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PARALLEL BARRIER EFFECTIVENESS UNDER FREE-FLOWING TRAFFIC CONDITIONS

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FINAL REPORT

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FEDERAL HIGHWAY ADMINISTRATION
Office of Engineering and Highway Operations
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FOREWORD

Noise is an important environmental consideration to highway planners and designers. It can annoy and cause psychological or physiological harm, depending on frequency characteristics and loudness. The U.S. Department of Transportation and state transportation agencies are charged with the responsibility of optimizing compatibility of highway operations with environmental concerns. Highway noise problems have been addressed by numerous investigations including evaluations of the following:

1. Highway noise sources and highway noise reference mean emission levels.
2. Noise impacts at receptor locations.
3. The effects of site geometry, meteorology, ground surface conditions and barriers on highway noise propagation.
4. Alternative methods of mitigating highway noise impacts.

The use of noise barriers along highways is one of the principal means of mitigating highway noise. As a result, the Federal Highway Administration has initiated a study to examine the effectiveness of highway noise barriers, "Evaluation of Performance of Experimental Highway Noise Barriers." This study was initially directed at the evaluation of parallel barriers under controlled traffic conditions at an experimental test site located at Dulles International Airport near Washington, D.C. The main results of this study have been reported in FHWA-RD-90-105, "Parallel Barrier Effectiveness, Dulles Noise Barrier Project".

This publication reports on the effectiveness of a parallel barrier located along Interstate 495 in Montgomery County, Maryland. It will be of interest to engineers and others involved in the mitigation of highway noise. All data pertaining to experimental conditions and measurements have been archived at the Volpe National Transportation Systems Center.

Thomas J. Ptak
Director, Office of Engineering
and
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NOTICE

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FHWA Contact: Robert E. Armstrong, HEP-41, Office of Environment and Planning. This study, through pooled funds, was supported by the highway agencies of the following states: AZ, CA, CT, FL, GA, HI, IA, MD, MA, MI, NJ, NY, OH, PA, VA, WA, and WI.

The U.S. Department of Transportation, Research and Special Programs Administration, Volpe National Transportation Systems Center, in support of the Federal Highway Administration and seventeen sponsoring state transportation agencies is conducting a National Pooled-Fund Study (NPFS), HP&R 0002-136, "Evaluation of Performance of Experimental Highway Noise Barriers." The first publication supporting the NPFS, FHWA-RD-90-105, "Parallel Barrier Effectiveness, Dulles Noise Barrier Project", presented measured results and evaluations of parallel barriers subject to controlled traffic conditions. This document is the second publication supporting the NPFS. It presents the results of a measurement study performed at a highway noise barrier site located along Interstate 495 in Montgomery County, Maryland. The objective of the study was to measure the degradation in acoustic performance of a highway noise barrier due to the close proximity of a parallel barrier on the opposite side of the roadway. The test site selected for measurments consisted of a contiguous arrangement of two parallel reflective noise barriers followed by a single noise barrier. Five-minute, energy-averaged, A-weighted noise levels were computed from data measured simultaneously at identical heights and offset positions behind the single and parallel barrier arrangements. Measured results show barrier insertion loss degradations of .6 to 2.8 dBA, dependent on microphone height and offset distance behind the barrier. In addition, three parallel-barrier prediction programs were used to model the study site (BARRIER, BARRIER-X, and IMAGE-3). A comparison of the measured and predicted results is presented.

Noise, Highway Noise, Parallel Noise Barrier Degradation, Multiple Reflections, Reflective Barrier, Absorptive Barrier

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PREFACE

This document presents the results of a highway noise measurement study conducted by the U.S. Department of Transportation, Research

and Special Programs Administration, Volpe National Transportation Systems Center (U.S.DOT/RSPA/VNTSC) in support of the Federal Highway Administration (FHWA), Office of Engineering and Highway Operations Research and Development, and the National Pooled-Fund Study (NPFS), HP&R 0002-136, "Evaluation of Performance of Experimental Highway Noise Barriers." Field measurements were conducted at a highway noise barrier site located in Montgomery County, Maryland, on the westbound side of Interstate Route 495. Field data were obtained, processed, and analyzed by the Volpe Center's Noise Measurement and Assessment Facility (NMAF).

Major contributions of NMAF staff members are as follows: Amanda S. Keller provided measurement support in the field, as well as data reduction and processing support. Cynthia S.Y. Lee assisted in reducing and preparing the data for presentation. Field support was also provided by: Howard A. Jongedyk and Dennis G. Sixbey, FHWA-McLean, VA; Robert E. Armstrong and Steven A. Ronning, FHWA-Washington; and Kenneth D. Polcak, Maryland State Highway Administration (MSHA).

The seventeen state transportation agencies participating in the NPFS were very helpful in identifying potential measurement sites for this study. In particular, special thanks for taking time out of their busy schedules to guide NMAF personnel on a tour of potential sites within their respective states go to: William McColl, New York State DOT, James Byers and Robert Keller, Pennsylvania DOT, Steven Frasier and Bruce Purdue, Virginia DOT, and Kenneth D. Polcak, MSHA. Special thanks also goes to the Virginia Highway and Transportation Research Council who were responsible for the printing of this document.

Section 4.4 of this document describes how three highway noise modeling programs were used to predict barrier insertion loss degradation for the site tested in this study. The authors express their sincere appreciation to the developers of these programs, Dr. Simon Slutsky, formerly of Brooklyn Polytechnic Institute, and Dr.

William Bowlby, of Bowlby & Associates, Inc., and of Vanderbilt University, for their assistance in the predictive analysis. Dr. Slutsky provided extensive guidance and commentary during the NMAF's running of his programs, while Bowlby & Associates, Inc., under contract to the Volpe Center, performed an independent predictive evaluation of barrier insertion loss degradation.

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1.0 INTRODUCTION

This document presents the results of a highway noise measurement study conducted in Montgomery County, Maryland, during the period October 7 through 11, 1991, by the U.S. Department of Transportation, Research and Special Programs Administration, Volpe National Transportation Systems Center (U.S.DOT/RSPA/VNTSC) in support of the Federal Highway Administration (FHWA), Office of Engineering and Highway Operations Research and Development, and the National Pooled-Fund Study (NPFS), HP&R 0002-136, "Evaluation of Performance of Experimental Highway Noise Barriers." The NPFS consists of a panel of representatives from seventeen states: Arizona, California, Connecticut, Florida, Georgia, Hawaii, Iowa, Maryland, Massachusetts, Michigan, New Jersey, New York, Ohio, Pennsylvania, Virginia, Washington, and Wisconsin. This measurement study examined the degrading effects of multiple reflections on the performance of parallel highway noise barriers.

1.1 BACKGROUND

The most common method of reducing highway noise impact on a community is the construction of traffic noise barriers. In cases where noise impacted communities exist on both sides of a roadway, parallel barriers are often the only method of reducing the impact on both communities. The degrading effects on the performance, i.e., barrier insertion loss, of a noise barrier due to the presence of a parallel reflective noise barrier on the opposite side of a roadway have been studied extensively since the early 1970's. Although experts agree the degrading effects are caused by multiple reflections between the two barriers, there are conflicting opinions on the magnitude of the problem. In fact, several state transportation agencies have precluded the construction of parallel noise barriers until their degrading effects can be quantified. A plethora of literature currently exists on parallel barriers and their degrading effects;[1-29] however, with the exception of a highly restrictive FHWA nomograph,[24] there is no nationally accepted method of predicting parallel-barrier insertion loss degradation or nationally accepted guideline to help decide when a problem may exist.

In the early part of 1987, the FHWA, with funding support from ten state transportation agencies, initiated a study to examine, among other things, the degrading effects of parallel highway noise barriers. As part of the FHWA/NPFS, the Volpe Center's Noise Measurement and Assessment Facility (NMAF) conducted measurements on an experimental highway noise barrier at Dulles International Airport in Chantilly, Virginia, during the period May to August, 1989. Among the results of the Dulles study,[8] parallel-barrier insertion loss degradations of 2 to 6 dBA were measured. These degradations were dependent upon both source characteristics, e.g. frequency spectra, and receiver position. Based on the results of the Dulles study, many of the Pooled-Fund participants indicated interest in expanding the study program to representative parallel noise barrier installations, i.e., installations located on typical United States roadways and exposed to free-flowing traffic conditions. Subsequently, in December, 1990, the NMAF distributed a Test Plan[30] to the FHWA and the sponsoring state transportation agencies, which outlined work to be performed in 1991. Accompanying the Test Plan was a request for candidate measurement sites within each state. In April and May, 1991, candidate sites within the states of Pennsylvania, New York, Virginia, and Maryland were inspected. Of the more than thirty sites visited, only one came close to satisfying all NMAF measurement criteria.

1.2 MEASUREMENT SITE

The site selected for measurements was located in Montgomery County, Maryland, on the westbound side of Interstate Route 495 (Washington Beltway), approximately ½ mile west of U.S. Route 29. For measurement purposes, the site was divided into two sub-sites separated by approximately 900 ft, a parallel-barrier test site, Site 1, and a single barrier test site, Site 2 (see Figure 1). Site 1 contained two 19 ft high (average height, relative to roadway elevation), concrete, post and panel type noise barriers, constructed in parallel to one another on opposite sides of the eight-lane roadway (see Figure 2). Site 2 was essentially equivalent to Site 1, but without a reflective barrier on the opposite side of the roadway (see Figure 3). The terrain behind the barriers in both sites was essentially flat, covered with low-cut grass, and contained no reflective structures. Five-minute energy-averaged, A-weighted noise levels (L_{eq} (5 min)) were computed from data measured simultaneously at identical heights and offset positions in Sites 1 and 2. The arithmetic difference between the L_{eq} (5 min) values computed for identical microphone positions in each site provided a measure of the barrier insertion loss degradation ($()_{IL}$).

There were two differences between Sites 1 and 2 which are worthy of note:

1. The barrier in Site 2 was 1 ft lower, relative to roadway elevation, than the barrier in Site 1. The effects of this height difference are discussed in Section 4.4.4.

2. Site 1 was located in a local playground bordered on the North by Forest Glen Road, a low volume roadway which passes approximately 150 vehicles per hour during peak travel periods. The traffic on this roadway was carefully monitored for later correlation with the measured acoustic data (see Section 4.1).

The two 19 ft high reflective barriers in Site 1 were separated by a distance of approximately 164 ft. This translates into a separation-distance to barrier-height ratio (W/H) of slightly less than 9:1. A 1978 study[17] concluded that when the ratio of separation-distance to barrier-height exceeds 20:1, multiple reflections are unimportant. However, the author's criteria for characterizing the multiple reflections as unimportant are unclear. A more recent study[14] conducted by the California Department of Transportation (Caltrans) recommends: "to avoid a risk of perceptible reduction in performance of each of two parallel reflective noise barriers, the width-to-average-height (W/H) ratio should be at least 10:1." The author of the Caltrans study defines a perceptible reduction in performance as

3 dBA or greater. On the basis of the Caltrans study, it was anticipated that an insertion loss degradation as large as 3 dBA would be measured at the chosen test site. A 3 dBA degradation may be perceptible by the human ear, according to a 1974 American Association of State Highway and Transportation Officials (ASHTO) publication,[31] which states that the smallest change in noise level perceptible by the human ear is approximately 3 dBA.

1.3 OBJECTIVES

The objective of this study was to measure the reduction in acoustic performance of a highway noise barrier due to the close proximity of a parallel barrier on the opposite side of the roadway. The measured results will be used to:

- Establish a guideline for identifying parallel noise barrier sites that are potentially subject to performance degradations of 3 dBA or more.

- Evaluate existing highway-noise-prediction computer programs which are capable of accounting for the degrading effects of multiple reflections between parallel highway noise barriers.

figure 1

figure 2

figure 3

2.0 EXPERIMENTAL APPROACH

2.1 MICROPHONE CONFIGURATION

Eight microphones were deployed on four masts, four microphones in the parallel-barrier site, Site 1, and four in the single barrier site, Site 2. Two stationary reference masts were fitted with one microphone each, placed at a height corresponding to 5 ft above the barrier edge in each site, while two portable masts were fitted with three microphones each, placed at heights of -8 ft (low), +2.5 ft (middle), and +13 ft (high), relative to the height of the barrier. When referring to microphone heights, the high, middle, and low convention will be used for the remainder of this document. The two portable masts were simultaneously placed at one of three offset positions in each test site (16, 65.5, or 131 ft), and moved as a pair at designated times during the measurement day, per Table 1. Note: since ground elevation varied independently in the two measurement sites, microphone height was held constant relative to the height of the top edge of the barrier, rather than relative to the ground plane.

2.2 NOISE MEASUREMENT INSTRUMENTATION

Each noise measurement system consisted of a General Radio Model 1962-9610 random incidence electret microphone, connected to a Larson Davis Model 827-0V preamplifier. The microphone/preamplifier system was mounted in an insulated nylon holder and connected via cable to a Larson Davis Model 820 Type 1 Precision Integrating Sound Level Meter/Environmental Noise Analyzer (LD 820). The microphone/preamplifier combination 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.[32] Bruel and Kjaer Model UA0237 windscreens were placed atop each microphone to reduce the effects of wind-generated noise on the microphone diaphragm.

Pre-processing and storage of the measured noise level data were accomplished by the LD 820. Each unit was programmed to continuously measure, energy average and store A-weighted noise levels with fast sound-level-meter response characteristics at a rate of two data records each second (½-second averages). Programmed thus, each unit was capable of continuous operation for a period of just over 12 hours.

2.3 METEOROLOGICAL MEASUREMENT INSTRUMENTATION

A Climatronics Model EWS weather station was deployed in Site 2 at the midway point between the 65.5 and 131 ft offset positions to measure and continuously record temperature, humidity, wind speed and wind direction (see Figure 1). Wind speed and direction were measured at a height of 27 ft above the ground (height equivalent to the height of the highest noise measurement position); temperature and humidity were measured at a height of 5 ft above the ground. The operator assigned to the weather station was responsible for time marking the strip chart periodically and making note of cloud cover as well as significant changes in weather conditions.

2.4 TRAFFIC MEASUREMENT INSTRUMENTATION

Traffic speed was obtained with a CMI doppler radar set up 20 ft off the edge of the rightmost westbound travel lane, approximately 300 ft west of the microphone centerline in the parallel-barrier measurement site (see Figure 1). The doppler radar was directed at the departing westbound traffic, thus minimizing the possibility of individual vehicles slowing down after detecting the radar signal. Readings were observed visually from the radar's digital display and recorded continuously during each test run at a rate of approximately one reading every 10 seconds.

A Panasonic Model AG170 video camera was set up on the U.S. Route 29 overpass to record pass-by traffic on the eight-lane interstate during each test run. In addition to visual traffic monitoring, each test run was annotated with pertinent event information. The video camera was time-synchronized with the LD 820's, so that the noise data could be correlated with the traffic data.

2.5 MEASUREMENT PROCEDURES

Noise measurement system preparation, including calibration, universal time synchronization, and a measurement of each system's electronic noise floor was performed at the start of each measurement day. For consistency, a single acoustic calibrator with an output sound pressure level of 114 dB *re* 20 :Pa was used on all eight systems. Following system preparation, the four masts were raised into place at the reference position and at the designated measurement offset in each site, per Table 1. With the four masts stabilized and in position, the eight LD 820's were programmed to begin continuous data collection at a rate of two samples per second.

A communication link was set up between personnel at Sites 1 and 2, the radar station and the video camera station by means of four Motorola Model HT-220 walkie-talkies. During each test run, personnel assigned to Sites 1 and 2 were responsible for announcing the beginning and end of each test run, documenting vehicle pass-bys on Forest Glen Road, and making note of additional sources of potential contamination, e.g., aircraft flyovers, emergency vehicle sirens, etc. Upon receiving notification of the start of each run, personnel at the radar station began recording vehicle speeds for a period of five minutes. Notification of the start was given 30 seconds early to allow personnel at the video camera station to record pass-by traffic on the eight-lane interstate for a period of six minutes, i.e., 30 seconds before and after each test run.

After collecting data for ten consecutive five-minute test runs (five-minute spacing between each run), the four measurement masts were lowered to the ground and approximately 30 seconds of calibration data were measured and stored. The two portable three-microphone masts were then moved to the next offset position, and the four masts (two reference and two portable) were raised into position for ten additional five-minute test runs. Again, the masts were lowered and 30 seconds of calibration data were measured and stored. The two portable masts were then moved to the third measurement offset, and the four masts were raised into position for an additional ten runs. After a total of thirty five-minute test runs (10 each with the portable masts at the three offset positions in each site), the four masts were lowered to the ground and final calibration data were measured and stored. Table 1 depicts the schedule for the three measurement days.

At the culmination of each measurement day, the ½-second noise data stored in each LD 820 were downloaded to an AST Premium Exec Model 386SX/20 notebook computer and stored on floppy disk for later off-line processing.

A listing of the instrumentation used in this study, including calibration information, is provided in Appendix E.

TABLE 1: MEASUREMENT STUDY TEST SCHEDULE
MARYLAND I495 BARRIER TEST SITE - 1991

	October 8, 1991		October 9, 1991		October 10, 1991	
Test Run #	Start Time	Mast Offset (ft)	Start Time	Mast Offset (ft)	Start Time	Mast Offset (ft)
1	10:40	16	9:45	131	9:45	131
2	10:50	16	9:55	131	9:55	131
3	11:05	16	10:05	131	10:05	131
4	11:15	16	10:15	131	10:15	131
5	11:25	16	10:25	131	10:25	131
6	11:35	16	-	-	10:35	131
7	11:45	16	10:45	131	10:45	131
8	11:55	16	10:55	131	10:55	131
9	12:05	16	11:05	131	-	-
10	12:15	16	11:15	131	-	-
***** SYSTEM CALIBRATION - THREE MICROPHONE MAST MOVED *****						
11	13:05	131	11:45	65.5	11:45	16
12	-	-	11:55	65.5	11:55	16
13	13:25	131	12:05	65.5	12:05	16
14	13:35	131	12:15	65.5	12:15	16
15	13:45	131	12:25	65.5	12:25	16
16	13:55	131	12:35	65.5	12:35	16
17	14:05	131	12:45	65.5	12:45	16
18	14:15	131	12:55	65.5	12:55	16
19	14:25	131	13:05	65.5	-	-
20	14:35	131	13:15	65.5	13:15	16
***** SYSTEM CALIBRATION - THREE MICROPHONE MAST MOVED *****						
21	15:15	65.5	-	-	13:45	65.5
22	15:25	65.5	14:05	16	13:55	65.5
23	15:35	65.5	14:15	16	14:05	65.5
24	15:45	65.5	14:25	16	14:15	65.5
25	15:55	65.5	-	-	14:25	65.5
26	16:05	65.5	-	-	14:35	65.5
27	16:15	65.5	-	-	14:45	65.5
28	16:25	65.5	15:05	16	14:55	65.5
29	16:35	65.5	15:15	16	15:05	65.5
30	-	-	15:25	16	15:15	65.5
31	-	-	15:35	16	-	-

(-) Denotes test run was removed from the population of events to be analyzed (see Section 3.1 for an explanation).

3.0 DATA REDUCTION

3.1 NOISE DATA

Processing of the daily noise data files stored on floppy disk was accomplished off-line, using the LD 820 support software in tandem with the NMAF-developed computer program, RFILE. The LD 820 software was used to obtain a graphical history plot (noise level versus time) for the test runs identified in the field as potentially contaminated. These plots were examined and all questionable test runs were removed from the population of events to be processed.

The RFILE program, using the ½-second data stored in each file, was used to compute the equivalent A-weighted sound levels for each five-minute test run (L_{eq} (5 min)). The L_{eq} (5 min) values were adjusted using the measured calibration data per ANSI S12.8-1987,[33] and the results are displayed in Tables A1-A3, Appendix A. Note: no reference microphone adjustment was applied to the measured noise level data (see Section 6.3).

To account for the time-lag in west-bound traffic associated with the 900 ft separation distance between the two test sites, the L_{eq} (5 min) values for all microphones in Site 1 were computed using ½-second data beginning 10 seconds earlier than the event start times shown in Table 1. Select events re-run without the 10 second time lag produced differences of .1 dBA or less, indicating the time-lag was **not** a factor for such a small separation distance.

To obtain a measure of the insertion loss degradation due to the opposite reflective noise barrier ($)_{IL}$), the L_{eq} (5 min) values computed for identical measurement positions in each site were arithmetically subtracted (see Appendix A, Tables A4-A6). The resultant $)_{IL}$ values measured for the same receiver heights and offsets were then averaged together and are displayed in Figure 4, along with their respective standard deviations (F). Note: the $)_{IL}$ values displayed for the low and middle microphone, 131 ft offset, are based on L_{eq} values measured over a period shorter than five minutes (see Section 4.1 for an explanation).

3.2 METEOROLOGICAL DATA

The Climatronics Model EWS Weather Station was used to measure and record wind speed and direction, temperature, and humidity on a continuous strip-chart recorder with a paper speed of four inches per hour. Using the time marks recorded on the strip chart in the field as reference, a time scale was transposed on each chart and the five-minute measurement period for each test run was identified.

The average wind speed (miles per hour) and average wind direction *re* magnetic north (degrees) were computed for each five-minute test run. The five-minute averaged wind speed (WS) and direction (WD) were then used to compute the vector component of wind speed in the x-y plane from the source to the receiver (VWS) for each test run according to the following:

$$VWS = COS\ (WD) \cdot WS$$

where a negative VWS indicates the wind is blowing from receiver to source

Temperature, humidity, average wind speed and direction, and VWS are presented in Tables B1-B3, Appendix B. Note: cloud cover class 2, as defined in ANSI S12.8-1987, was observed for the duration of the three measurement days.

3.2.1 VECTOR WIND SPEED (VWS)

The barrier insertion loss degradation data ()$_{IL}$) measured for each microphone position were sorted according to VWS and grouped in 2-mph VWS categories (-6.9 to -5, -4.9 to -3, -2.9 to -1, -0.9 to +0.9, +1 to +2.9, +3 to +4.9, and +5 to +6.9). The grouped)$_{IL}$ values measured at each microphone position were averaged together and are presented as a function of VWS in Figures B1-B3, Appendix B. The choice of 2-mph VWS categories is based on a proposed revision to ANSI S12.8-1987, which states: "If it is desired to keep the acoustical error within ± 0.5 dB (for distances less than 70 m), reduce the limit to 1.0 m/s."

3.3 TRAFFIC DATA

The traffic data recorded on video cassette were used to obtain vehicle counts for each five-minute test run. Vehicles were counted and classified in three categories, automobiles (A), medium trucks (MT), and heavy trucks (HT), per FHWA specifications.[34] Vehicles were further grouped by direction (eastbound and westbound). The vehicle speed data were averaged over each test run and are presented in Tables C1-C3, Appendix C, along with the categorized vehicle counts.

3.3.1 TOTAL NUMBER OF VEHICLES

The barrier insertion loss degradation data ()$_{IL}$) measured for each microphone position were sorted according to the total number of vehicles to pass through the measurement site during a five-minute test run and grouped in 100-vehicle categories (600-699, 700-799, 800-899, etc.). The grouped)$_{IL}$ values measured at each microphone position were averaged together and are presented as a function of the total number of vehicles in Figures C1-C3, Appendix C.

3.3.2 PERCENTAGE OF TRUCKS

The barrier insertion loss degradation data ()$_{IL}$) measured for each microphone position were sorted according to the percentage of trucks to pass through the measurement site during a five-minute test run and grouped in 1% categories (4-4.9%, 5-5.9%, 6-6.9%, etc.). The grouped)$_{IL}$ values measured at each microphone position were averaged together and are presented as a function of the percentage of trucks in Figures C4-C6, Appendix C.

4.0 DISCUSSION OF RESULTS

4.1 BARRIER INSERTION LOSS DEGRADATION ()$_{IL}$)

The mean)$_{IL}$ values measured at each of the ten receiver locations are presented in Figure 4 along with respective standard deviations (F). In general, the)$_{IL}$ values increase with microphone height and offset distance behind the barrier. The)$_{IL}$ values range from a low of .6 dBA (high microphone, 16 ft offset) to a high of 2.8 dBA (high microphone, 131 ft offset). It is important to note that, at the reference position, the)$_{IL}$ value is extremely consistent (run to run), as evidenced by the small standard deviation (F=.17 dBA). Normally, a reference microphone is used to account for differences in the source-noise-emission levels from one test site to another, and any measured difference, assuming the criteria for terrain, ground and atmospheric equivalence are met, is due solely to changes in source characteristics. However, the consistency in the measured)$_{IL}$ values at the reference position indicates that the 1.2 dBA difference can **not** be attributed to variations in source-noise-emission levels between Sites 1 and 2, but rather to multiple reflections between the two parallel barriers.

As mentioned previously, the traffic on Forest Glen Road was carefully monitored for later correlation with the measured acoustic data. An examination of the measured ½-second noise data revealed that the L_{eq} (5 min) values computed for the low and middle microphone positions (131 ft offset, Site 1) were contaminated by individual vehicle pass-bys on Forest Glen Road. To eliminate the effects of the contamination, the L_{eq} values at these two microphones were recomputed, excluding noise data easily identified as emanating from vehicle pass-bys on Forest Glen Road. The adjusted)$_{IL}$ values are presented in Figure 4. After adjustment, it is noted that the)$_{IL}$ values measured at the 131 ft offset follow a trend similar to that noted in the Dulles study at the 88 ft offset, i.e., the)$_{IL}$ value is largest for the high microphone and decreases slightly with microphone height.

4.2 $)_{IL}$ VERSUS VECTOR WIND SPEED (VWS)

The data displayed in Figures B1-B3, Appendix B, present the $)_{IL}$ values as a function of VWS. To simplify the presentation, test runs were combined according to 2-mph VWS categories, e.g., the $)_{IL}$ values for all runs with a VWS of -4.9 to -3 mph were arithmetical- ly averaged to obtain the mean $)_{IL}$ value for a VWS of -4 mph.

As can be seen, the $)_{IL}$ value is independent of VWS at all microphone heights and mast offsets. In fact, at the reference and the 16 ft offset positions, the $)_{IL}$/VWS relationship is essentially a straight line with zero slope.

4.3 $)_{IL}$ AS A FUNCTION OF TRAFFIC DATA

The traffic count data presented in Tables C1-C3, Appendix C, are displayed in various graphical formats to establish dependence with the $)_{IL}$ value.

4.3.1 $)_{IL}$ VERSUS TOTAL NUMBER OF VEHICLES

Figures C1-C3, Appendix C, present the $)_{IL}$ value as a function of the total number of vehicles to pass through the measurement site during a five-minute test run (autos, medium trucks, and heavy trucks combined). To simplify the presentation, test runs were combined according to 100-vehicle categories, e.g., the $)_{IL}$ values for all runs with a total number of vehicles between 700 and 799 were arithmetically averaged to obtain the mean $)_{IL}$ value for 750 total vehicles.

As can be seen, the mean $)_{IL}$ value is independent of the total number of vehicles. It is important to note that the wide range of traffic volumes observed, 650 to 1400 vehicles per five-minute test period (7800 to 16800 vehicles per hour), corresponds to a Level-of-Service (LOS) *B* through *E*, as defined in the "Highway Capacity Manual, Special Report 209."[35]

4.3.2 $)_{IL}$ VERSUS PERCENTAGE OF TRUCKS

Figures C4-C6, Appendix C, present the $)_{IL}$ value as a function of the percentage of trucks to pass through the measurement site during a five-minute test run (medium and heavy trucks combined). To simplify the presentation, test runs were combined according to the percentage of trucks, e.g., the $)_{IL}$ values for all runs with a truck percentage of between 4 and 4.9 were arithmetically averaged to obtain the mean $)_{IL}$ value for a percentage of trucks of 4.5.

As can be seen, the mean $)_{IL}$ value is independent of the percentage of trucks to pass through the measurement site during a five-minute test run. This may be due to the small range of percentages represented (4-14). However, it is important to note that a January, 1978, NMAF measurement study[36] which selected highway sites on the basis of being representative of traffic flow throughout the United States, observed truck percentages which were generally in the 4-14% range.

4.4 COMPUTER MODELING: COMPARISON OF MEASURED AND PREDICTED INSERTION LOSS DEGRADATION

The highway noise prediction programs, BARRIER - Version 2.1, BARRIER-X - Version 2.1,[25,26] and IMAGE-3 - Version 3.11,[3] all of which have the unique capability of accounting for the effects of multiple reflections between parallel highway noise barriers, were used to predict the insertion loss degradations ($)_{IL}$) at the microphone heights and mast offsets tested in this study. In running these programs, the following assumptions were made:

! Roadside barrier facades were modeled with Sabine absorption coefficients ("$_{Sab}$) of 0.05 (5% of sound incident on the barrier facade is absorbed, i.e., 95% reflective barrier). The "$_{Sab}$ values would normally vary slightly with frequency, however exact values were not available. The 0.05 value chosen is considered typical for a reflective concrete barrier.[24] Note: the normalized barrier impedance value in the Barrier-X input file (Z = 79.5+04) is essentially equivalent to an "$_{Sab}$ of 0.05.[37]

! In order to account for the slope of the terrain leading to the base of the barrier (see Figures 2 and 3), the lower portion of the near wall (wall behind which measurements were made) was assigned an "$_{Sab}$ of 1.0 (100% of sound incident on the barrier facade is absorbed, i.e., 0% reflective barrier).

! The FHWA-approved equivalent source heights[34] were assumed (autos: 0 ft, medium trucks: 2.3 ft, heavy trucks: 8 ft).

! The FHWA-approved octave band A-weighted frequency levels for autos, medium and heavy trucks at operating speeds of 57 mph[38] were assumed (BARRIER and BARRIER-X).

! The FHWA-approved overall A-weighted sound levels for autos, medium and heavy trucks at operating speeds of 57 mph[34] were assumed (IMAGE-3).

An example input file for each prediction program is presented in Appendix D. Microphone offset distances and traffic counts were adjusted, as appropriate.

4.4.1 REFERENCE MICROPHONE POSITION

A comparison of the measured and predicted)$_{IL}$ values at the reference microphone position is presented in Table 2a.

TABLE 2a: COMPARISON OF MEASURED AND PREDICTED)$_{IL}$
REFERENCE MICROPHONE POSITION

DATA SET**	MICROPHONE POSITION	MEASURED)$_{IL}$ (dBA)	PREDICTED)$_{IL}$, MEASURED-PREDICTED)$_{IL}$ (dBA): BARRIER PRED	BARRIER M-P*	BARRIER-X PRED	BARRIER-X M-P*	IMAGE-3 PRED	IMAGE-3 M-P*
1	Ref	1.1	0.25	+0.9	0.25	+0.9	0.9	+0.2
2	Ref	1.2	0.25	+1.0	0.25	+1.0	1.0	+0.2
3	Ref	1.2	0.25	+1.0	0.25	+1.0	0.9	+0.3

* Measured - Predicted)$_{IL}$ (dBA)
** Data sets 1, 2, and 3 correspond to measurements made with the portable three-microphone masts at the 16, 65.5 and 131 ft offsets, respectively. The position of the reference microphone remained constant throughout the study.

As can be seen, the IMAGE-3 program underpredicted)$_{IL}$ by between .2 and .3 dBA, while the BARRIER and BARRIER-X programs underpredicted $)_{IL}$ by between .9 and 1.0 dBA. Note: the term underprediction indicates the measured insertion loss degradation ($)_{IL}$) was greater than that predicted by the models.

<u>4.4.2 HIGH, MIDDLE, AND LOW MICROPHONE POSITIONS</u>

A comparison of the measured and predicted $)_{IL}$ values at the high, middle and low microphone positions is presented in Table 2b. In general, fairly good agreement was obtained between the measured and predicted $)_{IL}$ values at the 16 ft mast offset (measured minus predicted # .6 dBA).

TABLE 2b: COMPARISON OF MEASURED AND PREDICTED $)_{IL}$ HIGH, MIDDLE, AND LOW MICROPHONE POSITION

OFFSET (FT)	MICROPHONE POSITION	MEASURED $)_{IL}$ (dBA)	PREDICTED $)_{IL}$, MEASURED-PREDICTED $)_{IL}$ (dBA): BARRIER PRED	BARRIER M-P*	BARRIER-X PRED	BARRIER-X M-P*	IMAGE-3 PRED	IMAGE-3 M-P*
16	High	0.6	0.10	+0.5	0.09	+0.5	0.9	-0.3
	Mid	2.4	2.02	+0.4	1.87	+0.5	1.8	+0.6
	Low	1.5	1.53	0.0	0.99	+0.5	1.6	-0.1
65.5	High	2.2	0.35	+1.9	0.91	+1.3	2.7	-0.5
	Mid	2.1	4.52	-2.4	4.70	-2.6	3.0	-0.9
	Low	1.9	3.81	-1.9	4.12	-2.2	2.8	-0.9
131	High	2.8	4.46	-1.7	5.07	-2.3	2.9	-0.1
	Mid	2.5 **	4.74	-2.2	5.13	-2.6	4.5	-2.0
	Low	2.4 **	3.78	-1.4	3.64	-1.2	3.8	-1.4

* Measured - Predicted $)_{IL}$ (dBA)
** Adjusted (see Section 4.1)

In addition, the overall trends in the 16 ft data, measured versus predicted, were similar, i.e., the largest and smallest $)_{IL}$ values were obtained at the middle and high microphones, respectively. It is interesting to note that the $)_{IL}$ values predicted by both BARRIER and BARRIER-X, high microphone, were considerably smaller than those measured. A similar result was observed at the reference position (as discussed previously). Note: the reference microphone and the high microphone (16 ft offset) are in the illuminated zone behind the near barrier, unlike the other eight microphones, which are in the shadow zone behind the barrier.

At the 65.5 and 131 ft offsets the correlation between measured and predicted $)_{IL}$ deteriorates. The predicted $)_{IL}$ values obtained using IMAGE-3, BARRIER, and BARRIER-X were between .1 and 2.0 dBA high, 1.9 dBA low and 2.4 dBA high, and 1.3 dBA low and 2.6 dBA high, respectively, when compared with the measured $)_{IL}$ values. With two exceptions (high microphone, 65.5 ft offset, BARRIER and BARRIER-X), the $)_{IL}$ values at the 65.5 and 131 ft offsets were overpredicted by the models.

4.4.3 AN ANALYSIS OF THE OVERPREDICTION AT THE 65.5 AND 131 FT MAST OFFSETS

An analysis was performed to help explain the consistent overprediction at the 65.5 and 131 ft mast offsets. As part of this effort, the following differences were identified between the actual test site and the site the prediction programs were capable of modeling:

! The models are not capable of accounting for the slight curve in the roadway.

! BARRIER and BARRIER-X are not capable of accounting for the difference in road elevation from the eastbound to the westbound travel lanes (approximately 1.5 ft).

! IMAGE-3 in not capable of accounting for the effects of noise "flanking" around the ends of the barrier.

The first two factors identified above were considered insignificant. Regarding factor three, whereas the noise level contributions due to flanking may intuitively help to explain the overprediction at the 65.5 and 131 ft offset distances, these contributions were considered insignificant at this test site for the following reasons (see Figure 1): 1.) The near barrier (barrier behind which measurements were made) extended approximately 2000 ft to the east and 1200 ft to the west of the measurement microphones in Site 1 (parallel-barrier site); 2.) The near barrier extended almost 3000 ft to the east and 250 ft to the west of the measurement microphones in Site 2 (single barrier site). Normally, a noise level contribution would be expected at the 65.5 and 131 ft offsets (due to flanking) with only a 250 ft barrier extension. However, the combination of the roadway curving away from the barrier, and the roadway sloping downward (2 ft of elevation per 100 ft of roadway) results in a 10-12 ft earth berm (effective height relative to roadway elevation) extending past the end of the 250 ft stretch of barrier.

One possible explanation for the consistent overprediction at the 65.5 and 131 ft offset distances is the method by which IMAGE-3, BARRIER, and BARRIER-X represent multiple reflections. As discussed in Ref. 3, the IMAGE-3 program models multiple reflections using the theory of geometrical acoustics (ray acoustics or image theory). Image theory is used to trace the acoustic paths (assuming plane wave propagation) between the receiver and both the actual and effective (image) acoustic sources (see Refs. 3 and 25 for a detailed description of the theory). The BARRIER and BARRIER-X programs extend the ray theory approach to include the effects of sound scatter at: 1.) the barrier top edge; 2.) the pavement-wayside edge; and 3.) the impedance discontinuities at three discrete barrier heights (BARRIER-X only). Nevertheless, each prediction program neglects several potentially important factors, e.g., sound energy scatter when the acoustic ray strikes the barrier facade, vehicle shielding of the multiple reflected sound paths between the barriers, and the shielding effects due to the 3 ft Jersey barrier in the center of the roadway. Neglecting these factors may result in an overprediction of the insertion loss degradation $( )_{IL}$) at the receiver positions most sensitive to multiple reflections (65.5 and 131 ft receivers).

4.4.4 BARRIER HEIGHT DIFFERENCE (SITE 1 VERSUS SITE 2)

As mentioned previously, the near barrier in Site 2 was 1 ft lower (relative to roadway elevation) than the near barrier in Site 1. The 1 ft difference was expected to have minimal effects on the value of)$_{IL}$, based on pre-measurement estimates using STAMINA 2.0 (the current FHWA highway noise prediction program). BARRIER, BARRIER-X and IMAGE-3 confirmed this expectation. By using all three modeling programs, the insertion loss degradation, associated with the 1 ft difference in barrier height, was estimated to be between 0 and .2 dBA low at the 16 ft offset, and 0 and .4 dBA low at the 65.5 and 131 ft offsets.

figure 4

5.0 CONCLUSIONS

Conclusions based on the findings of this study can be summarized as follows:

! The mean barrier insertion loss degradation ( )$_{IL}$) due to multiple reflections between the two vertical reflective noise barriers ranged from .6 to 2.8 dBA, depending on microphone height and offset distance behind the barrier.

! The mean)$_{IL}$ value at each of the ten microphone locations would not be perceived by the human ear, using the 3 dBA perception criterion discussed in Section 1.2.

! The)$_{IL}$ values showed no dependency on vector wind speed (VWS).

! The)$_{IL}$ values showed no dependency on traffic volume for the range of volumes represented in this study (7800 to 16800 vehicles per hour).

! The)$_{IL}$ values showed no dependency on the percentage of trucks on the roadway for the range of percentages represented in this study (4 to 14).

! The consistency (run to run) of the)$_{IL}$ values derived from measurements at the reference microphone position indicates that they can be attributed solely to reflections from the opposite barrier, and not to random variations in source-noise-emission levels between Sites 1 and 2. As a result, the reference microphone adjustment procedure in ANSI S12.8-1987 is not appropriate for parallel-barrier measurements and, as discussed in Section 3.1, was not applied in this study. A similar conclusion was reached in the Dulles study.

! The three prediction programs used to model the test site (BARRIER, BARRIER-X and IMAGE-3) underpredicted the value of $)_{IL}$ at the reference position.

! The predicted $)_{IL}$ values are in fairly good agreement with the measured results at the 16 ft offset position for all three prediction programs (high, middle and low microphone positions).

! With two exceptions, the three prediction programs over-predicted the value of $)_{IL}$ at the 65.5 and 131 ft offset positions (high, middle and low microphones).

6.0 RECOMMENDATIONS

6.1 SEPARATION-DISTANCE TO BARRIER-HEIGHT RATIO (W/H)

The separation-distance to barrier-height ratio (W/H) is defined as the ratio of total distance between parallel noise barriers, including roadway, median, shoulder and terrain width, to the average height of the two barriers, relative to roadway elevation. This ratio appears to be the best available method of characterizing barrier insertion loss degradation ($)_{IL}$). Table 3 shows the W/H ratio and corresponding maximum $)_{IL}$ values derived from measurments at similar receiver locations in this study, the Dulles study, and the Caltrans study referred to in Section 1.2 of this document.

TABLE 3: COMPARISON OF W/H RATIOS AND MAXIMUM $)_{IL}$

	W/H	Max. $)_{IL}$ (dBA)	Mic. Height/Offset (ft)*
Dulles Study	6:1	6.2	+16/88
This Study	9:1	2.8	+13/131
Caltrans Study	15:1	1.4	+10/75,+10/200

* Microphone height in feet, relative to the top of the barrier, and microphone offset in feet behind the barrier.

Based on the results presented in Table 3, a minimum W/H ratio of 10:1 is recommended to avoid a perceptible degradation in barrier insertion loss. This recommendation is based on the 3 dBA perception criterion discussed in Section 1.2 and leaves sufficient leeway to account for most site specific variations. A minimum W/H ratio of 10:1 was among the recommendations in the aforementioned Caltrans study.

One caveat to the 10:1 guideline is that the two parallel barriers should be similar in height. For example, if two parallel barriers, one 20 ft high and the other 10 ft high (average height relative to roadway elevation equivalent to 15 ft) are separated by a distance of 150 ft (W/H ratio equivalent to 10:1), barrier insertion loss degradations on the side of the roadway opposite the 20 ft high barrier may be considerably larger than 3 dBA; degradations on the side of the roadway opposite the 10 ft high barrier would likely be very close to zero.

If a $)_{IL}$ value greater than 3 dBA can be tolerated, a minimum W/H ratio should be chosen appropriately. However, caution is advised when W/H ratios are less than 8:1, because the (W/H)/$)_{IL}$ relationship does not appear to be linear, i.e., $)_{IL}$ increases rapidly with decreasing W/H, as evidenced by the results of the Dulles study. Conversely, for a W/H ratio of 20:1 or greater, it is unlikely that an insertion loss degradation would be measurable at all.

6.2 HOW TO MINIMIZE THE INSERTION LOSS DEGRADATION ($)_{IL}$)

Among the thirty parallel highway noise barrier sites visited by NMAF personnel in April and May, 1991, there were a few which, upon initial inspection, did not appear to meet the 10:1 W/H requirement. If a designer is faced with a situation where the 10:1 requirement cannot be met and a $)_{IL}$ value greater than 3 dBA cannot be tolerated, several methods of minimizing the performance degradation are suggested:

1. ***Constructing earth berms instead of installing commercially available highway noise barriers (see Ref. 19)-*** Because of the sloped shape of berms, they tend to redirect the sound skyward, àla tilting (see Method 3). **Note:** The construction of earth berms should be the first method considered by a designer since berms tend to be considerably less expensive than the more conventional noise wall; however right-of-way requirements can severely restrict their applicability.

2. ***Applying commercially available acoustically absorptive treatment to the roadside face of either one or both of the parallel noise barriers (see Refs. 3,5,8,13,15,19,20,24-26)-*****Note:** application of treatment to just one of the two barriers will eliminate the multiple reflections; however noise barrier insertion loss can (theoretically) still be degraded by as much as 3 dBA on the side of the roadway opposite the reflective barrier (due to a single reflection); typically a single reflection results in little if any degradation.[13] Application of absorptive

treatment is the only feasible method of minimizing the multiple reflections, once the barriers have been installed.

3. ***Tilting one of the two barriers outward, away from the road, thus redirecting the sound skyward (see Refs. 8,17-19,24-27)-*** **Note**: care must be taken when using this method in a highly congested urban setting where upper-story residents (residents opposite the tilted barrier) may suffer increased noise levels due to the redirected sound.

4. ***Increasing barrier height (see Ref. 24)-*** Although barrier insertion loss degradation increases with increased barrier height, barrier insertion loss increases at a greater rate. The cited Reference states that if the degradation is 3 dB or less, increasing barrier height may be the most practical approach. Based on this recommendation, increasing barrier height is probably **not** economically feasible for W/H ratios of less than 10:1.

5. ***Enclosing the roadway in a tunnel-like structure (see Refs. 6, 21-23) -*** Although this method is probably the most effective means of eliminating the multiple reflections, it is probably the least desirable, due to the significant increase in construction costs.

Each of these methods has limitations and in most cases involves increased cost, when compared with the more conventional parallel reflective highway noise barriers. If the 10:1 ratio cannot be maintained, a cost/benefit analysis is recommended to determine which of the above methods is most appropriate.

6.3 REFERENCE MICROPHONE ADJUSTMENT

In May, 1991, the Acoustical Society of America's S12-6 Working Group (WG) met at Vanderbilt University in Nashville, TN, with the objective of performing a final evaluation of ANSI S12.8-1987, "Methods for Determination of Insertion Loss of Outdoor Noise Barriers," based on the results of the NMAF Dulles study and the Caltrans Route 99 study.

Among the conclusions of the WG, the current reference microphone adjustment procedure, per ANSI S12.8-1987, is incorrect, especially in the case of a parallel-barrier configuration.

In a memorandum submitted to the Acoustical Society of America, the WG proposed applying a reflection/edge diffraction correction to noise levels measured at the reference microphone in the "AFTER" site, i.e., the site of interest where a noise barrier is in place, prior to performing the normal reference microphone adjustment. The memorandum includes the following paragraph:

> "It is possible that the introduction of the barrier will increase sound pressure levels at the reference microphone due to induced multiple reflections between source and the barrier and/or edge diffraction at the top of the barrier. A 0.5 dB increase in sound level at the reference microphone located above the barrier may be considered typical and should be included as a correction factor to the reference microphone data, unless further analysis of the propagation characteristics of source/barrier/microphone configuration justifies other values. **Larger corrections for multiple reflections may be considered in the case of parallel barriers or enclosures.**"

The present study, along with two previous NMAF studies,[8,39 (see Appendix F)] have shown that a 1 dBA correction is typical in the case of parallel barriers. However, this correction is also dependent on the W/H ratio, and smaller corrections can be expected as the W/H ratio increases.

Note: no corrections for multiple reflections were applied to the data measured in this study. The objective of this study was to quantify barrier insertion loss degradation, not barrier insertion loss. When barrier insertion loss measurements are performed, the proposed correction procedure and subsequent reference microphone adjustment are recommended.

6.4 COMPUTER MODELING

Up to this point in the document, barrier insertion loss degradation ($)_{IL}$) has been referred to in terms of human perceptibility, i.e., if the degradation is less than 3 dBA, it would not be perceived by the human ear, and a barrier designer need not address methods of minimizing it. However, when it comes to accurate noise level prediction, multiple reflections and the resultant $)_{IL}$ **cannot** be neglected. In most parallel-barrier arrangements, multiple reflections must be considered and an accurate, user-friendly method for predicting the degrading effects is required.

The three parallel-barrier prediction programs used in the present study to model the test site were: BARRIER, BARRIER-X, and IMAGE-3. In general, reasonable results were obtained at the 16 ft offset with all three programs; however, at the 65.5 and 131 ft offsets, each program tended to overpredict the $)_{IL}$ value (by as much as 2.6 dBA). Although these programs have undergone some prior evaluation through field data, e.g., IMAGE-3 on Interstate 440 in Nashville, TN,[40] and BARRIER and BARRIER-X in the Dulles study, additional evaluation is required. Specifically, additional evaluation may help to explain, and possibly correct the following: 1.) the reason for the underprediction of the $)_{IL}$ value at the reference position and the high microphone position, 16 ft offset (BARRIER and BARRIER-X); and 2.) the general overprediction at the 65.5 and 131 ft offsets by all three programs.

Although these programs were originally intended to be used as supplements to STAMINA 2.0, their multiple reflection algorithms, when thoroughly validated, may provide a good foundation for the parallel-barrier-analysis portion of the next generation of FHWA-approved highway-noise-prediction software.

6.5 FUTURE WORK

Although the present study has recommended a guideline for identifying parallel-barrier sites which are potentially subject to a perceptible degradation, it would be beneficial to perform measurements at additional sites with a variety of W/H ratios to expand upon the existing database and foster continued prediction model evaluation. However, the biggest problem is identifying sites that are "measurable". Past studies have cited the lack of a good test site as the major obstacle to quantifying barrier insertion loss degradations through field measurements.[12,29] As mentioned earlier in this document, of the more than thirty potential sites visited prior to this measurement study, only the one tested was acceptable. Additional suggestions for potential measurement sites would be appreciated.

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Appendix A

CALIBRATION CORRECTED L_{eq} (5 MIN) AND BARRIER INSERTION LOSS DEGRADATIONS, $)_{IL}$

This Appendix presents the calibration corrected L_{eq} (5 min) data (Tables A1 - A3), and the barrier insertion loss degradations (Tables A4 - A6), as discussed in Section 3.1. Included in these Tables is pertinent event information such as test date, test run number, event start time, mast offset and microphone position.

March 1, 1992

Table A1

CALIBRATION CORRECTED L_{eq} (5 MIN) DATA
OCTOBER 8, 1991

Test Run #	Start Time	Mast Offset (ft)	SITE #1 (Parallel) REF	HIGH	MID	LOW	SITE #2 (Single) REF	HIGH	MID	LOW
1	10:40		81.80	80.15	75.00	67.20	80.65	79.30	72.50	65.65
2	10:50		81.40	79.85	74.70	66.70	80.15	78.90	71.60	64.95
3	11:05		81.00	79.55	73.50	66.00	80.05	78.80	71.40	64.75
4	11:15		81.60	80.05	74.70	66.80	80.55	79.30	71.80	65.15
5	11:25	16	81.40	79.75	74.40	66.50	80.25	79.10	71.50	64.85
6	11:35		81.30	79.75	73.80	66.30	80.15	79.00	71.20	64.75
7	11:45		81.20	79.45	74.00	66.40	80.05	78.80	71.40	64.65
8	11:55		81.60	79.95	74.30	66.80	80.55	79.10	72.10	65.25
9	12:05		81.10	79.35	74.00	66.20	80.15	78.80	71.10	64.45
10	12:15		81.60	79.75	74.30	66.70	80.55	79.20	71.50	64.85
11	13:05		82.30	69.55	66.80	65.15	81.05	66.65	64.15	61.60
12	-		-	-	-	-	-	-	-	-
13	13:25		82.10	69.45	66.90	64.95	81.15	66.45	63.65	61.10
14	13:35		82.00	69.15	66.40	64.35	80.95	66.25	63.55	60.90
15	13:45	131	82.00	69.65	66.90	65.25	80.85	66.65	64.05	61.30
16	13:55		82.00	69.45	66.60	64.75	80.95	66.65	63.95	61.20
17	14:05		82.00	69.55	66.80	64.85	80.85	66.75	63.95	61.40
18	14:15		82.10	69.75	66.80	65.05	80.85	66.75	64.15	61.60
19	14:25		82.60	69.95	67.20	65.55	81.55	67.05	64.45	61.80
20	14:35		82.60	69.95	67.30	65.65	81.55	67.35	64.65	61.90
21	15:15		82.60	74.40	69.50	66.35	81.55	72.20	67.55	64.30
22	15:25		82.10	74.00	69.00	65.85	81.15	71.80	66.75	63.70
23	15:35		82.50	74.10	69.30	66.25	81.45	72.00	67.25	64.20
24	15:45		82.60	74.00	69.10	66.05	81.75	72.30	67.15	64.20
25	15:55	65.5	82.40	74.00	69.10	65.95	81.35	72.00	66.85	63.80
26	16:05		82.30	74.10	69.20	66.05	81.15	72.10	67.15	64.10
27	16:15		82.20	73.70	69.00	65.95	81.15	71.90	67.05	64.00
28	16:25		82.40	73.90	69.10	66.05	81.35	72.00	66.95	63.90
29	16:35		82.40	73.90	69.20	66.25	80.95	72.10	67.35	64.20
30	-		-	-	-	-	-	-	-	-

(-) Denotes test run was removed from the population of events to be analyzed (see Section 3.1 for an explanation).

Table A2

CALIBRATION CORRECTED L_{eq} (5 MIN) DATA
OCTOBER 9, 1991

Test	Start	Mast	SITE #1 (Parallel)				SITE #2 (Single)			
Run #	Time	Offset (ft)	REF	HIGH	MID	LOW	REF	HIGH	MID	LOW
1	9:45		82.50	70.20	67.40	65.65	81.60	67.90	65.25	62.80
2	9:55		82.10	70.00	67.10	65.25	81.10	67.10	64.65	62.30
3	10:05		82.10	69.90	67.10	65.45	81.00	67.00	64.55	62.10
4	10:15		82.50	70.20	67.40	65.65	81.20	68.20	65.45	62.90
5	10:25	131	82.20	69.80	67.30	65.55	81.00	67.80	65.35	62.80
6	-		-	-	-	-	-	-	-	-
7	10:45		82.20	70.20	67.30	65.45	81.00	66.80	64.35	61.90
8	10:55		82.20	70.60	67.70	65.95	80.90	67.60	64.85	62.20
9	11:05		82.10	70.00	67.10	65.25	80.80	66.90	64.35	61.90
10	11:15		82.30	70.10	67.40	65.65	81.10	67.00	64.55	62.00
11	11:45		81.85	74.20	69.55	65.95	80.65	71.55	67.10	64.05
12	11:55		83.05	74.70	70.05	66.55	81.25	72.15	67.90	64.75
13	12:05		81.75	73.90	69.05	65.65	80.45	71.35	66.80	63.95
14	12:15		82.35	74.30	69.65	66.25	81.25	72.05	67.40	64.35
15	12:25	65.5	82.15	73.80	69.25	65.95	80.95	71.35	66.90	63.95
16	12:35		82.15	73.50	68.95	65.55	80.95	71.25	66.50	63.65
17	12:45		82.55	74.10	69.55	66.15	81.15	71.95	67.50	64.35
18	12:55		82.25	74.00	69.55	66.15	80.95	71.95	67.60	64.45
19	13:05		81.95	73.70	69.15	65.65	80.85	71.45	67.30	64.05
20	13:15		82.25	74.30	69.65	66.15	81.25	72.25	67.90	64.65
21	-		-	-	-	-	-	-	-	-
22	14:05		82.20	80.25	75.00	67.40	81.20	80.00	72.85	66.15
23	14:15		82.10	80.45	75.10	67.40	81.30	80.00	72.75	65.95
24	14:25		82.70	81.05	76.00	68.20	81.50	80.30	73.35	66.65
25	-		-	-	-	-	-	-	-	-
26	-	16	-	-	-	-	-	-	-	-
27	-		-	-	-	-	-	-	-	-
28	15:05		81.50	79.85	74.40	66.90	80.80	79.50	72.35	65.75
29	15:15		82.60	80.95	75.60	68.00	81.80	80.50	73.15	66.75
30	15:25		82.40	80.85	75.60	67.70	81.20	80.10	72.85	66.15
31	15:35		82.40	80.75	75.50	67.90	81.40	80.30	73.15	66.45

(-) Denotes test run was removed from the population of events to be analyzed (see Section 3.1 for an explanation).

Table A3

CALIBRATION CORRECTED L_{eq} (5 MIN) DATA
OCTOBER 10, 1991

Test	Start	Mast	SITE #1 (Parallel)				SITE #2 (Single)			
Run #	Time	Offset (ft)	REF	HIGH	MID	LOW	REF	HIGH	MID	LOW
1	9:45		83.20	71.05	68.75	66.90	81.90	68.15	65.80	63.70
2	9:55		82.10	69.85	67.45	65.50	80.90	66.95	64.70	62.50
3	10:05		82.50	70.25	67.65	65.70	81.20	67.65	65.40	63.00
4	10:15		82.40	69.95	67.35	65.50	80.80	67.25	65.00	62.50
5	10:25	131	82.70	70.15	67.65	66.00	81.50	67.65	65.50	62.90
6	10:35		82.40	70.35	67.95	66.40	81.10	67.55	65.20	62.80
7	10:45		82.50	70.15	67.85	65.90	81.20	67.35	65.20	62.80
8	10:55		81.70	69.65	67.25	65.60	80.40	67.05	64.80	62.70
9	-		-	-	-	-	-	-	-	-
10	-		-	-	-	-	-	-	-	-
11	11:45		82.35	80.50	75.45	67.55	81.15	79.95	73.25	-
12	11:55		82.85	80.90	76.25	-	81.55	80.25	74.35	-
13	12:05		82.05	80.30	74.85	67.05	80.95	79.45	72.35	-
14	12:15		82.05	80.20	74.75	67.05	80.75	79.35	72.05	-
15	12:25	16	82.05	80.20	74.85	66.75	80.95	79.65	72.75	-
16	12:35		82.05	79.90	74.65	66.85	80.75	79.45	72.45	-
17	12:45		82.05	80.10	74.55	66.75	80.95	79.55	72.45	-
18	12:55		81.45	79.40	74.25	66.25	80.25	79.15	72.15	-
19	-		-	-	-	-	-	-	-	-
20	13:15		82.35	80.40	75.05	67.05	81.25	80.05	72.95	-
21	13:45		82.65	74.55	69.90	66.45	81.30	72.15	67.65	-
22	13:55		81.75	73.45	68.70	65.35	80.70	71.55	66.85	-
23	14:05		81.85	73.75	69.10	65.65	80.80	71.35	66.55	-
24	14:15		82.15	73.75	69.20	65.95	81.00	71.85	67.55	-
25	14:25	65.5	82.05	73.95	69.00	65.75	80.90	71.55	66.85	-
26	14:35		82.45	74.15	69.60	66.15	81.50	72.15	67.45	-
27	14:45		82.55	74.25	69.50	66.35	81.30	72.05	67.65	-
28	14:55		82.55	74.25	69.60	66.35	81.50	71.95	67.45	-
29	15:05		82.75	74.35	69.90	66.75	81.50	72.05	67.45	-
30	15:15		82.45	74.05	69.40	66.05	81.10	71.85	66.95	-

(-) Denotes test run was removed from the population of events to be analyzed (see Section 3.1 for an explanation).

Table A4

BARRIER INSERTION LOSS DEGRADATIONS, $)_{IL}$ (dBA) 16 FT MAST OFFSET

Test Run#	Test Date	REF	HIGH	MID	LOW
1		1.15	0.85	2.50	1.55
2		1.25	0.95	3.10	1.75
3		0.95	0.75	2.10	1.25
4		1.05	0.75	2.90	1.65
5	10/08/91	1.15	0.65	2.90	1.65
6		1.15	0.75	2.60	1.55
7		1.15	0.65	2.60	1.75
8		1.05	0.85	2.20	1.55
9		0.95	0.55	2.90	1.75
10		1.05	0.55	2.80	1.85
22		1.00	0.25	2.15	1.25
23		0.80	0.45	2.35	1.45
24		1.20	0.75	2.65	1.55
25		-	-	-	-
26	10/09/91	-	-	-	-
27		-	-	-	-
28		0.70	0.35	2.05	1.15
29		0.80	0.45	2.45	1.25
30		1.20	0.75	2.75	1.55
31		1.00	0.45	2.35	1.45
11		1.20	0.55	2.20	-
12		1.30	0.65	1.90	-
13		1.10	0.85	2.50	-
14		1.30	0.85	2.70	-
15	10/10/91	1.10	0.55	2.10	-
16		1.30	0.45	2.20	-
17		1.10	0.55	2.10	-
18		1.20	0.25	2.10	-
19		-	-	-	-
20		1.10	0.35	2.10	-
Mean $)_{IL}$		1.09	0.61	2.43	1.53
F		0.16	0.20	0.33	0.20
Error*		-	0.34	0.53	0.37

(-) Denotes test run was removed from the population of events to be analyzed (see Section 3.1 for an explanation).
* Error computed per ANSI S12.8-1987 (see sample error computation at the end of this appendix).

Table A5

BARRIER INSERTION LOSS DEGRADATIONS,)$_{IL}$ (dBA)
65.5 FT MAST OFFSET

Test Run#	Test Date	REF	HIGH	MID	LOW
21		1.05	2.20	1.95	2.05
22		0.95	2.20	2.25	2.15
23		1.05	2.10	2.05	2.05
24		0.85	1.70	1.95	1.85
25	10/08/91	1.05	2.00	2.25	2.15
26		1.15	2.00	2.05	1.95
27		1.05	1.80	1.95	1.95
28		1.05	1.90	2.15	2.15
29		1.45	1.80	1.85	2.05
30		-	-	-	-
11		1.20	2.65	2.45	1.90
12		1.80	2.55	2.15	1.80
13		1.30	2.55	2.25	1.70
14		1.10	2.25	2.25	1.90
15	10/09/91	1.20	2.45	2.35	2.00
16		1.20	2.25	2.45	1.90
17		1.40	2.15	2.05	1.80
18		1.30	2.05	1.95	1.70
19		1.10	2.25	1.85	1.60
20		1.00	2.05	1.75	1.50
21		-	-	-	-
21		1.35	2.40	2.25	-
22		1.05	1.90	1.85	-
23		1.05	2.40	2.55	-
24		1.15	1.90	1.65	-
25	10/10/91	1.15	2.40	2.15	-
26		0.95	2.00	2.15	-
27		1.25	2.20	1.85	-
28		1.05	2.30	2.15	-
29		1.25	2.30	2.45	-
30		1.35	2.20	2.45	-
Mean)$_{IL}$		1.17	2.17	2.12	1.90
F		0.19	0.24	0.23	0.19
Error*		-	0.37	0.54	0.59

(-) Denotes test run was removed from the population of events to be analyzed (see Section 3.1 for an explanation).
* Error computed per ANSI S12.8-1987 (see sample error computation at the end of this appendix).

Table A6

BARRIER INSERTION LOSS DEGRADATIONS, $)_{IL}$ (dBA)
131 FT MAST OFFSET

Test Run#	Test Date	REF	HIGH	MID	LOW
11		1.25	2.90	2.65	3.55
12		-	-	-	-
13		0.95	3.00	3.25	3.85
14		1.05	2.90	2.85	3.45
15	10/08/91	1.15	3.00	2.85	3.95
16		1.05	2.80	2.65	3.55
17		1.15	2.80	2.85	3.45
18		1.25	3.00	2.65	3.45
19		1.05	2.90	2.75	3.75
20		1.05	2.60	2.65	3.75
1		0.90	2.30	2.15	2.85
2		1.00	2.90	2.45	2.95
3		1.10	2.90	2.55	3.35
4		1.30	2.00	1.95	2.75
5	10/09/91	1.20	2.00	1.95	2.75
6		-	-	-	-
7		1.20	3.40	2.95	3.55
8		1.30	3.00	2.85	3.75
9		1.30	3.10	2.75	3.35
10		1.20	3.10	2.85	3.65
1		1.30	2.90	2.95	3.20
2		1.20	2.90	2.75	3.00
3		1.30	2.60	2.25	2.70
4		1.60	2.70	2.35	3.00
5	10/10/91	1.20	2.50	2.15	3.10
6		1.30	2.80	2.75	3.60
7		1.30	2.80	2.65	3.10
8		1.30	2.60	2.45	2.90
9		-	-	-	-
10		-	-	-	-
Mean $)_{IL}$		1.19	2.78	2.61	3.32
F		0.15	0.32	0.32	0.37
Error*		-	0.56	0.67	0.77

(-) Denotes test run was removed from the population of events to be analyzed (see Section 3.1 for an explanation).
* Error computed per ANSI S12.8-1987 (see sample error computation at the end of this appendix).

March 1, 1992

SAMPLE ERROR COMPUTATION
HIGH MICROPHONE POSITION - 16 ft MAST OFFSET

Compute Variance* for:

Site 1 (Parallel Barrier Site):

Background (Not computed if measured noise level exceeds the background level by 10 dB):
Reference Microphone Position..0.0
High Microphone Position..0.0
Difference (Calibration corrected source levels at reference microphone position minus calibration corrected source levels at the high microphone position)..........................0.032

Site 2 (Single Barrier Site):

Background (Not computed if measured noise level exceeds the background level by 10 dB):
Reference Microphone Position..0.0
High Microphone Position..0.0
Difference (Calibration corrected source levels at reference microphone position minus calibration corrected source levels at the high microphone position)..........................0.012

Bias:

Type	Amount (dB)	Amount/2	$(\text{Amount}/2)^2$	
Calibrator	0.25	0.125	.016	0.016
Calibration Drift (Site 1)	0.40	0.200	.040	0.040
Calibration Drift (Site 2)	0.23	0.115	.013	0.013

Sum of Variances (Sum of above items)...0.113

Standard Error (Square root of Sum of Variances)...0.34

* Note: Variance = $(F)^2 = [n'(X_i^2) - ('X_i)^2]/[n(n-1)]$; where n is number of levels and X_i is value of i^{th} level.

Appendix B
METEOROLOGICAL DATA

This Appendix presents the five-minute average meteorological data, including wind speed (mph), wind direction *re* magnetic north (degrees), temperature (°F), relative humidity (%), and vector wind speed (mph) (Tables B1 - B3), as discussed in Section 3.2. Also presented, in Figures B1-B3, are the plots of insertion loss degradation ( )$_{IL}$) versus vector wind speed (VWS) for the 16, 65.5 and 131 ft mast offsets, respectively.

Table B1

METEOROLOGICAL DATA
FIVE-MINUTE AVERAGE VALUES
OCTOBER 8, 1991

Test Run#	Start Time	Wind Speed (mph)	Wind* Dir (<)	Temp (<F)	Rel Hum (%)	VWS (mph)
1	10:40	6.5	65	56	46	2.7
2	10:50	7.0	80	57	45	1.2
3	11:05	4.0	130	58	44	-2.6
4	11:15	7.5	100	58	43	-1.3
5	11:25	5.5	105	58	43	-1.4
6	11:35	5.8	150	58	42	-5.0
7	11:45	7.5	115	59	41	-3.2
8	11:55	9.0	65	60	40	3.8
9	12:05	2.5	195	61	40	-2.4
10	12:15	8.0	155	61	40	-7.3
11	13:05	4.5	195	66	38	-4.3
12	-	-	-	-	-	-
13	13:25	4.8	15	67	34	4.6
14	13:35	6.2	35	66	33	5.1
15	13:45	5.5	325	67	32	4.5
16	13:55	8.3	10	67	32	8.2
17	14:05	4.8	350	67	32	4.7
18	14:15	3.3	45	66	32	2.3
19	14:25	6.8	70	64	32	2.3
20	14:35	4.5	330	64	32	3.9
21	15:15	6.8	345	67	32	6.6
22	15:25	4.3	20	66	32	4.0
23	15:35	5.1	50	67	32	3.3
24	15:45	4.2	35	67	30	3.4
25	15:55	6.8	340	68	30	6.4
26	16:05	3.8	15	69	30	3.7
27	16:15	5.5	30	68	30	4.8
28	16:25	3.9	30	68	30	3.4
29	16:35	6.5	40	67	29	5.0
30	-	-	-	-	-	-

* Wind Direction *re* Magnetic North
(-) Denotes test run was removed from the population of events to be analyzed (see Section 3.1 for an explanation).

Table B2

METEOROLOGICAL DATA
FIVE-MINUTE AVERAGE VALUES
OCTOBER 9, 1991

Test Run#	Start Time	Wind Speed (mph)	Wind* Dir (<)	Temp (<F)	Rel Hum (%)	VWS (mph)
1	9:45	4.3	90	55	62	0.0
2	9:55	3.0	105	56	61	-0.8
3	10:05	4.8	125	58	60	-2.8
4	10:15	6.3	80	57	58	1.1
5	10:25	8.0	115	58	57	-3.4
6	-	-	-	-	-	-
7	10:45	3.8	40	60	56	2.9
8	10:55	6.8	65	60	55	2.9
9	11:05	4.8	50	61	54	3.1
10	11:15	4.5	55	61	53	2.6
11	11:45	5.5	70	63	51	1.9
12	11:55	5.0	85	63	50	0.5
13	12:05	9.5	145	63	48	-7.8
14	12:15	8.3	130	66	47	-5.3
15	12:25	5.5	120	68	45	-2.8
16	12:35	4.8	120	69	44	-2.4
17	12:45	7.5	100	70	42	-1.3
18	12:55	9.8	100	68	41	-1.7
19	13:05	8.3	95	69	39	-0.7
20	13:15	9.5	100	68	38	-1.6
21	-	-	-	-	-	-
22	14:05	7.8	100	72	37	-1.4
23	14:15	10.0	90	71	37	0.0
24	14:25	5.8	100	70	37	-1.0
25	-	-	-	-	-	-
26	-	-	-	-	-	-
27	-	-	-	-	-	-
28	15:05	6.3	105	67	38	-1.6
29	15:15	7.0	130	67	38	-4.5
30	15:25	5.5	145	68	38	-4.5
31	15:35	4.5	105	70	37	-1.2

* Wind Direction *re* Magnetic North
(-) Denotes test run was removed from the population of events to be analyzed (see Section 3.1 for an explanation).

U.S. Department of Transportation
Research and Special Programs Administration
Volpe National Transportation Systems Center
Noise Measurement and Assessment Facility

Table B3

METEOROLOGICAL DATA
FIVE-MINUTE AVERAGE VALUES
OCTOBER 10, 1991

Test Run#	Start Time	Wind Speed (mph)	Wind* Dir (<)	Temp (<F)	Rel Hum (%)	VWS (mph)
1	9:45	2.5	30	56	75	2.2
2	9:55	4.3	55	57	75	2.4
3	10:05	5.0	70	59	73	1.7
4	10:15	5.8	85	59	71	0.5
5	10:25	4.8	75	59	68	1.2
6	10:35	4.5	80	60	67	0.8
7	10:45	6.3	70	61	65	2.2
8	10:55	6.0	80	61	64	1.0
9	-	-	-	-	-	-
10	-	-	-	-	-	-
11	11:45	3.8	25	66	59	3.4
12	11:55	4.0	55	67	57	2.3
13	12:05	3.5	120	69	56	-1.8
14	12:15	3.3	90	70	54	0.0
15	12:25	4.0	100	71	53	-0.7
16	12:35	6.3	30	71	52	5.4
17	12:45	3.5	90	72	50	0.0
18	12:55	5.0	310	73	49	3.2
19	-	-	-	-	-	-
20	13:15	5.3	210	73	48	-4.6
21	13:45	6.8	220	73	44	-5.2
22	13:55	7.0	15	73	44	6.8
23	14:05	6.3	0	73	43	6.3
24	14:15	7.0	80	73	43	1.2
25	14:25	6.0	15	72	42	5.8
26	14:35	4.3	10	71	43	4.2
27	14:45	4.0	350	72	43	3.9
28	14:55	5.8	65	71	44	2.4
29	15:05	4.0	335	73	44	3.6
30	15:15	4.8	40	74	43	3.7

* Wind Direction *re* Magnetic North
(-) Denotes test run was removed from the population of events to be analyzed (see Section 3.1 for an explanation).

Appendix C
TRAFFIC DATA

This Appendix presents the traffic summary data for each five-minute test run, categorized according to vehicle type, i.e., autos (A), medium trucks (MT) and heavy trucks (HT), and direction of traffic flow (Tables C1-C3). The average vehicle speed and corresponding standard deviation for each test run are also included in these Tables. In addition, the insertion loss degradation ($)_{IL}$) versus total number of vehicles, and $)_{IL}$ versus percentage of trucks are presented in Figures C1-C3 and C4-C6, respectively.

March 1, 1992

Table C1

FIVE-MINUTE VEHICLE COUNT AND AVERAGE SPEED DATA
OCTOBER 8, 1991

Test	Start	West Bound			East Bound			Avg	Std
Run # (F)	Time	A	MT	HT	A	MT	HT	Speed (mph)	Deviation
1	10:40	407	7	31	322	9	38	60.1	3.4
2	10:50	351	8	36	348	12	26	60.5	3.4
3	11:05	319	8	20	340	10	29	59.9	3.7
4	11:15	317	16	25	338	10	37	60.1	3.2
5	11:25	335	14	25	342	12	39	58.9	3.1
6	11:35	363	8	32	335	6	38	58.2	3.3
7	11:45	332	8	20	375	8	35	58.4	3.8
8	11:55	340	11	22	320	11	33	58.3	3.9
9	12:05	291	10	23	354	7	28	60.1	3.5
10	12:15	374	10	25	404	12	40	59.0	3.5
11	13:05	381	17	29	357	7	41	57.4	2.6
12	-	-	-	-	-	-	-	-	-
13	13:25	373	15	37	370	5	31	57.1	3.8
14	13:35	353	7	32	365	6	39	60.2	4.3
15	13:45	397	7	30	384	5	34	59.2	5.1
16	13:55	353	10	35	380	8	39	57.2	3.6
17	14:05	409	12	22	360	5	47	60.3	3.6
18	14:15	402	10	18	463	6	38	58.2	3.9
19	14:25	411	12	51	476	9	40	57.7	3.7
20	14:35	408	10	41	459	19	27	58.5	4.0
21	15:15	505	11	24	594	8	36	58.6	4.1
22	15:25	457	5	23	618	11	42	59.3	2.9
23	15:35	572	4	24	690	10	35	57.0	3.5
24	15:45	576	8	30	750	5	33	57.5	2.6
25	15:55	523	5	22	688	9	27	59.2	3.9
26	16:05	547	5	22	811	8	46	58.6	3.4
27	16:15	494	5	27	862	5	31	60.1	2.8
28	16:25	505	7	28	737	3	29	58.9	2.4
29	16:35	513	5	16	848	8	28	59.4	3.2
30	-	-	-	-	-	-	-	-	-

(-) Denotes test run was removed from the population of events to be analyzed (see Section 3.1 for an explanation).

March 1, 1992

Table C2

FIVE-MINUTE VEHICLE COUNT AND AVERAGE SPEED DATA
OCTOBER 9, 1991

Test	Start	West Bound			East Bound			Avg	Std
Run # (F)	Time	A	MT	HT	A	MT	HT	Speed (mph)	Deviation
1	9:45	418	4	42	392	0	38	56.1	4.1
2	9:55	437	4	39	385	6	30	57.6	3.8
3	10:05	411	9	49	321	7	30	57.8	3.0
4	10:15	346	8	49	344	16	31	57.5	3.8
5	10:25	381	5	48	323	5	45	57.8	4.0
6	-	-	-	-	-	-	-	-	-
7	10:45	371	3	42	366	8	35	57.7	2.5
8	10:55	360	4	46	353	5	45	58.1	3.2
9	11:05	338	6	41	328	8	36	58.1	3.0
10	11:15	362	4	47	307	7	35	57.6	4.2
11	11:45	371	6	37	351	6	39	56.7	3.2
12	11:55	328	5	55	364	8	43	58.2	4.0
13	12:05	322	4	32	366	5	40	59.0	4.7
14	12:15	358	2	50	367	5	56	56.4	4.3
15	12:25	389	3	39	367	7	35	57.0	3.9
16	12:35	419	6	38	365	6	30	57.2	4.5
17	12:45	377	6	31	360	3	38	57.5	3.4
18	12:55	394	5	28	338	4	30	59.0	3.9
19	13:05	394	3	40	398	8	29	57.8	4.7
20	13:15	419	5	31	391	8	36	57.5	4.5
21	-	-	-	-	-	-	-	-	-
22	14:05	385	8	49	427	11	33	58.2	3.8
23	14:15	391	4	40	459	5	42	58.6	3.6
24	14:25	409	1	39	463	14	30	58.7	3.1
25	-	-	-	-	-	-	-	-	-
26	-	-	-	-	-	-	-	-	-
27	-	-	-	-	-	-	-	-	-
28	15:05	426	3	33	499	10	33	57.3	4.1
29	15:15	500	3	39	699	5	51	56.3	4.5
30	15:25	507	3	17	678	7	32	59.0	4.0
31	15:35	476	7	32	704	9	39	57.6	2.3

(-) Denotes test run was removed from the population of events to be analyzed (see Section 3.1 for an explanation).

March 1, 1992

Table C3

FIVE-MINUTE VEHICLE COUNT AND AVERAGE SPEED DATA
OCTOBER 10, 1991

Test Run # (F)	Start Time	West Bound A	West Bound MT	West Bound HT	East Bound A	East Bound MT	East Bound HT	Avg Speed (mph)	Std Deviation
1	9:45	458	3	53	454	1	44	56.2	4.2
2	9:55	420	9	36	389	3	19	56.4	3.9
3	10:05	387	8	41	391	3	44	56.6	5.4
4	10:15	403	5	46	403	4	48	55.7	4.9
5	10:25	350	3	64	433	3	36	56.6	5.1
6	10:35	396	3	53	373	8	53	56.8	4.2
7	10:45	348	3	54	351	10	39	57.8	4.5
8	10:55	319	4	52	321	6	32	57.2	4.6
9	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-	-
11	11:45	370	3	41	428	7	55	56.4	4.3
12	11:55	364	3	47	422	11	42	56.9	5.7
13	12:05	352	4	48	375	4	41	58.3	5.0
14	12:15	397	2	38	426	4	39	56.0	4.1
15	12:25	416	4	39	384	6	47	56.4	4.6
16	12:35	397	3	34	411	5	49	58.9	3.6
17	12:45	424	3	49	377	6	44	57.5	3.3
18	12:55	408	2	28	364	2	39	56.8	2.7
19	-	-	-	-	-	-	-	-	-
20	13:15	346	3	37	342	8	30	58.2	5.0
21	13:45	404	4	43	423	4	52	59.9	5.1
22	13:55	378	2	33	392	1	44	57.9	5.8
23	14:05	422	4	30	392	9	44	56.5	5.3
24	14:15	399	2	36	392	2	41	58.7	4.6
25	14:25	413	2	40	444	1	49	58.3	4.3
26	14:35	407	2	44	448	5	45	57.1	3.7
27	14:45	484	1	39	584	8	48	56.3	4.2
28	14:55	464	0	40	563	13	44	58.1	4.1
29	15:05	492	2	39	620	5	48	58.2	3.5
30	15:15	532	5	36	712	8	40	58.2	4.5

(-) Denotes test run was removed from the population of events to be analyzed (see Section 3.1 for an explanation).

Appendix D
COMPUTER MODELING

This Appendix presents example input files for BARRIER - Version 2.1, BARRIER-X - Version 2.1, and IMAGE-3 - Version 3.11, as discussed in Section 4.4. Microphone offset distances and traffic counts were adjusted, as appropriate. Readers are directed to references 3, 25 and 26 for additional information on these prediction programs.

SAMPLE INPUT FILE FOR BARRIER - VERSION 2.1
65.5 FT MAST OFFSET - PARALLEL BARRIER SITE

```
'I495 PARALLEL BARRIER SITE - SITE 1, PARALLEL- 65.5 FT'
'FHWA STANDARD SPECTRA FROM STAMINA 1.0 USERS GUIDE'
'VEHICLE SOURCE HEIGHTS PER FHWA/FL/DOT/MO-89-382'
'PARAMETER LIMITS USED IN PROGRAM; INPUT ARRAYS MAY EXCEED THESE'
'NNR    NNLAN   NNST    NNV     NNZ     SHFLAG'
  4       8      1       3       6        1
' '
'HIGHWAY LANE DIMENSIONS'
'LANW   MEDW    SHWL    SHWR    TSWL    TSWR    YL1     YL2='
 12.0   12.0    32.0    24.0    0.0     0.0    2000    -200
' '
'A-WEIGHT CORRECTIONS IN dB'
'AWT(OCT)='     -26.2  -16.1  -8.6   -3.2   0.0   1.2   1.0  -1.1
' '
'HIGHWAY LANE SURFACE FLOW RESISTANCE'
'SIGT   SIGS    SIGM    SIGP='
1.5E+5  1.E+6   3.E+7   3.E+7
' '
'BARRIER X-LOCATIONS ;NOTE XP1=XP2,XP3=XP4'
'XP1 =  XP2  ;  XP3 =   XP4='
 0.0    0.0     164.    164.
' '
'BARRIER Y-LOCATIONS'
'YP1    YP2     YP3     YP4='
2000.  -200.   2000.   -200.
' '
'BARRIER ANGLE (OUTWARD), IN DEGREES'
'PHILD  PHIRD='
   0.     0.
' '
'LEFT BARRIER PANEL WIDTH ;JFLAG=PANEL NUMBER FROM BOTTOM'
'WPL(JFLAG)='   5.5    10.0     4.83
' '
'RIGHT BARRIER PANEL WIDTH'
'WPR(JFLAG)='   1.5    10.0     5.5
' '
'LEFT BARRIER REFLECTION COEFFICIENTS'
'BRFLL(JOCT,JFLAG)='
'JOCT=          1       2       3       4       5       6       7       8'
'JFLAG=1'       .00     .00     .00     .00     .00     .00     .00     .00
'JFLAG=2'       .95     .95     .95     .95     .95     .95     .95     .95
'JFLAG=3'       .95     .95     .95     .95     .95     .95     .95     .95
' '
'RIGHT BARRIER REFLECTION COEFFICIENTS'
'BRFLR(JOCT,JFLAG)='
'JOCT=          1       2       3       4       5       6       7       8'
'JFLAG=1'       .95     .95     .95     .95     .95     .95     .95     .95
'JFLAG=2'       .95     .95     .95     .95     .95     .95     .95     .95
'JFLAG=3'       .95     .95     .95     .95     .95     .95     .95     .95
' '
'VEHICLES/HOUR IN LANE NLAN AND FOR VEHICLE TYPE NV. NOTE A;ENTER VALUES-- '
'--LIMITS OF INDICES (NNLAN,NNV) '
'VOL(NLAN,NV)='
'NLAN=        1     2     3     4     5     6     7     8     9    10'
'NV=1'     1329. 1329. 1329. 1329. 1575. 1575. 1575. 1575.    0.    0.
'NV=2'       12.   12.   12.   12.   18.   18.   18.   18.    0.    0.
'NV=3'      102.  102.  102.  102.  117.  117.  117.  117.    0.    0.
'NV=4'        0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
'NV=5'        0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
' '
```

```
'VEHICLE SPEED,MPH IN LANE NLAN AND VEHICLE TYPE NV. SEE NOTE A '
'SPD(NLAN,NV)='
'NLAN           1     2     3     4     5     6     7     8'    9    10'
'NV=1'          57.   57.  57.   57.   57.   57.   57.   57.    0.    0.
'NV=2'          57.   57.  57.   57.   57.   57.   57.   57.    0.    0.
'NV=3'          57.   57.  57.   57.   57.   57.   57.   57.    0.    0.
'NV=4'          0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
'NV=5'          0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
' '
'SOURCE HEIGHT,FOR VEHICLE TYPE NV AND SOURCE TYPE NST. SEE NOTE A'
'SH(NV,NST)='
'NV=            1       2       3       4       5'
'NST=1'         0.0     2.3     8.0     0.0     0.0
'NST=2'         0.0     0.0     0.0     0.0     0.0
'NST=3'         0.0     0.0     0.0     0.0     0.0
' '
'SOURCE STRENGTH, IN dB (UNCORRECTED FOR A-WT) AT 50 FT. IN FREE SPACE--'
'--WITH DEPENDENCE ON SOURCE TYPE NST, VEHICLE TYPE NV. SEE NOTE A'
'LS(JOCT,NV,NST)='
'JOCT=          1       2       3       4       5       6       7       8'
'NV=1 NST=1'    69.5    67.9    64.7    74.2    64.8    64.2    56.3    52.2
'NV=2 NST=1'    80.3    80.2    79.6    76.8    75.8    73.6    65.3    59.0
'NV=3 NST=1'    84.2    82.5    82.7    80.5    79.7    74.9    69.0    61.9
'NV=4 NST=1'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=5 NST=1'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=1 NST=2'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=2 NST=2'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=3 NST=2'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=4 NST=2'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=5 NST=2'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=1 NST=3'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=2 NST=3'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=3 NST=3'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=4 NST=3'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=5 NST=3'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
' '
'RECEIVER PARAMETERS. '
'       AXR(NR) AYR(NR) AZR(NR) AZRG(NR) ASIGG(NR) '
'NR=1'    -0.2   0.0    25.33    0.0      3.0E+7
'NR=2'   -65.5   0.0    12.33    6.5      1.5E+5
'NR=3'   -65.5   0.0    22.83    6.5      1.5E+5
'NR=4'   -65.5   0.0    33.33    6.5      1.5E+5
'NR=5'     0.0   0.0     0.0     0.0      0.0
'NR=6'     0.0   0.0     0.0     0.0      0.0
'NR=7'     0.0   0.0     0.0     0.0      0.0
'NR=8'     0.0   0.0     0.0     0.0      0.0
'NR=9'     0.0   0.0     0.0     0.0      0.0
'NR=10'    0.0   0.0     0.0     0.0      0.0
'NR=11'    0.0   0.0     0.0     0.0      0.0
'NR=12'    0.0   0.0     0.0     0.0      0.0
'NR=13'    0.0   0.0     0.0     0.0      0.0
'NR=14'    0.0   0.0     0.0     0.0      0.0
'NR=15'    0.0   0.0     0.0     0.0      0.0
'NR=16'    0.0   0.0     0.0     0.0      0.0
'NR=17'    0.0   0.0     0.0     0.0      0.0
'NR=18'    0.0   0.0     0.0     0.0      0.0
'NR=19'    0.0   0.0     0.0     0.0      0.0
'NR=20'    0.0   0.0     0.0     0.0      0.0
' '
```

```
'ATMOSPHERIC ABSORPTION; dB PER THOUSAND FEET'
'JOCT=           1      2      3      4      5      6      7      8'
'ATMOS(JOCT)='  .051   .165   .395   .643   1.00   2.18   6.75   24.50


**************************************************************************
              TABLE OF ATMOSPHERIC ABSORPTION, dB/1000 ft.
          (placed here for easy transfer to data block above)

 JOCT=      |        1      2      3     4      5      6      7       8
 -------------------------------------------------------------------
 REL. HUM.,% |
            |
 10         |        .107   .193   .369   1.01   3.45   11.70  31.00  55.30
 20         |        .092   .202   .331   .597   1.56   5.31   19.00  58.75
 30         |        .074   .197   .365   .563   1.14   3.33   11.90  42.25
 40         |        .061   .183   .388   .597   1.02   2.54   8.52          31.26
 50         |        .051   .165   .395   .643   1.00   2.18   6.75          24.50
 60         |        .043   .150   .391   .686   1.03   2.00   5.71          20.91
 80         |        .033   .123   .365   .746   1.13   1.89   4.63          15.44
```

65.5 FT MAST OFFSET - PARALLEL BARRIER SITE

```
'I495 PARALLEL BARRIER SITE - SITE 1, PARALLEL- 65.5 FT'
'FHWA STANDARD SPECTRA FROM STAMINA 1.0 USERS GUIDE'
'VEHICLE SOURCE HEIGHTS PER FHWA/FL/DOT/MO-89-382'
'PARAMETER LIMITS USED IN PROGRAM; INPUT ARRAYS MAY EXCEED THESE'
'NNR    NNLAN   NNST    NNV     NNZ     SHFLAG'
  4       8      1       3       6        1
' '
'HIGHWAY LANE DIMENSIONS'
'LANW   MEDW    SHWL    SHWR    TSWL    TSWR    YL1     YL2='
 12.0   12.0    32.0    24.0    0.0     0.0    2000.   -200.
' '
'A-WEIGHT CORRECTIONS IN dB'
'AWT(OCT)='     -26.2  -16.1  -8.6   -3.2   0.0   1.2   1.0  -1.1
' '
'HIGHWAY LANE SURFACE FLOW RESISTANCE'
'SIGT   SIGS    SIGM    SIGP='
1.5E+5  1.0E+6  3.0E+7     3.0E+7
' '
'BARRIER X-LOCATIONS ;NOTE XP1=XP2,XP3=XP4'
'XP1 =  XP2  ;  XP3 =   XP4='
 0.0    0.0     164.    164.
' '
'BARRIER Y-LOCATIONS'
'YP1    YP2     YP3     YP4='
2000.  -200.   2000.   -200.
' '
'BARRIER ANGLE (OUTWARD), IN DEGREES'
'PHILD  PHIRD='
   0.     0.
' '
'HEIGHT OF LEFT BARRIER IMPED. DISCONT.;JFLAG=PANEL NUMBER FROM BOTTOM'
'HBDL(JFLAG)='  5.5     15.5    20.33
' '
'HEIGHT OF LEFT BARRIER IMPED. DISCONT.'
'HBDR(JFLAG)='  1.5     11.5    17.0
' '
'LEFT BARRIER IMPEDANCE (NORMALIZED)'
'JOCT=          1       2       3       4       5       6       7       8'
'JFLAG=1'
'REAL IMPED'    1.0     1.0     1.0     1.0     1.0    1.0     1.0     1.0
'IMAG IMPED'    0.00    0.00    0.00    0.00    0.00   0.00    0.00    0.00
'JFLAG=2'
'REAL IMPED'    79.5    79.5    79.5    79.5    79.5   79.5    79.5    79.5
'IMAG IMPED'    0.00    0.00    0.00    0.00    0.00   0.00    0.00    0.00
'JFLAG=3'
'REAL IMPED'    79.5    79.5    79.5    79.5    79.5   79.5    79.5    79.5
'IMAG IMPED'    0.00    0.00    0.00    0.00    0.00   0.00    0.00    0.00
' '
'RIGHT BARRIER IMPEDANCE (NORMALIZED)'
'JOCT=          1       2       3       4       5       6       7       8'
'JFLAG=1'
'REAL IMPED'    79.5    79.5    79.5    79.5    79.5   79.5    79.5    79.5
'IMAG IMPED'    0.00    0.00    0.00    0.00    0.00   0.00    0.00    0.00
'JFLAG=2'
'REAL IMPED'    79.5    79.5    79.5    79.5    79.5   79.5    79.5    79.5
'IMAG IMPED'    0.00    0.00    0.00    0.00    0.00   0.00    0.00    0.00
'JFLAG=3'
'REAL IMPED'    79.5    79.5    79.5    79.5    79.5   79.5    79.5    79.5
'IMAG IMPED'    0.00    0.00    0.00    0.00    0.00   0.00    0.00    0.00
' '
```

```
'VEHICLES/HOUR IN LANE NLAN AND FOR VEHICLE TYPE NV. NOTE A;ENTER VALUES-- '
'--LIMITS OF INDICES (NNLAN,NNV) '
'VOL(NLAN,NV)='
'NLAN=        1     2     3     4     5     6     7     8     9    10'
'NV=1'      1329. 1329. 1329. 1329. 1575. 1575. 1575. 1575.   0.    0.
'NV=2'        12.   12.   12.   12.   18.   18.   18.   18.   0.    0.
'NV=3'       102.  102.  102.  102.  117.  117.  117.  117.   0.    0.
'NV=4'        0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
'NV=5'        0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
' '
'VEHICLE SPEED,MPH IN LANE NLAN AND VEHICLE TYPE NV. SEE NOTE A '
'SPD(NLAN,NV)='
'NLAN           1     2     3     4     5     6     7     8'    9    10'
'NV=1'          57.   57.   57.   57.   57.   57.   57.   57.   0.    0.
'NV=2'          57.   57.   57.   57.   57.   57.   57.   57.   0.    0.
'NV=3'          57.   57.   57.   57.   57.   57.   57.   57.   0.    0.
'NV=4'          0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
'NV=5'          0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
' '
'SOURCE HEIGHT,FOR VEHICLE TYPE NV AND SOURCE TYPE NST. SEE NOTE A'
'SH(NV,NST)='
'NV=            1       2       3       4       5'
'NST=1'         0.0     2.30    8.0     0.0     0.0
'NST=2'         0.0     0.0     0.0     0.0     0.0
'NST=3'         0.0     0.0     0.0     0.0     0.0
' '
'SOURCE STRENGTH, IN dB (UNCORRECTED FOR A-WT) AT 50 FT. IN FREE SPACE--'
'--WITH DEPENDENCE ON SOURCE TYPE NST, VEHICLE TYPE NV. SEE NOTE A'
'LS(JOCT,NV,NST)='
'JOCT=          1       2       3       4       5       6       7       8'
'NV=1 NST=1'    69.5    67.9    64.7    74.2    64.8    64.2    56.3    52.2
'NV=2 NST=1'    80.3    80.2    79.6    76.8    75.8    73.6    65.3    59.0
'NV=3 NST=1'    84.2    82.5    82.7    80.5    79.7    74.9    69.0    61.9
'NV=4 NST=1'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=5 NST=1'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=1 NST=2'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=2 NST=2'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=3 NST=2'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=4 NST=2'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=5 NST=2'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=1 NST=3'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=2 NST=3'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=3 NST=3'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=4 NST=3'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
'NV=5 NST=3'    0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
' '
'RECEIVER PARAMETERS. '
'       AXR(NR) AYR(NR) AZR(NR) AZRG(NR) ASIGG(NR) '
'NR=1'   -0.2   0.0    25.33    0.0      3.0E+7
'NR=2'  -65.5   0.0    12.33    6.5      1.5E+5
'NR=3'  -65.5   0.0    22.83    6.5      1.5E+5
'NR=4'  -65.5   0.0    33.33    6.5      1.5E+5
'NR=5'  0.0     0.0     0.0     0.0      0.0
'NR=6'  0.0     0.0     0.0     0.0      0.0
'NR=7'  0.0     0.0     0.0     0.0      0.0
'NR=8'  0.0     0.0     0.0     0.0      0.0
'NR=9'  0.0     0.0     0.0     0.0      0.0
'NR=10' 0.0     0.0     0.0     0.0      0.0
'NR=11' 0.0     0.0     0.0     0.0      0.0
'NR=12' 0.0     0.0     0.0     0.0      0.0
```

```
'NR=13' 0.0     0.0     0.0     0.0      0.0
'NR=14' 0.0     0.0     0.0     0.0      0.0
'NR=15' 0.0     0.0     0.0     0.0      0.0
'NR=16' 0.0     0.0     0.0     0.0      0.0
'NR=17' 0.0     0.0     0.0     0.0      0.0
'NR=18' 0.0     0.0     0.0     0.0      0.0
'NR=19' 0.0     0.0     0.0     0.0      0.0
'NR=20' 0.0     0.0     0.0     0.0      0.0
' '
'ATMOSPHERIC ABSORPTION; dB PER THOUSAND FEET'
'JOCT=           1      2      3      4      5      6      7      8'
'ATMOS(JOCT)='  .051   .165   .395   .643   1.00   2.18   6.75           24.50


************************************************************************
              TABLE OF ATMOSPHERIC ABSORPTION, dB/1000 ft.
          (placed here for easy transfer to data block above)

 JOCT=     |         1       2      3      4      5     6       7      8
 -------------------------------------------------------------------
 REL. HUM.,% |
           |
 10        |        .107   .193   .369   1.01   3.45   11.70  31.00  55.30
 20        |        .092   .202   .331   .597   1.56   5.31   19.00  58.75
 30        |        .074   .197   .365   .563   1.14   3.33   11.90  42.25
 40        |        .061   .183   .388   .597   1.02   2.54   8.52          31.26
 50        |        .051   .165   .395   .643   1.00   2.18   6.75          24.50
 60        |        .043   .150   .391   .686   1.03   2.00   5.71          20.91
 80        |        .033   .123   .365   .746   1.13   1.89   4.63          15.44
```


SAMPLE INPUT FILE FOR IMAGE-3 - VERSION 3.11
65.5 FT MAST OFFSET - PARALLEL BARRIER SITE

Appendix E

INSTRUCTIONS FOR WORKING THE PAPER-AND-PENCIL TEST

Appendix E

INSTRUMENTATION DOCUMENTATION

This Appendix documents the instrumentation used in this study. Included are manufacturers' names, model numbers, VNTSC control numbers, and serial numbers (S/N). In the case of the sound level meters (SLM), measurement location is also specified, e.g., Site 1: High.

Item #	Description (Model/Type)	VNTSC #	S/N
1a	Larson Davis Model 820 Type 1 SLM (Site 1: Ref)	NONE	0104
1b	Larson Davis Model 827-0V Preamplifier	NONE	0104
1c	General Radio Model 1962-9610 Microphone	NONE	10550
2a	Larson Davis Model 820 Type 1 SLM (Site 1: High)	NONE	0106
2b	Larson Davis Model 827-0V Preamplifier	NONE	0102
2c	General Radio Model 1962-9610 Microphone	NONE	12774
3a	Larson Davis Model 820 Type 1 SLM (Site 1: Mid)	31642	0113
3b	Larson Davis Model 827-0V Preamplifier	NONE	0113
3c	General Radio Model 1962-9610 Microphone	NONE	14334
4a	Larson Davis Model 820 Type 1 SLM (Site 1: Low)	31639	0117
4b	Larson Davis Model 827-0V Preamplifier	NONE	0117
4c	General Radio Model 1962-9610 Microphone	NONE	12643
5a	Larson Davis Model 820 Type 1 SLM (Site 2: Ref)	31640	0100
5b	Larson Davis Model 827-0V Preamplifier	NONE	0100
5c	General Radio Model 1962-9610 Microphone	NONE	14421
6a	Larson Davis Model 820 Type 1 SLM (Site 2: High)	31638	0110
6b	Larson Davis Model 827-0V Preamplifier	NONE	0110
6c	General Radio Model 1962-9610 Microphone	NONE	14503
7a	Larson Davis Model 820 Type 1 SLM (Site 2: Mid)	31637	0118
7b	Larson Davis Model 827-0V Preamplifier	NONE	0118
7c	General Radio Model 1962-9610 Microphone	NONE	10489
8a	Larson Davis Model 820 Type 1 SLM (Site 2: Low)	NONE	0107
8b	Larson Davis Model 827-0V Preamplifier	NONE	0107
8c	General Radio Model 1962-9610 Microphone	NONE	11707
9a	Larson Davis Model 820 Type 1 SLM (Spare) (Used at Site 2, low position on 10/10/91)	NONE	0170
10	General Radio Model 1987 Minical Sound Level Calibrator (Output Sound Pressure Level: 114 or 94 dB *re* 20 :PA, ±0.25 dB)	NONE	21128
11	CMI Model JF100 Doppler Radar Gun	13822	1303
12	Climatronics Model EWS Weather Station (Chart Speed: four inches per hour)	NONE	871

Item #	Description (Model/Type)	VNTSC #	S/N
13	Panasonic Model AG-170 Video Camera *	NONE	K8HD03002
14	AST Premium Exec Model 386SX/20 Notebook Computer	31784	USN1042658 500795-201
15	Compaq LTE Model 286 Notebook Computer (Spare)	31317	6102HAF -40377

The sound level meters and preamplifiers are calibrated at Larson Davis Laboratories, Inc., on a yearly basis and routinely checked for linearity and functionality at the Noise Measurement and Assessment Facility (NMAF). The microphones and calibrators are calibrated annually and checked prior to field measurements at the NMAF. Calibrator and microphone calibration is traceable to the National Institute of Standards and Technology (formerly the National Bureau of Standards).

The doppler radar gun was periodically checked in the field with a calibrated tuning fork. Meteorological instrumentation was calibrated prior to field measurements per manufacturer's specifications.

* Courtesy of Kenneth D. Polcak and the Maryland State Highway Administration.

Appendix F

REFERENCE MICROPHONE PLACEMENT

DULLES NOISE BARRIER PROJECT

This Appendix contains a revised version of a previously unpublished document, DTS-75-HW127-LR3A, Rev. 1 - April, 1992, "Reference Microphone Placement, Dulles Noise Barrier Project".

DTS-75-HW127-LR3A
REV. 1 - APRIL, 1992

REFERENCE MICROPHONE PLACEMENT
Dulles Noise Barrier Project

Gregg G. Fleming
Edward J. Rickley

FEBRUARY 1991

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U.S. DEPARTMENT OF TRANSPORTATION
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RESEARCH AND SPECIAL PROGRAMS ADMINISTRATION
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F2

1.0 Background

Barrier insertion loss is by definition the difference in noise level at a microphone before and after installation of a barrier, under the assumption that the noise source, terrain, ground, and atmospheric conditions are unchanged or equivalent. To monitor changes in the noise source, a reference microphone is placed at an identical position in both the BEFORE case (no barrier) and the AFTER case (barrier present) [ANSI, 87-1]. Proper placement of the reference microphone is the main topic of this document.

The ANSI Standard, "Methods for Determination of Insertion Loss of Outdoor Noise Barriers", S12.8-1987, recommends positioning the reference microphone 1.5 meters (approximately 5 ft) directly above the top edge of the barrier. However, a recent study has shown that this placement may result in errors in reported insertion loss of approximately 1 dBA [Fleming, Rickley, 90-2]. As a result, the 1.5 meter positioning of the reference microphone, as recommended by the Standard, may not be appropriate in all circumstances, especially when an opposite reflective barrier is present.

1.2 Introduction

The U.S. Department of Transportation, Research and Special Programs Administration, Volpe National Transportation Systems Center (U.S.DOT/RSPA/VNTSC), in support of the Office of Engineering and Highway Operations Research and Development, Federal Highway Administration (FHWA), and a National Pooled-Fund Panel (representing 17 States: Arizona, California, Connecticut, Florida, Georgia, Hawaii, Iowa, Maryland, Massachusetts, Michigan, New Jersey, New York, Ohio, Pennsylvania, Virginia, Washington and Wisconsin), conducted a field study to determine proper placement of the reference microphone for monitoring source stability. Measurements were conducted on August 28-29, 1990, at the FHWA's experimental barrier test site at Dulles International Airport in Chantilly, Virginia.

The installation, located on a two-lane asphalt service road at Dulles Airport, was comprised of a barrier test site and a physically equivalent test site (simulating the before barrier case). The barrier site was comprised of two 14-ft high vertical noise barriers constructed in parallel on opposite sides of the road (500 ft and 250 ft long, respectively). The roadside faces of the two barriers consisted of hard reflective plywood. The equivalent site, directly adjacent to the barrier site was a 250 ft wide flat grassy open field with the same physical characteristics as the barrier site.

1.3 Objective

The objective of this study was to: 1.) verify previous measurement results; and 2.) provide recommendations for proper placement of the reference microphone.

F4

2.0 Experimental Approach

2.1 Microphone Configuration

Eight reference microphones (five at the barrier site and three at the equivalent site) were deployed on two masts in direct line of sight with the roadway. The five microphones at the barrier site were set at heights of 19, 20, 21, 22 and 23 ft above the ground plane, corresponding to heights of 5, 6, 7, 8, and 9 ft directly above the edge of the barrier (Figure 1). The three reference microphones at the equivalent site were placed on a mast at heights of 19, 21, and 23 ft above the ground. This mast was placed at an identical offset position from the roadway to that at the barrier site.

Figure F1: Barrier Site Microphone Placement

Two tests were performed, a parallel barrier test and a single barrier test. For the parallel barrier test, the mast at the barrier site was placed in the center of the 500 ft barrier directly opposite the 250 ft barrier (Position A, Figure 2). For the single barrier test, the mast was moved to Position Z, 62.5 ft in from the north edge of the 500 ft barrier. This positioning insured no reflections from the 250 ft barrier on the opposite side of the roadway. The mast at the equivalent site was located at position A' during both tests.

2.2 Test Site

The roadside terrain between the source and reference microphones was essentially the same at both the equivalent and barrier sites. Both sites were surveyed to obtain exact ground contours and the differences in the two sites can be summarized as follows: 1.) the roadside drainage ditch is approximately one ft deeper (relative to roadway elevation) at the equivalent site compared with the barrier site; and 2.) the ground plane below the equivalent site reference mast is approximately 1.2 ft lower than that at the barrier site (relative to roadway elevation) [Fleming, Rickley, 90-2]. The effects of these terrain differences are considered negligible since: 1.) the ground-reflected sound path, from the source to the microphone for each source position on the roadway is unaffected by the drainage ditch and 2.) the difference in propagation distance associated with the 1.2 ft difference in ground elevation would account for less than 0.1 dBA difference in measured levels at the equivalent and barrier sites.

The surrounding ground at the equivalent and barrier sites was hard-packed clay covered with low-cut grass. For these measurements, the two reference masts were placed at their respective sites less than 400 ft apart and the ground throughout appeared homogeneous. In addition, the Barrier-X highway noise modeling program showed that, even if there were small changes in ground characteristics, these changes would have had a negligible effect on measured levels at microphones 19 to 23 ft above the ground plane [Slutsky, 87-3].

2.3 Measurement System

The Federal Highway Administration's mobile noise measurement van was used for all on-line data collection and processing. 500 ft of cable provided power to the microphone pre-amplifiers and fed acoustic data from the microphones back to the eight-channel noise measurement and analysis system inside the van. The acoustic data were processed by eight Cetec Ivie Model IE-30A 1/3-octave spectrum analyzers, digitized via the on-board IBM PC/AT computer, and stored away on floppy disk.

A Climatronics Model EWS weather station was deployed at a midway point between the two measurement sites to continually record temperature, humidity, wind speed and direction. A CMI doppler radar was set up 400 ft to the north of the 500 ft barrier to measure the speed of the two test trucks as they passed through the measurement area. Any test run where speeds deviated by more than 2 mph or which was judged contaminated by local ambient was repeated.

For more detailed information on the measurement and analysis system, see Ref. 2.

2.4 System Checkout

At the beginning of each measurement day, a complete system checkout was performed on all eight measurement systems. To minimize interaction between systems and to establish the electronic noise floor of each system, a passive microphone simulator was substituted for each microphone. In addition, the frequency response of each system was tested by recording a 20-second sample of pink noise. System calibration at two levels was performed before and after each measurement day, using four two-level GR1987 minical acoustic calibrators. To minimize systematic error, each calibrator was numbered and used on the same system throughout the measurements. Four systems were calibrated simultaneously, and 10 seconds of data were stored in computer memory.

2.5 Noise Sources

Two test trucks were used as noise sources. Truck A (see Figure 3) was a large diesel-powered dump truck with a vertical exhaust stack about ten ft high; truck C (see Figure 4) was a smaller-scale dump truck with a horizontal exhaust stack which was about 2 ft off the ground.

The driver of each truck was instructed to obtain a maximum achievable rate of speed prior to entering the test area and hold it constant (with no gear changes), as the vehicle was driven through the test site. The speed of each vehicle was continually recorded at the radar station. To further insure source stability, test runs where speed deviations were greater than 2 mph were repeated.

2.6 Data Collection

For both parallel and single barrier tests, the data during each pass-by were simultaneously collected from the eight measurement channels and stored on floppy disk in contiguous ¼-second data records for subsequent off-line processing.

2.6.1 Parallel Barrier Test

With system checkout completed and the two masts set up at positions A and A', traffic at both ends of the service road was stopped and the two test trucks were driven individually down the service road in a north to south direction (Figure 2). For measurements made on August 28, 1990, a total of six good test runs were made with each test vehicle (three each for the near and far lanes). On August 29, 1990, a total of nine good test runs were made with each test vehicle (three each for the near and far lanes and three runs with each truck driven down the center of the roadway) to increase statistical accuracy of the

data and to insure source stability as the trucks passed through the equivalent and barrier sites.

2.6.2 Single Barrier Test

With testing completed for the parallel barrier scenario, the mast at the barrier site was moved from position A to position Z (62.5 ft from the north edge of the 500 ft barrier). Six additional test runs were performed on August 28, 1990, and nine additional test runs were performed on August 29, 1990.

FIGURE F3: TRUCK A - SPECTRUM AND SUMMARY SPECIFICATIONS

YEAR: 1987 MAKE/MODEL: GMC GENERAL

ENGINE: 6 CYL DIESEL EXHAUST STACK: 10' VERT

AVG SPEED (mph): 35.8 STD DEV: 0.7 GEAR @ RPM: 6th @ 2000

FIGURE F4: TRUCK C - SPECTRUM AND SUMMARY SPECIFICATIONS

YEAR: 1979	MAKE/MODEL: FORD
ENGINE: 8 CYL GAS/360 cu	EXHAUST STACK: 2' HORZ
AVG SPEED (mph): 29.6 STD DEV: 1.7	GEAR @ RPM: 4th @ NA

3.0 Data Reduction

3.1 Sound Exposure Level (SEL)

Processing of the collected data was accomplished off-line using the VNTSC processing program, HWNOISE [VNTSC, 89-4], to obtain a graphical presentation of the A-weighted level versus time (time history) of each truck pass-by. Each time history was examined for possible external interference and any questionable files were discarded. For the remaining data files, the stored ¼-second record containing the maximum level recorded was identified and a period corresponding to two records before and two records after maximum was marked for data processing. Since one quarter second averaging was used in data collection, the data processing period selected was 1.25 seconds in duration and corresponds to a finite roadway segment of approximately 70 ft.

The Sound Exposure Level over this 1.25 second period was calculated for the eight microphones at the equivalent and barrier sites. No ambient adjustment was required for this data.

3.2 Source Adjustment

The Sound Exposure Level measured at each microphone height at the barrier site was subtracted from that measured at the identical height at the equivalent site to obtain the measured source adjustment.

Because no measurements were made at the 20 and 22 ft heights at the equivalent site, the SEL data at these two positions were interpolated from the data measured at the 19, 21, and 23 ft equivalent site microphones. Thus, the resultant source adjustments calculated for the 19, 21, and 23 ft heights were measured directly, while the source adjustments calculated for the 20 and 22 ft heights were interpolated.

3.3 Two-Day Average

The source adjustments calculated at similar heights for the two measurement days were then averaged together to obtain the final averaged source adjustment at each of five measurement heights (19, 20, 21, 22, and 23 ft). The final averaged source adjustments are presented in Figures 5 and 6 for the single barrier scenario, trucks A and C, respectively, and in Figures 7 and 8 for the parallel barrier scenario, trucks A and C, respectively.

4.0 Results

The measurement of barrier insertion loss (difference in measured noise levels at a microphone before and after installation of a barrier) depends upon the equivalence of the noise source, terrain, ground, and atmospheric conditions for before and after measurements. The reference microphone is used to account for differences in the emitted levels from the source in the before and after case (equivalent and barrier sites, respectively). Any difference in the emitted levels measured, from the before to the after case, assuming the criteria for terrain, ground and atmospheric equivalence are met, is termed source adjustment.

As discussed in Section 2.2, terrain and ground equivalence have essentially been established at the Dulles site. Since all noise measurements were performed simultaneously at the equivalent and barrier sites under low wind and relatively stable atmospheric conditions and since extensive care was taken with the truck sources to insure constant noise emissions as the trucks passed through the equivalent and barrier sites (see Section 2.5), a source adjustment of zero was expected. However, as seen in Figures 5 through 8, a difference as high as 1.8 dBA was measured and varied with the type of source, the barrier configuration, the source position on the roadway, and the height of the reference microphone above the barrier.

4.1 "Source Adjustment" - Single Barrier Case

As shown in Figure 5, the "source adjustments" obtained for truck A (high vertical exhaust stack), in the near and far lanes, are essentially identical and vary between -.1 and -.7 dBA with reference microphone height above the barrier. The "source adjustment" with truck A in the center of the roadway is essentially 0 dBA.

For truck C (low horizontal exhaust), the "source adjustments" in the near and far lanes were again in good agreement and varied between 0 and -.8 dBA with reference microphone height above the barrier (Figure 6). However, the "source adjustment" with truck C in the center of the two lane roadway is about -1.0 dBA. In addition, it is about 1.0 dBA more negative than that measured with truck A in the center of the roadway.

4.2 "Source Adjustment" - Parallel Barrier Case

Figure 7 shows the "source adjustment" obtained for truck A. Although there is no specific lane-to-lane trend as was the case in the single barrier scenario, the "source adjustment" is on average .5 dBA larger (in the negative direction) than that obtained for

the single barrier case. This increase in the negative direction appears to be associated with the multiple reflections between the two parallel reflective barriers.

For truck C, Figure 8, the "source adjustment" is on average .75 dBA more negative than that obtained for the single-barrier case. This increment again appears to be due to multiple reflections between the two parallel barriers. In general, the "source adjustment" with truck C in the center of the roadway was considerably more negative than that obtained for both the near and far lanes. This agrees well with the single barrier data and appears to affirm the dependance of the "source adjustment" on both equivalent source height and source position between the two barriers.

4.3 Reference Microphone Height

The 19-ft reference height used in this study corresponds to a reference position of 5 ft directly above the edge of the barrier, as recommended in the ANSI standard. This was the reference height used in the 1989 Dulles tests. As can be seen in Figures 5 through 8, "the source adjustment" at the 19 ft reference receiver, although in good agreement with the 1989 tests, had a consistently larger deviation from zero as compared with the data measured at the other four reference microphone heights. Based on the data presented in Figures 5 through 8, it appears that positioning the reference microphone six ft above the edge of the barrier is a better compromise than the 5 ft positioning.

Since the data obtained during this study were limited to one test site and two controlled truck sources there may be some site/source bias in the "source adjustment" data. As a result, additional test data at both single and parallel barrier sites with varied geometries and a mix of traffic conditions are required to determine a site and/or source specific correction for the "source adjustment" to account for source height, source position, and/or multiple reflections. The eventual goal will be to develop a means of predicting the appropriate "source adjustment" correction for a given test scenario.

5.0 Conclusions and Recommendations

Conclusions based on the findings of this study can be summarized as follows:

! Good agreement was obtained between this data and the 1989 Dulles barrier data.

! The "source adjustment" is affected by equivalent source height, source position relative to the barrier(s), and the presence of an opposite reflective barrier.

! A site specific correction may be required for the "source adjustment" to account for source height, source position, and/or multiple reflections.*

* In May, 1991, the Acoustical Society of America's S12-6 Working

Group (WG) met at Vanderbilt University in Nashville, TN, with the objective of performing a final evaluation of ANSI S12.8-1987, "Methods for Determination of Insertion Loss of Outdoor Noise Barriers," based on the results of the NMAF Dulles study and the Caltrans Route 99 study [Hendriks, 91-5]. Among the conclusions of the WG, the current reference microphone adjustment procedure, per ANSI S12.8-1987, is incorrect, especially in the case of a parallel-barrier configuration.

In a memorandum submitted to the Acoustical Society of America, the WG proposed applying a reflection/edge diffraction correction to noise levels measured at the reference microphone in the "AFTER" site, i.e., the site of interest where a noise barrier is in place, prior to performing the normal reference microphone adjustment. The memorandum includes the following paragraph:

> "It is possible that the introduction of the barrier will increase sound pressure levels at the reference microphone due to induced multiple reflections between source and the barrier and/or edge diffraction at the top of the barrier. A 0.5 dB increase in sound level at the reference microphone located above the barrier may be considered typical and should be included as a correction factor to the reference microphone data, unless further analysis of the propagation characteristics of source/barrier/microphone configuration justifies other values. **Larger corrections for multiple reflections may be considered in the case of parallel barriers or enclosures.**"

6.0 References

1. Methods for Determination of Insertion Loss of Outdoor Noise Barriers. Report ANSI S12.8-1987. American National Standards Institute, New York, 1987.

2. Fleming, G.G., Rickley, E.J., Parallel Barrier Effectiveness, Dulles Noise Barrier Project, Report No. FHWA-RD-90-105, Transportation Systems Center, May 1990.

3. Slutsky, Simon; Bertoni, H.L.; Polytechnic Institute of New York, Parallel Noise Barrier Prediction Procedure: Description and Analysis of Tilted Absorptive Barriers, Report 1, Prepared for the Transportation Systems Center, 1987.

4. HWNOISE Program User's Guide. Report No. DOT-TSC-HW927-LR5, Transportation Systems Center, September 1989.

5. Hendriks, R.W., Field Evaluation of Acoustical Performance of Parallel Highway Noise Barriers Along Route 99 in Sacramento,

California, Report No. FHWA-CA-TL-91-01, Sacramento, CA: California Department of Transportation, Division of New Technology, Materials and Research, January, 1991.

150 Copies