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PARALLEL BARRIER EFFECTIVENESS
Dulles Noise Barrier Project

Gregg G. Fleming
Edward J. Rickley

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U.S. DEPARTMENT OF TRANSPORTATION

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RESEARCH AND SPECIAL PROGRAMS ADMINISTRATION
TRANSPORTATION SYSTEMS CENTER • CAMBRIDGE MA 02142

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RESEARCH AND DEVELOPMENT • FEDERAL HIGHWAY ADMINISTRATION
6300 GEORGETOWN PIKE • MCLEAN VA 22101-2296

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PREFACE

This report documents the results of a highway noise measurement program conducted by the U.S. Department of Transportation, Research and Special Programs Administration, Transportation Systems Center (U.S.DOT/RSPA/TSC) in support of the Office of Engineering and Highway Operations Research and Development, Federal Highway Administration (FHWA), and a National Pooled-Fund Panel representing 14 States. Field measurements were conducted on 12 highway noise barrier configurations at a test site at Dulles International Airport in Chantilly, Virginia. Field data were obtained, reduced, and analyzed by the Transportation Systems Center (TSC).

Within the TSC the following individuals made major contributions: Richard Daesen was responsible for the data gathering and processing programs developed for this project. Vincent Sesto and Gary Levenson assisted in reducing the data and preparing it for presentation. Measurement support in the field was provided by ENSCO, Inc., under contract to Arthur D. Little, Inc. (ADL), Vanderbilt University, and Hope Associates, Inc. Barrier preparation, including configuration changes, were made by Hope Associates, Inc., under the direction of Dr. Howard A. Jongedyk and Mr. Jim Koca of the Federal Highway Administration. Dr. Jongedyk sponsored and was an integral part in ensuring the success of this program. Acentech, Inc. under contract to ADL, assisted the TSC in the data analysis. David Coate was the principal participant from Acentech, Inc. The Federal Highway Administration's Electronics Laboratory, under the

direction of Ken Moore, assisted in preparing the measurement system for mobile operation.

During the course of this program, members of the 14 supporting states have offered their continued guidance, support, and direction. Special thanks must go to Ken Polcak of Maryland DOT for his assistance in the field, and to the state of Virginia who were responsible for publishing this document and providing a truck for field measurements.

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In an effort to minimize the cost and maximize the effectiveness of highway r barriers, the Federal Highway Administration (FHWA) and a National Pooled Fu Panel (made up of 14 States) funded a field study program on an experimenta highway noise barrier. A test barrier was constructed in 1984 at a site at Du International Airport in Chantilly, Virginia. The study, conducted from Ma to August 1989 by the U.S. Department of Transportation, Research and Special Programs Administration, Transportation Systems Center (U.S.DOT/RSPA/TSC), fo on the use of absorptive treatment and tilting as a means of improving the insertion loss (specifically, single event moving point source insertion loss $_{SEL}$) of two parallel highway noise barriers. Measurements were conducted with controlled moving point sources (trucks) and an artificial fixed-point source (speaker system).

Results show : (1) the addition of absorptive treatment to the roadside face two vertical, parallel, highway noise barriers eliminated multiple reflection was found to improve the insertion loss (2 dB to 6 dB); (2) tilting proved to effective alternative to absorptive treatment in eliminating the multiple reflections and subsequent degradation in performance of two vertical reflect barriers; (3) additional verification needs to be performed with an artificia fixed-point source before it can be recommended as a viable alternative to ac highway traffic in measuring barrier effectiveness; and (4) although the 'BAR 2.1' computer program cannot model the Dulles test situation exactly, and act ground impedance data were not available, the trends in the predicted inserti loss data were in good agreement with the predicted results although lower in absolute level.

1.0 INTRODUCTION

Highway noise mitigation procedures have been implemented in the United States for more than 15 years. To date, over 700 miles of highway noise barriers have been constructed along United States roadways and another 700 miles are slated for construction over the next ten to fifteen years. In total, more than 600 million dollars have been spent on highway noise barrier construction in the United States.

The U.S. Department of Transportation, Research and Special Programs Administration, Transportation Systems Center (U.S.DOT/RSPA/TSC), in support of the Office of Engineering and Highway Operations Research and Development, Federal Highway Administration (FHWA), and a National Pooled-Fund Panel (representing 14 States: California, Connecticut, Florida, Georgia, Hawaii, Iowa, Maryland, Massachusetts, Michigan, New Jersey, New York, Ohio, Pennsylvania, and Virginia), conducted field measurements on an experimental barrier constructed at a test site at Dulles International Airport in Chantilly, Virginia. Twelve barrier configurations were tested from May 1989 to August 1989.

The installation, located on a two-lane asphalt service road at the Airport, was comprised of a barrier test site and a physically equivalent test site. The barrier site contained two 14-foot high experimental barriers constructed parallel to one another on opposite sides of the Airport service road. The parallel barriers could be arranged to have absorptive and/or reflective faces, or be tilted at angles of 7, 15, and 90 degrees with respect to vertical. A 90 degree tilt angle simulated effective removal of the barrier. The equivalent site, directly adjacent to the barrier site, was a 250-foot wide flat, grassy, open field with the same physical characteristics as the barrier site.

1.1 OBJECTIVE

The objective of this study was to evaluate, through field measurements, the effectiveness of a variety of highway noise barrier configurations in mitigating highway noise. The results obtained from the 12 barrier configurations tested will be used to provide improved guidance in the design and construction of highway noise barriers. Specifically the collected data will be used to: 1) determine whether a vertical, reflective, parallel barrier construction (Test 9, Table 2) results in a degradation in overall performance, and if it does, how to counteract that degradation; 2) assist in the refinement of existing highway noise barrier prediction models; and 3) in as much as the tests followed the recommendations in the ANSI Standard S12.8-1987, "Methods for Determination of Insertion Loss of Outdoor Noise Barriers", the results will also be used to evaluate that standard [ANSI 87-1].

1.2 TEST SITE, BARRIER DESIGN AND CONSTRUCTION

The study site was a large open field with a two-lane service road running through its center. The terrain was essentially flat and made up of hard-packed clay covered with low-cut field grass. The study site was divided into a 500-foot barrier test site and a 250-foot equivalent test site. The equivalent test site was physically identical to the barrier test site with no obstructions. Both sites were surveyed to obtain exact ground contours (see Table 1 and Figures 3 - 5). The barrier site contained a 500-foot long, 14-foot high barrier whose base was at a distance of 37 feet from one side of the service road, and a 250-foot long, 14-foot high barrier whose base was at a distance of 19 feet from the opposite side of the service road. Measurements were made simultaneously behind the 500-foot barrier, and at the equivalent site which was on the same side of the roadway as the 500-foot barrier.

To minimize noise interference from airport operations, all measurements were conducted between 10 PM and 6 AM when Dulles Airport was closed to air traffic; however, the aircraft maintenance area, which was less than 1/2 mile from the barrier test site, was active all night. As a result, ambient conditions were less than ideal and several barrier configurations were tested two and three times before satisfactory data were obtained.

The barrier, made up of independently adjustable bays, was designed by Pennsylvania State University and constructed by the Long Fence Company in 1984 under contract to the FHWA. Each bay was eight-feet wide and consisted of a tiltable metal frame with 3/4-inch plywood and tongue-in-groove wooden decking. The bays were pivoted on vertical angle iron columns in such a manner that adjacent bays were separated by less than l/2 inch. All gaps were filled with an acoustically absorptive weather-strip-like material to minimize sound leakage. A hinged bottom pan assembly sealed any gaps beneath the frame which resulted from barrier tilt (See Figure 1).

Absorptive material (3-inch thick fiberglass batts, mounted in wood frames) was attached to the front of each bay to change the roadside barrier characteristics from reflective to absorptive. The absorptive panels were constructed in four-foot, two-foot, and one-foot heights (See Figure 2).

The fiberglass material was tested per the ASTM National Standard Recommended Practice 384-88 (Standing Wave Tube) by Acentech, Inc., at the Bolt Beranek and Newman, Inc., laboratory facilities in Cambridge, MA. It was found to have a Noise Reduction Coefficient (NRC) of .82 with sound absorption coefficients of .53, .90, .91, and .92 at octave band center frequencies of 250 hz, 500 hz, 1 khz, and 2 khz, respectively. See Appendix J for testing procedures and a detailed summary of the results, including the complex impedance of the absorptive material.

Figure 1 : Rear View of the 500-foot Barrier
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Figure 2 : Front View of the 500 foot Absorptive Barrier
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1.3 SOURCES

With the test barrier built on the airport service road, the opportunity to evaluate the barrier under free flowing highway conditions was lost. Testing was limited to measurements of controlled moving point sources (2 trucks with vertical exhaust stacks, and 2 trucks with horizontal exhaust stacks) and an artificial fixed-point source broadcasting octave-bands of pink noise.

A controlled moving point source is a unique source and should not be confused with a stationary point source, whose sound level falls off at a rate of 6 dB/DD (dB per distance doubling) or with an infinite line source, whose sound level falls off at 3 dB/DD (neglecting all effects except for geometric spreading). A sound level pass-by envelope of 5 to 7 seconds was processed for each controlled moving point source pass-by, which corresponds to measurements from a finite roadway segment of approximately 250 to 350 feet. For receivers up to 80-feet from the roadway, the controlled moving point sources on this finite roadway segment will behave as a line source, and as such a drop-off rate of approximately 3 dB/DD can be expected. Beyond 80-feet, where the angle subtended by the finite roadway is less than 74 degrees (half-angle of 37 degrees relative to the perpendicular drawn from source to receiver), the controlled moving point source will behave more as a point source with a drop-off rate approaching 6 dB/DD. For the Dulles test site, measurements were made at receiver offsets of 37 (reference), 50, 75 and 125 feet. The controlled moving point sources over this 250 to 350 foot finite roadway segment behave essentially as a line source at all the receiver positions (approximately 3 dB/DD), except at the 125-foot offset where the drop-off rate approached point source conditions (approximately 6 dB/DD).

In addition, measurements were made with an artificial fixed-point source. The artificial fixed-point source was **not** an omni-directional system. As a result, all the contributions in sound level due to reflections (off the ground and direct reflections off the opposite parallel barrier) may not have been accounted for. As a result, the simulated insertion loss data presented do not effectively represent the reflective parallel barrier configurations tested.

2.0 EXPERIMENTAL APPROACH (METHODS)

2.1 MICROPHONE CONFIGURATION

Eight microphones (four behind the 500-foot barrier and four at the equivalent site) were deployed on four masts. A reference microphone was placed 5 feet directly above the top of the 14-foot high barrier at position A. A second reference microphone was set-up at the equivalent site, also at the height of 19 feet at the same distance from the edge of the roadway, position A' (Figure 3). Six additional microphones were set up on two portable masts (three microphones each) at heights of 6, 19, and 30 feet.

For the controlled moving-point source measurements, the portable masts were placed at positions B and B' (50 foot offset), and moved as a pair to positions C and C' (75 foot offset), and positions D and D' (125 foot offset) (Figure 3).

For the artificial fixed-point source measurements, with the source on the roadway in front of the 500-foot barrier, the two portable masts were placed at positions B and C. With the source on the roadway in front of the equivalent site, the masts were placed at positions B' and C' (See Figure 15).

Up to 500 feet of cable were used to provide power to the microphone pre-amplifiers and to feed the acoustic data from the microphones to the storage and analysis system inside the measurement van.

2.2 INSTRUMENTATION

The Federal Highway Administration assembled a mobile noise measurement laboratory which was used for on-line data collection and processing. The fully equipped eight channel noise measurement and analysis system was set up approximately 250 feet from the edge of the service road, at position F (Figure 3). Two portable generators provided power to the system. They were set up behind the van and acoustically shielded with fiberglass baffles to elim-inate the possibility of acoustic contamination to the test data.

2.2.1 ON-LINE DATA COLLECTION AND STORAGE SYSTEM

General Radio (GenRad) Model 1962-9610 random incidence microphones attached to Cetec Ivie Model IE3P pre-amplifiers were used on all eight measurement systems. Each microphone system was positioned one foot away from the mast and placed in its shadow as viewed from the roadway. This positioning insured minimum errors due to reflections from the mast structure [Rickley 78-2] (See Figure 6). Analog data from the eight microphone systems were fed through approximately 500 feet of cable to the mobile laboratory for processing and storage on an IBM PC-AT computer. Processing was accomplished by eight portable Cetec Ivie Model IE-30A 1/3-octave spectrum analyzers interfaced with the on-board computer. A special interface allowed a timing signal, the detected 1/3-octave output (25 Hz-20 kHz), and the A-weighted level from the eight Ivie analyzers to be multiplexed through a Data Translations 2821-16SE analog-to-digital converter card into computer memory. The data were input to the computer at a rate of one record per 125 milliseconds and was energy averaged into one-second records and stored on floppy disk in the form of ASCII text files for off-line processing. In addition to the measured acoustic data, each file contained a two line file identification header along with analyzer switch settings. In this form, the data were ready for off-line processing using the special processing program 'HWNOISE' to obtain selected noise level indices [TSC 90-3].

Figure 6 : Mast Orientation in the Barrier Site
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At the beginning of each measurement day, a complete system checkout was performed. To minimize interaction between systems and to establish the electronic noise floor of each system, a passive microphone simulator (dummy microphone) was substituted for each microphone. In addition, the frequency response of each system was obtained by recording a 20-second sample of pink noise from a Cetec Ivie Model IE-20B random noise generator.

System calibration at two levels was performed at the start and end of each measurement day using four two-level GR Model 1987 minical acoustic calibrators. These calibrators provide a signal of 1000 Hz at two levels, 114 dB and 94 dB re 20 micropascal. To minimize systematic errors, each calibrator was numbered and used on the same system throughout the measurements. The levels of the four calibrators were compared with each other on a single measurement system prior to use, to insure their relative levels remained stable. Four systems were calibrated simultaneously, and ten seconds of calibration data were stored away in computer memory. The calibration data were used as reference levels to adjust the absolute range of each channel of the measurement system.

A Climatronics Model EWS weather station was deployed at a midway point between the two measurement sites, 190 feet from the edge of the roadway (Position E, Figure 3), to measure and continually record temperature, humidity, wind speed, and wind direction. Wind speed and wind direction were measured at a height of ten feet while the temperature and the humidity were measured at a height of nine feet above the ground. The operator assigned to the weath-er station recorded time of day on the strip charts and made note of any significant changes in weather conditions (see Figure 7).

Figure 7 : Climatronics EWS Weather Station
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Figure 8 : CMI Doppler Radar Station
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For the controlled moving source measurements, a CMI doppler radar was set up approximately 300 feet to the north of the 500 feet barrier (Position G, Figure 3) to measure the speed of the four test vehicles as they passed through the measurement area (Figure 8). Readings were taken manually from the digital display and recorded continuously (approximately one every two seconds) during the pass-by of each test vehicle (See Appendix H, Tables H1-H12). Figure 9 depicts a block diagram of the data collection and storage system used for this program.

2.3 EXPERIMENTAL PROCEDURE

Table 2 contains an ordered summary of the 12 barrier configurations tested with the four individual controlled moving sources (trucks). In addition, nine of the twelve configurations were tested using a speaker system as an artificial fixed-point source.

2.3.1 CONTROLLED MOVING SOURCE DATA COLLECTION

With system checkout completed and the four masts set up in positions A & A' and B & B' (Figure 3), traffic at both ends of the service road was stopped, and the four test vehicles, truck A, truck B, truck C, and truck D were driven as individual moving point sources through the test site in a north to south direction. The driver of each vehicle was instructed to obtain a maximum achievable rate of speed prior to entering the test area and hold it constant (with no gear change) as the vehicle was driven through the test site. Because of the limited amount of roadway for acceleration and deceleration, speeds were limited to between 35 and 40 mph. Each test vehicle's speed was continually recorded at the radar station as it was driven through the test area.

For the initial run, each of the four trucks were driven down the road through the test area individually. Due to rigid time constraints, all successive runs were made with trucks A & B and trucks C & D driven down the service road in tandem with sufficient spacing to insure no acoustic interference between the individual moving point source noise data from each vehicle. For consistency, the same four vehicles were used throughout the 12 measurements, but due to personnel availability some changes in truck drivers was necessary. See Figures 10 through 13 for vehicle photos, summary specifications, and 1/3 octave band spectra. To increase the statistical accuracy of the measurements, an effort was made to obtain data from three "good" runs (runs with no external interference) at each mast offset position.

With testing at mast positions B & B' completed, the two masts in positions B & B' were then moved to positions C & C', where data from three additional tandem runs were collected. The two masts were then moved to positions D & D', where three final data runs were made with each test vehicle.

Data were simultaneously collected from the eight measurement channels and stored on floppy disk in contiguous one-second data records. The start and end points of data collection were such as to insure that the entire pass-by envelope was captured at all measuring systems, along with ten seconds of ambient data at the end of each test vehicle pass-by. Throughout the tests, meteorological data were continually measured and recorded on a Climatronics Model EWS strip chart recorder (See Appendix H, Tables H1-H12).

A communication link was set-up between the test director and staff by means of four Motorola Model HT-220 walkie-talkies to evaluate the acceptability of the data collected for each vehicle pass-by. The data run was deemed "good" if: 1) no acoustic interference from airport operations was observed; 2) a constant vehicle speed with no gear changes was maintained; and 3) in the case of tandem runs, sufficient spacing between vehicles was maintained.

2.3.2 ARTIFICIAL FIXED-POINT SOURCE DATA COLLECTION

With the four masts deployed in positions A, A', B, and C, the horn speaker system (Figure 14) was set up on the service road between the two barriers at each of the four positions (W, X, Y, and Z) as shown in Figure 15. The speaker system was set up at each position on the roadway at two equivalent source heights (4-feet and 2.25-feet), measured from the cone of the speaker to the ground [Glegg 89-4]. Eight octave bands (125 Hz to 8 kHz) of recorded pink noise was broadcast (each approximately 12 seconds in duration), with the speaker axis oriented toward the center of the microphone array, from each of four positions and two source heights on the roadway.

**Figure 14 : Artificial Fixed-Point Source Horn Speaker System
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Prior to broadcasting the eight octave bands of pink noise, all traffic on the service road was stopped. Data measured by the eight microphone systems were stored on floppy disk.

The two portable masts were then moved from positions B & C behind the 500-foot barrier, to positions B' & C' in the equivalent site. With the masts at positions A,A',B',and C', the speaker system was alternately set up at each of the four positions along the service road in front of the equivalent site (positions W', X', Y', and Z', Figure 15). The recorded octave bands of pink noise were broadcast as above at the two source heights, and data were measured and stored on floppy disk.

In an effort to obtain a measure of the effect of a double barrier (Test #2, Table 2) the artificial source was set up on the grass behind the 250-foot barrier at a source height of 4-feet (Figure 15). Recorded octave bands of pink noise were broadcast and data was recorded at mast positions A, B, and C behind the 500-foot barrier. The artificial source was then set up in a corresponding position on the grass in the open field opposite the equivalent site. Again pink noise was broadcast and measurements were made at mast positions A', B', and C' in the equivalent site.

The octave bands of pink noise were recorded and reproduced on a Sony Model TCD-5M cassette deck. The signal was amplified with an Ithaco Model 451 Amplifier in tandem with an Altec Lansing Model 1593B, 75 watt RMS amplifier, and broadcast with a University Sound horn speaker Model GH and driver Model ID-60. The gain of the system was set to produce a level of 117 dB at 1 kHz, 4 feet from the cone of the speaker. The output, four feet from the cone of

the speaker, was monitored, using a Bruel & Kjaer 2230 integrating sound level meter, to obtain a measure of the stability of the emissions and the near field frequency response of the speaker. The output of the sound level meter was continuously recorded on an Esterline Angus Model MS411BB graphic level recorder.

3.0 DATA REDUCTION

Processing of the data files stored on floppy disk for the 12 barrier configurations was accomplished off-line, using the TSC processing program 'HWNOISE'. 'HWNOISE' is a user-friendly analysis program for processing acoustic data collected by the Federal Highway Administration's mobile noise measurement laboratory. With the menu driven program, calibration adjustments are applied to the raw data files and the data are processed according to the user's requirements. The processed one-second averages of the A-weighted and 1/3-octave sound pressure level data can be displayed in tabular and graphical form, as required (See Appendix I, Tables I1-I72, Figures I1-I48). Appendix A contains a step-by-step processing example using data collected from the controlled moving source data runs.

3.1 CONTROLLED MOVING SOURCE DATA

The TSC processing program, 'HWNOISE' was first used on all the data files to obtain a graphical presentation of the A-weighted level versus time (time history) of each controlled moving source pass-by. The time histories were examined and an uncontaminated time period (containing no gear changes) was identified for data processing for the four microphones at the equivalent and barrier sites. The period of data to be processed (5 to 7 seconds in duration) was chosen such that it contained the 10-dB down points of each truck's sound pressure level envelope, as measured at the reference microphone position in each site. The 5 to 7 second period corresponds to a finite roadway segment of 250 to 350 feet. The single event Sound Exposure Levels (SEL) were then calculated over the period selected at the four microphones at the barrier site and the four microphones at the equivalent site (See Appendix I, Tables I1-I36). The calculated SEL levels at each of the eight microphone positions were adjusted to account for contamination by background ambient levels, as appropriate (See Section 11.2.1, ANSI S12.8-1987).

Note: The SEL level measured for the controlled moving point sources is related to the L_{eq} measured for a line source over the same finite roadway segment.

3.1.1 SEL INSERTION LOSS (IL_{SEL})

The ambient adjusted single event SEL levels measured behind the barrier were subtracted from those measured at similar locations at the equivalent site to obtain a measure of the barrier's effectiveness for each controlled moving point source (truck) pass-by, that is, the Barrier Insertion Loss based on the SEL for a moving point source (IL_{SEL}). The IL_{SEL} was calculated at each of the three microphone heights (6, 19, and 30 feet) at each of the three mast offset positions (50, 75, and 125 feet). To increase the statistical accuracy of the data, the IL_{SEL} data from three "good" runs at each measurement position (where available) were averaged to obtain the final averaged IL_{SEL} value.

The difference between the source levels measured at the reference microphone in each site was used as a source adjustment, since it was thought to have resulted from changes in the controlled source as it passed through the test area. The source-corrected IL_{SEL} was obtained by applying this source adjustment to the IL_{SEL} averages measured at the high, middle, and low microphone positions for each of the three mast offset positions (See Section 11.3.1, ANSI S12.8

1987). The measured source adjustment for each test series is shown in Appendix B, Figures B1-B3, and as shown is generally consistent from test to test, with a few exceptions. For the test of barrier configurations 7, 9, and 11, the operator of Truck A was not the regular driver. On these three occasions, the driver attained a higher gear prior to entering the measurement area, and as a result the vehicle was still accelerating at the beginning of the test area, which translated into a higher than normal SEL level measured at the reference microphone at the equivalent site.

The large source adjustment seen for truck B, Test configuration 8, was attributed to this driver's unfamiliarity with truck B, since, after the first few runs, the adjustment was significantly reduced and in line with the other driver of that truck.

3.1.2 LA_{MAX} INSERTION LOSS (IL_{LAMAX})

The maximum A-weighted sound pressure level LA_{max} (See Appendix I, Tables I37-I72) measured behind the barrier were subtracted from those measured at similar locations at the equivalent site for each truck pass-by to obtain the LA_{max} - based Barrier Insertion Loss for a controlled moving point source (IL_{LAmax}). The IL_{LAmax} data were adjusted for effects of ambient, as required, and for deviations in source level, as in Section 3.1.1 for the IL_{SEL} data, to obtain the final adjusted IL_{LAmax} for each barrier configuration tested at each of the microphone heights and mast offsets. See Appendix B, Figures B4-B6 for the source adjustments applied to the LA_{max} data.

3.2 ARTIFICIAL SOURCE DATA

Several adjustments were performed on the data collected with the artificial fixed-point source to put it into a form for simulating a truck pass-by.

First, an eight-second period centered within each 12-seconds of octave band data broadcast was identified at the reference microphone at each measurement site. The one-third octave band levels (125 Hz to 6.3 kHz) were extracted from the octave-band data broadcast, and the average one-third octave levels were calculated over the same eight second period (eight second L_{eq}) for each of the seven microphone positions at each measurement site. This procedure was carried out on the collected-data files for measurements made at each of the four artificial source test points along the roadway (0, 50, 100, and 150 feet downtrack, referenced to the microphone array) at both the equivalent site and the barrier site.

Each one-third octave-band spectrum, at all microphones, was then adjusted in level to compensate for the irregularities in the frequency response of the horn speaker, measured at the near field monitor, four feet from the cone of the speaker. This resulted in a near flat spectrum as measured at the two reference microphones at each site (125 Hz to 6.3 kHZ).

The corrected one-third octave-band L_{eq} spectrum was further adjusted to simulate the measured frequency spectrum of a truck source (See Figures 10 - 13). This was accomplished by applying a spectral source adjustment to the corrected L_{eq} spectrum. The source adjustment applied to the L_{eq} spectrum was derived from

actual source data measured at the reference microphones at the time of LA_{max} during testing of the controlled moving sources (four trucks).

A seven-second measurement of a truck pass-by, at a speed of approximately 50 fps (34 mph), was simulated using the above corrected artificial source data to represent a 1-second L_{eq}

measurement from the pass-by at points 0, 50, 100, and 150 feet downtrack and at like points uptrack on the service road at -50,-100,and -150 feet. That is, the seven 1-second intervals of the simulated truck pass-by were made up of adjusted L_{eq} data from points Z', Y', X', W', X', Y', and Z' on the roadway (Figure 15) at the equivalent site. Similarly, a seven-second pass-by at the barrier site was simulated using adjusted L_{eq} data from points Z, Y, X, W, X, Y, and Z (Figure 15).

Measurements of the pass-by of each of the four trucks tested as controlled moving point sources was thus simulated at all microphone positions at the equivalent and barrier sites. The simulated single event SEL level of the 7-second pass-by was then calculated at each microphone.

3.2.1 SEL INSERTION LOSS (IL_{SIMSEL})

The simulated SEL levels calculated for receiver locations behind the barrier were subtracted from those for similar locations at the equivalent site to obtain a measure of the barrier's effectiveness, that is, the barrier insertion loss (IL_{SIMSEL}) based on the single event SEL of a simulated moving point source. The IL_{SIMSEL} was calculated for each of the three microphone heights (6, 19, and 30 feet) at each of the two mast offset positions (50 and 75 feet). Source level adjustments were applied to the IL_{SIMSEL} data based on differences measured at the reference microphone position in each site. No ambient adjustments were required for the artificial fixed-point source data.

Barrier IL_{SIMSEL} values, as above, were calculated for two equivalent source heights, 4 feet and 2.25 feet, for the 9 barrier configurations tested.

3.2.2 LA_{max} INSERTION LOSS ($IL_{SIMLAMAX}$)

The maximum A-weighted sound pressure levels LA_{max} measured behind the barrier were subtracted from those measured at similar locations at the equivalent site for each simulated pass-by to obtain the LA_{max} -based Barrier Insertion Loss for a simulated moving point source ($IL_{SIMLAMAX}$). The $IL_{SIMLAMAX}$ data were adjusted to compensate for source level deviations using the differences measured at the reference microphone position, as in Section 3.2.1 for the IL_{SIMSEL} data. No adjustment for ambient level was required.

Barrier $IL_{SIMLAMAX}$ data, as above, were calculated for two equivalent source heights, 4 feet and 2.25 feet, for the 9 barrier configurations tested.

4.0 DISCUSSION OF RESULTS

Results of the SEL insertion loss (IL_{SEL}) and the LA_{MAX} insertion loss (insertion loss at the time of LA_{MAX}) for the four controlled moving point sources (trucks) are presented in Appendix C, Figures C1-C12, and Appendix D, Figures D1-D12, respectively. Data for the four test trucks are presented in a manner which allows for a direct comparison of the effectiveness of the 12 barrier configurations tested (see Table 2 for barrier test configuration key). A direct comparison between the insertion loss values measured using controlled moving point sources and the simulated point sources (using artificial fixed-point source data) is presented in Appendix E, Figures E1-E8 for the SEL insertion loss data and in Appendix F, Figures F1-F8 for the insertion loss measured at the time of LA_{MAX}. Also presented is the predicted barrier insertion loss data obtained using Barrier 2.1 [Slutsky 87-5,6] (See Appendix G, Figures G1-G12). Meteorological data and the test vehicle speed data are presented in Appendix H, Tables H1 through H12. A preliminary analysis of the meteorological data for a limited number of data runs suggest that wind may have effected the measured noise levels, however the following discussion does not consider meteorological effects because an in depth analysis is required.

4.1 CONTROLLED MOVING SOURCE DATA - SEL INSERTION LOSS IL_{SEL}

4.1.1 50 FT MAST OFFSET POSITION

As shown, the IL_{SEL} measured at the high microphone position (30 feet) at the 50 foot mast offset, for all four trucks is approximately 1 dB and is independent of barrier configuration (see Table 2 for barrier configuration key). This is an expected result since the line of sight from source to receiver at the high microphone position is not broken by the 500-foot barrier; that is, it is not within the shadow zone of the barrier.

At the middle microphone position (19 feet), the four test trucks produce generally similar IL_{SEL} results (approximately 6 dB) for all 12 barrier configurations; however, a slight degradation in the barrier performance is seen for Test 9 (two vertical reflective barriers) as compared to Test 2 (two vertical absorptive barriers). Here, the resulting multiple sound paths due to reflections between the parallel barriers are beginning to degrade the performance of the barrier.

In the case of Test 5 (both barriers at 15 degrees and absorptive), with the 500-foot barrier tilted to 15 degrees, the middle microphone was not completely within the shadow zone of the barrier, resulting in a slight degradation in IL_{SEL}. This is most discernable for trucks A and B due to their high vertical exhaust stacks.

At the lowest microphone position (6 feet), trucks A, B, and C yielded similar results for Tests 1 through 6, where both barriers were absorptive (IL_{SEL}= 17, 19, and 18 dB respectively). For Test configurations 7 through 12, where either one or both of the parallel barriers were reflective, a slightly lower overall IL_{SEL} was measured for trucks A, B, and C as compared to the absorptive tests. The IL_{SEL} results for truck D at the low microphone position are seen to be lower than those for the other three trucks (4 to 6 dB lower). This is expected after examining the frequency spectra of the four test trucks (see Figures 10-13). The spectrum of truck D is dominated by low-frequency energy (below 100 Hz), as compared to trucks A, B, and C, and a fourteen-foot test barrier (twelve-foot effective height due to ground elevation below the barrier) is less effective in attenuating these low-frequency emissions because of diffractive bending of the longer wavelengths. Typical spectral data measured at the low microphone position behind the barrier and in the open field for truck A illustrate this fact (Figure 16). While the one-third octave frequencies below 100 Hz are attenuated from 0 to 10 dB, frequencies above 1 kHz are attenuated by as much as 25 dB.

4.1.2 75 FT MAST OFFSET POSITION

At the 75 foot offset position, the highest microphone (30 feet) is beginning to enter the shadow zone of the 500-foot barrier, and an IL_{SEL} of 3 to 4 dB was measured for all four trucks with minimal influence from different barrier configurations.

In general, the IL_{SEL} measured at the middle microphone (19 feet) was consistent for all four test trucks, approx. 10 to 13 dB, with one obvious exception; the IL_{SEL} associated with Test 9 (two vertical reflective barriers) as compared with Test 2 (two vertical absorptive barriers) is 3 to 5 dB lower for all four test trucks, because of the multiple reflected sound paths.

At the low microphone position (6 feet), an IL_{SEL} of 16 to 18 dB was measured for trucks A, B, and C for the absorptive barrier configurations (Tests 1-6). For the reflective configurations (Tests 7-12), the IL_{SEL} of trucks A and C appear to be independent of barrier configuration; while for truck B, a slightly higher overall insertion loss was obtained for Tests 8 and 12 (15 degree tilt angle) as compared to Tests 7,10,and 11 (7 degree tilt angle). Note the loss of data for truck B at the low microphone, which resulted from the less than ideal ambient noise level at the Dulles test site. The IL_{SEL} measured for truck D at the low microphone was between 4 and 6 dB lower than that measured for the other three trucks and was essentially independent of barrier configuration.

4.1.3 125 FT MAST OFFSET POSITION

The degradation in the measured IL_{SEL} data resulting from the multiple reflected sound paths, with both barriers vertical and reflective (Test 9), is most pronounced at the high microphone (30 feet) at the 125 foot mast offset position (4 to 6 dB). Although most of the data at the low and the middle microphone positions were either masked or had a large ambient correction applied to it, the trends in the IL_{SEL} data obtained for truck A are similar to those obtained at the 50 foot and the 75 foot mast offsets; however, the IL_{SEL} data obtained for trucks B, C, and D at the low and middle microphone position (where available) followed no discernable trends.

4.2 CONTROLLED MOVING SOURCE DATA - LA_{MAX} INSERTION LOSS (IL_{LAMAX})

The IL_{LAMAX} data obtained for all four test trucks were slightly greater than the IL_{SEL} data. This is an expected result since the barrier's effective height is less for a source traveling over a 250-foot line segment (finite segment for the SEL measurements) than for a source traveling over a 50-foot line segment (finite segment for the LA_{MAX} measurements over a 1-second averaging period).

50 FT MAST OFFSET

75 FT MAST OFFSET

125 FT MAST OFFSET

FIGURE 16: ONE THIRD OCTAVE SPECTRA MEASURED AT THE LOW MIC AT THE TIME OF LA_{MAX}-TRUCK A

4.3 SIMULATED MOVING SOURCE DATA - SEL INSERTION LOSS (IL_{SIMSEL})

The simulated single event moving point source insertion loss (IL_{SIMSEL}) data, measured at the 2.25-foot source height, are presented for direct comparison in Appendix E, Figures E1 through E8, along with the controlled moving point source insertion loss (IL_{SEL}) data for the absorptive barrier configurations (Tests 1-6). The insertion loss data (IL_{SIMSEL}) measured at the 4-foot source height are presented in Appendix E, Tables E1-E4.

Note: The artificial fixed-point source was **not** an omni-directional system. As a result, all the contributions in sound level due to reflections (off the ground and direct reflections off the opposite parallel barrier) may not have been accounted for. As a result, the IL_{SIMSEL} data presented do not effectively represent the reflective parallel barrier configurations tested and no comparison should be made with the controlled moving source data for the reflective parallel barrier configurations (Tests 7-12).

4.3.1 50 FT MAST OFFSET POSITION

The IL_{SIMSEL} data obtained at the high microphone position (30 feet for the 2.25-foot artificial source data) are in good agreement with the controlled moving source data for all four test trucks and are independent of barrier configuration for Tests 1-6.

The IL_{SIMSEL} results obtained at the middle microphone position (19 feet for the 2.25-foot source) were 0 to 3 dB lower than the IL_{SEL} data measured for trucks A, B, C, and D (Tests 1-6).

At the low microphone position (6 feet), the IL_{SIMSEL} results (2.25-foot source) obtained for trucks A, B, and C were between 0 and 3 dB lower than those for the controlled moving source. Conversely, the IL_{SIMSEL} results (2.25-foot source) obtained for truck D at the low microphone position was about 2 dB higher than those for the controlled moving source. This inconsistency obtained for truck D can be attributed to the truck's spectral characteristics and the low-end frequency response limitations of the horn speaker below 125 Hz. A modified version of 'HWNOISE', which calculated Sound Exposure

Levels over a reduced bandwidth (eliminating one-third octave band data below 125 Hz), was used to reprocess selected controlled moving source pass-by data (trucks). The results showed that since the spectrum of truck D was so dominated by low- frequency energy, the elimination of that energy resulted in a 2 dB increase in the IL_{SEL} results for truck D. This would bring the IL_{SEL} and the IL_{SIMSEL} into good agreement. For trucks A, B, and C, no significant change in the IL_{SEL} was observed after reprocessing selected pass-by data with the reduced noise bandwidth.

The trends in the insertion loss data (IL_{SIMSEL}) obtained for both the 2.25-foot and the 4-foot artificial source were in good agreement with the insertion loss data measured for the controlled moving source pass-bys, however the IL_{SIMSEL} data were consistently lower in level. Specifically the IL_{SIMSEL} measured at the low and middle microphone heights (50 foot offset position) for the 4-foot artificial source was 1 to 3 dB lower as compared with the 2.25-foot artificial source data, which, in turn, were 0 to 3 dB lower than the controlled moving source IL_{SEL} data (trucks).

Note: The IL_{SIMSEL} data for configurations 7 through 12 follow the trends and levels of the IL_{SIMSEL} data obtained for configurations 1 through 6, reemphasizing the limitation in the directionality of the artificial source. See the note in Section 4.3.

4.3.2 75 FT MAST OFFSET POSITION

The IL_{SIMSEL} data obtained for Tests 1-6 at the 75 foot mast offset (2.25-foot source) under-predicted the controlled moving source IL_{SEL} data for trucks A, B, and C by 1 to 4 dB, for all three microphone heights (6, 19, and 30 feet). For truck D, the IL_{SIMSEL} data, measured at the high and middle microphone positions were similar to the results obtained for trucks A, B, and C. However, the reduced bandwidth (no data below 125 Hz) of the artificial source resulted in a 2.0 dB over-prediction of the insertion loss data measured at the low microphone position for truck D. This was confirmed, as in Section 4.3.1.

According to FHWA criteria [Bowlby 82-7], truck A is classified as a heavy truck (HT) and the other three test trucks are medium trucks (MT). Recent studies [Glegg 89-4] have shown that the equivalent source height of vehicles classified as MT is 2.25-feet (.7 meters). A comparison of the 2.25-foot and the 4-foot simulated moving source IL_{SIMSEL} data with the controlled moving source IL_{SEL} data shows that the 2.25-foot source data are in closer agreement. This comparison also suggests that a lower equivalent source height would have resulted in an even closer agreement, and that the equivalent source height for medium trucks is lower than 2.25 feet or the simple artificial source used was not effective.

4.4 SIMULATED MOVING SOURCE DATA-LA$_{MAX}$ INSERTION LOSS (IL$_{SIMLAMAX}$)

The $IL_{SIMLAMAX}$ data are slightly greater than the IL_{SIMSEL} data and are presented without further comment in Appendix F, Figures F1 - F8 and Tables F1-F4 (See Section 4.2).

The $IL_{SIMLAMAX}$ results for the special test of a double-wall noise barrier (as discussed in Section 2.3.2) are presented in Appendix F, Table F5. The data obtained at the 30 foot and the 19 foot microphone height are similar for the three offset positions (9 to 13 dB), while the full effect of the double barrier is seen at the low microphone ($IL_{SIMLAMAX}$ = 20 dB for truck D and 24 to 27 dB for trucks A, B, and C). The lower insertion loss levels obtained for truck D at the low microphone (6 feet) are expected, and can be attributed to its low-frequency-dominated spectrum.

4.5 MODELING: COMPARISON OF MEASURED AND PREDICTED INSERTION LOSS

The highway noise modeling program, Barrier 2.1, was used to obtain insertion loss values for the 12 barrier configurations tested at Dulles. The predicted insertion loss is presented in Appendix G, Figures G1-G12, along with a sample input file.

As can be seen, virtually no variation in the predicted insertion loss was obtained from one configuration to the next, with the exception of Test Configuration 9 (two vertical reflective barriers). The 1 to 6 dB degradation in barrier performance for Test 9 as compared to the performance of Test 2 (two vertical absorptive barriers), predicted by Barrier 2.1, was in good agreement with the measured results (Appendix C, Figures C1-C12). While the trends in the predicted and the measured data were similar, the absolute insertion loss values predicted by Barrier 2.1 were 3 to 5 dB lower than those measured. The largest differences occurred at the middle microphone (19-feet), 50-foot offset, and at the high microphone (30-feet), 75-foot offset. The propagation path from a source at a height of 2.25-feet (as modeled in Barrier 2.1) to these receivers is on the edge between the bright zone and the shadow zone of the Dulles barrier. If the source were modeled slightly below the 2.25-foot source height, the line of sight (as predicted by Barrier 2.1) would be broken by the barrier and a larger insertion loss would be predicted, resulting in a closer overall correlation at these and at all other microphone positions.

The ground impedance parameter in Barrier 2.1 modeled the Dulles test site as a soft absorptive surface. However, a subsequent analysis showed a better correlation between the predicted and measured results would be obtained (especially at the low microphone position), if the ground were modeled as a hard reflective surface. Although the Dulles test site was covered with low-cut grass (implying a soft absorptive surface), the soil consisted of hard-packed clay and perhaps should have been modeled more as a hard reflective surface.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The insertion loss results presented in Appendix C are representative of the relative effectiveness of the Dulles barrier in mitigating the effects of the controlled moving sources tested. Due to the limited roadway at the Dulles test site, free flowing highway conditions could not be simulated.

The noise emissions of the moving point sources tested were analyzed for a finite roadway segment of approximately 250 to 350 feet in length, centered on the 500-foot barrier. The SEL data measured of this unique source is related to the L_{eq} of a line source of the same finite length (250 to 350 feet). Its level is influenced by the barrier over the finite roadway segment in exactly the same manner as the L_{eq} of a line source is influenced. Hence, the insertion loss measured utilizing the SEL data represents the effectiveness of the barrier in mitigating a finite line source of approximately 250 to 350 feet.

5.1 EFFECT OF ABSORPTIVE TREATMENT AND BARRIER TILT

A recurring trend found in all the insertion loss data presented is the large degradation in barrier performance associated with two vertical reflective highway noise barriers (Test 9). The addition of absorptive treatment to the roadside face of two vertical reflective barriers improved barrier insertion loss 2 to 6 dB by eliminating the multiple reflected sound paths.

Tilting proved to be an effective alternative to absorptive treatment in eliminating the multiple reflections and the resulting degradation in performance of two vertical reflective barriers.For the Dulles test site geometry, tilting either one or both of the barriers to an angle of 15 degrees was slightly more effective in improving the measured insertion loss than a 7 degree tilt angle. However, the effectiveness of a particular barrier tilt angle is a function of the geometry of the installation site; that is, as the distance between two parallel barriers, or the height of either of the barriers changes, the insertion loss is likely to change, and a different tilt angle may be found to be more effective. Therefore, it should not be assumed that a specific tilt angle is a sufficient substitute for absorptive treatment in all construction applications.

Once verified for accuracy, prediction models can be used to determine the optimum tilt angle for a specific site geometry.

A cost benefit analysis is required to determine whether a 2 to 6 dB improvement in effectiveness is sufficient to justify the additional cost associated with absorptive treatment or barrier tilting.

5.2 PREDICTED MODELING

Although the Barrier 2.1 program was used to model a single site geometry in the present study, it is capable of analyzing a variety of geometries, including various distances between barriers, and barriers with various tilt angles. A comparison of the measured results with those predicted using Barrier 2.1 showed that, while the trends in both sets of data were similar, the predicted insertion loss values were 3 to 5 dB lower than those measured.

The Barrier 2.1 prediction model is dependent on several input parameters, including barrier tilt angle, barrier reflection coefficients, ground impedance, and source height. The ground impedance parameter was chosen as to model the Dulles test site, with Barrier 2.1, as a soft absorptive surface. A subsequent analysis showed a better correlation between the predicted and measured results would be obtained (especially at the low microphone position), if the ground were modeled as a hard reflective surface. Although the ground was covered with low-cut grass, the soil consisted of hard-packed clay and perhaps should have been modeled more as a hard reflective surface. In addition, if the source were modeled slightly below the 2.25-foot source height suggested by Reference 4, a closer overall correlation would have been obtained at all microphone positions. Thus, a better estimation of the ground impedance and the source height parameter is needed, as a minimum, before the measured and predicted results can be compared with any degree of confidence.

The Barrier 2.1 modeling program has several limitations which are currently being corrected: 1.) The program is unable to accept ground elevations below a fixed road grade elevation of zero feet (receiver parameter AZR(NR)). As a result, for the Dulles prediction, the ground elevations under data microphones were modeled at road grade elevation, instead of approximately two feet below road grade (See Figures 4 and 5). 2.) While the program considers ground reflections in the equivalent site, it does not take into account ground reflections at the barrier site, an effect most important at the barrier site reference microphone. 3.) The program does not allow for travel lanes with no traffic volume. As a result, the second lane at the Dulles test site was modeled as an extension of the hard shoulder of the roadway.

5.3 EVALUATION OF THE STANDARD (S12.8-1987)

A comparison of the insertion loss data for the artificial source and the controlled moving source suggests that a source height lower than 2.25-feet would have yielded a closer correlation. To conclude that truck A (ten foot vertical exhaust stack), for example, has an equivalent source height lower than 2.25-feet makes no intuitive sense, especially since tire noise at speeds of 35 to 40 mph is minimal. As a result, we can conclude that the "simple" artificial source used in the Dulles barrier tests was unsuccessful at attempting to model a single moving point source pass-by.

The University Sound horn speaker system was chosen because of its uncharacteristically high sound pressure level (SPL) output for a rated input as compared to commercially available loudspeakers. Both low-end frequency response (below 125 Hz) and source directionality were sacrificed in favor of the high output level. As discussed in section 4.3.1, the effects due to the limited frequency response were minimal because the data presented in this report are A-weighted. However, the directionality limitations of the speaker may be the main source of differences between the actual and simulated source pass-bys.

The University Sound horn speaker produced a flat frequency response within a 15 degree cone relative to its axis. During testing the axis of the speaker was orientated toward the center of the microphone array, thus maximizing the direct propagation path. As a result, ground reflected sound paths (as from an omni-directional source) were inadvertently minimized. To properly simulate the noise radiated from a truck, all the direct and reflected sound paths must be artificially created. To do this requires either a high-powered omni-directional speaker system or an array of horn-type speakers orientated as required to simulate all the direct and reflected sound paths. Additional verification needs to performed with an artificial fixed-point source before it can be recommended as a viable alternative to actual highway traffic.

Section 11.3.1 of the ANSI S12.8-1987 standard suggests that the insertion loss measured at a receiver position should be adjusted based on level differences obtained at the reference position; that is, any difference in level measured at the reference position is due solely to a change in the source from the BEFORE (equivalent site) to the AFTER (barrier site) case, and the insertion loss levels measured at all receiver positions should be adjusted accordingly. The source adjustment measured at the reference microphone for this study was approximately -1 dBA, for all four test trucks (See Figures B1-B3), including the artificial fixed-point source, and the insertion loss data were adjusted as recommended by the standard. However, the consistency of the measured difference (over 300 data runs for twelve barrier configurations) indicates that it may not be attributable solely to a change in the source level, especially since the -1 dBA adjustment was also measured for the artificial fixed-point source. Since the same calibrator was used for the two reference microphones, the possibility of a different relative calibration level can be ruled out. Another possibility that was ruled out is that the parallel barrier construction introduced an additional reflected sound path which increased the level at the barrier site reference microphone. If this were the case, the -1 dBA adjustment would only be present for the reflective barrier configurations (Tests 7-12). A third possibility is that the -1 dBA adjustment may be related to unknown site differences. However, the site profiles show that the barrier and equivalent sites are almost identical (Figures 4 and 5).

The standard recommends placing the reference microphone 1.5 meters above the top edge of the barrier to eliminate the effects of edge scatter. It is possible that the reference microphone needs to be placed even higher. Additional field measurements are required to determine the height above the barrier top edge at which scatter effects become negligible.

6.0 RECOMMENDED FUTURE WORK

The following recommendations for future work are based on suggestions from the FHWA, the fourteen supporting state transportation agencies, and several recognized experts on highway noise abatement:

- Modify Barrier 2.1 and BarrierX (a modified version of Barrier 2.1) as needed. The major concern of most state transportation agencies is the lack of a highway modeling program which considers the effects of barrier tilting, separation distance between barriers, and multiple reflected sound paths. Both Barrier 2.1 and BarrierX take these parameters into consideration but have not been thoroughly tested. The large data base resulting from the Dulles project provides the necessary information for verification. In addition, a better estimation of the source height and the ground impedance parameters should be obtained.

- Examine the effects of meteorological data on the measured noise levels. Preliminary analysis of the meteorological data suggests that wind may have effected the measured noise levels. Recent studies have shown that noise levels measured at a receiver position close to a roadway can be largely influenced by meteorological effects [Wayson 89-8].

- Perform additional theoretical verification using prediction models other than Barrier 2.1 and BarrierX, for example IMAGE-3 [Bowlby 83-9].

- Investigate the effects of barrier tilt in urban areas where multiple story apartment buildings are a consideration.
- Investigate the effects due to shorter Jersey crash barriers positioned on roadway medium strips between parallel noise barriers.
- Examine the impact on reflected sound paths resulting from a "zig zag" barrier design.
- Research the weathering effects of various absorptive materials.

- Investigate the economic considerations of tilted and absorptive noise barriers with the goal of developing design guidelines or standards.

Highway noise barriers can be aesthetically unappealing to the eye and, as a result, many state transportation agencies have recognized a need to explore other avenues of highway noise mitigation. At least one state has an on-going study and several states have indicated an interest in roadway treatments and different pavement composites as a means of reducing highway noise, specifically tire noise [Polcak 89-10].

The recent FHWA Environmental Policy Statement identifies highway noise control as an important environmental issue for the 1990's and beyond [Larson 90-11]. It states that: "It is FHWA policy to ensure that all reasonable and feasible mitigation measures are incorporated into projects to minimize noise impacts, and enhance the surrounding noise environment to the extent practicable." Noise barriers are one means of achieving this goal, and the above recommend work will provide additional guidance in their efficient design and construction.

APPENDIX A
CONTROLLED MOVING SOURCE CORRECTION PROCEDURE

INTRODUCTION:

This Appendix outlines the step-by-step procedure followed to obtain the corrected barrier insertion loss levels for the controlled moving source pass-bys presented in Appendix C, Figures C1-C12. The three example data runs are from measurements made of actual truck pass-bys (truck A), obtained on 7/12/89, with the measurement mast at the 50 foot mast offset.

STEP 1:

From the A-weighted level versus time (time history) plot (selection 0 in the plot menu) obtained from 'HWNOISE', choose a time period for calculating the SEL_{AWT} at microphones 5 - 8, then choose a time period of equal length for calculating the SEL_{AWT} at microphones 1 - 4.

STEP 2:

From the A-weighted time history plot, select a time period (equal in length to that chosen for the event) which is a good representation of the background noise at the two lowest microphones (mic 4 and mic 8). The length of the period used to calculate the ambient level must be the same as that used to calculate the SEL_{AWT}. Use the ambient levels to adjust the measured SEL_{AWT} as needed at each of the eight microphone positions (See Table 3 in the ANSI S12.8-1987).

BARRIER SITE 50'OFFSET	MEASURED SOURCE SEL	MEASURED BACKGROUND SEL	DIFFERENCE (SOURCE - BACKGROUND)	BACKGROUND ADJUSTMENT	ADJUSTED SEL_{ADJ}
REF MIC	83.5	49.1	34.4	0.0	83.5
HGH MIC	82.2	49.1	33.1	0.0	82.2
MID MIC	78.5	49.1	29.4	0.0	78.5
LOW MIC	64.2	49.1	15.1	0.0	64.2

EQUIV	MEASURED	MEASURED	DIFFERENCE	BACKGROUND	ADJUSTED

SITE 50'OFFSET	SOURCE SEL	BACKGROUND SEL	(SOURCE - BACKGROUND)	ADJUSTMENT	SEL_{ADJ}
REF MIC	82.3	55.5	26.8	0.0	82.3
HGH MIC	81.1	55.5	25.6	0.0	81.1
MID MIC	81.7	55.5	26.2	0.0	81.7
LOW MIC	80.7	55.5	25.2	0.0	80.7

STEP 3:

Subtract the ambient adjusted SEL_{AWT} at similar microphones to obtain the ambient adjusted Awt insertion loss SEL levels (IL_{SEL}).

ADJSEL(REF)-ADJSEL(REF)= -1.2 dB

ADJSEL(HGH)-ADJSEL(HGH)= -1.1 dB

ADJSEL(MID)-ADJSEL(MID)= 3.2 dB

ADJSEL(LOW)-ADJSEL(LOW)= 16.5 dB

STEP 4:

Repeat steps 1 - 3 on all similar data runs (steps 4a-4f).

STEP 4a:

From the A-weighted level versus time (time history) plot obtained for 'HWNOISE' of the second test run, choose a time period for calculating the SEL_{AWT} at microphones 5 - 8, then choose an period of equal length for calculating the SEL_{AWT} at microphones 1 - 4.

STEP 4b:

From the A-weighted time history plot, select a time period (equal in length to that chosen for the event) which is a good representation of the background noise at the two lowest microphones (mic 4 and mic 8). The length of the period used to calculate the ambient level must be the same as that used to calculate the SEL_{AWT}. Use the ambient levels to adjust the measured SEL_{AWT} as needed at each of the eight microphone positions (See Table 3 in the ANSI S12.8-1987).

BARRIER SITE 50'OFFSET	MEASURED SOURCE SEL	MEASURED BACKGROUND SEL	DIFFERENCE (SOURCE - BACKGROUND)	BACKGROUND ADJUSTMENT	ADJUSTED SEL_{ADJ}
REF MIC	83.6	53.4	30.2	0.0	83.6
HGH MIC	82.4	53.4	29.0	0.0	82.4
MID MIC	78.5	53.4	25.1	0.0	78.5
LOW MIC	64.4	53.4	11.0	0.0	64.4

EQUIV SITE 50'OFFSET	MEASURED SOURCE SEL	MEASURED BACKGROUND SEL	DIFFERENCE (SOURCE - BACKGROUND)	BACKGROUND ADJUSTMENT	ADJUSTED SEL_{ADJ}

REF MIC	82.5	53.6	28.9	0.0	82.5
HGH MIC	81.3	53.6	27.7	0.0	81.3
MID MIC	81.5	53.6	27.9	0.0	81.5
LOW MIC	80.7	53.6	27.1	0.0	80.7

STEP 4c:

Subtract the ambient adjusted SEL_{AWT} at similar microphones to obtain the ambient adjusted Awt insertion loss SEL levels (IL_{SEL}).

ADJSEL(REF)-ADJSEL(REF)= -1.1 dB

ADJSEL(HGH)-ADJSEL(HGH)= -1.1 dB

ADJSEL(MID)-ADJSEL(MID)= 3.0 dB

ADJSEL(LOW)-ADJSEL(LOW)= 16.3 dB

STEP 4d:

From the Awt level versus time (time history) plot obtained from 'HWNOISE' of the third test run, choose a time period for calculating the SEL_{AWT} at microphones 5 - 8, then choose an period of equal length for calculating the SEL_{AWT} at microphones 1 - 4.

STEP 4e:

From the A-weighted time history plot, select a time period (equal in length to that chosen for the event) which is a good representation of the background noise at the two lowest microphones (mic 4 and mic 8). The length of the period used to calculate the ambient level must be the same as that used to calculate the SEL_{AWT}. Use the ambient levels to adjust the measured SEL_{AWT} as needed at each of the eight microphone positions (See Table 3 in the ANSI S12.8-1987).

BARRIER SITE 50'OFFSET	MEASURED SOURCE SEL	MEASURED BACKGROUND SEL	DIFFERENCE (SOURCE - BACKGROUND)	BACKGROUND ADJUSTMENT	ADJUSTED SEL_{ADJ}
REF MIC	83.7	51.9	31.8	0.0	83.7
HGH MIC	82.4	51.9	30.5	0.0	82.4
MID MIC	78.5	51.9	26.6	0.0	78.5
LOW MIC	64.5	51.9	12.6	0.0	64.5

EQUIV SITE 50'OFFSET	MEASURED SOURCE SEL	MEASURED BACKGROUND SEL	DIFFERENCE (SOURCE - BACKGROUND)	BACKGROUND ADJUSTMENT	ADJUSTED SEL_{ADJ}
REF MIC	82.5	53.6	28.9	0.0	82.5
HGH MIC	81.1	53.6	27.5	0.0	81.1

MID MIC	81.8	53.6	28.2	0.0	81.8
LOW MIC	81.1	53.6	27.5	0.0	81.1

STEP 4f:

Subtract the ambient adjusted SEL_{AWT} at similar microphones to obtain the ambient adjusted Awt insertion loss SEL levels (IL_{SEL}).

ADJSEL(REF)-ADJSEL(REF)= -1.2 dB

ADJSEL(HGH)-ADJSEL(HGH)= -1.3 dB

ADJSEL(MID)-ADJSEL(MID)= 3.3 dB

ADJSEL(LOW)-ADJSEL(LOW)= 16.6 dB

STEP 5:

Obtain the average of the ambient adjusted A-weighted insertion loss levels (IL_{SEL}) from all similar runs along with their corresponding standard deviations.

AMBIENT ADJUSTED INSERTION LOSS				AVERAGE IL_{SEL}	
EQUIVALENT - BARRIER	RUN 1	RUN 2	RUN 3	SEL_{ADJ}	STD DEV.
SEL_{ADJ} (REF)-SEL_{ADJ} (REF)	-1.2	-1.1	-1.2	-1.17	0.05
SEL_{ADJ} (HGH)-SEL_{ADJ} (HGH)	-1.1	-1.1	-1.3	-1.17	0.12
SEL_{ADJ} (MID)-SEL_{ADJ} (MID)	3.2	3.0	3.3	3.17	0.15
SEL_{ADJ} (LOW)-SEL_{ADJ} (LOW)	16.5	16.3	16.6	16.50	0.15

STEP 6:

Adjust the average IL_{SEL} levels obtained at the high, middle and low microphones to compensate for any difference in level obtained at the reference microphone position as the controlled moving source passed through the test area (See Section 11.3.1, ANSI S12.8 1987).

SOURCE CORRECTED INSERTION LOSS (IL_{SEL})

TRUCK A - 50' OFFSET - 7/12/89

$IL_{SEL}(REF) = 0.00$ dB
$IL_{SEL}(HGH) = 0.00$ dB
$IL_{SEL}(MID) = 4.34$ dB
$IL_{SEL}(LOW) = 17.67$ dB

APPENDIX B
SOURCE ADJUSTMENTS

This Appendix contains the controlled moving point source adjustments that were applied to the IL_{SEL} data as was discussed in Section 3.1.1 (Figures B1 through B3), along with the adjustments that were applied to the IL_{LAMAX} data as discussed in Section 3.1.2 (Figures B4 through B6).

APPENDIX C

IL_{SEL} VERSUS BARRIER CONFIGURATION

This Appendix presents the results of the SEL insertion loss (IL_{SEL}) for the four controlled moving point sources (trucks), as discussed in Sections 4.1.1-4.1.3, Figures C1-C12. Included in the Figures is the standard deviation plotted around the average value. Where only one run was available no standard deviation is given.

APPENDIX D

IL_{LAMAX} VERSUS BARRIER CONFIGURATION

This Appendix presents the results of the LA_{MAX} insertion loss (IL_{LAMAX}) for the four controlled moving point sources (trucks), as discussed in Section 4.2, Figures D1-D12. Included in the Figures is the standard deviation plotted around the average value. Where only one run was available no standard deviation is given.

APPENDIX E

IL_{SIMSEL} VERSUS BARRIER CONFIGURATION

This Appendix presents the simulated single event moving point source insertion loss (IL_{SIMSEL}) data (2.25-foot equivalent source height), Figures E1 through E8, along with the controlled moving source insertion loss (IL_{SEL}) data for the absorptive configurations (Tests 1-6).

Also presented, is the simulated single event moving point source insertion loss (IL_{SIMSEL}) data measured at the 4-foot equivalent source height, Tables E1-E4.

APPENDIX F

$IL_{SIMLAMAX}$ VERSUS BARRIER CONFIGURATION

This Appendix presents the simulated single event moving point source insertion loss ($IL_{SIMLAMAX}$) data (2.25-foot equivalent source height) Figures F1 through F8, along with the controlled moving source Insertion Loss (IL_{LAMAX}) data for the absorptive configurations (Tests 1-6).

Also presented, is the simulated single event moving point source insertion loss ($IL_{SIMLAMAX}$) data measured at the 4-foot equivalent source height, Tables F1-F4.

As discussed in Section 4.4, the simulated moving point source insertion loss ($IL_{SIMLAMAX}$) results obtained with the speaker system set-up on the grass behind the 250 foot barrier are also presented in Table F5.

APPENDIX G
PREDICTED INSERTION LOSS USING 'BARRIER 2.1'

This Appendix presents the insertion loss results predicted using the 'BARRIER 2.1' highway noise barrier modeling program, Figures G1-G12. An example input file is also presented in this Appendix. Barrier configuration parameters were modified as required according to Table 2.

APPENDIX H
METEOROLOGICAL DATA AND TEST VEHICLE SPEED DATA

This Appendix presents weather data and test vehicle speed data for the 12 noise barrier configurations tested, Tables H1-H12. **Note** the following:

> "ICAL X - Y" denotes initial calibration on measurement systems X through Y.
>
> "TK X - Y" denotes a controlled moving point source data run with a truck, X, and a mast offset of Y (feet).
>
> "ASE X'@Y" denotes a data run with the artificial fixed-point source positioned in the equivalent site at the Y offset position along the road and set to a source height of X (feet).
>
> "ASB X'@Y" denotes a data run with the artificial fixed-point source positioned in the barrier site at the Y offset position along the road and set to a height of X (feet).
>
> "FCAL X - Y" denotes final calibration on measurement systems X through Y.
>
> "AMBIENT" denotes a 30 second sample of ambient noise data being collected.

APPENDIX I
MEASURED DATA

INTRODUCTION:

Data from the eight microphone systems deployed were fed through up to 500 feet of cable to the mobile noise laboratory for storage and off-line processing, using the 'HWNOISE' processing program. This Appendix presents typical one-third octave-band measured spectra at each microphone height and mast offset for the four individual test trucks along with overall A-weighted source levels and ambient levels measured from the eight microphone systems.

MEASURED ONE-THIRD OCTAVE DATA:

One-third octave spectra measured at the time of LA_{MAX} at the receiver positions behind the barrier and the receiver positions in the open field are presented in Figures I1-I12 for truck A, Figures I13-I24 for truck B, Figures I25-I36 for truck C, and Figures I37-I48 for truck D. A comparison of the spectra obtained at similar microphone positions shows the frequency dependent attenuation characteristics of the Dulles test barrier.

MEASURED SEL_{AWT} AND MAX_{AWT} DATA:

Tables I1 through I36 contain the unadjusted A-weighted Sound Exposure Levels (SEL_{AWT}) measured at each of the eight microphone positions, while Tables I37 through I72 contain the unadjusted maximum levels (MAX_{AWT}).

APPENDIX J
RESULTS OF TESTING THE ABSORPTIVE TREATMENT

INTRODUCTION:

The absorptive fiberglass material installed on the roadside face of the Dulles barrier was tested per the ASTM National Standard Recommended Practice 384-88 (standing wave tube method) and 423C-77 (reverberation room method) by Acentech Inc., at the Bolt, Beranek and Newman, Inc., laboratory facilities in Cambridge, MA. The quantity measured was the acoustic absorption coefficient ( ) defined as the ratio of the sound power absorbed on a surface divided by the sound power incident on the same surface.

In order to evaluate any degradation effects due to weathering, two samples of the absorptive material were tested, one having been exposed to the weathering elements for several years, while the other sample was protected. Results showed that no significant difference in the absorption qualities of the material were measurable below 2.5 khz when comparing the weathered sample with the protected sample. This Appendix presents the testing procedures, along with a detailed summary of the results.

PROCEDURE : STANDING WAVE TUBE METHOD

The normal incidence absorption coefficient was measured for the weathered and the protected samples using methods described in the ASTM National Standard Recommended Practice 384-88. This method requires a small sample of the material under test to be placed in the end of a hollow rigid tube (standing wave tube) where it acts as the end stop of the tube. A speaker, placed at the other end of the tube produced pure tone-discrete sinusoidal frequencies of sound resulting in a standing wave of sound pressure maxima and minima. A moveable probe microphone was inserted into the tube and was positioned to measure these pressure maxima and minima. Two different-sized tubes were employed to cover as large a frequency range as possible, extending from 100 Hz to 6300 Hz one-third octave bands inclusive. With the measured pressure maxima and minima documented for the nineteen 1/3 octave band frequencies (100 Hz to 6300 Hz), the absorption coefficient at those frequencies were calculated as follows (See Tables J1 and J2):

$$SWR=((P_{MAX}/P_{MIN}) - 1)/((P_{MAX}/P_{MIN}) + 1)$$

where SWR = Standing Wave Ratio

P_{MAX} = Maximum Sound Pressure at a given frequency

P_{MIN} = Minimum Sound Pressure at a given frequency

The normal incidence absorption coefficient can be calculated by:

$$= (4SWR)/(SWR^2 + 2SWR +1) \quad \text{Note: } 0 < \quad < 1$$

From the absorption coefficient, the reflection coefficient ($_r$), defined as the ratio of sound power reflected from a surface divided by the sound power impinging on the same surface can be calculated as follows:

$$_r = 1 - \qquad \text{Note: } 0 < {}_r < 1$$

Also of interest was the complex impedance of the material which can be calculated as follows:

$$Re(Z_n/\ c) = \frac{1 - r^2}{1 + r^2 - 2rCOS0}$$

$$Im(Z_n/\ c) = \frac{2rSIN0}{1 + r^2 - 2rCOS0}$$

where r = 1 - and

$$0 = \frac{Y_1}{(\ /4)} - 1$$

Y_1 is the distance between the sample and the first sound pressure minimum.

EQUIPMENT: STANDING WAVE TUBE METHOD

The following instrumentation and accessories were employed during the data collection procedure using the standing wave tube.

Make/Model	Description	Serial No.
B&K Type 4002	Standing Wave Tube	68692
B&K Type 2231	Precision Sound Level Meter	1437321
B&K Type 1625	Full & Third Octave Filter	1436988
B&K Type BZ7103	Frequency Analysis Module	N/A
B&K Type 4230	Acoustic Calibrator	1472192
B&K Type ZI9101	Digital Interface (RS-232)	N/A
B&K Type SLM0.03	Interfacing Software	N/A
Toshiba T1200	Laptop Computer	04943413
HP 202C	Low Frequency Oscillator	757
HP 5383A	Frequency Counter	2116A04507

PROCEDURE: REVERBERATION ROOM METHOD

The random incidence absorption coefficient was measured using the methods described in the ASTM National Standard Recommended Practice 423C-77. This method requires that a suitable reverberation room be used as to insure a diffuse sound field at all frequencies of interest. In order to accomplish this requirement, a large-vaned diffuser was erected inside the reverberation chamber. The diffuser was used to scatter the sound fields more effectively and to yield more random room modes.

The first step was to measure the reverberation time (T60) of the test room when it did not include the material to be tested. The reverberation time is defined as the time, in seconds, that it takes for sound to decay 60 dB, or a linear factor of 1/1,000,000 in accordance with the accepted Sabine definition. The reverberation time is dependent on the size (volume) of the test facility and the amount of sound absorption (in sabines) within the room. For a given sized room, the greater the absorption, the shorter the reverberation time, and vice-versa. The absorption coefficient will also vary with frequency and thus must be measured at all frequencies in question. In this case, the one-third octave frequency range of 100 Hz to 6300 Hz was examined for comparison with the results obtained using the standing wave tube method.

The reverberation times were measured with a specially-programmed sound level meter/reverberation analyzer. A bandwidth limited noise impulse was generated by the sound level meter and broadcast into the room through a powered loud speaker. The sound level meter immediately began measuring, and recorded the time for the sound impulse to acoustically decay 60 dB. This procedure was repeated automatically at all frequency bandwidths of interest, and the reverberation times were measured at eight different locations within the reverberation room to spatially average the sound field in the room. With the reverberation times for different frequencies defined for the empty room, the test specimen of absorptive material was placed on the floor of the reverberation room. The above procedure was repeated and the reverberation times for the nineteen one-third octave bands (100 Hz to 6300 Hz) were measured at the same eight locations within the room.

The absorption coefficient at the various frequencies were then calculated for the test sample. Since the reverberation times are dependent on absorption within the room, and the only change was the addition of the absorptive specimen, it follows that any change in measured reverberation times was entirely attributable to the specimen. Consequently, the absorption coefficients at different frequencies could be calculated from the general Sabine equation (See Tables J3 and J4):

$$A = (0.049 \text{ X Volume}) ((1/T_1) - (1/T_2))$$

where A = the change in measured absorption area

T_1 = reverberation time with sample in room

T_2 = reverberation time of empty room

Volume = room volume (cubic feet)

Knowing the change in absorption area at each frequency due to the introduction of the specimen, the absorption coefficient can be calculated as follows:

$= A / S$ Note: $0 < \; < 1$

where S = the surface area of the specimen (sq. ft.)

EQUIPMENT: REVERBERATION ROOM METHOD

The following list of instrumentation and accessories were used during the reverberation room measurements.

Make/Model	Description	Serial No.
BBN Reverb Room	Lab A at 50 Moulton St., Cambridge, MA	
B&K Type 2231	Precision Sound Level Meter	1437321
B&K Type 1625	Full & Third Octave Filter	1436988
B&K Type 4155	Condenser Microphone	4179770
B&K Type 4230	Acoustic Calibrator	1472192
B&K Type ZI9101	Digital Interface (RS-232)	N/A
B&K Type SLM0.03	Interfacing Software	N/A
Toshiba T1200	Laptop Computer	04943413
BBN Noise Box	Powered Loud Speaker	15025

SUMMARY OF RESULTS

No physical differences were observed between the weathered and protected samples except that the weathered sample had lost most of its exterior plastic coating and was to some degree sun bleached on its exposed side. Consequently, little change in the absorption coefficient was anticipated except at the high frequencies (above 2.5 khz).

The results of the standing wave tube method for determining the normal incident absorption coefficient are presented in Tables J1 and J2 and Figure J2 and J3. The absorption coefficient was relatively small at the lower frequencies (100 Hz to 400 Hz) and increased steadily, approaching total absorption (unity), 500 Hz up to 2000 Hz. At high frequencies (above 2 khz), the absorption coefficient of the weathered sample was actually greater than that of the protected sample. This result is due to the loss of the plastic coating on the weathered sample, thus permitting the sound to impinge directly on the glass fiber material. This effect is to be expected at the higher frequencies where the wavelengths are close to the thickness of the plastic sheeting.

Similar results were found for the two tested samples using the reverberation room technique (see Tables J3 and J4, and Figures J4 and J5). Unfortunately, due to the limited size of the sample material under test, the lower frequency (100 Hz to 315 Hz) measurements were not as reliable as those for the mid and high frequencies (400 Hz to 6300 Hz). Nevertheless, the overall trends in the data obtained for the standing wave tube and reverberation room methods were similar. Slightly greater absorption coefficients

were obtained with the reverberation room method than with the standing wave tube method, probably due to edge and diffraction effects, a phenomenon not completely understood (See Figure J1 ref: ASTM C423-77 & B&K Type 4002 Instruction Manual). Rather than adjusting the data for the reverberation room effects, the measured data and calculated results are reported, as suggested in the ASTM Standard.

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WHERE TO FIND KEY INFORMATION IN THIS DOCUMENT

TO FIND...	LOOK IN...
1. Controlled moving point source data correction procedure.	Appendix A
2. Measured moving point source adjustments as measured at	Appendix B