levels for typical sections of the highway.

Reverberation Tests

This approach was borrowed from the field of room acoustics. The presence of reflective surfaces within a room causes reflections, increasing the amount of reverberation in the room. On the other hand, the addition of sound-absorbing material to some of the surfaces within the room can reduce reflections, decreasing the amount of reverberation.

The area within the underpass was considered as a "room." The open areas of the underpass were assumed to have complete absorption—that is, any ray exiting the underpass into the open air would not be reflected. The pavement, the understructure of the bridge, and the vertical retaining walls of the bridge abutment were treated as surfaces that could reflect energy.

The purpose of the reverberation test was to find the noise decay rate (RT60), an indicator of the amount of reflected rays present, of the whole underpass as a single system. The hypothesis was that the decay rate might be quite long for the before condition. Once the sound-absorbing material was installed, after measurements were expected to reveal a more rapid decay rate, indicating the effect of the sound-absorbing material.

A sound source, placed in the median at the center of the underpass, was used to introduce pink noise into the underpass for 3 to 5 s until the energy was dissipated throughout the whole underpass. When the noise level stabilized, the source was abruptly stopped. Both the initial noise and its subsequent decay were recorded with digital tape recorders at various points throughout the underpass.

The noise recorded with the digital tape recorders was analyzed using a real-time analyzer to obtain decay times (RT60 times) for the underpass. The RT60 is defined as the amount of time required for the sound level to drop 60 dB.

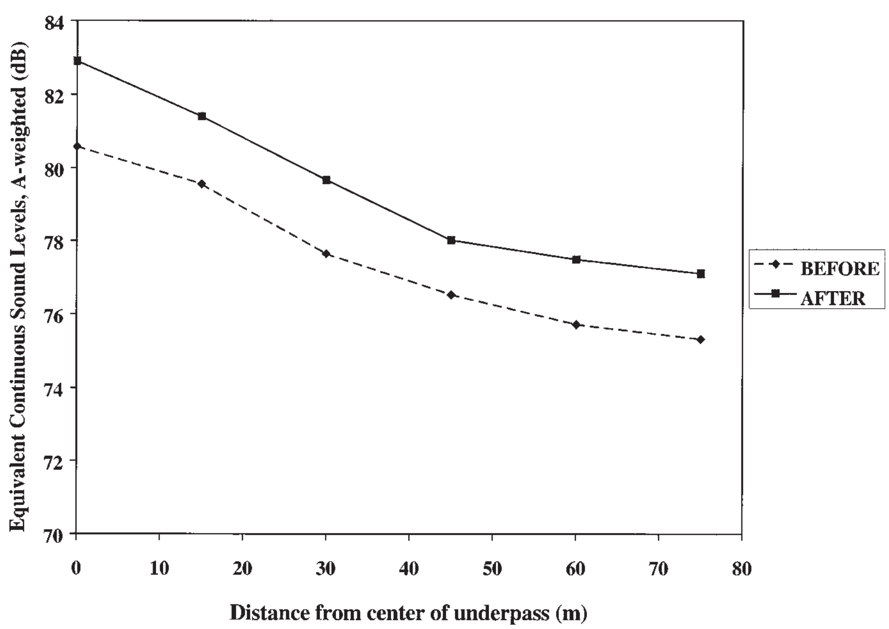

FIGURE 2 Change in sound levels with change in distance from center of the underpass.

For comparison with measurements, the decay time for the underpass was also predicted by the Sabine formula as given in Equation 1 (*2,3*):

$$T = \frac{0.161 \times V}{A} \tag{1}$$

where

T = reverberation (i.e., decay) time (s),
V = volume of the room (m^3),
0.161 = an empirical constant (Sabins/m), and
A = absorption of the room (m^2 or Sabins as given in Equation 2).

$$A = \alpha_1 * S_1 + \alpha_2 * S_2 + \alpha_3 * S_3 + \cdots + \alpha_n * S_n \tag{2}$$

where α_1, α_2, α_3 . . . . α_n are the absorption coefficients of the different surfaces of the room, and S_1, S_2, S_3 . . . S_n are their respective areas (m^2).

The measured and predicted before and after decay times of the underpass as a single system are presented in Table 3. The change of 0.09 s in decay time is insignificant. That is, the overall decay time was virtually unaffected by the installation of the sound-absorbing material on the bridge abutment walls. From Table 3, it is clear that the change in decay time was less than predicted, although the predicted change was small.

In summary, the Sabine formula was never intended for use with a highway underpass. Its application, along with the assumptions involved, was an experiment to determine whether the results might correlate with other measurements. Interestingly, there was good agreement between the measured and predicted results. Apart from the caveats mentioned, the predicted results suggest that more sound-absorbing material would be needed to significantly reduce the decay time. The measured results are consistent with this conclusion.

Constant Level Source Tests

The use of an artificial source provides a controlled noise level to ensure that the tests performed before and after the abatement measure are based on the same source level. An artificial constant source level with broadband noise has a repeatable level throughout the frequency range. Sound-absorbing material is more effective in some frequency bands than others. Therefore, the ability to measure changes in levels at different frequency bands was an advantage.

A variation in noise levels for a given receiver might be expected due to changes in the position of the source. For a ray reflected from a vertical wall of the underpass, the angle of incidence must equal the angle of reflection. Therefore, the position of the source relative to a receiver could determine the number of reflections possible. Hence, the source was positioned at a number of points on the median within the underpass and on each end of the underpass. The receivers were located along the roadside.

TABLE 3 Decay Times (RT60s) Measured and Predicted for the Whole Underpass as a Single System

	BEFORE (Second)	AFTER (Second)	Change in decay (Second)
Measured	2.04	1.95	-0.09
Predicted	1.77	1.43	-0.34

This test was to be performed before and after the installation of the sound-absorbing material to evaluate the effectiveness of the material in reducing the noise levels. The average levels measured at each receiver for the source placed at various positions before and after the abatement measure are presented in Figure 3. From Figure 3, it can be seen that the noise level at receiver 1 is highest when the source is placed at the center of the underpass (source position C; see Figure 1). The geometry for this source-receiver condition may have allowed reflections to contribute to the noise level for this receiver. For receivers 3 and 6, the noise level decreases as the source is moved from position A to position E. From Figure 3, it can be seen that there has been a small reduction in sound levels for the after case. This reduction is attributed to the sound-absorbing material on the walls of the underpass.

Impulse Tests

An impulse signal was generated and emitted from the sound source placed at various positions along the roadway centerline. The purpose of this test was to identify possible reflections, unlike the constant level source test wherein the noise levels were being monitored. The results, however, were inconclusive, mainly because of background noise contamination.

Discussion of Experimental Results

The results of the field measurements indicated that applying sound-absorbing material to the vertical retaining walls produced only a small change to the noise environment in the vicinity of the underpass. A number of potential explanations for this unexpected conclusion were considered.

1. *Multiple reflections may not be a problem in this situation.* While this explanation could be supported by the small difference in noise levels for the right-of-way and residential measurements, it is contradicted (at least for receivers near the underpass) by the centerline and reverberation measurements. If multiple reflections were not a problem, the measured average traffic noise levels should have been the same for all microphone positions in the centerline measurements. Further, the reverberation tests, while indicating little changes in the decay rate, did record long decay times, which demonstrate the presence of reflections. Because there are no measurements with and without the underpass, this conclusion cannot be refuted for residential receivers.
2. *The sound-absorbing material was defective.* The results of the field measurements would be consistent with the conclusion that the sound-absorbing material was defective. However, the material used was a standard sound-absorbing material produced by a reputable manufacturer with a laboratory-certified noise reduction coefficient (NRC) of 1.0. Therefore, such a conclusion did not appear valid in this case.
3. *Untreated surfaces were responsible for significant portions of reflected energy.* Because only the vertical retaining walls were treated with sound-absorbing materials, multiple reflections could occur between untreated surfaces. Perhaps the untreated surfaces were more significant than originally thought. The experimental data were consistent with such an interpretation.

At this point in the investigation, it was realized that a better understanding of sound propagation in the region of the underpass was

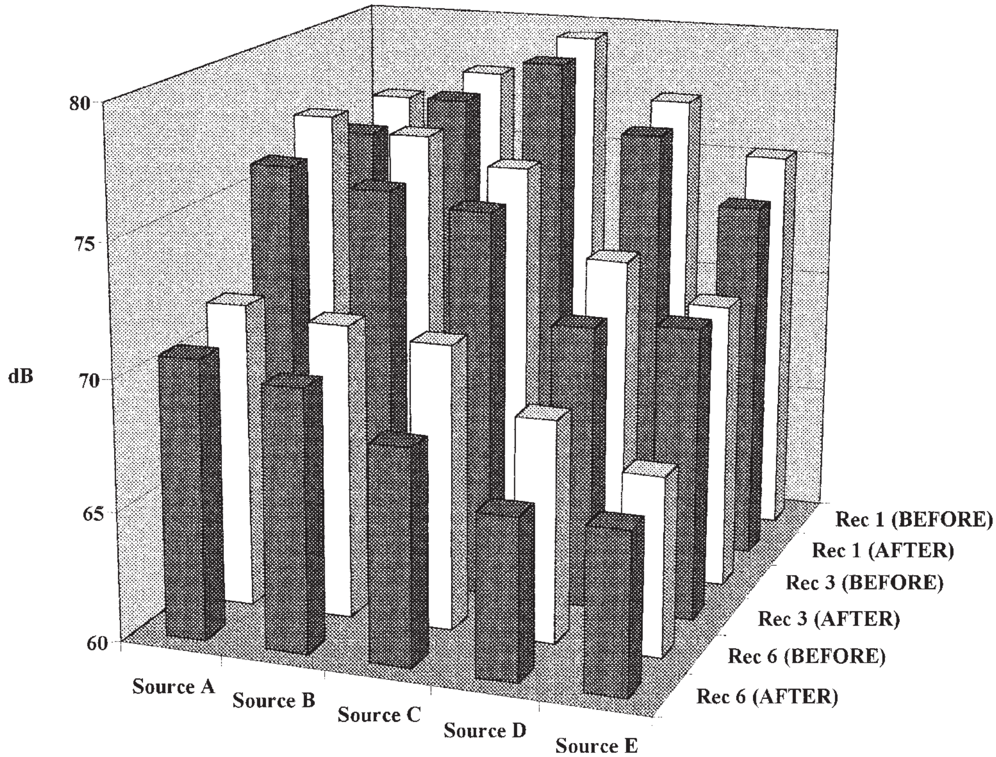

FIGURE 3 Averaged noise levels for each receiver with the source placed at various positions before and after the installation of sound-absorbing material.

needed. Therefore, the theoretical work for a model and its computer implementation were undertaken. The next section summarizes the procedure and the result of the modeling effort.

THEORETICAL APPROACH

A parallel surfaces image model was developed to analyze the noise propagation at highway underpasses. This modeling involved the development of the equations and relationships needed to analyze the various paths that sound waves could take to reach a receiver near a highway underpass. Due to space limitations, only a summary of the theory and the computer implementation to determine the contribution of these sound waves to the overall sound level for a receiver will be given.

Ray Paths at a Highway Underpass

Noise can be propagated from the source to a receiver either by direct rays or by reflected rays at a highway underpass. Direct rays travel from the source to the receiver without being reflected or diffracted. Therefore, direct rays can exist only when the line of sight between source and receiver is not broken.

Rays can be reflected from walls, pavement, or the understructure of the overpass. The multiple reflections can involve attenuation due to absorption by surfaces that are not perfect reflectors. Figure 4 shows a case of reflections from walls, and Figure 5 shows a case of reflections from the understructure.

Many rays are emitted from any single segment of the source. For a given number of reflections, however, there is only one path that a ray can take to reach a potential receiver. The ray's horizontal and vertical angles with respect to the source characterize this path. Rays emitted at other angles may pass by the receiver or be reflected elsewhere. Therefore, each ray must be analyzed to determine if it can reach the receiver.

In the development of this theory, only reflections between parallel surfaces were accounted for. Therefore, two sets of reflections—namely, reflections from walls and reflections from pavement and understructure—were analyzed.

The existence of reflected rays is checked by means of an image ray analysis. In the case of reflected rays, an image source is a location from which the ray appears to originate. This analysis gives the exact location of each reflection.

For each reflection, the perpendicular horizontal distance between the image source and the receiver increases. The increasing distance is used in the calculation of attenuation due to geometric divergence and atmospheric absorption. Thus, rays that undergo many reflections will contribute less to the predicted levels at a receiver.

To check for the existence of a reflected ray, it is necessary to compute the coordinates of the point where the ray would strike the plane of a reflective surface. The determination of these coordinates also assists in assigning the correct absorption coefficient to rays that strike the surface. The process of identifying direct and reflected rays must be carried out for each finite element of the traffic source, for each lane of the highway. The Federal Highway Administration equations for traffic noise propagation are then used to predict the contribution of each ray to noise levels at the receiver (*4*).

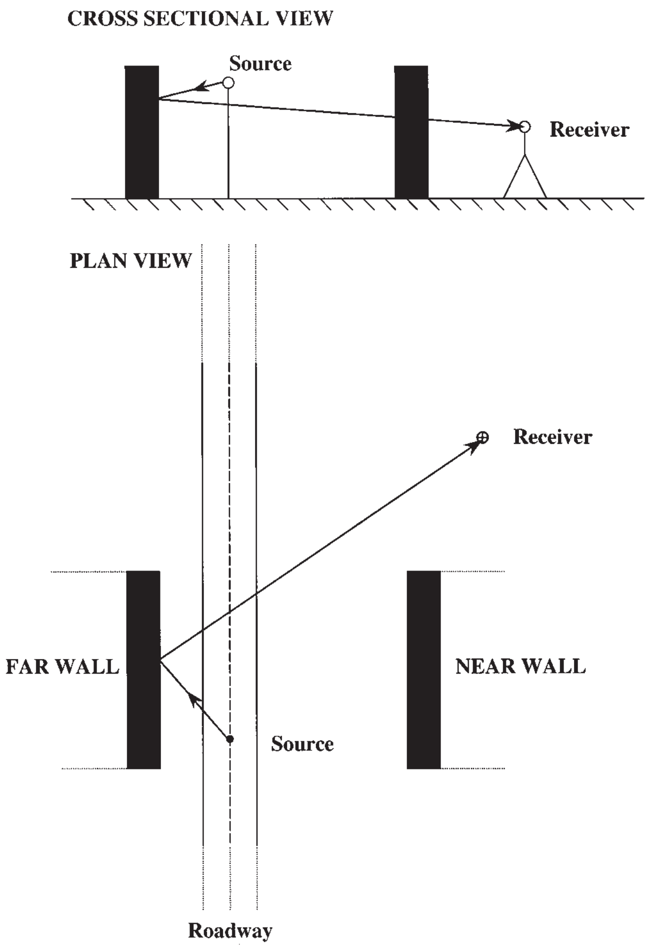

FIGURE 4 Sound wave reflected from walls.

Computer Implementation

The theoretical analysis is implemented in the computer program Highway Underpass Model (HUM). The primary objective of HUM is to determine the difference in sound levels at receivers due to reflections caused by a highway underpass. The model is not intended to predict the difference in levels with and without the underpass itself, a very complex prediction due to the effect of differing terrain conditions.

HUM identifies and analyzes the direct and reflected rays that contribute to the noise level for receivers in the vicinity of a highway underpass. The influence of reflections from a highway underpass, or the effect of sound-absorbing material that could be applied to underpass surfaces, is determined from the difference in predicted levels at a receiver. For example, an underpass can be analyzed without any sound-absorbing material and then analyzed with sound-absorbing treatment. The difference in levels can be used in evaluating the abatement measure. Further, the model can be used to identify the location of reflections. Therefore, the relative importance of each reflective surface can be evaluated, and areas for sound-absorbing treatment can be rated in order of priority.

Model Predictions

The predicted results were compared with the results of the field measurements. The measured and predicted differences in sound levels before and after the installation of sound-absorbing material are presented in Table 4. HUM predicted a mean difference of –0.32 dB, which corresponds to a decrease in sound level of 0.32 dB. A mean difference of –0.56 dB, corresponding to a decrease in noise levels of 0.56 dB, was measured in the field.

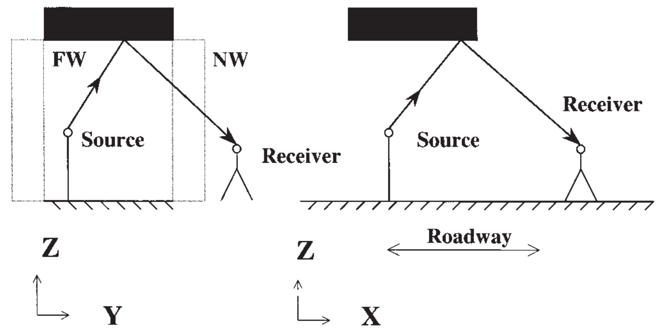

FIGURE 5 Sound wave reflected from understructure.

Modeling of Understructure

In order to investigate the potential for controlling reflections, the I-675 underpass was also modeled with sound-absorbing material having an NRC of 1.0 on the understructure of the underpass. The reduction in noise levels predicted by the model due to the sound-absorbing material on the understructure is presented in Table 5. The mean reduction in sound levels was 1.22 dB when the understructure alone was modeled with sound-absorbing material, compared to a mean reduction of 0.32 dB when the walls alone were modeled with sound-absorbing material. The results from Table 5 indicate that installing sound-absorbing material on the understructure is more effective than installing it on the walls. This analysis also indicates that reflections from the pavement and understructure make a more significant contribution to the sound levels for a typical receiver located outside the underpass than reflections from the walls. This finding, based on the model results, suggests that the original hypothesis of greater contribution from wall reflections was not correct.

CONCLUSIONS

Summary

It was hypothesized that multiple reflections were responsible for higher noise levels perceived by residents living close to the I-675 underpass at Alexanderville-Bellbrook Road. Measurements were conducted to evaluate the effectiveness of installing sound-absorbing material on the vertical walls of the underpass. Multiple measurement approaches (centerline measurements, right-of-way measurements, reverberation tests, constant level source tests, and impulse tests) were adopted. Conventional before and after sound-level measurements at several nearby residences also were performed. The data from the field measurements were reduced and analyzed. The results of the field measurements indicated that the installation of sound-absorbing material on the vertical walls of the underpass was not effective in reducing the noise levels. To investigate this outcome further, a computer program, the Highway Underpass Model (HUM), was developed to assist in the analysis of

TABLE 4 Measured and Predicted Difference in Noise Levels Before and After Installation of Sound-Absorbing Material on Walls of Underpass

Receiver number	Difference in BEFORE and AFTER levels as predicted by HUM	Difference in BEFORE and AFTER levels as measured in the field.
1	-1.1	0.0
2	-0.1	-0.1
3	-0.2	-0.9
4	-0.1	-0.5
5	-0.1	-1.3
Mean :	-0.32	-0.56

TABLE 5 Predicted Noise Levels for Underpass with No Sound-Absorbing Material on Walls and with Sound-Absorbing Material on Understructure

Receiver number	Predicted noise levels for underpass with no sound absorbing material (dB).	Predicted noise levels for underpass with sound absorbing material on understructure (dB).	Reduction in noise levels due to sound absorbing material on understructure (dB).
1	72.3	70.9	1.4
2	70.8	69.8	2.0
3	67.9	66.8	0.9
4	67.3	66.1	1.2
5	66.9	66.3	0.6
Mean :			1.22

noise propagation at a highway underpass. The model was used to analyze the effect of sound-absorbing material on the understructure and also to analyze the effect of a sound-absorbing pavement.

Findings

1. Based on field measurements, the placement of sound-absorbing material on the abutment walls of the I-675 underpass was not effective in reducing noise levels. This finding addresses the location of the sound-absorbing material, not the acoustical properties of the material itself.
2. The results of field measurements were confirmed by prediction from the computer simulation.
3. Based on the results of the computer simulation, application of sound-absorbing material to the understructure would be more effective in reducing noise levels than installation of sound-absorbing material on the walls.
4. Multiple reflections are the primary reason for the noise level increase at a highway underpass.
5. A sound-absorbing pavement could assist in reducing noise levels at a highway underpass.

These findings are based on both measurements made at I-675 underpass and computer modeling of the same underpass. These findings are not necessarily applicable to all underpasses.

ACKNOWLEDGMENT

This study was sponsored by the Ohio Department of Transportation.

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