NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **144**

HIGHWAY NOISE

A FIELD EVALUATION OF TRAFFIC NOISE REDUCTION MEASURES

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NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING

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B. ANDREW KUGLER AND ALLAN G. PIERSOL
BOLT BERANEK AND NEWMAN
CANOGA PARK, CALIFORNIA

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:

- HIGHWAY DESIGN
- ROAD USER CHARACTERISTICS
- URBAN COMMUNITY VALUES

HIGHWAY RESEARCH BOARD
DIVISION OF ENGINEERING   NATIONAL RESEARCH COUNCIL
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The program is developed on the basis of research needs identified by chief administrators of the highway departments and by committees of AASHO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Highway Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By Staff
Highway Research Board

This report will be of interest to highway engineers and other students of noise impact related to highway design. Its significance lies in the evaluation and modification of noise control prediction procedures outlined in *NCHRP Report 117,* "Highway Noise—A Design Guide for Highway Engineers." The modified procedures offer a means of evaluating the noise reduction qualities of roadside barriers, elevated and depressed highway sections, and roadside structures.

The project on which this report is based is the third in a series of studies conducted by Bolt Beranek and Newman under contract to the NCHRP. Earlier projects were reported in *NCHRP Report 78,* "Highway Noise—Measurement, Simulation, and Mixed Reactions," and *NCHRP Report 117,* "Highway Noise—A Design Guide for Highway Engineers." In the present project, the objectives were to evaluate by field studies the noise-reducing characteristics of various noise-control constructions and thereby to confirm or modify prediction procedures that had been based primarily on model and theoretical studies.

The report describes the selection of sites used in field evaluations, the techniques used in the collection and reduction of noise data, and the analyses designed to assess the parameters that might influence the effectiveness of different noise-reducing measures. These parameters, which were measured at each site simultaneously with the acoustic characteristics, included traffic volumes, speeds, truck/automobile mix, and prevailing environmental conditions of a terrain and meteorological nature. Thus, in addition to providing an opportunity for comparing observed versus predicted characteristics of noise-reduction measures, the field data collection served to demonstrate further that the modified design guides could be employed for the most part without concern for variations in these parameters.

The report concludes with recommendations for additional research into highway noise problems and presents detailed appendices that incorporate the modified procedures to be employed in design evaluation (Appendix C). Continuation of the highway noise research developed from this and the previous studies is expected to examine noise sources, noise control measures, and their economics, and to develop improved recommendations for highway noise level criteria.

CONTENTS

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The field measurement studies and data reduction program were accomplished largely by Mr. Horonjeff and Mr. Kugler. Robert P. Costello and Stewart W. Ferguson assisted in many of the field measurements and in the data reduction phase. Mr. Piersol was responsible for the analysis and interpretation of the field noise data. Special thanks are due to Dr. Sanford Fidell for his contributions to the final report and analysis of the photographic data, and to Myles A. Simpson and Nicolaas H. Reddingius for the Modified Line Source Model computer simulation.

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Special thanks are also due to all the state highway departments contacted in the site identification program. Their prompt response and enthusiasm in connection with this project are appreciated.

HIGHWAY NOISE

A FIELD EVALUATION OF TRAFFIC NOISE REDUCTION MEASURES

SUMMARY

A study completed in 1970 resulted in a Design Guide document (*NCHRP Report 117*) that sets forth systematic procedures for the calculation of highway noise levels. The various noise prediction techniques presented in that Design Guide were derived from a vast assortment of theoretical and empirical information. Hence, it is appropriate that key procedures in the Design Guide be evaluated using actual field data for selected highway configurations under various normal traffic and environmental conditions. Of special interest are the procedures for predicting the noise reduction available from different highway noise shielding techniques. The ultimate goal is to validate the Design Guide procedures and, if necessary, modify them to more accurately reflect the results of actual field measurements. Such was the purpose of the study reported herein.

The study considered four basic highway noise reduction constructions: (1) roadside barriers, (2) elevated highway sections, (3) depressed highway sections, and (4) roadside structures. To minimize the number of variables to be evaluated, strict criteria were imposed on the selection of the test sites. After a thorough search in 30 states, 6 test sites were selected for field evaluation. Of these sites, three were located in California, two in Minnesota, and one in Michigan. They consisted of one roadside barrier case, two elevated highway cases, one depressed highway case, and two cases involving roadside structures.

For each selected test site, a comprehensive measurement plan was developed. The measurement program was designed to fully describe the acoustic characteristics of each site, and to assess the contribution of traffic and environmental parameters to the over-all noise reduction characteristics of each highway geometry. Acoustic measurements were taken at various distances from the roadway and at different heights above the ground to obtain a spatial description of the sites. Simultaneous measurements of traffic volume, traffic speed, and truck mix, as well as measurements of the prevailing environmental conditions, were made during each test. The measurements were obtained under as many different traffic conditions as possible.

The noise data acquired in the field were reduced statistically in terms of the L_{10} and L_{50} noise level descriptors used in the Design Guide so that a direct comparison could be made between actual field conditions and prediction techniques. The measured data were then converted to excess noise reductions at various locations (distances from the roadway and heights above the ground) by subtracting shielded L_{50} levels from estimated free-field L_{50} levels. Measured data were compared to predicted noise reductions using various noise prediction techniques. Emphasis was placed on the procedures of the Design Guide and those of a more recent method for predicting barrier attenuation where the traffic noise is assumed to be a line

of incoherent sources. The agreement between measured and predicted results was assessed in terms of various statistical parameters (e.g., average discrepancy, standard deviation of the discrepancy).

For the roadside barrier, elevated highway, and depressed highway configurations, the results of the evaluation indicate that the Design Guide procedures tend to underpredict the noise reductions at locations involving small path length differences (i.e., the difference between the direct path between source and receiver and the shortest path over the barrier), and overpredict the noise reductions at locations distant from the roadway when the intervening terrain is free of ground cover. The first problem is due to deficiencies in the basic barrier attenuation model implemented by the Design Guide; the second is associated with the fixed free-field propagation loss factor of 4.5 dB decrease per doubling of distance assumed by the Design Guide. There is also a tendency for the Design Guide procedures to underpredict the noise reduction for truck traffic.

Based on the foregoing observations, the Design Guide procedures for predicting noise reductions due to roadside barriers and elevated and depressed highway configurations were modified in three ways: (1) the basic barrier attenuation model in the Design Guide was replaced by a more recently derived Line Source Model; (2) the free-field loss factor of 4.5 dBA per doubling of distance was replaced by a factor more appropriate for the type of ground cover at the test sites; and (3) the noise reduction adjustment for trucks was altered to yield more realistic corrections from the viewpoint of the Line Source Model. New predictions were then made using the modified procedures, and the results were compared to the measured noise reduction data as before. The results confirm that the modifications eliminate nearly all of the previously observed discrepancies.

For the case of roadside structures, the results of the evaluation indicate that the Design Guide underpredicts the noise reductions due to a single row of structures (one-story houses), but overpredicts for multiple rows of structures. A modified version of the Line Source Model, applied successfully to other noise reduction configurations, was found to provide more accurate noise reduction predictions for roadside structures as well. However, proper application of the model to this case requires unduly elaborate calculations as a result of the intermittent nature of the shielding provided by roadside structures.

The results reveal no direct evidence of a significant influence of traffic and environmental factors (other than truck mix) on the accuracy of the Design Guide noise reduction predictions. Specifically, the accuracy of the predictions appears to be independent of traffic volume and speed, as well as temperature and small amounts of wind (less than 8 mph). However, there is reason to believe that wind could strongly influence the noise reduction performance of various noise control configurations under certain conditions.

The results of the study indicate that modifications of the Design Guide procedures are needed for all four highway configurations to improve the accuracy of the noise reduction predictions. The necessary modifications are presented in the form of new noise reduction calculation procedures for inclusion in the Design Guide. These modifications should greatly increase the utility of the Design Guide as a tool for highway engineers.

The study also produced considerable data for highway traffic noise that might be useful in other studies of this general subject.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

STATEMENT OF PROBLEM

Traffic noise generated on modern highways is a major source of environmental noise pollution. There are urgent needs not only for realistic highway noise standards, but also for engineering tools that can be implemented by highway designers to control this form of noise pollution. In a recent study, *NCHRP Report 117* (*1*), of which this project is a continuation, systematic procedures for the calculation of highway noise levels were presented in the form of a Design Guide for highway noise prediction.

The methods specified in the Design Guide represent a good first step toward the solution of traffic noise problems. They allow a highway engineer to predict the expected noise levels for particular highway configurations, and to assess the changes in noise levels due to modifications of highway geometry. However, because the Design Guide methods were based in part on theoretical model studies involving many simplifying assumptions, it was apparent that a detailed investigation of certain noise-control measures under field conditions was necessary. Specifically, additional verification of the procedures recommended for calculating the noise reduction characteristics of highway barriers and elevated or depressed highway configurations was believed to be in order.

Several theoretical and empirical methods previously have been proposed for calculating how barriers reduce the sound level from a point source (*2, 3, 4, 5, 6, 7*). However, the applicability of these methods to field situations is questionable because an actual highway entails a source that is distributed over the roadway geometry. Furthermore, the spectrum varies widely both in frequency and in time. In developing the Design Guide, a limited field measurement program was conducted to verify theoretical predictions. As a result of this program, procedures were modified to account for an extended noise source. More recently, a further refined model for predicting barrier noise reductions has been suggested (*8*) where the noise source is modified to represent an incoherent line source. However, various traffic characteristics and environmental conditions that influence the noise reduction provided by a barrier or elevated/depressed roadway configuration remain only partially understood. Additional field data under actual highway conditions are still necessary to evaluate the applicability of these results.

Another form of traffic noise control involves the use of roadside structures. For example, commercial or industrial buildings adjoining a highway or housing activities that are not sensitive to high noise levels can be used effectively as a shield to protect a more distant residential community. Such construction can be an effective means of noise control for existing roadways where land use next to the roadway permits such development, or where a rebuilding program is contemplated. A British study (*10*) on the subject was published in October 1971. Further, when one is predicting noise levels due to a proposed highway, it is important to know the amount of excess noise reduction afforded to the rest of the community by the first few rows of houses. At present, only limited data are available, collected primarily in previous studies under this project (*1, 9*). However, these prediction procedures require refinement if the method is to be widely used as an effective means of highway noise control. A field evaluation program to determine the efficiency of this noise reduction source was therefore required. Also, the high cost of implementing such traffic noise reduction measures, either in existing roadways or in future designs, demanded a more accurate assessment of their noise reduction characteristics.

OBJECTIVES

In view of the limited prior field data, and the need for more accurate prediction techniques for the noise reduction performance of various highway constructions, the objectives of this study were to:

1. Review and analyze the present state of the art in the prediction of acoustic performance for various noise reduction constructions. The constructions to be considered included (a) roadside barriers, (b) elevated highway sections, (c) depressed highway sections, and (d) roadside structures.
2. Locate operational examples of typical constructions and conduct a data acquisition program to collect field noise reduction measurements.
3. Interpret the field data in terms of the parameters that modify the noise reduction effectiveness of each construction.
4. Relate the foregoing information to current prediction techniques, and validate or modify the current procedures in *NCHRP Report 117* (*1*).
5. Prepare, when appropriate, corrected noise prediction procedures for the various constructions in a form that can be incorporated into *NCHRP Report 117*.

ORGANIZATION OF REPORT

This report is organized in accordance with the chronological conduct of the research effort. Chapter One includes a statement of the basic research approach, followed by a discussion of the criteria for selecting measurement sites. (The sites are described in Appendix F.) Measurement procedures at each site, and data reduction programs, are discussed.

Chapter Two deals with the findings of the research program. The noise reduction characteristics measured for the four basic highway geometries are discussed and evaluated

in comparison to the analytical model used in *NCHRP Report 117*, and other models. The influence of various parameters, both traffic and environmental, on the noise reduction characteristics of the test sites is discussed.

Modifications to present prediction techniques suggested by the results of the present study are discussed in Chapter Three. Emphasis is placed on upgrading the procedures in *NCHRP Report 117*.

The study conclusions, based on a comparative analysis of the findings and suggestions for future research, appear in Chapter Four. The Appendices contain associated information developed during this study.

RESEARCH APPROACH

The basic goal of this project was to quantify and evaluate the effects of various highway geometries on highway noise reduction under field conditions. The initial task was to define, locate, and select the basic highway geometries to be evaluated. Four different configurations were chosen: (1) elevated highways; (2) depressed highways; (3) roadside barriers or earth berms; and (4) roadside structures. After an intensive search of existing configurations throughout the United States, six test sites were selected for acoustical evaluation.

The next step was to design a measurement program for each test site that would be capable of collecting data to support an adequate site description in acoustic terms. This was followed by the data acquisition program in which the sites were evaluated. The maximal number of traffic conditions were measured and recorded within the time constraints for the field evaluation of each site. Although the study goal was to evaluate each site under a broad range of traffic conditions (i.e., high and low traffic volumes, different truck-to-auto mixes, etc.), data collection was necessarily confined to conditions found at each site.

The last step was reduction and evaluation of the field data in terms of the traffic, environmental, and geometric parameters of interest. This was logically followed by evaluation of field data against other models (i.e., *NCHRP Report 117*) to determine agreement and upgrade the current procedures as necessary.

LOCATION AND SELECTION OF FIELD TEST SITES

Two basic approaches were available to the field evaluation program required by this project. The first approach consists of actually creating a test site at which a comprehensive measurement program can be conducted. For example, in the case of a barrier, a test wall could be built to conform exactly with desired geometric characteristics. Moreover, the test wall could be located in an area where all the desired traffic conditions exist. The parameters of the wall could then be changed at will by increasing its height or length, or by treating it with an acoustically absorbent material.

The second approach relies on evaluating existing field situations. This approach demands the identification of suitable configurations for evaluation. Because the parameters of the barrier (in this case) cannot be varied, several field situations must be found and evaluated to obtain data over the desired range of configuration parameters for that purpose. Because of the restrictions imposed by the funds allotted for this program, the latter approach was used.

The field survey approach presents a number of practical difficulties. First, a successful field evaluation program requires that each test site be of uniform geometry for a considerable distance—a situation difficult to find in practice. For example, the requirements of the elevated highway section were a constant elevation over the surrounding terrain (within ±10 percent of height) for at least 3,500 ft. It further requires that the terrain next to the highway be reasonably flat and void of any structures or noise sources that might otherwise interfere with the field measurements. These requirements are necessary to minimize the number of variables inherent in the description of the site geometry and to achieve the desired simple line noise source. In addition, traffic requirements must be considered. The program plan called for a range of traffic conditions where the vehicle volume and truck-to-automobile ratio varied.

All these requirements were summarized in a memorandum that was sent to 30 state highway departments. An attached cover letter explained the purpose of the study and requested the departments' assistance in locating such sites throughout their state's highway network.* Approximately 75 percent of the states responded to the inquiry. However, only eight states were successful in locating highway sites that met the required criteria. (See Table 1).

From the preliminary analysis of the suggested sites, 15 were selected for on-the-spot evaluation. Field trips were made to the sites in California, Iowa, Minnesota, and Louisiana. Six primary sites were selected on the basis of the field trips:

1. California—roadside barrier.
2. California—elevated highway configuration.
3. California—elevated highway configuration.
4. Minnesota—depressed highway configuration.
5. Minnesota—roadside structures.
6. Michigan—roadside structures.

In addition, four secondary sites were selected. Although these sites do not meet all the requirements specified in the memorandum, they contain a number of features that were of interest in this project:

7. Iowa—elevated highway configuration.
8. Iowa—roadside structures.
9. Minnesota—depressed highway configuration.
10. California—roadside structures.

The objective was to fully evaluate all six primary sites, with measurements undertaken at the secondary sites only as budget and schedule permitted.

DATA ACQUISITION PROGRAM

The data acquisition program was intended to permit evaluation of the effects of as many highway variables on noise as possible. Some of the factors that affect noise levels are

* An expanded version of the field site and traffic condition requirements appears in Appendix E.

inherent in the geometry of the test site. For example, an elevated highway cross-section can be represented by the roadway width, elevation over the surrounding terrain or receiver location, distance between roadway and receiver, etc. The primary objective was to evaluate the effects of these constant geometric factors on highway noise. However, two other groups of factors must be considered in fully describing a highway noise situation: (1) traffic parameters, and (2) effects of weather and ground conditions.

The description of traffic parameters is essential to the understanding of traffic noise data. Such variables as vehicle volume, truck-to-automobile mix ratio, and average traffic speed on the roadway must be known before meaningful interpretation of noise data is possible.

The propagation of traffic noise is influenced by terrain conditions, wind conditions, temperature gradients, and humidity. The effect of the ground plane on sound propagation, especially for receiver locations close to the ground, also should be considered.

The objective of the measurement program was thus to identify the contributions of these three major groups of factors to the over-all noise reduction characteristics of each test site. To satisfy this objective, measurements were made, as discussed in the following.

First, variables such as height and distance from source to the receiver were considered. Noise measurements were acquired at various distances from the highway (up to 600 ft from the near lane in some instances) and at different altitudes (up to 25 ft over surrounding terrain). This was done to obtain a spatial description of the noise field. Typically, four monitoring stations were used simultaneously, with 10-min tape recordings obtained at each location.

Second, traffic data were acquired simultaneously with noise measurements. Three variables measured were average speed, traffic volume, and truck mix (T/A) ratio. Speed measurements were obtained by sequential photographs of the traffic, taken at a 250-millisec framing rate. Traffic volume information was obtained in the field by counting both automobiles and trucks during the tape-recording period.

Third, careful measurements of weather conditions were obtained approximately every one-half hour during the tape-recording periods. Temperature, humidity, wind intensity, and wind direction were recorded. Instrumentation and measurement techniques used for both acoustic and nonacoustic data are described in Appendix A.

In Appendix F each test site is described with respect to measurement locations, traffic conditions, and the data acquisition process.

DATA REDUCTION PROGRAM

Noise Data—Statistical Analysis

One of the main tasks of the data reduction program was the statistical analysis of the acoustic data tape recorded in the field. This was done by first reducing each data sample in terms of the "A-weighted" sound pressure levels. Then, the data were analyzed by passing each sample through a "statistical distribution analyzer." A computer program developed for this project was used to calculate the statistical descriptors used in *NCHRP Report 117,* as well as other measures of noise. The instrumentation and data reduction techniques are described in Appendix A. Figure 1 shows a sample of the resulting computer output. These results were obtained for two data samples at Site 3 (San Diego Freeway). The particular station shown represents the "reference location"; i.e., the microphone location near the highway with unobstructed view of the traffic pattern. In addition to the L_{50} and L_{10} levels used in *NCHRP Report 117,* the program calculates many other descriptors of noise. For example, the NPL level corresponds to the Noise Pollution Level, a descriptor (developed in Great Britain) that is gaining increasing acceptance as a measure of subjective response to certain types of noise.

TABLE 1

RESPONSE TO INQUIRY FORMS

	NO. OF SITES IDENTIFIED, BY TYPE			
STATE	DEPRESSED	ELEVATED	BARRIER	ROADSIDE STRUCTURE
California	1	2	1	2
Colorado	—	—	—	1
Iowa	—	2	—	1
Illinois	—	2	—	2
Louisiana	—	1	—	1
Massachusetts	—	1	—	1
Michigan	2	1	—	1
Minnesota	3	—	—	1

For completeness, a summary of the noise data corresponding to L_{50} and L_{10} descriptors as well as the calculated value of NPL and TNI for each test site and sample run are included in Appendix A (Tables A-1 through A-6).

The distribution of the L_x levels in Figure 1 represents the percentage of time a given noise level is exceeded over the 10-min measurement period. *NCHRP Report 78* (*9*) assumes that traffic noise is normally distributed in time. A plot of the L_x noise level data for a particular set of measurements on normal distribution paper shows that this assumption is reasonable (Fig. 2). The data deviate from the normality assumption below L_{90} and above L_{10}. However, within those limits ($L_{10} > L_x > L_{90}$) the results are within 1.0 dB. This was found to be true for all plotted data except Site 1, which is discussed later. In the plotted case, the microphone was located 5 ft above the ground.

A straight line on this graph indicates that the data are normal; the slope indicates the value of standard deviation. If the test sample were of infinite length, the true mean would correspond to the median or L_{50} value. For the 10-min sample used in these studies, the two numbers were found to fall within ±1.0 dB under normal-to-heavy traffic flow conditions.

Site 1 was a very lightly traveled road. In such cases, acoustic data (dBA) cannot be normally distributed because the background ambient noise truncates the lower end of the distribution curve, causing a skewness toward

```
                                        San Diego Frwy
LISTING OF STATISTICAL ANALYSIS FOR SITE 3 LOCATION 1
                                                    Reference Location
SAMPLE NUMBER =    15  @ TIME =   0640 HRS.

MEAN = 73.67     (ST. DEV = 2.552)   ENERGY MEAN = 74.68
NPL  = 81.21     NPL' =     80.32    TNI =          65.52

        L  1   =    82.49*
        L  3   =    80.70
        L  5   =    79.14
        L 10   =    76.89*
        L 20   =    74.91
        L 30   =    74.42
        L 40   =    73.92
        L 50   =    73.43*
        L 60   =    72.94
        L 70   =    72.41
        L 80   =    71.54
        L 90   =    70.68*
        L 95   =    70.24
        L 97   =    70.07
        L 99   =    68.58

SAMPLE NUMBER =    16  @ TIME =   0655 HRS.

MEAN = 73.01     (ST. DEV = 2.186)   ENERGY MEAN = 73.71
NPL  = 79.31     NPL' =     78.43    TNI =          60.99

        L  1   =    80.68*
        L  3   =    78.58
        L  5   =    77.26
        L 10   =    75.57*
        L 20   =    74.53
        L 30   =    73.96
        L 40   =    73.40
        L 50   =    72.83*
        L 60   =    72.25
        L 70   =    71.64
        L 80   =    71.04
        L 90   =    70.43*
        L 95   =    70.13
        L 97   =    70.01
        L 99   =    68.39
```

Figure 1. Statistical analysis of highway noise data, Site 3.

the higher dBA values. This skewness is apparent in the dBA distribution data for Site 1, particularly at Station A (see Fig. A-9). The L_{50} data for Site 1, however, should be acceptably reliable because the distribution is reasonably well-behaved in the vicinity of the median level.

Traffic Volume and Mix Data

The traffic volume and truck mix ratio (T/A) data collected during the noise measurement study were reduced as shown in Table 2. The total volume (automobile volume and truck volume) was computed in terms of an hourly basis, and the truck-to-auto traffic mix ratio was reduced to a percentage. The information is presented as a function of all lanes, and for opposite traffic flows. Appendix A gives these data for the other test sites.

Average Traffic Speed

Another computer program developed under this project was used to analyze and obtain average traffic speed information. During each 10-min highway noise sample a high-speed camera recorded the highway activity (four exposures per second). The photographic data were then reduced by projecting the film negative on a Grafacon tablet connected to a PDP-8 computer. By selecting and recording the location of a car or truck on two consecutive frames, and by averaging this information over a number of events, an accurate description of the average speed in each traffic lane was obtained.

Figure 3 shows a sample computer output. Lanes 1 through 4 correspond to the near lanes from the measurement position; lanes 5 through 8 correspond to the far lanes. In each case an average speed over all four lanes was computed. This information is summarized together with the traffic volume data and given in Table 2 and in

TABLE 2

TRAFFIC VOLUME AND AVERAGE SPEED CONDITIONS DURING NOISE MEASUREMENT PERIODS, SITE 2

	ALL LANES (8)					NEAR LANES (4)					FAR LANES (4)				
	VOLUME (VPH)				AVG.	VOLUME (VPH)				AVG.	VOLUME (VPH)				AVG.
RUN NO.	TOTAL	AUTO	TRUCK	T/A (%)	SPEED (MPH)	TOTAL	AUTO	TRUCK	T/A (%)	SPEED (MPH)	TOTAL	AUTO	TRUCK	T/A (%)	SPEED (MPH)
1	13,650	13,206	444	3.3	53.2	7590	7410	180	2.4	50.2	6060	5796	264	4.5	56.2
2	13,110	12,630	480	3.8	50.5	6210	6006	204	3.3	43.7	6900	6624	276	4.1	56.4
3	12,360	12,048	312	2.5	56.2	6540	6456	84	1.3	48.4	5820	5592	228	4.0	64.1
4	13,080	12,660	480	3.3	55.0	7230	7074	156	2.2	48.0	5850	5586	264	4.7	62.0
5	11,280	10,920	360	3.2	57.7	5970	5790	180	3.1	55.9	5310	5130	180	3.5	59.5
6	10,410	9,870	540	5.4	51.3	5220	4992	228	4.5	51.2	5190	4878	312	6.3	51.5
7	10,560	9,960	600	6.0	56.1	5640	5292	348	6.5	55.6	4920	4668	252	5.3	57.7
8	12,090	11,562	528	4.5	52.7	5640	5376	264	4.9	51.3	6450	6186	264	4.2	54.1
9	13,080	12,600	480	3.8	51.2	6450	6330	120	1.8	53.8	6630	6270	360	5.7	50.2
10	14,070	13,638	432	3.1	55.1	6900	6720	180	2.6	55.0	7170	6918	252	3.6	55.2
11	13,140	12,816	324	2.5	60.1	7440	7260	180	2.4	58.7	5700	5556	144	2.5	61.5
12	14,070	13,722	348	2.5	55.0	7230	7110	170	1.6	56.0	6840	6612	228	3.4	54.0
13	11,760	11,460	300	2.6	51.4	4080	3816	264	6.9	52.9	7680	7644	36	0.4	49.9
14	12,630	12,354	276	2.2	47.4	4680	4488	192	4.2	49.4	7950	7866	84	1.0	45.4
15	14,430	14,166	264	1.8	52.0	6330	6150	180	2.9	55.0	8100	8016	84	1.0	49.0
16	11,130	10,746	384	3.5	57.6	5040	4788	252	5.2	54.5	6090	5958	132	2.2	60.8
17	11,400	10,968	432	3.9	60.2	5070	4866	204	4.1	57.5	6330	6102	225	0.7	63.0
18	11,910	11,478	432	3.7	58.3	5730	5526	204	3.6	57.1	6180	5952	228	3.8	59.5
19	11,370	10,962	408	3.7	59.0	5760	5544	216	3.8	58.0	5610	5418	192	3.5	60.0
20	12,450	12,030	420	3.4	56.0	5730	5502	228	4.1	54.1	6720	6528	192	2.9	58.0

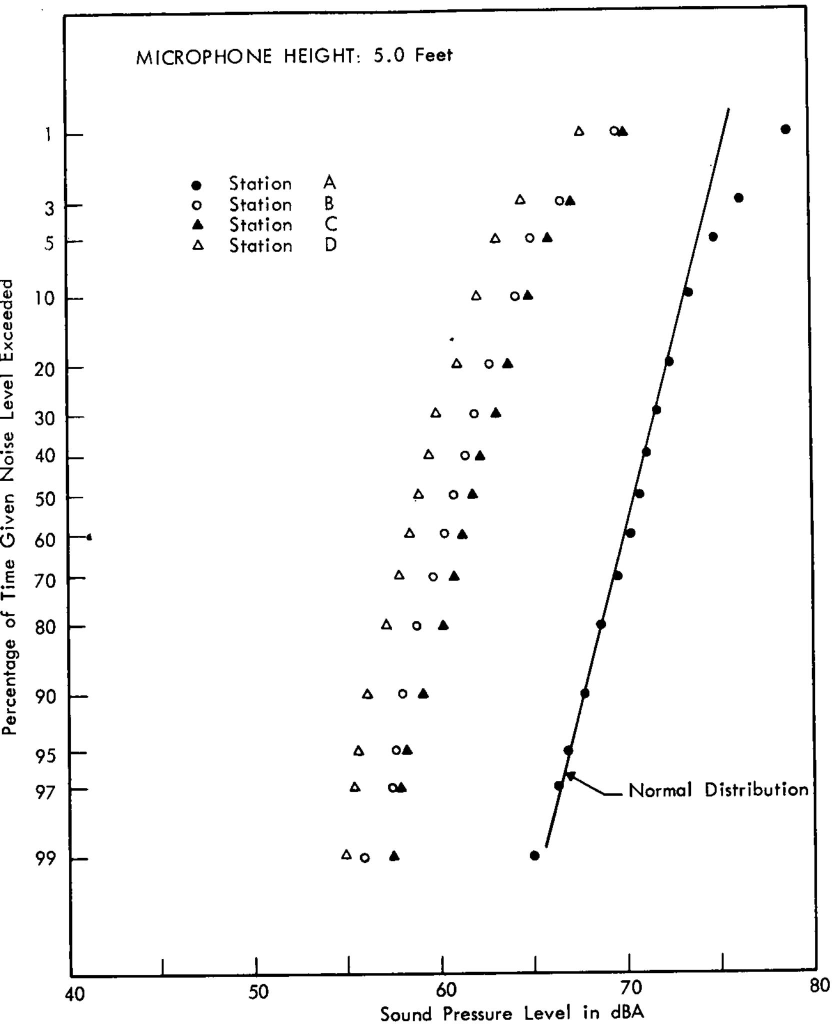

Figure 2. Cumulative distribution curves, Site 3.

```
AVERAGE TRAFFIC SPEED ANALYSIS
SITE #:     9   RUN #:     3    DATE: 9-29-71      TIME: 0

  LANE       SPEED (MPH)
   1             53.5
   2             57.9
   3             62.5
   4             64.0
          AVERAGE:        58.2

   5             59.8
   6             62.1
   7             62.3
   8             59.8
          AVERAGE:       61.1
```

Figure 3. Sample of average traffic speed data analysis, Site 9.

Appendix A. Instrumentation and equipment, as well as the procedures used in the reduction of the photographic information, are described in Appendix A.

Weather Data Reduction

Weather data obtained in the field (temperature, wind intensity and direction, and relative humidity) were summarized and included in Appendix A.

CHAPTER TWO

FINDINGS

GENERAL DATA EVALUATION PROCEDURES

Of primary concern in this study are the effectiveness and accuracy of procedures for predicting the noise reduction due to various highway noise control measures, as presented in *NCHRP Report 117,* "Highway Noise—A Design Guide for Highway Engineers" (*1*), referred to herein as the Design Guide. To this end, extensive evaluations were performed using the L_{50} levels computed from the measured highway noise data, plus the supplemental traffic flow and environmental data in Appendix A. The general evaluation procedures were as follows.

The L_{50} noise levels computed from the measurements at each test site were converted to excess noise reductions at various locations (distances from the roadside and heights above the ground) by subtracting the shielded L_{50} levels from estimated free-field L_{50} levels. The free-field L_{50} levels at the shielded locations were estimated by extrapolating the L_{50} levels measured at free-field reference stations (Station A) based on the free-field noise propagation rule of 15 log *D* (4.5 dB decrease per doubling of distance), as suggested in the Design Guide. For this purpose, the distance, *D*, from the source was measured

in terms of the "single-lane-equivalent" distance, D_E, as shown in Figure 5 of the Design Guide. In an effort to provide maximum accuracy in the free-field noise estimates, equivalent distances were computed separately for the opposite traffic lanes and then combined to a single D_E after weighting for the differences in traffic flow in the two directions.

At each location where a measurement was obtained, a noise reduction was predicted using the Design Guide procedures. During the course of these predictions, it was found that the curves for various types of roadway shielding configurations (Figs. 9 through 11 of the Design Guide) did not cover the full range of geometric parameters associated with the available measurements. Hence, all predictions were based on the underlying Design Curve shown in Figure 8 of the Design Guide. A distinction between trucks and automobiles was made in accordance with Design Guide procedures. To hold computations to a manageable level, however, the predicted noise reductions were calculated only for two or three representative truck mix ratios at each site. Each measured noise reduction was then paired with the predicted noise reduction having the closest truck mix ratio to the actual value observed during that measurement.

After the data were reduced in a manner consistent with Design Guide procedures to a form permitting direct comparisons of measured and predicted noise reductions at specific locations, statistical studies were performed to assess the agreement between measured and predicted results in quantitative terms. These studies included assessments of the sensitivity of the prediction accuracy to such variables as traffic speed, volume, truck mix, temperature, and wind velocity. Based on the results of these assessments, modifications to the Design Guide procedures were formulated that hopefully would account for noted discrepancies. The agreement between measured and predicted noise reductions was then reassessed using the modified procedures.

DETAILED DATA EVALUATION PROCEDURES

The procedures used to evaluate the data represent conventional techniques of statistical data analysis, as presented in any standard textbook dealing with engineering statistics. The principal procedures are summarized here.

Average Discrepancy Studies

The simplest way to assess the agreement between measured and predicted noise reductions for each site is in terms of the average value and standard deviation of the discrepancies at the various measurement locations. Specifically, denoting the noise reductions by

x_i = predicted noise reduction at ith location, in dBA; and
y_i = measured noise reduction at ith location, in dBA; (1)

the discrepancy between measured and predicted noise reduction at the ith location may be defined as

$$\Delta_i = y_i - x_i \qquad (2)$$

The average discrepancy for all n locations where measured and predicted noise reductions are available is then given by

$$\bar{\Delta} = \frac{1}{n} \sum_{i=1}^{n} \Delta_i \qquad (3)$$

The standard deviation of the discrepancy may be expressed as

$$s = \left[\frac{1}{n-1} \sum_{i=1}^{n} (\Delta_i - \bar{\Delta})^2 \right]^{\frac{1}{2}} \qquad (4)$$

The average discrepancy, $\bar{\Delta}$, describes the overall bias (systematic error) in the predicted noise reductions relative to the measured noise reductions. The standard deviation, s, describes the scatter (random error) in the predictions relative to the measurements. Ideally, if there were perfect agreement between measured and predicted results, both of these error terms would equal zero. In practice, there will always be some random error due to measurement system variabilities, if not prediction inaccuracies. This suggests that both the $\bar{\Delta}$ and s computed from a finite sample of n values of discrepancy will be random variables. Of particular concern is the average discrepancy, $\bar{\Delta}$, which usually will be nonzero even when the actual bias (the average discrepancy computed over an infinite number of locations) is zero. It is desirable to establish how large $\bar{\Delta}$ must be before it can be confidently stated that the actual bias is not zero; i.e., what value of $\bar{\Delta}$ constitutes a statistically significant difference from zero. This can be determined by applying a conventional null hypothesis test based on a Student t variable (*11*). If the test indicates the actual bias is significantly different from zero, $\bar{\Delta}$ can be used as an estimate for the actual bias. Furthermore, if the sample size is reasonably large (say, $n > 30$), $\bar{\Delta} \pm s$ can be used as an estimate for the interval that would include about two-thirds of the individual discrepancies at all possible locations.

Curve Fitting Studies

Even if the average discrepancy between measured and predicted noise reductions at a given site were not significantly different from zero, there could still be poor agreement between measured and predicted results. For example, the predicted noise reductions might be substantially higher than the measured reductions at locations near the roadside, but substantially lower at locations distant from the roadside. Such a situation could produce a very small average discrepancy in spite of the poor agreement between measured and predicted results.

One method of evaluating this possibility is to empirically fit a straight line to the measured versus the predicted noise reduction data, and then compare this line to the results expected for an ideal relationship. Let x and y denote predicted and measured noise reductions as defined in Eq. 1. It follows that a linear relationship between the predicted and measured results would be given by

$$y = \alpha + \beta x \qquad (5)$$

in which α is the intercept of the line and β is the slope.

For an ideal relationship, measured and predicted noise reductions at each location would be equal; i.e., $y = x$, meaning $\alpha = 0$ and $\beta = 1$ in Eq. 5.

Because of the scatter (random error) in the noise reduction data, it is clear that the individual noise reduction pairs (x_i, y_i) for the n different measurement locations usually would not fall on a single straight line even if there were a linear relationship between x and y. Hence, it is necessary to fit a straight line to the data in some logical manner. The usual procedure is to select the line that minimizes the sum of the squared deviations of the measured noise reduction values y_i from the line; i.e., to determine that line $y = a + bx$ which makes

$$Q = \sum_{i=1}^{n} (y_i - a - bx_i)^2 \qquad (6)$$

a minimum. It is readily shown (*12*) that the values of a and b that satisfy this requirement are given by

$$a = \bar{y} - b\bar{x} \qquad (7a)$$

$$b = \frac{\sum_{i=1}^{n} y_i(x_i - \bar{x})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \qquad (7b)$$

in which

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

The line defined by the intercept and slope of Eq. 7 is called a least squares line.

Because the straight line defined by Eq. 7 is computed from a finite sample of n paired values of predicted and measured noise reduction, both intercept a and slope b are random variables. Therefore, even if the actual intercept and slope, α and β (computed over an infinite sample), were zero and unity, respectively, the values of a and b usually would be different from zero and unity. Again, there is the problem of establishing how much a and b can deviate from zero and unity, respectively, before the difference is considered statistically significant. The procedures for making this decision are well defined (*12*).

Detailed Discrepancy Studies

A third procedure to assess the agreement between measured and predicted noise reductions for each site is to evaluate the average discrepancies at various distances from the roadside (computed by averaging over all heights at each distance), as well as the average discrepancies at various heights above the ground (computed by averaging over all distances at each height). Again, because of finite sample considerations, it is necessary to establish how much variation in the average discrepancy at various distances or heights would constitute a statistically significant difference. Such a determination is readily provided by conventional analysis of variance (AOV) procedures (*13*). If an AOV test indicates that the average discrepancy between measured and predicted noise reductions varies significantly with distance from the roadside and/or height above the ground, the computed average discrepancies can be used to assess the degree of variation.

Correlation Studies

The evaluation techniques discussed in the preceding sections are directed primarily at assessing the agreement of measured and predicted noise reductions as a function of site geometry. Beyond this is the need to assess agreement as a function of traffic variables (volume, speed, and truck mix ratio) as well as environmental factors (wind velocity and temperature). This can be accomplished by a correlation study on pair values of the measured discrepancy versus the traffic or environmental factor of interest.

For example, consider the possible relationship between traffic volume and the accuracy of the Design Guide noise reduction predictions. If the Design Guide has properly accounted for the influence of traffic volume in arriving at a predicted noise reduction, the discrepancies, Δ, between predicted and measured noise reductions should not vary significantly, on the average, with wide variations in traffic volume (all other factors similar). In other words, if the predictions correctly reflect the possible influence of traffic volume, the discrepancies between measurements and predictions should be uncorrelated with the traffic volume observed during each measurement.

The possible correlation between two factors (such as traffic volume and discrepancy) may be defined in terms of a single, real valued quantity called the correlation coefficient. To be specific, given a finite sample of paired observations, $x_i y_i$, $i = 1, 2, \ldots, n$, the correlation coefficient, r, is computed by

$$r = (s_{xy}/s_x s_y) \qquad (8)$$

in which

$s_{xy} = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})$ = sample covariance of x and y;

$s_x = \left[\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2\right]^{\frac{1}{2}}$ = sample standard deviation of x; and

$s_y = \left[\frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y})^2\right]^{\frac{1}{2}}$ = sample standard deviation of y.

The value of the correlation coefficient defined in Eq. 8 is bounded by ± 1. A value at either extreme would indicate a perfect linear dependence between the factors x and y. On the other hand, a value of $r \simeq 0$ would suggest that the factors x and y are unrelated (or that any relation that exists is highly nonlinear). Referring again to the example of traffic volume versus noise reduction discrepancy, a correlation coefficient of $r \simeq 0$ would indicate that the accuracy of the predictions is not influenced by traffic volume. Because of finite sample considerations there is a need to establish how far the coefficient r can deviate from zero before the difference should be considered statistically significant. Again, the procedures for making this decision are well defined (*12*).

EVALUATION OF DESIGN GUIDE PREDICTIONS

Agreement between the noise reductions measured at each site and the noise reductions predicted by the Design Guide was evaluated by the procedures outlined in the previous section. The results of the evaluations for the various noise shielding configurations offered by the six measurement sites are summarized here, followed by a discussion of traffic and environmental factors.

Roadside Barrier (Site 1)

The only site involving a roadside barrier configuration was Site 1. The measured noise reductions based on the L_{50} levels and the corresponding Design Guide predictions for the various locations at this site are given in Table B-1. The evaluations of these data are summarized in Table 3 and shown in Figure 4.

Table 3 indicates that there is no significant difference, on the average, between the measured and predicted noise reductions ($\bar{\Delta} = 1.10$ dBA does not constitute a statistically significant difference from zero for the sample size in question). However, the least squares line for the measured versus predicted results deviates significantly from an ideal relationship (see Fig. 4). The average discrepancy varies significantly with location, becoming increasingly worse as the distance from the roadside decreases and the distance above the ground increases.

Figure 4 shows that although the discrepancies appear to be random, there is a consistent tendency toward underprediction at those locations that are 15 and 20 ft above the ground; i.e., at the locations associated with the smallest values of the path length difference parameter, δ (defined in App. D). This observation is important because it is at these small values of δ that the Design Guide predictions differ most significantly from other noise reduction prediction techniques, as summarized in Appendix D.

Elevated Highway Configuration (Sites 2 and 3)

Two sites involved an elevated highway configuration: Site 2 and Site 3. The measured noise reductions based on L_{50} levels and the corresponding Design Guide predictions for the various locations at these two sites are given in Table B-2. The evaluations of the data for Site 2 are given in Table 4 and shown in Figure 5. Similar evaluations for Site 3 are given in Table 5 and shown in Figure 6.

Table 4 indicates that there is a significant difference, on the average, between measured and predicted noise reductions at Site 2 ($\bar{\Delta} = -1.33$ dBA does constitute a statistically significant difference from zero). Furthermore, the least squares line differs significantly from the ideal relationship, $y = x$ (see Fig. 5), and there is a significant difference in the average discrepancy at the various distances above the ground.

Table 5 indicates that the data for Site 3 reveal no significant difference, on the average, between measured and predicted noise reductions. The least squares line, however, deviates significantly from the ideal relationship, $y = x$ (see Fig. 6). As before, there is no significant variation in the average discrepancy with distance from the roadside, but a pronounced variation with height above the ground. Specifically, there is a tendency toward underprediction at the higher measurement locations where the value of the path length difference parameter, δ, is small, exactly as was observed for the roadside barrier case. This

TABLE 3

RESULTS OF DESIGN GUIDE PREDICTIONS, SITE 1

STATISTICAL PARAMETER USED FOR ASSESSMENT	RESULTS (dBA) COMPUTED	RESULTS (dBA) IDEAL	DIFF. STATIST. SIGNIF.? [a]
Avg. discrepancy, $\bar{\Delta}$	1.10	0	no
Standard deviation, s	3.77	0	—
Least squares line (Fig. 4):			
Intercept	6.12	0	yes
Slope	0.29	1.0	yes
Range of $\bar{\Delta}$ with:			
Dist. from roadside	7.0	0	yes
Ht. above ground	9.7	0	—

[a] All difference tests performed at 1% level of significance.

TABLE 4

RESULTS OF DESIGN GUIDE PREDICTIONS, SITE 2

STATISTICAL PARAMETER USED FOR ASSESSMENT	RESULTS (dBA) COMPUTED	RESULTS (dBA) IDEAL	DIFF. STATIST. SIGNIF.? [a]
Avg. discrepancy, $\bar{\Delta}$	−1.33	0	yes
Standard deviation, s	2.33	0	—
Least squares line (Fig. 5):			
Intercept	−2.76	0	yes
Slope	1.18	1.0	no
Range of $\bar{\Delta}$ with:			
Dist. from roadside	1.7	0	no
Ht. above ground	2.5	0	yes

[a] All difference tests performed at 1% level of significance.

TABLE 5

RESULTS OF DESIGN GUIDE PREDICTIONS, SITE 3

STATISTICAL PARAMETER USED FOR ASSESSMENT	RESULTS (dBA) COMPUTED	RESULTS (dBA) IDEAL	DIFF. STATIST. SIGNIF.? [a]
Avg. discrepancy, $\bar{\Delta}$	0.54	0	no
Standard deviation, s	2.78	0	—
Least squares line (Fig. 6):			
Intercept	1.60	0	yes
Slope	0.44	1.0	yes
Range of $\bar{\Delta}$ with:			
Dist. from roadside	1.8	0	no
Ht. above ground	5.5	0	yes

[a] All difference tests performed at 1% level of significance.

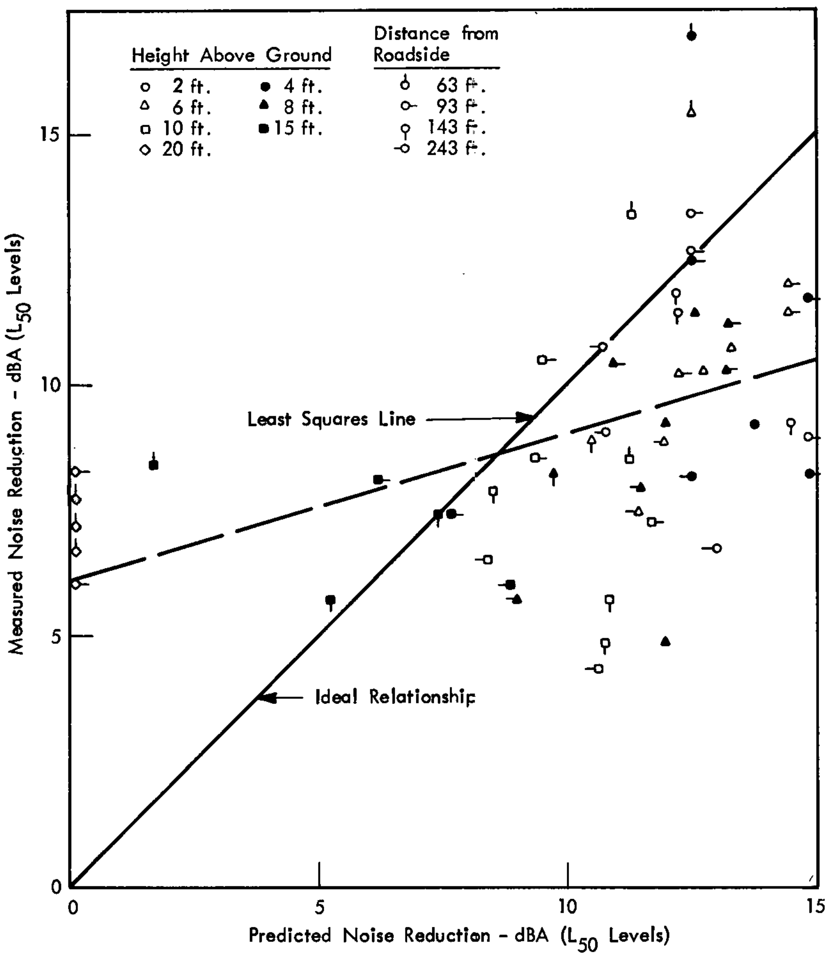

Figure 4. Measured vs predicted noise reductions, Site 1, using Design Guide predictions.

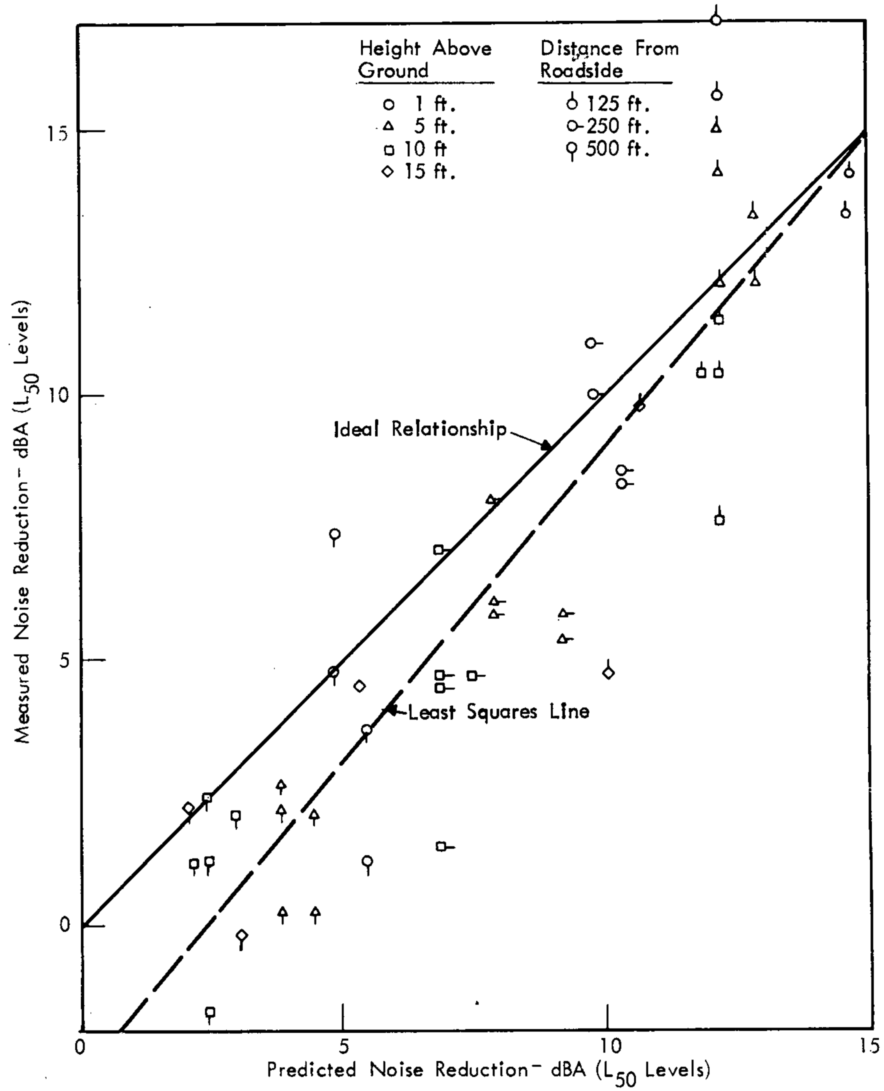

Figure 5. Measured vs predicted noise reductions, Site 2, using Design Guide predictions.

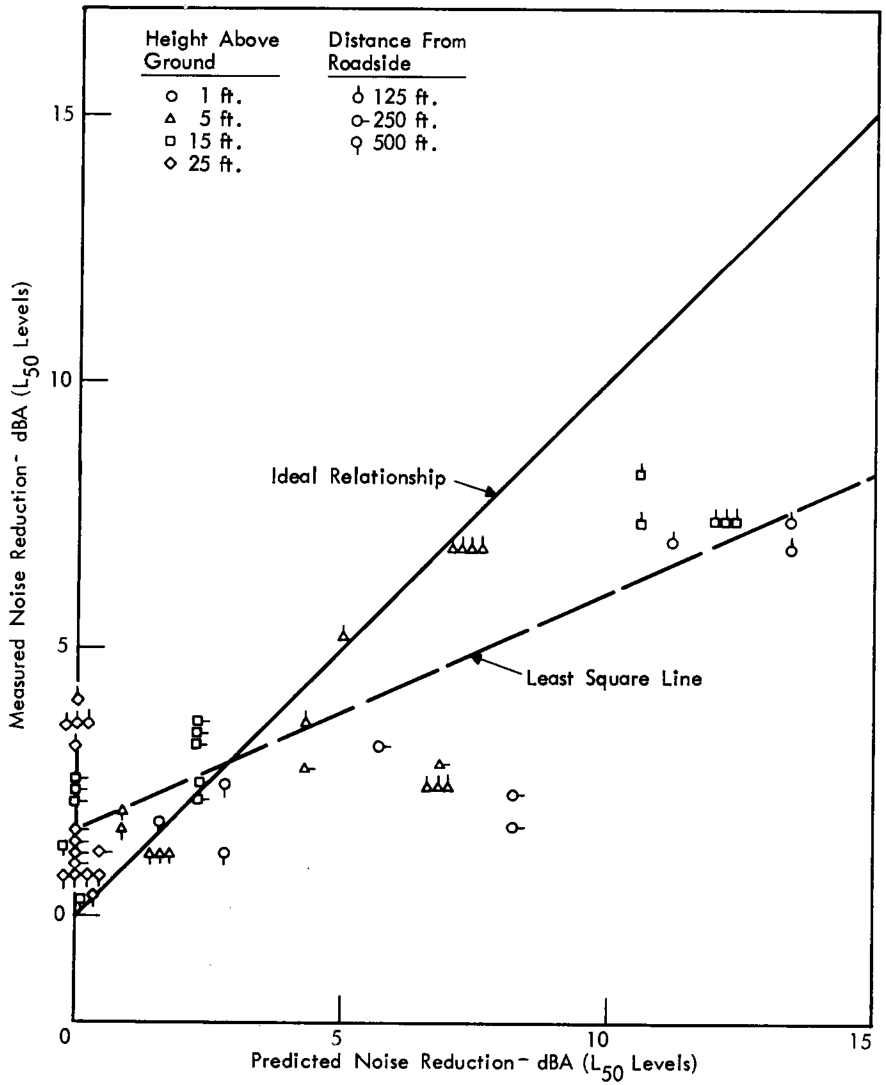

Figure 6. Measured vs predicted noise reductions, Site 3, using Design Guide predictions.

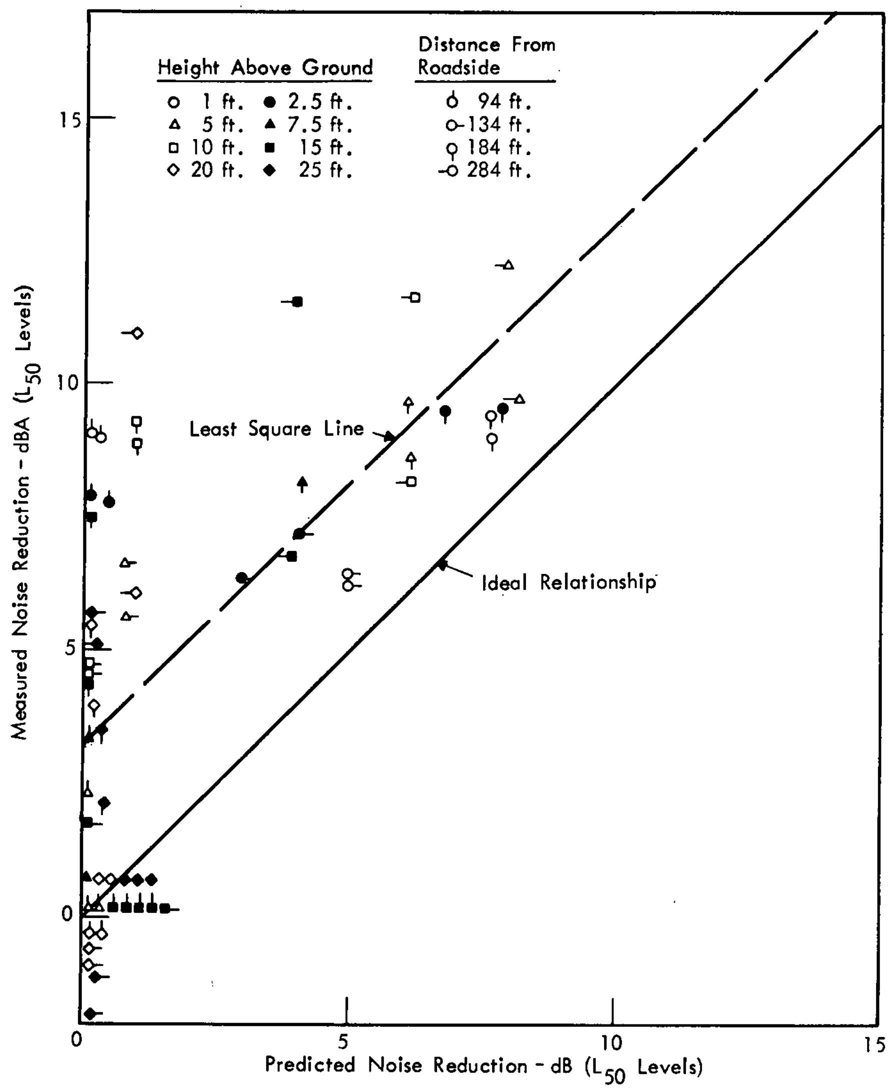

Figure 7. Measured vs predicted noise reductions, Site 9, using Design Guide predictions.

result is not pronounced in the data for Site 2 because the measurement locations for that site were never higher than 15 ft.

Depressed Highway Configuration (Site 9)

The only site involving a depressed highway configuration was Site 9. This site had certain undesirable features, the most important being the presence of houses within 200 ft of the roadside. This necessitated the use of a measurement location that was actually positioned between houses, raising the possibility of additional noise reduction due to structural shielding at this location.

The measured noise reductions based on L_{50} levels and the corresponding Design Guide predictions for the various locations are given in Table B-4. The evaluations of these data are given in Table 6 and shown in Figure 7. Table 6 indicates that the noise reductions predicted by the Design Guide are a full 3 dBA lower, on the average, than the measured noise reductions. Correspondingly, the least squares line, although it has the desired slope, is offset by 3dBA (see Fig. 7). The average discrepancy varies significantly with location, becoming increasingly worse as the distance from the roadside increases and as the distance above the ground decreases.

The lack of agreement between measured and predicted noise reductions for this site is disappointing, but not totally surprising. Referring to Figure 7, the majority of the measurement locations involved small values of the path length difference parameter, δ, resulting in predicted noise reductions of zero. This appears to be causing a bias toward underprediction, as observed in the data for Sites 1 and 3. Furthermore, there also appears to be a tendency to underpredict the noise reductions at the measurement points most distant from the roadway; i.e., those locations between houses. The excessive measured noise reduction at these distant locations is undoubtedly due to the additional shielding provided by the surrounding houses.

Roadside Structures (Sites 5 and 6)

Two sites involved shielding by roadside structures: Site 5 and Site 6. The shielding roadside structures were rows of houses situated parallel to the highway. The truck mix ratios at both sites during the measurements were unusually high—more than 20 percent for many of the measurements at Site 6.

The measured noise reductions based on L_{50} levels, and the corresponding Design Guide predictions for the various locations at these two sites are given in Table B-3. The evaluations of the data for Site 5 are given in Table 7 and shown in Figure 8. Similar evaluations for Site 6 are given in Table 8 and shown in Figure 9. Comparisons between measured and predicted results are made only for locations 5 ft above the ground, because this is the only height for which the Design Guide predictions are applicable. The distance of the measurement location from the roadside is identified in terms of the number of rows of intervening houses, as well as in feet from the roadside.

Table 7 indicates there is no significant difference, on the average, between the measured noise reductions and those predicted by the Design Guide for Site 5. Furthermore, there is no significant difference in the average discrepancy between measured and predicted results at the various measurement locations. Although the data available for this site are not sufficient to permit a decisive conclusion, the limited results do not reveal any significant difference in the noise reductions at the locations between houses compared to the locations at similar distances from the roadside, but behind houses.

The results for Site 6 (Table 8) indicate that there is again no significant difference, on the average, between measured and predicted noise reductions. However, there is a significant variation in the average discrepancy between measured and predicted results with location. Specifically,

TABLE 6

RESULTS OF DESIGN GUIDE PREDICTIONS, SITE 9

STATISTICAL PARAMETER USED FOR ASSESSMENT	RESULTS (dBA) COMPUTED	IDEAL	DIFF. STATIST. SIGNIF.? [a]
Avg. discrepancy, $\overline{\Delta}$	3.04	0	yes
Standard deviation, s	2.96	0	—
Least squares line (Fig. 7):			
Intercept	3.04	0	yes
Slope	1.00	1.0	no
Range of $\overline{\Delta}$ with:			
Dist. from roadside	2.9	0	yes
Ht. above ground	4.7	0	yes

[a] All difference tests performed at 1% level of significance.

TABLE 7

RESULTS OF DESIGN GUIDE PREDICTIONS, SITE 5

STATISTICAL PARAMETER USED FOR ASSESSMENT [b]	RESULTS (dBA) COMPUTED	IDEAL	DIFF. STATIST. SIGNIF.? [a]
Avg. discrepancy, $\overline{\Delta}$	0.15	0	no
Standard deviation, s	1.95	0	—
Range of $\overline{\Delta}$ with dist. from roadside	2.8	0	no

[a] All difference tests performed at 1% level of significance.
[b] Insufficient data for a meaningful least squares fit.

TABLE 8

RESULTS OF DESIGN GUIDE PREDICTIONS, SITE 6

STATISTICAL PARAMETER USED FOR ASSESSMENT [b]	RESULTS (dBA) COMPUTED	IDEAL	DIFF. STATIST. SIGNIF.? [a]
Avg. discrepancy, $\overline{\Delta}$	0.46	0	no
Standard deviation, s	3.18	0	—
Range of $\overline{\Delta}$ with dist. from roadside	6.0	0	yes

[a] All difference tests performed at 1% level of significance.
[b] Insufficient data for a meaningful least squares fit.

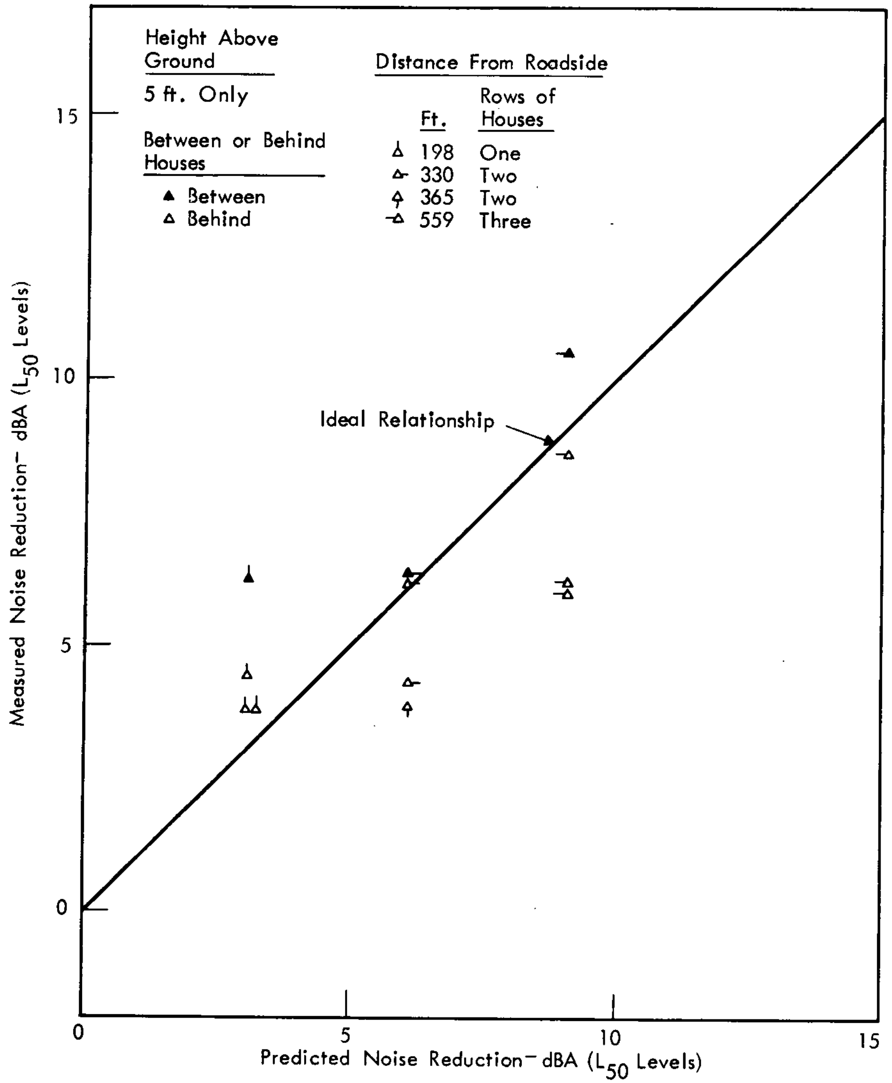

Figure 8. Measured vs predicted noise reductions, Site 5, using Design Guide predictions.

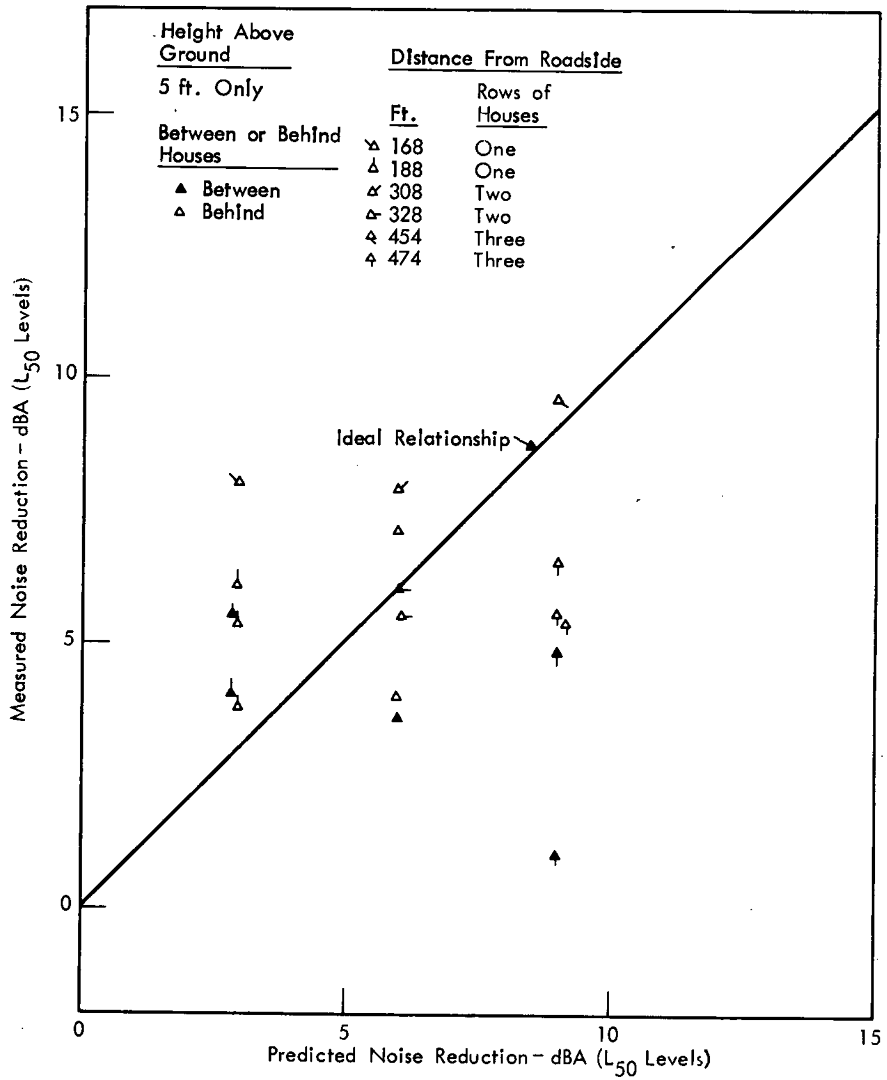

Figure 9. Measured vs predicted noise reductions, Site 6, using Design Guide predictions.

the Design Guide appears to underpredict the noise reductions at the locations nearest the roadside, and overpredict at those more distant from the roadside. Figure 9 shows that this is because the measured noise reductions do not vary significantly with location, whereas the predicted noise reductions do. As with Site 5, the limited data available for Site 6 do not reveal a significant difference for the between-house results compared to the behind-house results at similar distances from the roadside.

Influence of Traffic Parameters

Having assessed the agreement between the Design Guide predictions and the measured noise reductions for various site geometries and measurement locations, it is appropriate to investigate the agreement as a function of variations in critical traffic parameters. Of particular interest is the possible influence of three traffic variables: (1) vehicle volume, (2) vehicle speed, and (3) truck traffic mix ratio. These parameters were measured and recorded for each run at each site. The data are tabulated in Appendix A.

The analysis approach employed here involves a single-variable correlation study, as discussed previously. Specifically, those data for the site that provided the maximum spread in the traffic variable of interest were selected for study. Measurement runs from that site were then chosen to reflect the full range of the parameter of interest, while reflecting only minor variations in other parameters that might influence the predicted noise reductions. Where this was not possible, runs were selected so that variations in other parameters were balanced over the range of the parameter of interest. Finally, the correlation coefficient for the parameter of interest versus the discrepancy, Δ, between measured and predicted noise reduction was computed from the sample values. If the Design Guide has properly accounted for that traffic parameter in question, the correlation coefficient should not be significantly different from zero; i.e., there should be no relationship between the value of the parameter of interest and the discrepancy, Δ.

Before proceeding, two points should be emphasized. First, the experimental approach in this study involved the measurement of data for operational highway configurations under normal traffic conditions, as opposed to contrived configurations with planned and controlled traffic conditions. Hence, the data are far from ideal for a study of traffic variables because the spread in values for any given traffic variable is generally narrow. Second, traffic variables would be expected to have a much stronger influence on the absolute value of the traffic noise than on the noise reduction provided by a specific shielding configuration. It follows that a critical assessment of how well the Design Guide prediction procedures account for the various different traffic parameters should be based on an evaluation of predicted versus measured values of free-field traffic noise. In this study, however, emphasis was on the prediction of noise reductions provided by various shielding configurations rather than the prediction of absolute noise levels. Hence, the free-field measurements required for a critical assessment were not included in the data acquisition program.

Traffic Volume

Only Site 3 provided data for a reasonable spread of vehicle volume. Twelve runs at this site representing 36 measurements corresponding to traffic volumes of 2,520 to 7,750 vph were selected for analysis (Table 9). The vehicle speeds for the various runs fall in the relatively narrow range of 65 ±4 mph, which should acceptably suppress the possible influence of speed variations on the data. The truck mix ratios are less than 1.8 percent for all but two runs. For truck mix ratios of this magnitude, the traffic noise is controlled by the automobile traffic, meaning that the variation in the truck mix ratio from one run to the next should not have a significant influence on the results. The selected runs include data at each measurement location for three different traffic volumes: low, moderate, and high. This was done to suppress the influence of measurement location on the results.

In Table 9, the correlation coefficient for vehicle volume versus the discrepancy between measured and predicted noise reduction is $r = 0.05$. For the sample size of $n = 36$ paired values, a sample correlation coefficient of 0.05 does not constitute a significant difference from zero. Hence, there is no evidence to suggest that the accuracy of the Design Guide noise reduction predictions is influenced by traffic volume, at least for the site and range of vehicle volumes considered. It appears reasonable to assume that this conclusion can be extended to other sites and values of traffic volume.

Vehicle Speed

None of the six measurement sites provided data covering a sufficiently wide range of vehicle speeds for a meaningful analysis. Correlation and other comparative analyses were performed on limited data for Site 2, with negative results; i.e., no significant correlation between vehicle speed and noise reduction discrepancy was indicated. However, these results must be considered inconclusive because of the small sample size and the narrow range of values for the speed variable in the analysis.

Truck Mix Ratio

The data for Site 1 provided the best range of truck mix ratios for a correlation study. Twelve runs at this site representing 32 measurements corresponding to mix ratios of 1.9 to 16.1 percent were selected for analysis (Table 10). The vehicle speeds for the various runs fall in the relatively narrow range of 58.5 ±3.5 mph, and most measurement locations are represented for both low and high values of the mix ratio. The favorable conclusion from the previous study of vehicle volume dependence is used to justify the assumption here that the variations in traffic volume from one run to the next will not significantly influence the results.

In Table 10, the correlation coefficient for truck mix ratio versus discrepancy between measured and predicted noise reduction is $r = 0.55$. For the sample size of $n = 32$ paired values, a sample correlation coefficient of 0.55 constitutes a significant difference from zero (at the 1 percent

TABLE 9

TRAFFIC VOLUME VS DISCREPANCY DATA FOR DESIGN GUIDE NOISE REDUCTION PREDICTIONS, SITE 3

RANGE OF VOL.	RUN NO.	HT. (FT)	SPEED (MPH)	MIX RATIO (%)	VOL. (VPH)	DISCREPANCY (dBA) AT VAR. DISTANCES FROM ROAD		
						125 FT	250 FT	500 FT
Low	10	1	67	1.7	2940	6.5	6.5	1.6
	7	5	66	3.2	3090	2.3	0.6	−1.1
	8	15	65	1.5	2520	0.3	−0.2	−1.3
	9	25	60	1.4	2544	−3.9	−1.1	−0.7
Mid	14	1	65	0.4	6870	6.0	5.9	0.3
	11	5	64	1.8	6000	4.8	4.3	0.4
	12	15	69	0.4	6120	0.3	−1.2	−2.4
	13	25	65	0.8	6090	−3.6	−1.2	−0.8
High	18	1	65	3.0	7750	4.2	2.5	−0.2
	1	5	65	0.5	7404	4.8	4.3	0.4
	2	15	63	1.0	7440	0.3	−1.2	−2.4
	3	25	61	1.8	7440	−3.5	−1.0	−0.6

Sample correlation coeff. for vph vs ΔdBA—r=0.05.

TABLE 10

TRUCK MIX RATIO VS DISCREPANCY DATA FOR DESIGN GUIDE NOISE REDUCTION PREDICTIONS, SITE 1

RANGE OF MIX RATIO	RUN NO.	HT. (FT)	SPEED (MPH)	VOLUME (VPH)	TRUCK MIX RATIO (%)	DISCREPANCY (dBA) AT VAR. DISTANCES FROM ROAD		
						93 FT	143 FT	243 FT
Low	4	2	59	432	5.8	−5.9	−5.2	−6.2
	13	4	60	588	2.0	−6.6	−4.5	−4.3
	12	6	62	618	1.9	−2.5	−2.4	−3.0
	11	8	60	432	2.8	−1.9	−2.1	−3.4
	10	10	62	456	2.7	−4.5	−5.1	−6.3
	8	15	55	492	5.1	1.8	−0.4	−2.9
High	14	2	55	564	11.9	0.2	−0.5	−0.1
	20	4	60	346	16.1	−0.2	—	—
	2	6	57	348	16.0	−2.0	−1.6	—
	17	8	60	372	14.8	−0.5	−1.4	−3.2
	7	10	58	624	9.4	−0.8	−0.7	−1.8
	19	15	56	402	11.6	−0.3	0.4	—

Sample correlation coeff. for mix ratio vs ΔdBA—r=0.55.

level of significance). Hence, there is strong evidence to suggest that the Design Guide noise reduction prediction procedures do not properly account for trucks in the traffic flow.

Influence of Environmental Parameters

During the measurement program, various environmental parameters (including wind velocity and direction, air temperature, and relative humidity) were measured and recorded, as summarized in Appendix A. All measurements were made during the late summer months, and only when wind velocities were less than 15 mph to assure proper operation of microphones and instrumentation. Hence, the range of environmental factors during the measurement program did not include extremes. For almost all measurements, the wind velocity was less than 10 mph, the air temperature was between 60° and 85°F, and the relative humidity was between 40 and 90 percent. Under these circumstances, major variations in the noise reduction measurements due to environmental factors would not be expected. A review of the data for all sites confirms this expectation.

As an illustration, consider the environmental factors versus discrepancy data for Site 3 (Table 11). The data include 18 measurements at 9 locations when wind velocity was nil and the temperature was 62° to 70°F (Case A), and 18 additional measurements at the same 9 locations when average wind velocity was 4 to 8 mph and the temperature was 82° to 85°F (Case B). The average discrepancy between predicted and measured noise reductions for Case A is $\bar{\Delta} = -0.34$ dBA; the average discrepancy for Case B is 0.07 dBA. This minor difference of

about 0.4 dBA is not statistically significant. Similar results were observed for the other sites.

Wind can have a significant impact on the noise reduction provided by various shielding geometries under certain conditions. In particular, a wind of more than 10 mph in a direction parallel to the source-receiver axis will often produce excessive attenuation at receivers upwind from the source (*14*). Such effects were not evident in this study primarily because the necessary conditions were rarely present during the measurements at the various sites.

EVALUATION OF PREDICTIONS BY MODIFIED PROCEDURES

The results just presented reveal three significant deficiencies in the Design Guide procedures; i.e., the procedures:

1. Tend to underpredict the noise reduction afforded by the various shielding configurations at those locations where the value of the path length difference parameter, δ, is small; i.e., $\delta < 0.5$.
2. Do not accurately account for the difference between trucks and automobiles in the noise reduction prediction procedures.
3. Overpredict, at least in some cases, the free-field noise propagation losses due to ground attenuation.

TABLE 11

ENVIRONMENTAL FACTORS VS DISCREPANCY DATA FOR DESIGN GUIDE NOISE REDUCTION PREDICTIONS, SITE 3

CASE	RUN NO.	HT. (FT)	WIND VEL.[a] (MPH)	AIR TEMP.[a] (°F)	DISCREPANCY (dBA) AT VAR. DISTANCES FROM ROAD 125 FT	250 FT	500 FT
A	7	5	nil	70	2.3	0.6	−1.1
	8	15	nil	70	0.3	−0.2	−1.3
	9	25	nil	70	−3.9	−1.1	−0.7
	15	5	nil	62	3.2	1.5	−0.9
	16	15	nil	63	−0.3	0.7	−0.2
	17	25	nil	64	−3.5	−1.0	−0.6
B	1	5	8	83	4.8	4.3	0.4
	2	15	8	83	0.3	−1.2	−2.4
	3	25	7	83	−3.6	−1.2	−0.8
	6	5	8	84	4.8	4.3	0.4
	5	15	6	85	0.3	−1.2	−2.4
	4	25	4	85	−3.3	−1.5	−0.8

Case A: $\bar{\Delta} = -0.34$ dBA and $s = 1.73$ dBA.

Case B: $\bar{\Delta} = 0.07$ dBA and $s = 2.73$ dBA.

[a] Measured 8 ft above the ground. Wind direction N or NNW (approx. perpendicular to source-receiver axis).

The first two deficiencies are immediately apparent from the various statistical studies. The third deficiency is suggested by less obvious observations. Specifically, careful inspection of the data reveals an underlying tendency toward overprediction at the more distant locations from the roadside. This tendency is obscured at first by the counter trend toward underprediction due to the small values of δ associated with these same locations. An overprediction at distance locations suggests that the measured noise reductions may be too low because of errors in the free-field level estimates used to calculate the measured noise reductions. Attention is immediately drawn to the distance relationship of 15 log D (a propagation loss of 4.5 dB per doubling of distance) in the Design Guide, because this factor is 50 percent higher than the distance relationship of 10 log D (a loss of 3 dB per doubling of distance) that arises from theoretical considerations; i.e., assuming a continuous line source, the spreading loss is controlled by cylindrical divergence. The reason the Design Guide uses 15 log D rather than 10 log D is to allow for additional losses due to ground attenuation. This may be appropriate for sites with cultivated ground covers. Some of the sites involved in this study, however, did not have such ground covers. For example, surrounding terrain at both Sites 1 and 2 was freshly plowed farmland.

Based on the foregoing observations, the noise reduction data for representative sites were again evaluated with three major changes in the Design Guide procedures. First, the design curve for barrier attenuation (Fig. 8 of the Design Guide) was replaced by the barrier attenuation model for incoherent line sources proposed by Kurze and Anderson (*8*) and suggested in the handbook, *Noise and Vibration Control* (*14*). Details of this model, referred to herein as the Line Source Model, are given in Appendix D. Second, for the estimation of free-field noise levels needed to arrive at measured noise reductions, the propagation loss factor of 4.5 dB per doubling of distance, as assumed in the Design Guide, was replaced by the simple line source divergence factor of 3 dB per doubling of distance. Third, no distinction between trucks and automobiles was introduced into the noise reduction calculations. A possible correction for trucks is discussed in a following section.

After the foregoing changes were introduced, the measured and predicted noise reductions were recomputed and compared at various locations for three sites: Site 1—roadside barrier configuration; Site 2—elevated highway configuration; and Site 9—depressed highway configuration. Site 3 (the second elevated highway site) was omitted as redundant, and Sites 5 and 6 (the roadside structures sites) were not considered because the Line Source Model does not apply to this type of shielding. Roadside structures are discussed later. To help suppress extraneous errors in the evaluation, all measurement locations associated with negative values of the path length difference parameter, δ (locations above the line of sight to the source), and all measurement locations more than 300 ft from the roadway were omitted. The first restriction influenced data primarily at Site 9; the second applied only to Site 2. The results of the evaluations follow.

Roadside Barrier (Site 1)

The measured noise reductions based on the L_{50} levels, and the corresponding line source predictions for Site 1, are given in Table B-5. Evaluations of these data are given in Table 12 and shown in Figure 10.

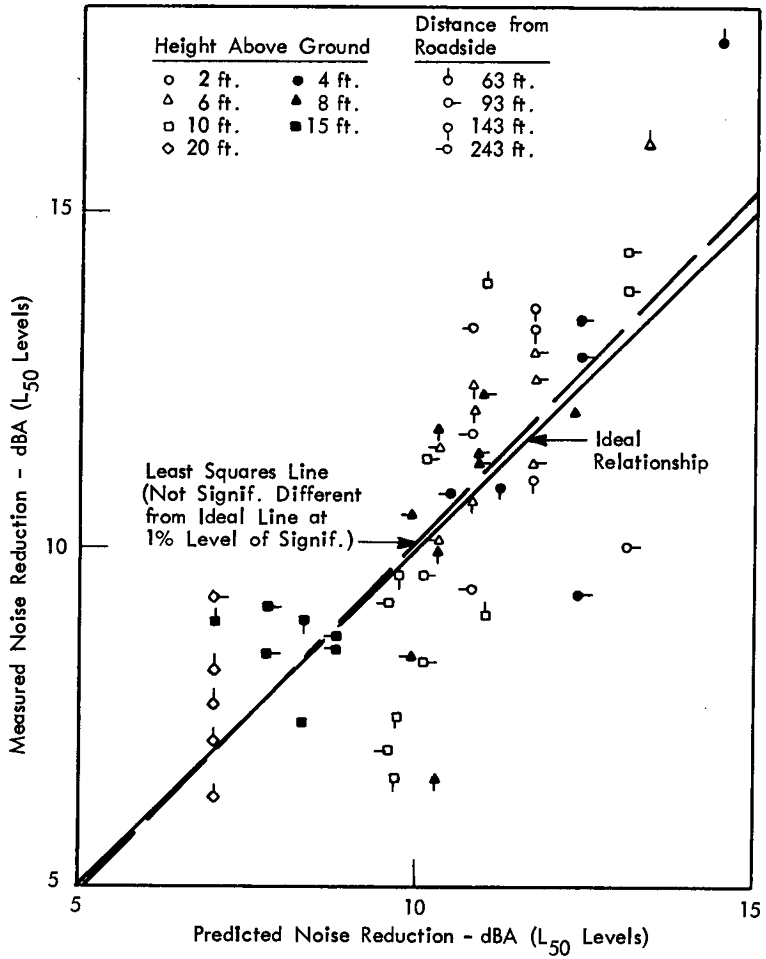

Figure 10. Measured vs predicted noise reductions, Site 1, using line source predictions.

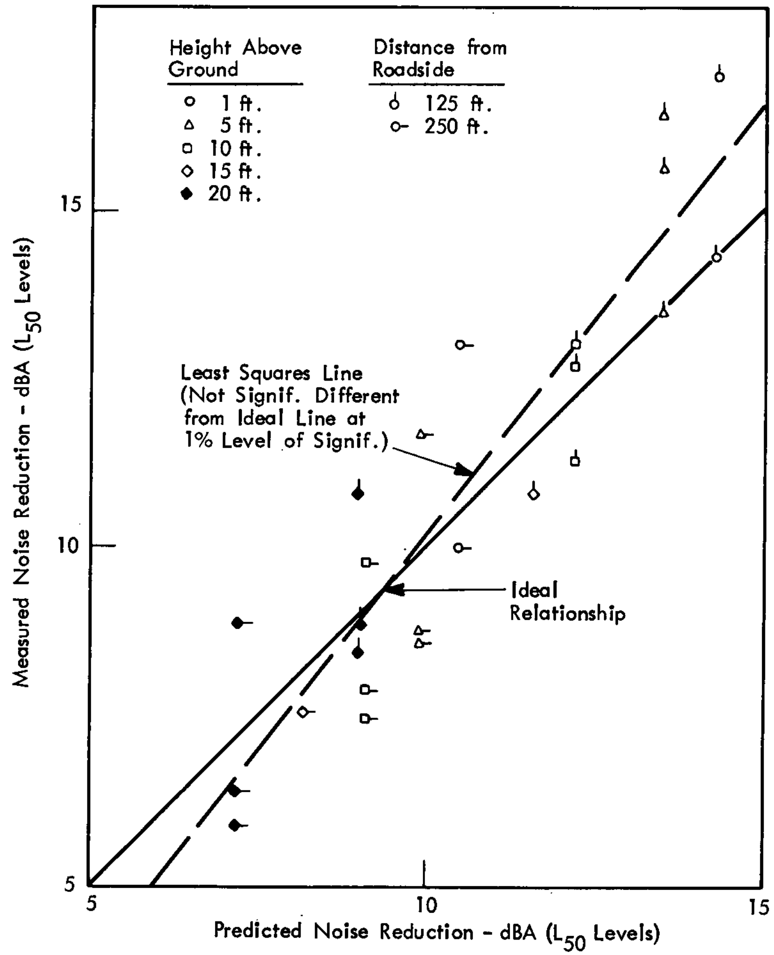

Figure 11. Measured vs predicted noise reductions, Site 2, using line source predictions.

The results in Table 12 show that the agreement between the measured noise reductions and those predicted by the Line Source Model not only is superior to that provided by the Design Guide predictions in Table 3, but also is now very good in all categories of assessment. Specifically, the discrepancy between measured and predicted results is not statistically significant when considered as a function of noise reduction magnitude, distance from the roadside, or height above the ground. Furthermore, the standard deviation of the discrepancy at individual locations is now only 1.59 dBA, down sharply from the 3.77 dBA result for the Design Guide predictions.

Elevated Highway Configuration (Site 2)

The measured noise reductions based on the L_{50} levels, and the corresponding line source predictions for Site 2, are given in Table B-6. Evaluations of these data are given in Table 13 and shown in Figure 11.

The results in Table 13 show that the line source predictions are in good agreement with the measurements in all categories of assessment. This compares to significant discrepancies in all but one category of assessment when the Design Guide procedures were applied, as in Table 4 and Figure 5. Furthermore, the standard deviation of the discrepancies at individual locations has been reduced from 2.33 dBA to 1.38 dBA.

Depressed Highway Configuration (Site 9)

The measured noise reductions based on the L_{50} levels, and the corresponding line source predictions for Site 9 are given in Table B-7. Evaluations are given in Table 14 and shown in Figure 12.

The results in Table 14 do reveal some physically small but statistically significant discrepancies between measured and predicted noise reductions for this site. That is, the measured noise reductions exceed the line source predictions by about 0.8 dBA on the average, and there is some variation in the agreement with distance from the roadside. However, the general agreement is far superior to that achieved using the Design Guide procedures, as summarized in Table 6. Furthermore, the standard deviation of the discrepancies at individual locations has been reduced to only 1.16 dBA, as compared to 1.96 dBA for the Design Guide predictions.

The remaining discrepancies between measured and predicted noise reductions at Site 9 might be due solely to an error in the free-field propagation loss factor used to arrive at the measured noise reductions. Unlike Sites 1 and 2, the neighboring terrain for Site 9 was not bare ground. Except for a street, the ground was well covered by grass and some foliage. Hence, there was ground attenuation not accounted for in the spreading loss factor of 3 dB per doubling of distance. To investigate this possibility further, the data were reanalyzed using a propagation loss factor of 4.5 dB per doubling of distance, as suggested in the Design Guide. This eliminated the two remaining significant discrepancies.

The important conclusion here is that the free-field propagation loss is significantly influenced by the nature of the ground cover. Furthermore, slight errors in the assumed propagation loss factor will translate into major errors in the noise levels predicted at distant locations. The use of a constant value for this factor in the Design Guide prediction procedures should be reconsidered.

TABLE 12

RESULTS OF LINE SOURCE PREDICTIONS, SITE 1

STATISTICAL PARAMETER USED FOR ASSESSMENT	RESULTS (dBA) COMPUTED	IDEAL	DIFF. STATIST. SIGNIF.? [a]
Avg. discrepancy, $\bar{\Delta}$	−0.18	0	no
Standard deviation, s_Δ	1.59	0	—
Lease squares line (Fig. 10):			
Intercept	−0.24	0	no
Slope	1.04	1.0	no
Range of $\bar{\Delta}$ with:			
Dist. from roadside	1.27	0	no
Ht. above ground	1.74	0	no

[a] All difference tests performed at 1% level of significance.

TABLE 13

RESULTS OF LINE SOURCE PREDICTIONS, SITE 2

STATISTICAL PARAMETER USED FOR ASSESSMENT	RESULTS (dBA) COMPUTED	IDEAL	DIFF. STATIST. SIGNIF.? [a]
Avg. discrepancy, $\bar{\Delta}$	−0.32	0	no
Standard deviation, s_Δ	1.38	0	—
Lease squares line (Fig. 11):			
Intercept	−2.62	0	no
Slope	1.28	1.0	no
Range of $\bar{\Delta}$ with:			
Dist. from roadside	1.10	0	no
Ht. above ground	1.56	0	no

[a] All difference tests performed at 1% level of significance.

TABLE 14

RESULTS OF LINE SOURCE PREDICTIONS, SITE 9

STATISTICAL PARAMETER USED FOR ASSESSMENT	RESULTS (dBA) COMPUTED	IDEAL	DIFF. STATIST. SIGNIF.? [a]
Avg. discrepancy, $\bar{\Delta}$	0.84	0	yes
Standard deviation, s_Δ	1.16	0	—
Lease squares line (Fig. 12):			
Intercept	−0.19	0	no
Slope	1.12	1.0	no
Range of $\bar{\Delta}$ with:			
Dist. from roadside	2.7	0	yes
Ht. above ground	1.4	0	no

[a] All difference tests performed at 1% level of significance.

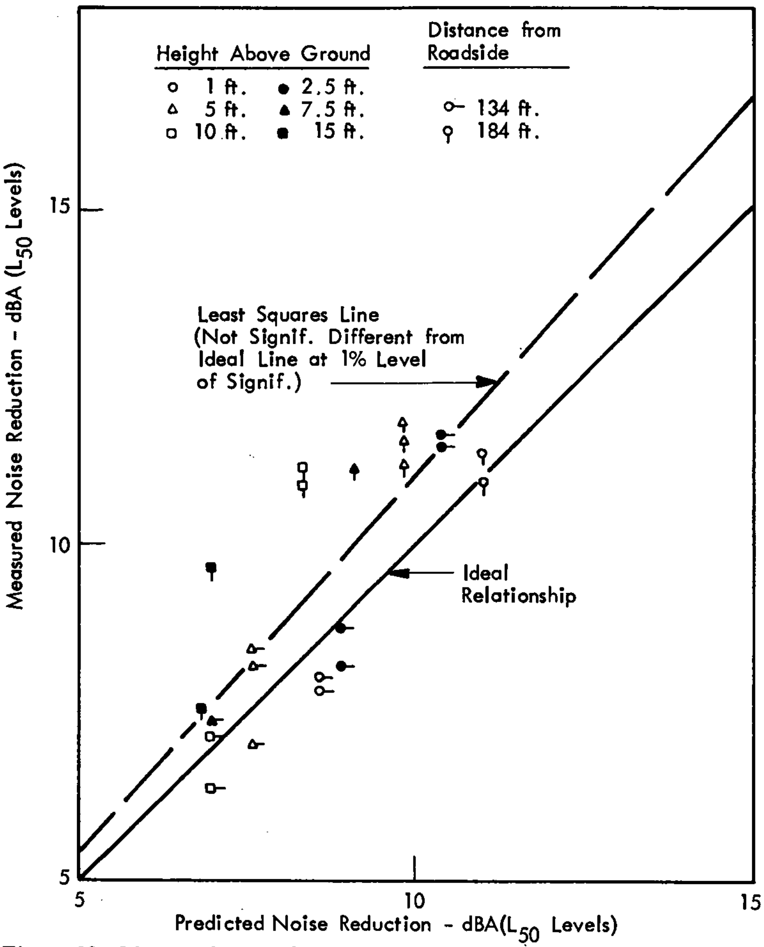

Figure 12. Measured vs predicted noise reductions, Site 9, using line source predictions.

FURTHER STUDY OF TRUCK NOISE ATTENUATION

In the preceding evaluations, noise reductions for various shielding configurations were predicted using the Line Source Model in a way that did not distinguish between trucks and automobiles. To be more specific, the noise reductions were computed assuming the traffic noise source was located at the level of the highway surface for all vehicles. This is probably a reasonable assumption for automobile traffic, where it is generally agreed that tire noise is the predominant source. For the case of trucks, however, many investigators believe the predominant source of noise, at least at speeds below 50 mph, is the exhaust stack that stands several feet above the highway surface. It is for this reason that the Design Guide differentiates between trucks and automobiles by assuming a barrier will provide 5 dBA less attenuation for trucks than for automobiles.

The correlation studies discussed earlier under "Influence of Traffic Parameters" indicate that the Design Guide correction for the attenuation of truck noise by barriers is generally excessive. On the other hand, some type of correction for trucks undoubtedly is warranted. To further investigate this issue, the correlation studies of discrepancy between measured and predicted noise reductions versus truck mix ratio, as summarized in Table 10, were repeated using the zero height line source predictions. The analysis produced a sample correlation coefficient of $r = 0.11$, which is not a statistically significant difference from zero for the sample size of $n = 32$. This result does not necessarily mean that the shielding efficiency for truck noise is the same as for automobile noise. It means only that any difference that may exist in the shielding efficiency is not sufficient to be detected in the data for the shielding configuration and traffic conditions represented by Site 1.

Roadside Barrier Data With Truck Correction

Given a barrier noise reduction prediction model like that proposed by Kurze and Anderson (*8*), the logical way to introduce an adjustment for trucks is to compute the path length difference for trucks based on a line source located at some reasonable distance above the highway surface. This will provide a path length difference value for trucks that is less than the value for automobiles and, hence, produce a lower predicted attenuation for trucks, all other things equal. The problem is to arrive at a meaningful equivalent height for truck noise. Such an equivalent height would undoubtedly be a function of the truck speed. Specifically, at the higher speeds, where tire noise is significant, one would expect the center of the noise source to be closer to the highway surface than at lower speeds, where exhaust stack noise predominates.

For the purposes of this investigation, a conservative estimate of 8 ft was assumed for the equivalent height of truck noise. Using this height, the noise reductions at Site 1 (the roadside barrier configuration) were recomputed (see Table B-8). These noise reduction predictions required independent estimations of the truck and automobile traffic noise, and the separate calculation of noise levels at the shielded locations due to each type of traffic. The truck and automobile traffic noise estimates were made using the procedures of the Design Guide. The resulting agreement between the measured noise reductions and those predicted with the Line Source Model, assuming the truck noise source to be 8 ft above the highway surface and the automobile noise source to be on the highway surface, are summarized in Table 15.

A comparison of the results in Table 15 with those computed previously with no adjustment for trucks in Table 12 shows that the 8-ft source height correction for trucks has no significant impact on agreement between measured and predicted results at Site 1. A correlation analysis of the discrepancy between measured and predicted results versus the truck mix ratio (see Table 10) yielded a sample correlation coefficient of $r = 0.35$, as compared to $r = 0.11$ for the uncorrected case. However, this value of r is still not quite high enough to constitute a statistically significant difference from zero for the sample size of $n = 32$. Hence, the results must be considered inconclusive, except to the extent that they demonstrate that an adjustment for trucks based on an assumed noise source height of up to 8 ft above the highway surface might be acceptable.

The noise reductions computed at a given location for a source height of 8 ft (applicable to trucks) were rarely

more than 3 dBA less than those computed at the same location for a source height of zero (applicable to automobiles). This is consistent with the results discussed previously, which suggest that the flat 5 dBA adjustment for trucks, as currently specified in the Design Guide, is excessive. However, the Line Source Model can produce widely different noise reduction predictions for trucks and automobiles under certain conditions not represented in the data for Site 1. Specifically, as the path length difference parameter, δ, passes from positive to negative values, the noise reduction predicted by the Kurze and Anderson model drops sharply from about 7 dBA to 0 dBA. With this in mind, consider the hypothetical case of a 5-ft-high observer shielded from highway noise by a 5-ft-high barrier. If the source height for truck noise is more than 5 ft high the observer would enjoy little or no protection from the barrier because the barrier is below his line-of-sight to the noise source. However, the tire noise from automobiles will still be reduced by more than 7 dBA because the barrier blocks his line-of-sight to this noise source.

Other Truck Noise Data

In 1971, the California Department of Highways (CDH) performed experiments at Site 1 to measure the noise reduction provided by the roadside barrier at that site, using a single unmuffled diesel truck as the source. The truck was driven repeatedly in both directions along the highway past the roadside barrier. On each run, the *maximum* noise levels in dBA were measured at equidistant locations on both sides of the roadway to arrive at a free-field and a shielded noise level. A measured noise reduction for each run was established by the difference between free-field and shielded data. The measurements were made at 80 ft and 60 ft from the center of the truck lane. The results are given in Table 16 together with predicted noise reductions at the two locations, assuming the height of the source above the highway surface is (1) 0 ft, and (2) 8 ft. Because the CDH measurements were based on maximum levels during a single truck passage, they actually reflect the barrier attenuation of a point source, rather than an incoherent line source. Hence, the predictions were arrived at by using the point source equivalent of the Line Source Model, as proposed by Maekawa (*2, 3, 14*) and outlined in Appendix D.

In Table 16, the results at the 80-ft location show excellent agreement between the CDH measurements and the predictions assuming an equivalent source height of 8 ft for the truck noise. At the 160-ft location, however, the best agreement is provided by the predictions assuming an equivalent source height of 0 ft. Again, the results appear to be inconclusive. The only proper way to resolve this issue is to obtain additional barrier attenuation data for trucks at locations near the line-of-sight to the truck.

FURTHER STUDY OF SHIELDING BY ROADSIDE STRUCTURES

The Design Guide procedure for calculating the noise reduction due to roadside structures is straightforward: it recommends 3 dBA of reduction for each row of structures up to a maximum of three rows. The results discussed previously indicate that this simple procedure produces noise reduction estimates of the right order of magnitude, but not with the accuracy demonstrated by procedures applicable to other types of shielding configurations. Hence, other possible prediction techniques were sought.

One possibility was to predict the net noise reduction provided by roadside structures using a Modified Line Source Model (see Appendix D). Specifically, the continuous line of traffic extending approximately one mile on each side of the receiver location was divided into 52 equally spaced increments. The reduction of noise from each increment was then calculated by computing the path length difference between that segment and the receiver, taking into account the full geometric details of the intervening structures. The shielded noise levels at the receiver location due to each segment were then summed to arrive at a total shielded noise level. The procedure requires considerable computation, but produces reasonably accurate predictions, as is demonstrated later herein.

Another technique involves an empirical model for noise reduction due to roadside structures arising from studies performed by the National Physical Laboratory in England (*10*). Based on extensive measurements of actual traffic noise, that study suggests that a good fit to noise reduction data for roadside structures (houses) is provided by

TABLE 15

RESULTS OF LINE SOURCE PREDICTIONS WITH TRUCK CORRECTION, SITE 1

STATISTICAL PARAMETER USED FOR ASSESSMENT	RESULTS (dBA) COMPUTED	IDEAL	DIFF. STATIST. SIGNIF.? [a]
Avg. discrepancy, $\bar{\Delta}$	0.47	0	no
Standard deviation, s_Δ	1.67	0	—
Lease squares line (Fig. 10):			
Intercept	0.46	0	no
Slope	1.00	1.0	no
Range of $\bar{\Delta}$ with:			
Dist. from roadside	1.09	0	no
Ht. above ground	1.49	0	no

[a] All difference tests performed at 1% level of significance.

TABLE 16

COMPARISON OF CDH MEASUREMENTS AND NOISE REDUCTION PREDICTIONS, SITE 1

DIST. FROM SOURCE (FT)	NOISE REDUCTION (dBA) AVG. CDH MEASUREMENTS	POINT SOURCE PREDICTIONS 0 FT	8 FT
80	15.6 ($n=20, s=1.6$)	17 ($\delta=2.8$)	16 ($\delta=2.0$)
160	15.4 ($n=10, s=1.6$)	15 ($\delta=1.8$)	12 ($\delta=0.65$)

$$NR = (16.6 - 0.21\mu) - (3.5 - 0.1\mu)\log_{10}y \quad (9)$$

in which μ is the percentage of open area at the housing frontage and y is the distance in meters behind the houses. Eq. 9 applies to the reduction in L_{10} levels at a height of 1.2 m above the ground for the range of values, $0 \leq \mu < 30$ and $1 \leq y < 100$ m.

A direct comparison of Eq. 9 to the measured noise reductions for roadside structures in this study (Sites 5 and 6) is difficult because the values of μ for the structures fall above the maximum value of 30 stated for Eq. 9; i.e., $\mu = 40$ for the houses at Site 5, and $\mu = 37$ for the houses at Site 6. The closest comparison is provided by the result of Eq. 9 at the upper limiting value of $\mu = 30$, which corresponds to a predicted noise reduction of approximately 10 dBA at distances of 1 to 100 m behind the houses. This approximate result is compared to the predictions of the Design Guide and the Modified Line Source Model, as well as the measured noise reductions at Sites 5 and 6, in Table 17.

TABLE 17

PREDICTED AND MEASURED NOISE REDUCTIONS FOR A SINGLE ROW OF HOUSES

		NOISE REDUCTION (dBA)	
PREDICTION PROCEDURE	HT.	SITE 5	SITE 6
Natl. Phys. Lab., Eq. 9	1.2 m	10 [a]	10 [a]
Design Guide	5 ft	3	3
Modified Line Source Model	5 ft	4.4	5.5
Measured (avg.)	5 ft	4.0 (n=3)	5.8 (n=4)

[a] Approx. noise reduction for L_{10} levels.

The results in Table 17 show that the modified line source predictions produce the best agreement with the measurements. The predictions of Eq. 9 provide the poorest agreement. Part of the discrepancy between Eq. 9 and the measured results may be due to (1) the inappropriately large values of μ for the two sites considered, and (2) the fact that Eq. 9 applies to L_{10} levels rather than L_{50} levels as used for the measurements and other predictions. However, it is believed that at least some of the discrepancy reflects a failure of Eq. 9 to fit data for structures that are significantly different from those used in its formulation; i.e., Eq. 9 was empirically derived from noise reduction data for closely spaced two-story homes. The Design Guide does not consider the housing height in arriving at predictions either, but the modified line source procedure does.

CHAPTER THREE

INTERPRETATIONS AND APPLICATIONS

The findings of this project provide considerable information that can be applied directly to the highway noise control problem through suggested changes in the procedures of the Design Guide (*NCHRP Report 117*) (*1*). These suggested changes are presented after a brief summary and interpretation of the more pertinent results of the research.

SUMMARY OF RESULTS AND INTERPRETATIONS

The pertinent results of the research for various types of highway noise shielding configurations are summarized in the following.

Roadside Barriers, and Elevated and Depressed Highways

A comparison of the Design Guide predictions with the measured noise reductions for a roadside barrier configuration, two elevated highway configurations, and a depressed highway configuration reveals consistent discrepancies of three types:

1. The Design Guide tends to underpredict noise reductions at locations where the value of the path length difference parameter, δ, is small.
2. The Design Guide tends, at some sites, to overpredict noise reductions at locations distant from the roadside.
3. The Design Guide tends, in most cases, to underpredict the noise reduction for truck traffic as opposed to automobile traffic (Table 10).

The first type of discrepancy is due to inadequacies in the basic barrier attenuation model assumed in the Design Guide (see Fig. D-4). The second type of discrepancy evolves from the free-field propagation loss rule of 4.5 dB per doubling of distance assumed in the Design Guide. This value is too large for level sites free of ground cover. The third type of discrepancy results from what now appears to be the generally excessive assumption in the Design Guide that shielding configurations of all types are 5 dBA less effective against truck noise than against automobile noise.

To verify the source of these discrepancies, the data for the sites in question were re-analyzed using a conventional

barrier attenuation model for incoherent line sources (Fig. D-3), and the theoretical spreading loss factor for line sources of 3 dB per doubling of distance. No adjustment in the predicted noise reductions was introduced for trucks. With these changes, the agreement between predicted and measured noise reductions was consistently good. Only minor discrepancies were noted at a single site, and those were easily explained by the influence of ground cover attenuation at that site.

Roadside Structures

A comparison of the Design Guide predictions with the measured noise reductions for two sites involving roadside structures (one-story houses) indicates reasonable agreement on the average, but not in detail (Figs. 8 and 9). The Design Guide underpredicts the measured noise reductions behind one row of houses and overpredicts those behind three rows of houses. A modified version of the Line Source Model used for other shielding configurations might provide more accurate predictions, but the required calculations can be exhausting because of the intermittent nature of roadside structure shielding. It is believed that the Design Guide procedures will suffice for this case if they are modified to reduce the bias toward underprediction for a single row of houses and overprediction for multiple rows of houses.

Traffic Effects

A comparison of the Design Guide predictions with the measured noise reductions for various traffic flow conditions reveals no significant variation in the accuracy of the noise reduction predictions with variations in traffic speed or volume. On the other hand, a significant variation in accuracy is revealed for varying truck mix ratios (Table 10). This variation can be suppressed to a statistically insignificant level by an appropriate modification of the Design Guide adjustment for truck traffic noise reduction.

Environmental Effects

A comparison of the Design Guide predictions with the measured noise reductions for various different environmental conditions reveals no significant variation in the accuracy of the noise reduction predictions with modest changes in temperature and wind (Table 11). Most of the data, however, were collected when wind velocities were less than 8 mph and in a single direction. Data from other sources (*14*) indicate that wind can have a significant impact on barrier noise reductions under certain conditions: wind velocities of more than 10 mph can be expected to reduce the actual noise reduction at locations downwind from the highway, and to increase the actual reduction at locations upwind from the highway.

SUGGESTED DESIGN GUIDE CHANGES

Based on the results of this project, the following specific changes are suggested in the Design Guide procedures for predicting the noise reduction provided by various highway noise shielding configurations:

1. For roadside barriers, elevated highways, and depressed highways, the noise reduction curves in Figures 8 through 11 of the Design Guide should be deleted and replaced by the single curve defining the attenuation of incoherent line sources by barriers, as suggested by Kurze and Anderson (*8, 14*). However, the maximum noise reduction should still be limited to 20 dBA, as detailed in Appendix C.
2. For roadside structures, the recommendation in the Design Guide (p. 9) should be modified to specify 4.5 dBA of noise reduction for the first row of structures, and 1.5 dBA of additional noise reduction for each additional row of structures, up to a limit of 10 dBA total reduction.
3. The arbitrary adjustment of −5 dBA for the barrier attenuation of truck noise, as specified in the Design Guide (p. 5), should be reduced to an adjustment of −3 dBA, as detailed in Appendix C.

Concerning the third change, a more accurate adjustment for trucks would probably be provided by a procedure in which the noise reduction is computed assuming the truck noise source is at some appropriate height above the highway surface. However, attempts to define such an appropriate height have been inconclusive. Furthermore, an adjustment of this type would greatly complicate the Design Guide procedures. The adjustment of −3 dBA should suffice in most cases.

Beyond these specific changes, it is suggested that a more general change in the Design Guide procedures be considered. The change relates to the coefficient of the $A \log D$ term in the basic traffic noise prediction model given in the Design Guide (Eqs. 24 and 25). This coefficient is currently fixed at $A = 15$, which translates into a propagation loss factor of 4.5 dBA per doubling of distance. Although a coefficient of $A = 15$ may be reasonable for many situations in urban regions, it appears to be too large for cases where the surrounding terrain is flat and free of ground cover. Consideration should be given to allowing a choice of values for A, ranging from $A = 10$ for bare level ground to $A = 15$ for cultivated land.

CHAPTER FOUR

SUGGESTIONS FOR FUTURE RESEARCH

During the course of this project, various aspects of traffic noise reduction were investigated. Central to this investigation were the measurement and evaluation of the noise reduction performance of various highway constructions under field conditions, with the final objective being a refinement of the procedures of the Design Guide. As in any application-oriented research, however, many questions were raised during the course of the study. The following paragraphs suggest some specific topics for future research that resulted from this study, as well as some general topics concerned with highway noise.

BASIC TRAFFIC NOISE MODEL

The measurements acquired during the study indicate that the basic traffic noise model suggested in *NCHRP Report 117* may not apply to all sections of the U.S. In particular, there is evidence that truck noise varies widely in character and magnitude from state to state. A noise survey of various selected sections of the U.S. would serve to determine this variability. With the benefit of appropriate adjustments to the basic traffic noise model, better estimates for the traffic noise for individual situations in different geographical locations would be obtained.

PROPAGATION OF TRAFFIC NOISE

The Design Guide procedures specify a noise propagation in the free-field condition of 4½ dB per doubling of distance. This estimate of highway noise propagation is too arbitrary. To establish a more appropriate estimate, however, additional studies of free-field noise propagation are needed.

The propagation of highway noise is a function of many variables; these can be grouped in three general categories: (1) traffic conditions, (2) environmental conditions, and (3) the geometrical description of the highway and surrounding terrain. The first category relates to the assumption of a line source. In most instances, the prevailing traffic conditions are such that a line source exists. For an average four-lane highway, this will be true when the total traffic volume exceeds perhaps 1,000 vph. However, in many instances when the traffic volumes are lower than this figure, this line source assumption is not rigorously correct. How traffic noise propagates with distance under low traffic flow conditions must therefore be determined. The second category involves the prediction of sound propagation under various weather conditions. Such variables as temperature and wind gradients affect noise propagation to a large degree and should be investigated. The third category involves the description of the ground plane between source and observer. Of special concern is the propagation of traffic noise over terrain with different types of ground cover. The final objective of the study should be to derive an improved model of sound propagation near highways.

HIGHWAY TRAFFIC NOISE CALCULATIONS

Actual application of the Design Guide in several expressway design studies has provided insight into the problems faced by designers for highways traversing established urban areas where both noise levels and land use are critical. In such cases, noise contours rather than single point noise level estimates are desirable. The large amount of data handling necessary to develop contours suggests that traffic noise calculations be computerized. Two distinct levels of complexity for computer calculations are suggested, to meet the widely varying needs of the highway designer.

One immediate approach is a computer program in which the Design Guide noise prediction methods can be digitized. The design data given in the tables and graphs would be stored in the computer, which would be used as a "look-up" device and "bookkeeper" to add and tabulate the various corrections for individual roadway elements, and to calculate the final estimated noise level.

The basic computer programming for such an approach is straightforward. However, it is believed that the program would be particularly useful if it were carefully prepared for a variety of either time-sharing or remote-terminal computers. Special emphasis should be given to developing an easy-to-use program that could be executed by engineers having access to a simple teletype input terminal.

Experience in estimating the noise environment for expressways and expressway interchanges in urban areas, particularly those having irregular terrain, suggests that application of the Design Guide procedures often requires serious simplifications of highway design and terrain features. Because of the complexity of the required calculations in such a situation, accompanied by the need for relatively accurate estimation of noise levels at many ground locations, a much more elaborate computer program development is envisioned. Such an approach would use a large-capacity, high-speed computer facility, and would be used primarily for detailed design studies of critical sections of expressway routes.

Rather than the approach adopted in the Design Guide, the whole topographical situation for the proposed design would be introduced into the computer storage. This could be done by graphical tracing of the detailed topographical maps developed for the expressway design. The ultimate output of the program would be the calculation of the noise levels for ground positions on a mesh or grid system. From the output of the grid values, noise contours could be

readily drawn by hand. Simulation of the traffic noise sources could be based on distribution of sources along the actual roads or routes of interest. Time distribution statistics might also be incorporated. For each computer program, a user's manual should be provided that includes examples in sufficient detail to permit practical use of the programs by designers not skilled in acoustics or computer programming.

EFFECTS OF TIME-VARYING NOISE ON SPEECH, SLEEP, AND ANNOYANCE

Considerable knowledge is available about the effects of steady-state noise on speech intelligibility and the relative annoyance of individual noise-producing events. However, the effects of time-varying noise and the multiplicity of noise events have not been thoroughly investigated. For example, accurate estimates can be made of the intelligibility of speech in a given steady noise environment. Similar predictions can be obtained for slowly varying, nonsteady-state noise at various points in time. On the other hand, there has been no investigation of the problem of an individual's over-all assessment of the environment if different amounts of speech interference or interruption are present over long periods of time.

A person's assessment of the noise environment when the number of noise events is varied is also unknown. It has been assumed that noisiness or annoyance varies in proportion to the acoustical energy (i.e., 3 dB per doubling) but it is difficult to demonstrate this in psychophysical tests.

A noise situation that continually reoccurs in traffic situations is the one in which a number of discrete noise events intrude on a relatively high-state background noise level (e.g., the presence of trucks on a busy freeway). This situation is poorly understood from the standpoint of either speech intelligibility or annoyance assessment. Other related problems exist that suggest the need for research to appropriately extrapolate the current knowledge of the effects of steady-state noise to nonsteady-state cases of practical importance. Such areas of research would include judgment tests to determine the effects of: (1) variation in amplitude vs number of events; (2) variations in the fluctuation of noise levels from long-term averages; and (3) the combinations of steady-state and discrete noise events of varying dynamic range and frequency of occurrence.

Additional areas of research involving speech interference should include tests to determine: (1) the effect of the amount of interruption on a person's assessment of his environment; and (2) the effect of the rate of interruptions and whether the interruptions are random or periodic.

HIGHWAY NOISE PROBLEM

One of the most important aspects of highway noise is the noise source. Therefore, there is a need to define the present state of the art in the noise generation mechanisms and control techniques for the individual components (e.g., engine exhaust, gears, tires) that make up the composite noise produced by motor vehicles in use on public highways. A better definition of the noise sources would contribute greatly to the logical development of practical noise-control measures in highway design. It would permit a more accurate assessment of expected acoustical performance, as well as the practical limitations of such noise-control factors as geometry, road surface, landscaping, and barrier design. Also included here would be an assessment of the practicality of acoustical noise-control measures that might be used at the community level beyond the highway right-of-way. Such measures might include proper zoning procedures near highways, the use of noise screens for residential areas, and proper construction codes and regulations for buildings near highways.

All such actions must be assessed from the point of view of federal and local legislative action on both motor-vehicle noise levels and acceptable noise levels in communities. Local or federal limitations on vehicle noise levels, highway noise standards, community noise ordinances, building codes, and any other identifiable legislative actions must be considered. The economic effects for the various noise control possibilities considered in the previous paragraphs should be evaluated. A cost/benefit model should be developed for assessing the practicality and effectiveness of individual noise-control strategies and means for evaluating the cost/benefit relationships for mixed strategies involved in source control, highway design, and community control of land use.

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APPENDIX A

DATA ACQUISITION AND DATA REDUCTION

DATA ACQUISITION

Acoustic Instrumentation Acquisition

Figure A-1 is a block diagram of the acoustic instrumentation used to acquire noise data. Four identical sets of equipment were used, one for each measurement station. The instrumentation at each station consisted of a 1-in. microphone with preamplifier and power supply units. All four stations were centrally coordinated from a single location where sound level meters and tape recorders were located (Fig. A-2). Thus, all four stations could be controlled simultaneously by one operator. A calibration signal was recorded at the start of each tape. This procedure was repeated at the end of each tape to detect potential changes during the data acquisition period. Before each measurement period, identification information was recorded on the tape specifying the test site, date, time, run number, measurement station and microphone evaluation, and the sound level meter attenuator setting. Communication between stations and the central recording location was by walkie-talkie radios or by hand signals when line-of-sight was available. The microphones were attached to a 25-ft stand (Fig. A-3); different microphone heights were achieved by sliding the microphone attachment on the stand.

Traffic Volume and T/A Mix Measurements

Highway noise levels are a function of the traffic conditions that exist during the evaluation period. Therefore, it is important to accurately measure traffic parameters such as vehicle volume, truck-to-automobile (T/A) mix, density of flow in each traffic direction, and average speed. These measurements must reflect the prevailing conditions on the roadway while the noise data are acquired. Figure A-4 shows a typical case and the information acquired. The upper part of the form contains the information necessary to (1) identify the test site and measurement number, and (2) compare traffic information with noise data.

The truck count was acquired by entering a bar in the Field Count Form for each truck in each traffic lane as it passed the measurement location. In Figure A-4 the test site is a four-lane facility, two lanes in each direction. Thus, the information in lanes 1 and 2 corresponds to traffic flow closest to the observer (measurement station); lanes 7 and 8 correspond to traffic flow farthest from the observer. Total traffic flow in each direction was counted by observing all vehicles passing the measurement station

and recording the information on field counters. Both total traffic volume and truck count information were acquired for the entire 10-min traffic noise data-recording period. Estimates of hourly traffic volume and truck volume were easily calculated from the data forms (Fig. A-4).

Average Traffic Speed Measurements

Average traffic speed on the roadway during the acoustic data acquisition period was measured photographically. A 35-mm camera, equipped with a 28-mm wide-angle lens, an automatic power pack attachment, and a 200-exposure roll, was used. The camera was located about 50 to 100 ft from the near lane (Fig. A-5). The exact distance depended on the restrictions and geometry of each site. The camera was oriented normal to and above the traffic stream such that a clear view of all traffic lanes was available. Data were acquired at a rate of four exposures per second so that a measurement of the distance traveled by any particular vehicle could be obtained from two consecutive exposures. A number of targets were placed, generally on the median fence, at 25-ft intervals in order to have a fixed reference location and a known distance.

Before each data acquisition run, run number, site number, time, and date were recorded on a screen and photographed to provide a description of the data. During each 10-min data acquisition period a series of 6 to 10 ten-exposure bursts were made, each sequence containing photographic data on vehicle speed for each lane. The distance between the camera location and all traffic lanes was carefully measured to assure high accuracy in the subsequent data reduction of the photographs.

Weather Data Acquisition

At approximately ½-hr intervals, information on weather conditions was acquired and recorded on the form shown in Figure A-4. Typically, wind intensity and direction, temperature, and relative humidity were measured. When appropriate and possible, temperature and wind gradient data also were collected by measuring and recording these parameters at two different heights (e.g., 5 and 25 ft above the ground).

DATA REDUCTION

Noise Data Reduction: Instrumentation and Procedure

Noise data tapes recorded in the field were analyzed statistically to evaluate various noise measures used in highway noise description. This was done by first reducing each data sample into A-weighted sound pressure levels, and then sampling the dBA time history with a statistical distribution analyzer. Figure A-6 is a block diagram of the instrumentation used.

Basically, the system consists of a tape recorder (nominally the same recorder used in the data acquisition portion), a sound level meter to amplify the tape-recorded data and apply the A-weighting network, and a level recorder-statistical distribution analyzer combination to sample the weighted signal in time by associating a noise level range with each sample. The analyzer consisted of an amplitude detector circuit divided into a number of

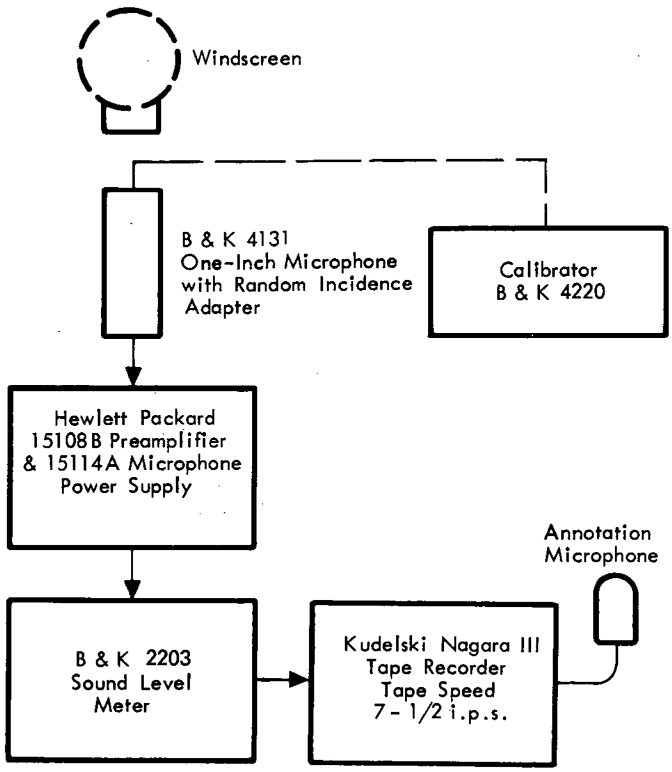


Figure A-1. Block diagram of acoustical instrumentation used in data acquisition program.

level increments or "windows." Each "window" corresponded to a range of 2.5 dB for current purposes. As the signal was sampled in time, the analyzer determined the "window" corresponding to the instantaneous noise level in dBA, and associated that level with the corresponding level range. Because the data were sampled at 0.3-sec intervals, and each measurement run consisted of a 10-min tape recording, 1,000 to 1,800 noise samples were obtained in each case. The variability in sample number was caused by editing out, in certain cases, those noise data associated with such events as aircraft overflights or local traffic. Figure A-7 shows the unsampled time history record that also was produced by the analysis. The amplifier-loudspeaker combination was used so that the operator could listen to the voice track describing each run, and edit the noise data when interference from other sources was present. Because the tapes were calibrated in the field by recording a known intensity signal at the beginning and end of each tape, the analyzed signal could be readily calibrated and associated with the correct noise level.

A computer program calculated the statistical descriptors used in *NCHRP Report 117,* as well as other measures of noise. The sample listing of the output is shown in Figure A-8. The output consists of the L_x levels * in terms of 15 percentiles. The most useful percentiles are obviously the L_{50} and L_{10} noise levels because they are used in *NCHRP Report 78* and *NCHRP Report 117* for noise

* L_x is defined as the noise level, measured in dBA, that is exceeded "*x* percent" of the time.

Figure A–2. Acoustical instrumentation; sound level meters and tape recorder units used at Site 6. (Courtesy of Michigan State Highway Dept., Research Lab. Div.)

calculations. The derivation of the descriptors is discussed in those reports. Figures A-9 through A-14 show a sample of the cumulative distribution for each test site evaluated during the study. If the data points fall on a straight line that would indicate a normal distribution of the traffic noise levels.

The Noise Pollution Level (NPL) (*15, 16*) and Traffic Noise Index (TNI) (*17*) noise descriptors (Fig. A-8) represent two measures of community noise developed in England in recent years. Both NPL and TNI descriptors use the basic L_{10}, L_{50}, and L_{90} noise descriptors in two terms. One term represents the equivalent continuous noise level; the other represents the fluctuation in noise levels. No further use of these descriptors is made in this report because they were calculated for information only.

Noise Data Statistical Analysis Results

The results of the statistical analysis described in the previous section are summarized in Tables A-1 through A-6. Each test site is identified by number and location. The data are summarized in terms of microphone heights above the ground plane, starting at the lowest height. Measurement stations are identified by letter designations; their horizontal distances from the near lane are noted in the proper column. The noise descriptors include the L_{10} and L_{50} noise levels as well as the calculated NPL and TNI values. In each case, the closest station to the roadside (Station A) is listed first, all others following as a function of distance from the highway.

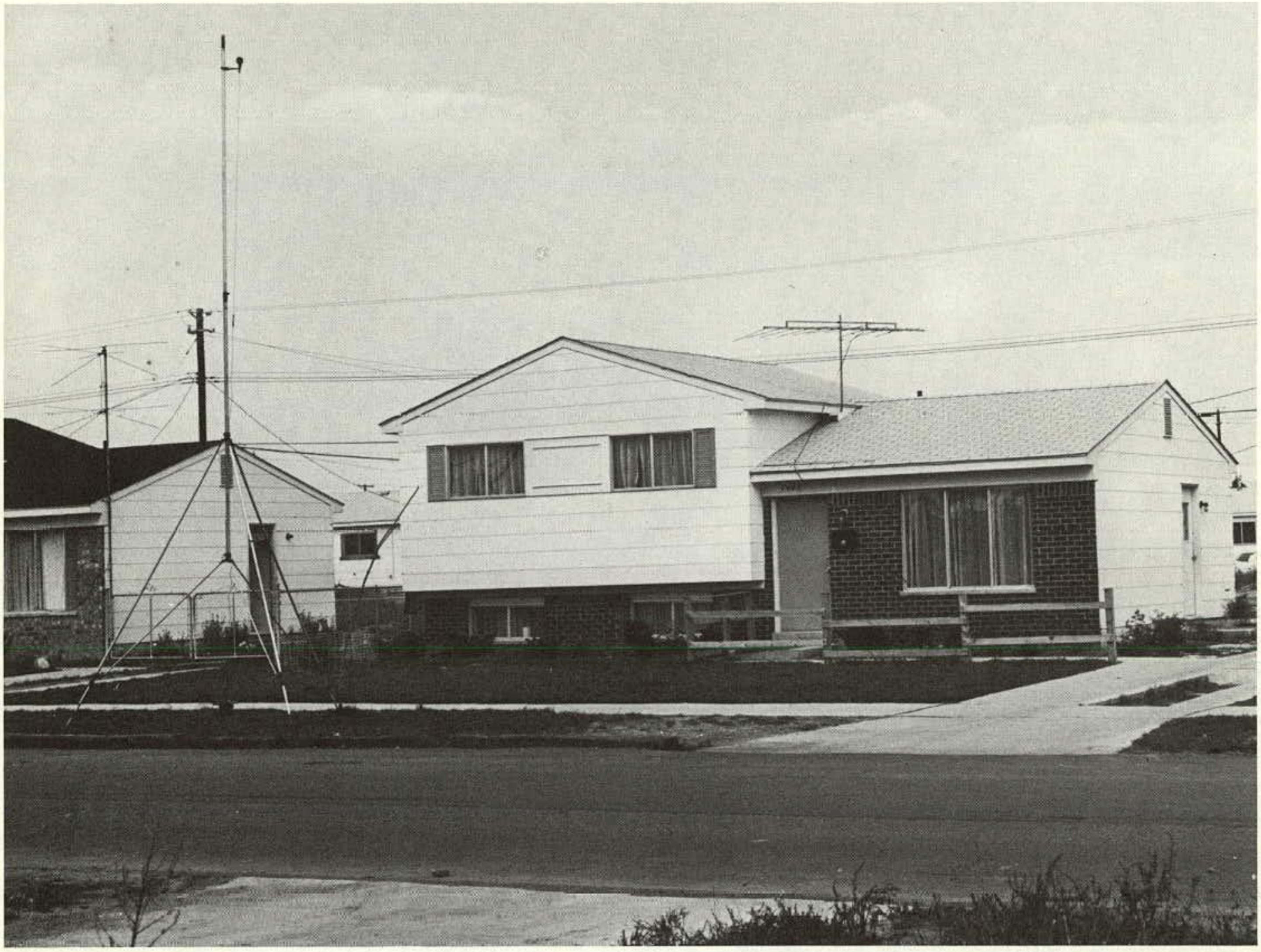


Figure A–3. Twenty-five-foot microphone stand; microphone at 25 ft. (*Courtesy of Michigan State Highway Dept., Research Lab. Div.*)

Traffic Volume and Traffic Mix Evaluation and Results

The traffic and truck count data were reduced by first calculating the total vehicle volume and total truck volume in terms of vehicles per hour. Each traffic flow direction was computed separately for both truck and total vehicle volume and summed to derive the total traffic flow past the measurement station. Tables A-7 through A-12 summarize the traffic data for the six test sites.

The information is presented in three categories:

• All lanes: Includes all traffic flowing past the observer. The number in parentheses refers to the total number of lanes.

• Near lanes: Includes the traffic flow direction closest to the observer.

• Far lanes: Includes the traffic flow direction farthest from the observer.

In all cases, T/A ratio or traffic mix was calculated in percentage as well. Average traffic speed is also summarized in these tables. The procedures used in the calculation of this variable are discussed in the following.

Average Traffic Speed Evaluation and Results

The photographic traffic data reduction system was designed to permit efficient assessment of the parameters of traffic flow at the noise measurement sites. This goal was accomplished by automating the assessment procedures to such an extent that a single semi-skilled operator could be guided by computer to process the data in rote fashion, without superfluous intermediate steps.

Data reduction was accomplished by a small digital computer interfaced to a graphic input device. The computer was a PDP-8; the input device was a Grafacon 1010A—a 10-in. by 10-in. translucent epoxy tablet in which 1024 fine copper wires are embedded in both X and Y directions. Rear projection of film strips of traffic conditions onto the tablet was accomplished by means of a stand-mounted

TRAFFIC AND TRUCK VOLUME COUNT FORM

HRB 3 - 7/2

Site No.:	5	Route :	35 W	Run No.:	1
Location :	RICHFIELD MINN.	Time :	12 : 20	Ref. Tape No.:	5

Date : 9-27-71
Engr. : BAK x PC

Lane No.	Count per Lane	60 / Count Time	Truck Volume per Hour	Estimate of Traffic Volume: 10 Minutes Count per Flow Direction	Estimate of Traffic Volume: Hourly Factor	Estimate of Traffic Volume: Traffic Volume vph
a	b	c	b & c			
1	32	6	192	335	6	2010
2	12	6	72			
3		6				
4		6				
5		6		299		1794
6		6				
7	5	6	30			
8	26	6	156			
Total	75		450	634		3804

ATMOSPHERIC MEASUREMENTS

Height	Temp.	Wind	Wind Dir.	Relative Humidity
1	65	4-	SW	90
15	65	4	SW	90

Note : Stations "B", "C", "D" at 5.0 Ft.

Observer ●

FIELD COUNT FORM

10-Minute Sample

Near Lane	卌 卌 卌 卌 卌 卌 ||
2	卌 卌 ||
3	
4	
Median	
5	
6	
7	卌
Far Lane	卌 卌 卌 卌 卌 |

Figure A-4. Traffic data acquisition form.

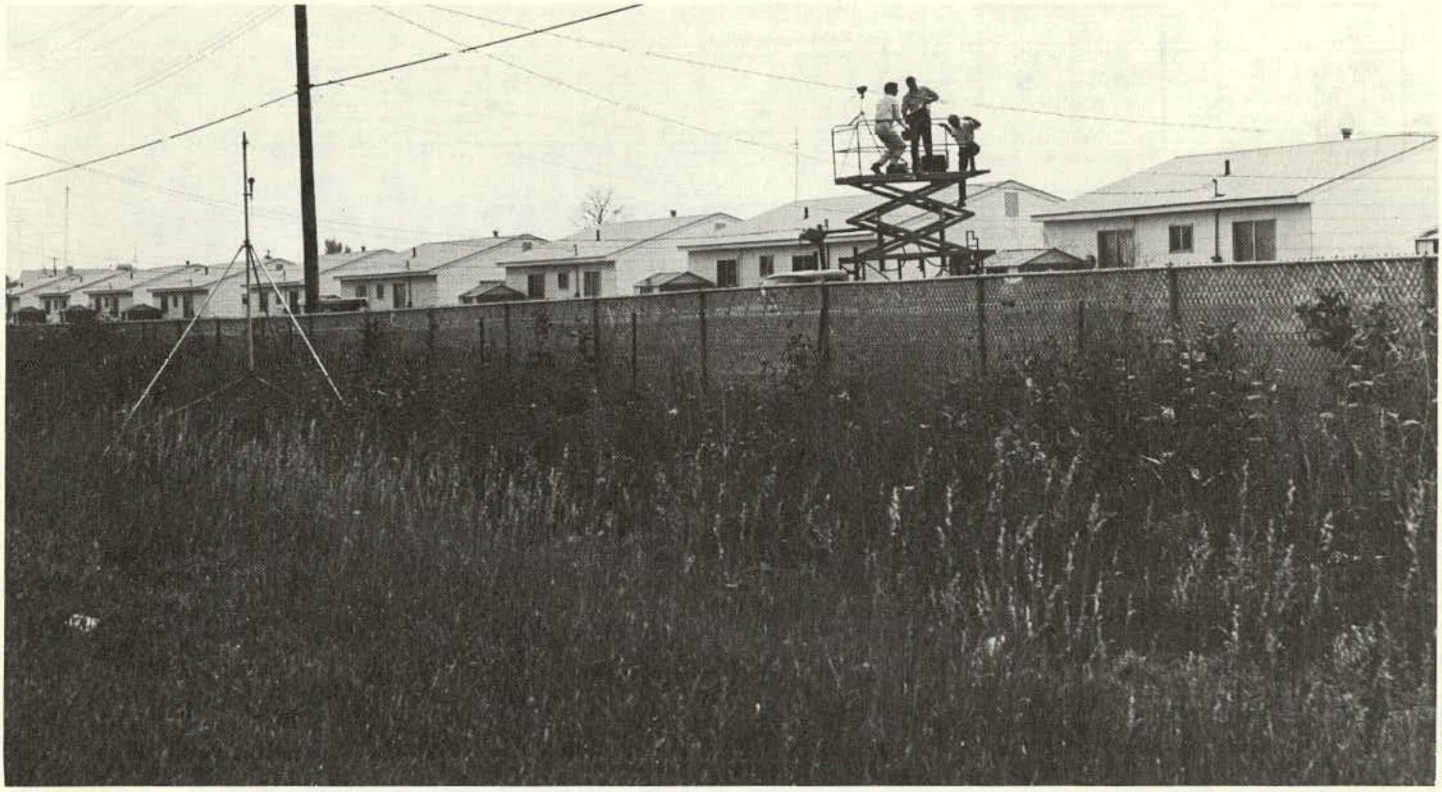


Figure A–5. Top: Lift and camera equipment, Site 6. Microphone location corresponds to Station A. Bottom: Relationship of camera to traffic. (Courtesy of Michigan State Highway Dept., Research Lab. Div.)

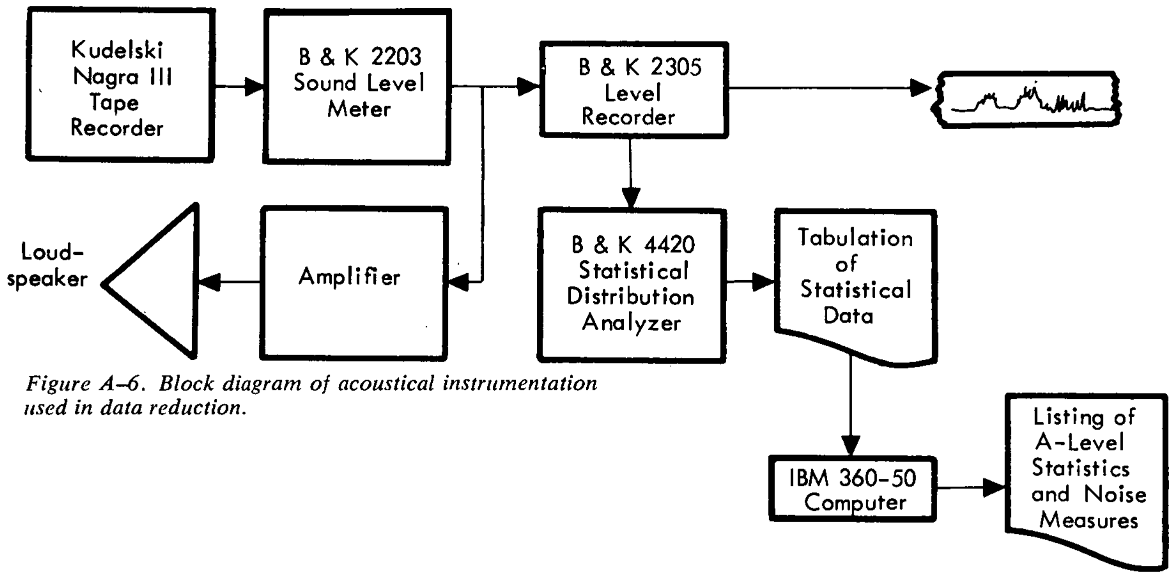


Figure A–6. Block diagram of acoustical instrumentation used in data reduction.

mirror and projector combination. The operator sat facing the tablet with film reels mounted above and behind the tablet, within convenient reach. A special stylus was used to indicate to the computer specific points on photographic frames.

At the beginning of a data reduction session the operator would load a long roll of 35-mm film composed of sequential frames of traffic flow taken at 250-msec intervals. The angle of acceptance of the lens, elevation of the camera position, and distance to the nearest traffic lane were contrived to permit the operator to distinguish individual ve-

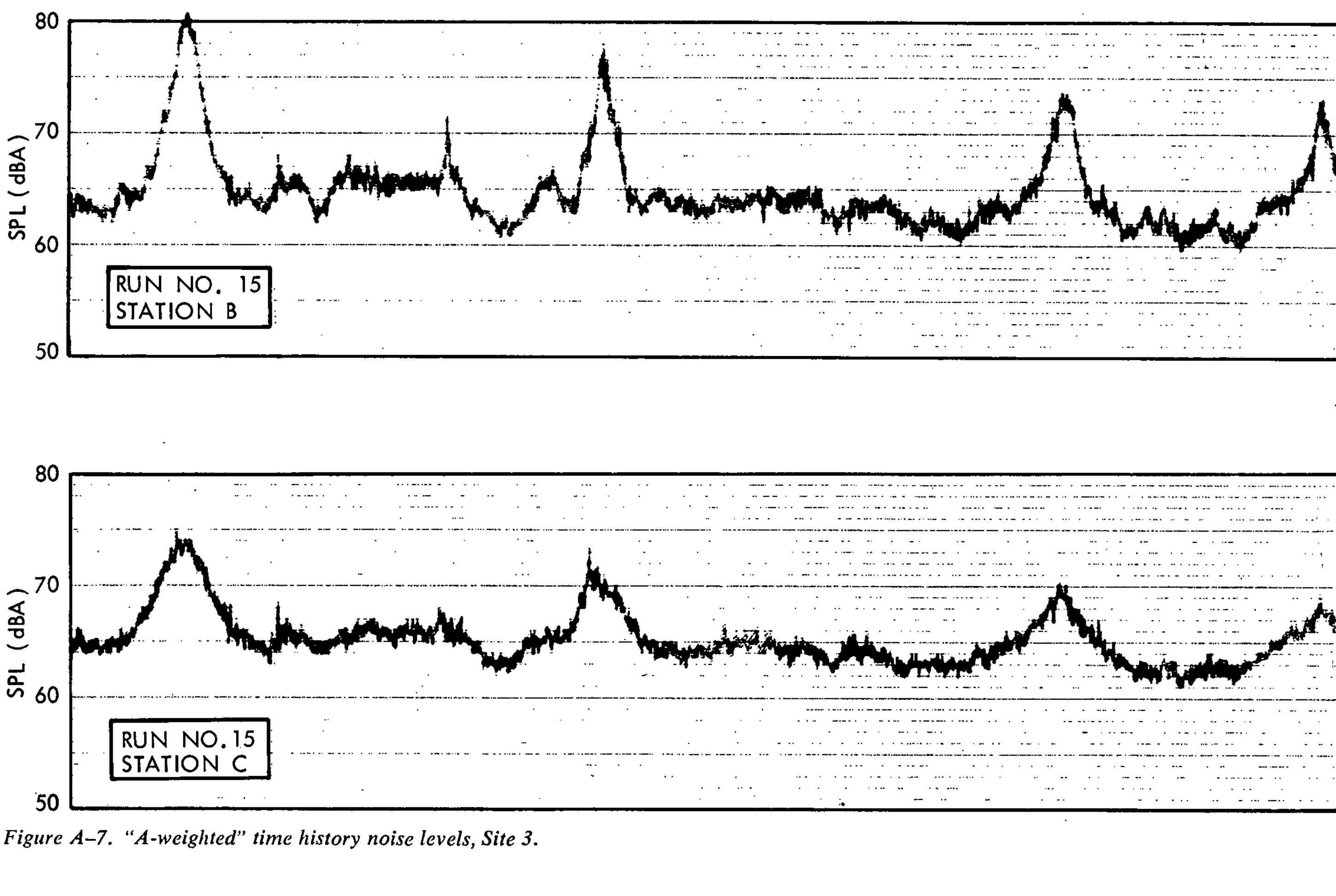


Figure A–7. "A-weighted" time history noise levels, Site 3.

hicles in as many as eight traffic lanes. Figure A-15 shows equipment and a sample of the photographic data.

A short conversation with the software, conducted by teletype, provided the program with the values of a few parameters needed to process data from an individual site. These parameters included the number of traffic lanes at the site, the distance from the camera to each of the lanes, and the number of vehicles in each lane.

The operator's next task was to provide the software with the information needed to calibrate the system. This was accomplished by projecting a single frame of a series of equidistantly spaced markers photographed at a known distance with the camera lens combination employed in the field. The operator indicated the calibration distance by touching the stylus to two of the markers.

Throughout the ensuing data reduction, the operator's actions were guided by an oscilloscopic display to the side of the tablet. The software instructed the operator in a step-by-step fashion by displaying messages appropriate to the sub-task at hand. For example, to commence data entry the computer signaled "SELECT TRAFFIC LANE." At this point the operator would determine by visual examination of the projected frame which lane(s) contained vehicles that could be tracked through a successive frame. On receipt of traffic lane identification, the computer signaled the operator to mark the position of a stationary reference point in the current frame that could also be located in the next frame. Once a reference point was marked, the computer would request the operator to indicate the vehicle's position.

The computer then signaled the operator to advance the film to the next frame and once again mark the positions of the reference point and the vehicle. The absolute value of the distance traveled by the vehicle with respect to the stationary point in the 250 msec that elapsed between successive frames thus determined the velocity of an individual vehicle. To lend added stability to the estimate of velocity so derived, the operator was permitted to identify and track up to six vehicles in each lane. The multiple estimates were averaged to arrive at an unbiased estimate of the average speed in each lane.

Extensive editing facilities were incorporated into the software system to give the operator as much flexibility as necessary to cope with irregularities in the photographic records. For example, if no vehicles could be found in a particular lane, the program permitted a "no data" entry. As a double check on the reasonableness of each individual data entry, the program displayed the distance traveled by the vehicle for confirmation by the operator. If the operator believed the distance was unreasonable (as, for example, might be the case in a mis-identification of the vehicle in successive frames), he could re-enter the same data.

```
                                        San Diego Frwy
LISTING OF STATISTICAL ANALYSIS FOR SITE 3 LOCATION 1
                                                   Reference Location
SAMPLE NUMBER =    15  @ TIME =  0640 HRS.

MEAN = 73.67     (ST. DEV = 2.552)  ENERGY MEAN = 74.68
NPL  = 81.21     NPL' =    80.32    TNI =          65.52

         L  1   =   82.49*
         L  3   =   80.70
         L  5   =   79.14
         L 10   =   76.89*
         L 20   =   74.91
         L 30   =   74.42
         L 40   =   73.92
         L 50   =   73.43*
         L 60   =   72.94
         L 70   =   72.41
         L 80   =   71.54
         L 90   =   70.68*
         L 95   =   70.24
         L 97   =   70.07
         L 99   =   68.58

SAMPLE NUMBER =    16  @ TIME =  0655 HRS.

MEAN = 73.01     (ST. DEV = 2.186)  ENERGY MEAN = 73.71
NPL  = 79.31     NPL' =    78.43    TNI =          60.99

         L  1   =   80.68*
         L  3   =   78.58
         L  5   =   77.26
         L 10   =   75.57*
         L 20   =   74.53
         L 30   =   73.96
         L 40   =   73.40
         L 50   =   72.83*
         L 60   =   72.25
         L 70   =   71.64
         L 80   =   71.04
         L 90   =   70.43*
         L 95   =   70.13
         L 97   =   70.01
         L 99   =   68.39
```

Figure A–8. Statistical analysis of highway noise data, Site 3.

At the conclusion of the data entry phase, a punched paper tape containing the raw data was automatically prepared. This tape provided hard copy of the basic data for subsequent analysis by a FORTRAN program. (Fig. 15 shows the resulting computer output.) The average speed information in each traffic flow direction and the average speed for all lanes is summarized in Tables A-7 through A-12.

Weather Data Reduction and Results

Weather data acquired during the test site evaluation included temperature, wind speed and direction, and humidity measurements. Temperature and wind gradient information were also collected when possible by taking temperature and wind data at two different heights above the ground. The gradient information was not considered accurate enough for purposes of this study and was therefore disregarded. Tables A-13 through A-18 give summaries of the weather information for the six test sites.

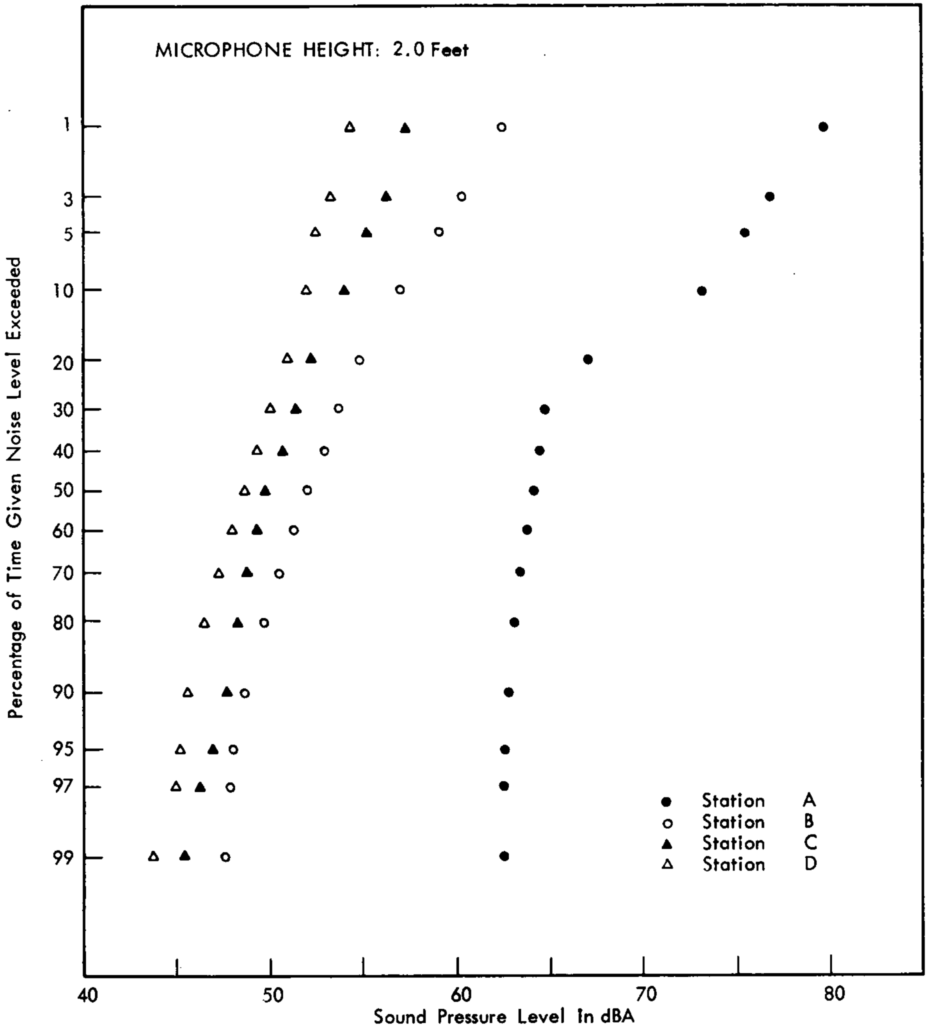


Figure A–9. Cumulative distribution curves, Site 1.

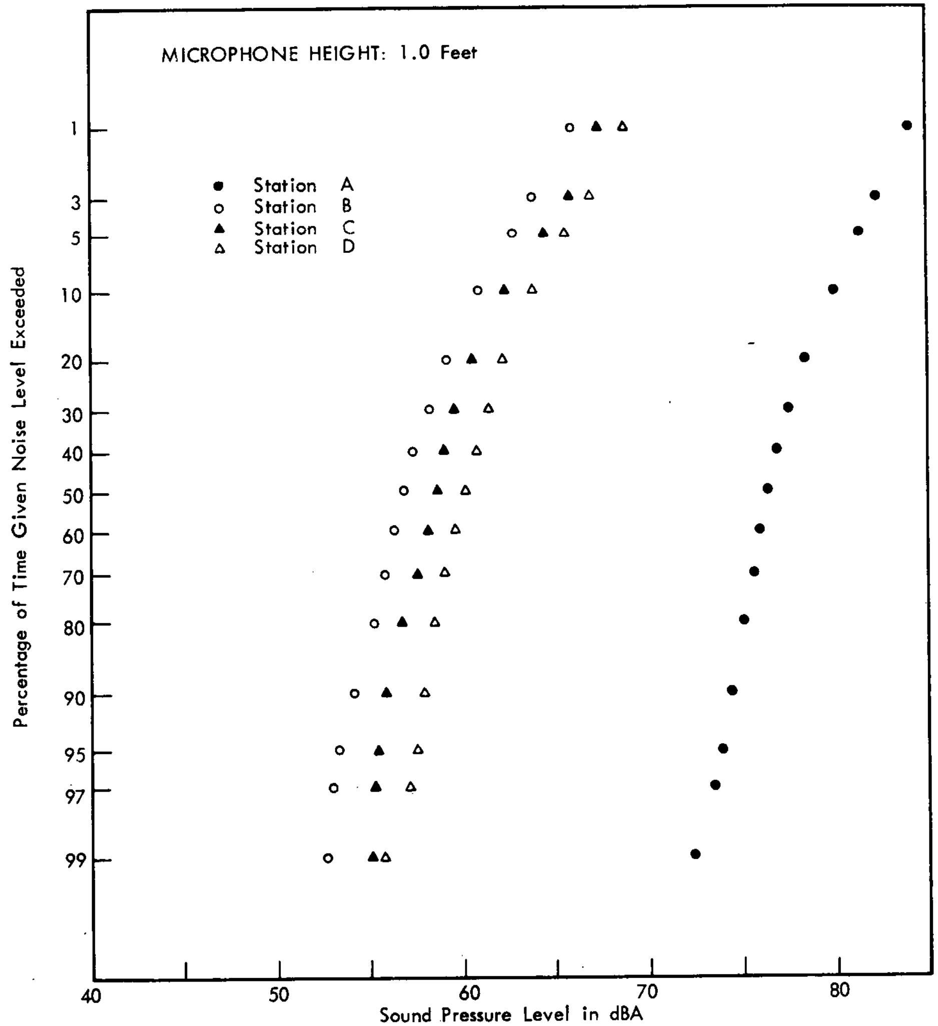


Figure A–10. Cumulative distribution curves, Site 2.

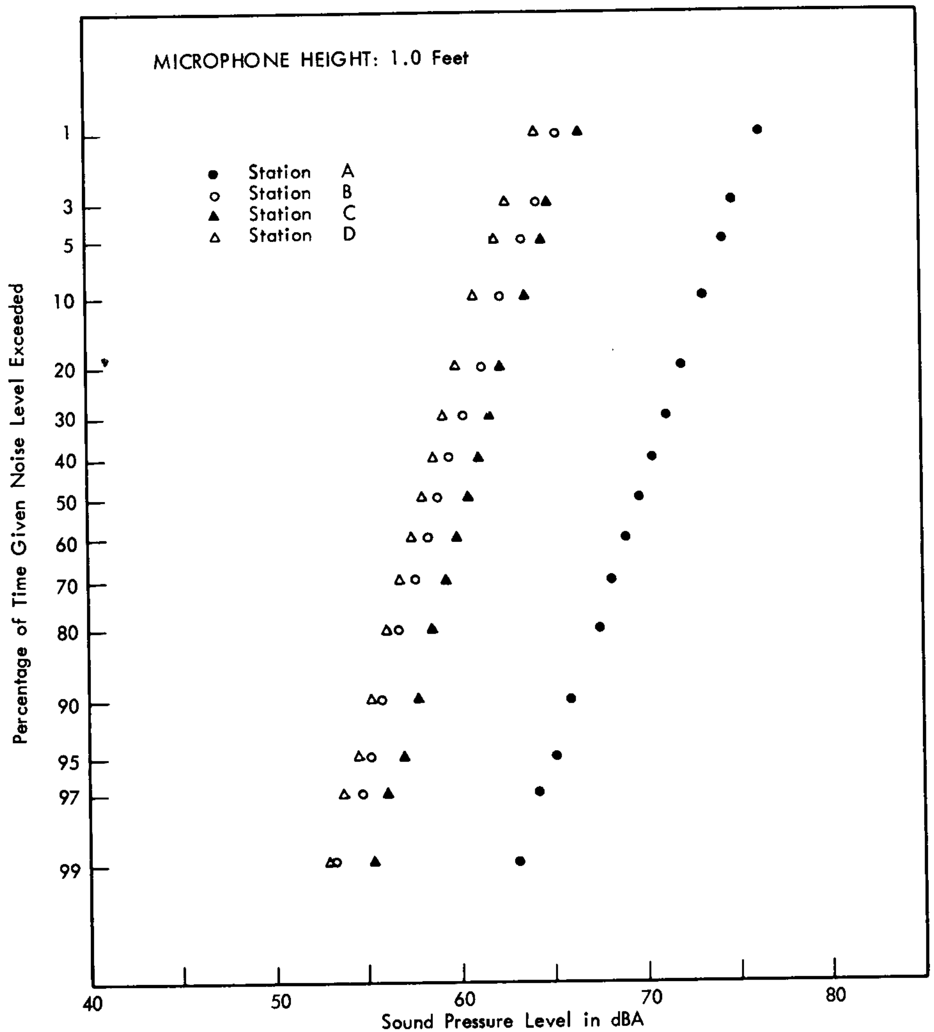


Figure A–11. Cumulative distribution curves, Site 3.

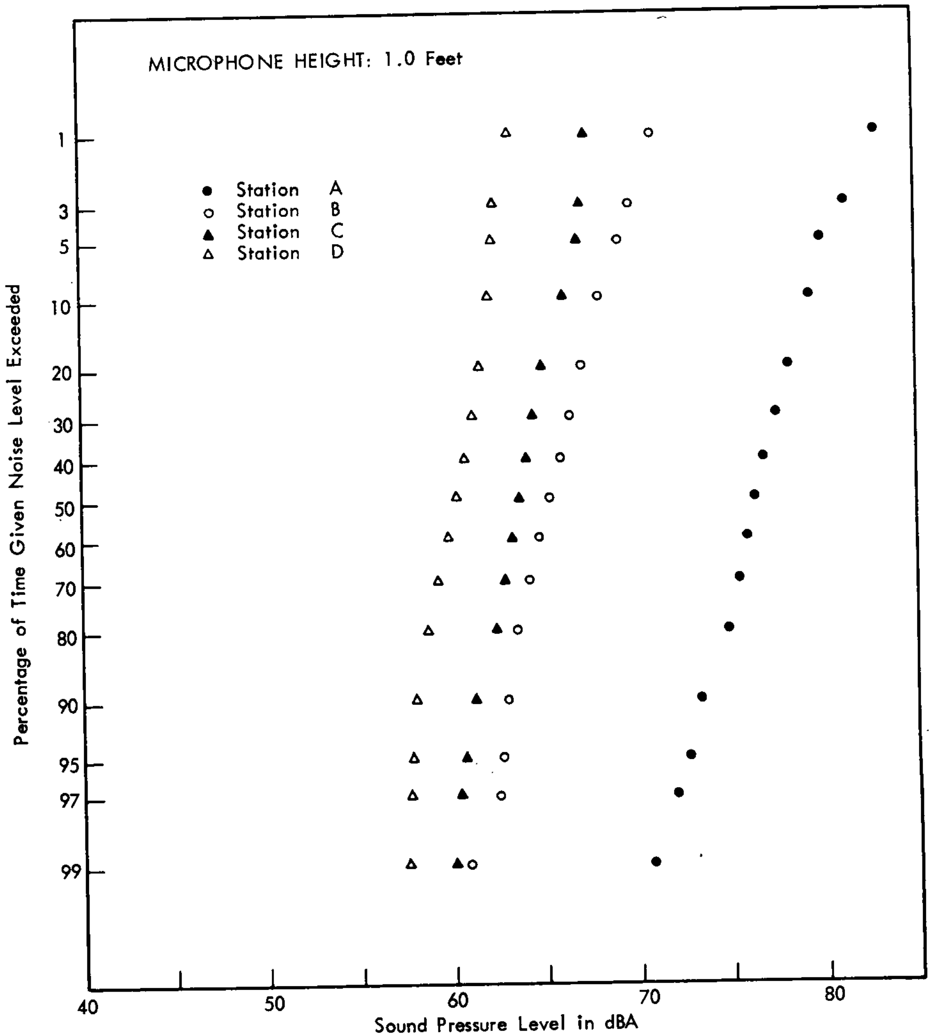


Figure A–12. Cumulative distribution curves, Site 5.

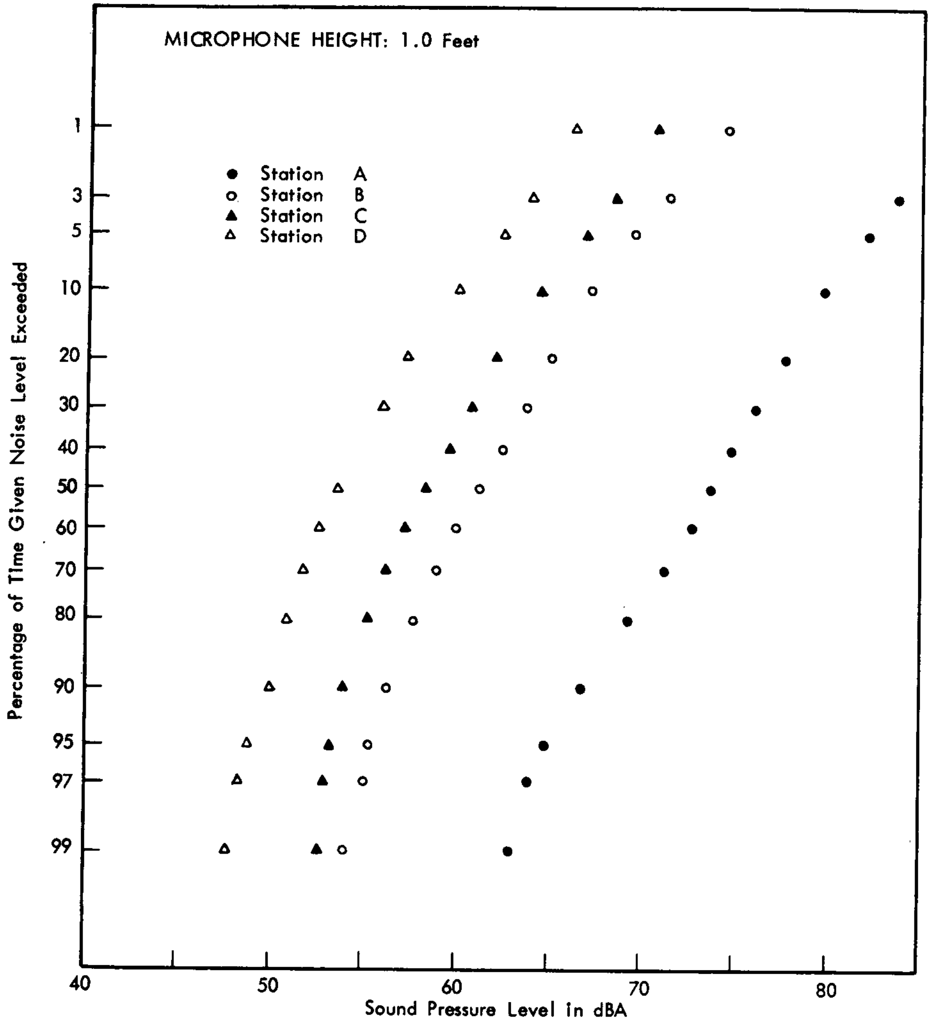


Figure A–13. Cumulative distribution curves, Site 6.

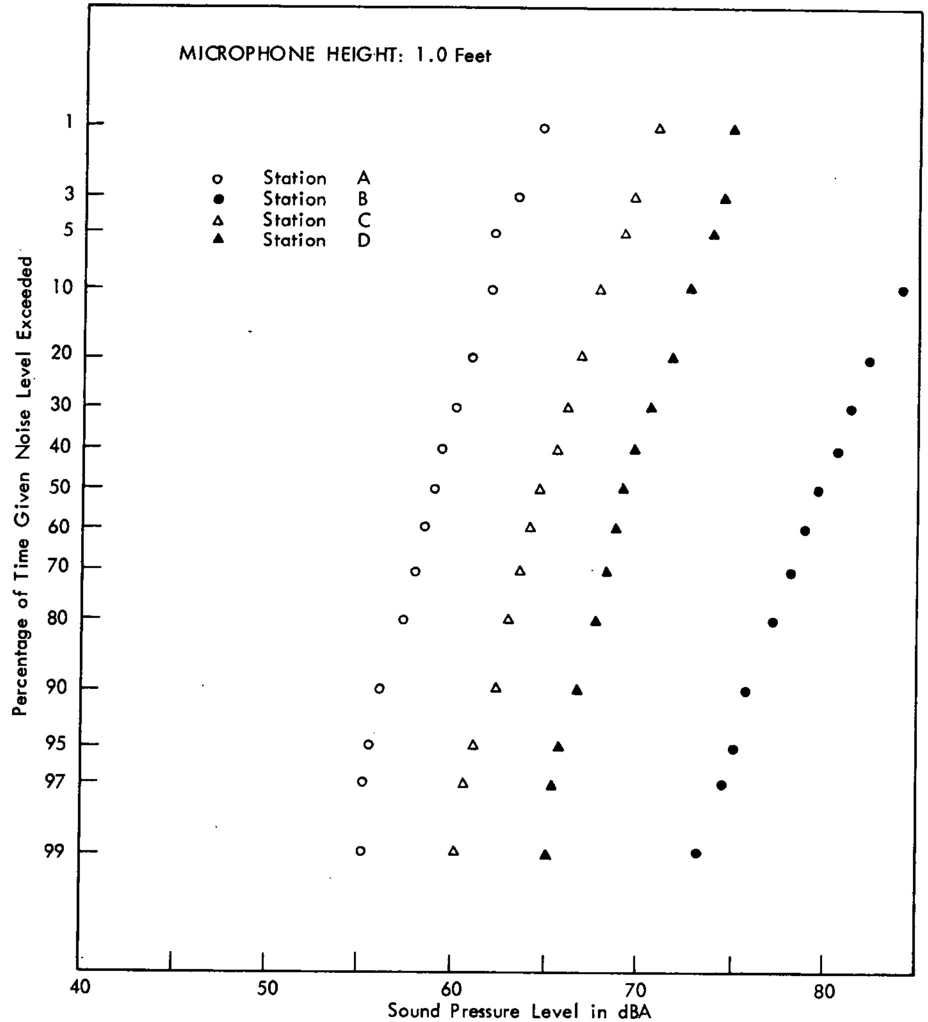


Figure A–14. Cumulative distribution curves, Site 9.

TABLE A–1

SUMMARY OF FIELD NOISE DATA STATISTICAL ANALYSIS RESULTS, SITE 1

MICROPHONE HEIGHT: 2.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
1	13:16	A	43	71.3	64.1	77.7	66.8
1	13:16	B	93	54.2	47.6	62.0	55.1
1	13:16	C	143	52.4	47.5	58.4	47.9
1	13:16	D	243	52.2	47.2	59.1	47.3
4	8:17	A	43	73.2	64.2	79.6	74.4
4	8:17	B	93	57.0	52.1	62.5	52.2
4	8:17	C	143	54.0	49.8	57.5	43.0
4	8:17	D	243	52.4	49.6	55.4	36.3
14	11:37	A	43	73.0	64.2	79.7	73.6
14	11:37	B	93	55.4	48.3	63.3	57.4
14	11:37	C	143	54.1	47.4	60.9	55.7
14	11:37	D	243	52.0	45.7	64.2	48.9

MICROPHONE HEIGHT: 4.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
13	11:27	A	43	73.6	65.2	79.9	75.3
13	11:27	B	93	57.0	53.8	60.4	45.7
13	11:27	C	143	54.3	50.9	57.6	43.0
13	11:27	D	243	53.0	49.2	62.6	42.8
15	13:09	A	43	72.8	64.3	78.4	72.6
15	13:09	B	93	55.0	49.4	62.5	56.7
16	9:15	A	43	70.6	54.7	83.6	93.7
16	9:15	B	93	54.4	46.9	61.8	58.0
16	9:15	C	143	53.3	46.9	59.5	53.5
16	9:15	D	243	54.2	46.9	60.5	56.8
20	11:49	A	43	75.0	64.7	89.2	81.2
20	11:49	B	93	57.1	49.2	69.6	66.8
21	12:43	A	43	73.2	64.3	80.3	74.4
21	12:43	E	63	52.9	45.8	59.6	52.4

MICROPHONE HEIGHT: 6.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
2	13:31	A	43	70.8	64.1	77.4	64.6
2	13:31	B	93	55.2	50.8	61.5	51.7
2	13:31	C	143	54.6	50.0	60.2	51.2
5	8:33	A	43	71.3	64.0	77.1	66.6
5	8:33	B	93	54.5	49.4	59.2	48.8
5	8:33	C	143	52.8	48.6	56.6	44.2
5	8:33	D	243	51.6	48.7	54.1	38.6
12	11:17	A	43	72.2	64.2	79.2	70.2
12	11:17	B	93	54.6	49.0	64.0	52.3
12	11:17	C	143	52.5	48.4	62.5	44.9
12	11:17	D	243	52.5	47.5	60.4	46.7
22	13:14	A	43	71.2	64.2	77.8	66.1
22	13:14	E	63	54.2	47.2	61.7	56.0

MICROPHONE HEIGHT: 8.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
3	13:47	A	43	69.1	64.0	73.1	57.8
3	13:47	B	93	55.9	50.5	62.0	53.4
3	13:47	C	143	59.9	54.0	71.0	68.5
6	8:48	A	43	72.4	64.4	78.0	71.1
6	8:48	B	93	55.3	50.0	60.0	50.3
6	8:48	C	143	53.7	49.4	57.7	47.3
6	8:48	D	243	52.0	48.7	55.1	40.8
11	10:57	A	43	71.6	57.5	84.8	96.6
11	10:57	B	93	53.7	48.9	57.9	47.5
11	10:57	C	143	52.5	48.8	57.2	43.5
11	10:57	D	243	51.4	47.8	55.1	40.1
17	9:32	A	43	72.9	64.3	81.6	72.8
17	9:32	B	93	58.1	50.8	68.8	66.2
17	9:32	C	143	57.9	50.9	67.2	64.9
17	9:32	D	243	58.3	50.7	67.0	65.0
23	13:38	A	43	72.3	64.3	77.4	70.6
23	13:38	E	63	56.4	51.3	62.0	55.2

MICROPHONE HEIGHT: 10.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
7	9:03	A	43	74.3	64.6	81.7	78.3
7	9:03	B	93	57.7	52.9	63.7	53.9
7	9:03	C	143	55.6	51.6	60.4	48.5
7	9:03	D	243	54.1	50.2	57.5	43.6
10	10:42	A	43	73.0	60.5	86.0	101.8
10	10:42	B	93	54.8	50.1	60.1	51.5
10	10:42	C	143	53.6	49.6	58.0	47.3
10	10:42	D	243	51.8	48.3	56.0	41.1
15	13:09	A	43	72.8	64.3	78.4	72.6
15	13:09	C	143	60.8	54.3	77.7	71.4
20	11:49	A	43	75.0	64.7	89.2	81.2
20	11:49	B	93	58.8	51.2	71.1	69.3
21	12:43	A	43	73.2	64.3	80.3	74.4
21	12:43	E	63	56.2	49.4	64.1	62.2
22	13:14	A	43	71.2	64.2	77.8	66.1
22	13:14	E	63	63.5	54.2	83.6	65.5

MICROPHONE HEIGHT: 12.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
9	10:32	A	43	73.3	64.5	82.6	74.5
9	10:32	B	93	58.8	53.4	68.6	62.8
9	10:32	C	143	58.9	53.0	68.9	63.9
9	10:32	D	243	58.7	51.9	84.3	104.9
18	10:06	A	43	72.3	64.2	82.5	70.8
18	10:06	B	93	67.2	62.5	107.2	134.6
18	10:06	C	143	59.8	51.7	69.3	67.4
18	10:06	D	243	59.8	53.0	68.1	64.3

MICROPHONE HEIGHT: 15.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
8	10:21	A	43	73.1	64.3	78.5	73.9
8	10:21	B	93	58.9	53.1	65.6	62.2
8	10:21	C	143	56.7	52.0	61.9	53.7
8	10:21	D	243	54.7	50.5	58.7	46.8
19	10:25	A	43	74.3	64.4	83.6	78.6
19	10:25	B	93	62.4	53.9	71.8	74.6
19	10:25	C	143	60.5	53.6	68.4	65.8
19	10:25	D	243	59.7	54.7	66.1	57.0
23	13:38	A	43	72.3	64.3	77.9	70.6
23	13:38	E	63	60.1	54.4	66.7	60.1

MICROPHONE HEIGHT: 20.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
15	13:09	A	43	72.8	64.3	78.4	72.6
15	13:09	B	93	59.4	53.0	67.8	63.6
20	11:49	A	43	75.0	64.7	89.2	81.2
20	11:49	B	93	62.7	55.5	73.5	61.8
21	12:43	A	43	73.2	64.3	80.3	74.4
21	12:43	E	63	65.2	55.1	74.1	71.9
22	13:14	A	43	71.2	64.2	77.8	66.1
22	13:14	E	63	64.6	55.5	72.8	69.2
23	13:38	A	43	72.3	64.3	77.4	70.6
23	13:38	E	63	65.9	57.0	74.4	74.0

TABLE A-2

SUMMARY OF FIELD NOISE DATA STATISTICAL ANALYSIS RESULTS, SITE 2

MICROPHONE HEIGHT: 1.0 FOOT

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
6	11:27	A	54	79.9	76.4	-	-
6	11:27	B	125	60.2	56.9	64.7	48.4
6	11:27	C	250	62.3	58.6	66.4	51.6
6	11:27	D	500	63.8	60.2	67.5	51.7
12	16:09	A	54	79.2	76.4	-	-
12	16:09	B	125	62.2	59.2	65.3	49.6
12	16:09	C	250	64.6	61.6	67.6	52.2
12	16:09	D	500	66.8	63.8	69.5	54.2

MICROPHONE HEIGHT: 5.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
1	15:26	A	54	82.5	79.0	86.0	70.3
1	15:26	B	125	64.4	60.1	67.9	53.8
1	15:26	C	250	68.9	65.4	73.0	56.5
1	15:26	D	500	67.9	64.9	71.1	53.6
5	11:10	A	54	81.6	76.9	-	-
5	11:10	B	125	63.4	58.8	69.0	57.3
5	11:10	C	250	65.7	61.4	71.1	59.7
5	11:10	D	500	67.9	63.3	73.1	64.7
11	15:54	A	54	78.5	75.3	-	-
11	15:54	B	125	62.5	59.3	68.0	49.8
11	15:54	C	250	65.1	61.9	70.0	52.8
11	15:54	D	500	66.8	63.6	70.1	54.3

MICROPHONE HEIGHT: 10.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
2	15:42	A	54	83.3	79.3	87.7	73.0
2	15:42	B	125	67.5	63.9	71.3	56.6
2	15:42	C	250	69.8	66.6	73.1	58.1
2	15:42	D	500	68.2	65.4	71.2	53.7
7	11:47	A	54	81.6	77.5	-	-
7	11:47	B	125	67.6	62.2	77.3	64.6
7	11:47	C	250	66.6	62.9	71.1	55.9
7	11:47	D	500	67.0	63.7	69.8	55.2
10	15:37	A	54	81.0	76.4	-	-
10	15:37	B	125	69.3	62.6	75.1	66.8
10	15:37	C	250	69.7	64.1	75.1	65.6
10	15:37	D	500	69.7	65.0	74.1	60.8

MICROPHONE HEIGHT: 15.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
3	15:56	A	54	81.2	78.5	83.5	67.2
3	15:56	B	125	67.1	64.4	69.3	50.4
3	15:56	C	250	68.6	66.1	70.8	54.1
3	15:56	D	500	67.3	64.5	69.9	51.3

MICROPHONE HEIGHT: 20.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
4	16:11	A	54	81.5	78.6	84.1	68.1
4	16:11	B	125	69.7	67.2	71.9	52.7
4	16:11	C	250	69.8	67.9	71.9	52.4
4	16:11	D	500	67.4	65.8	69.6	49.4
8	12:03	A	54	80.3	77.0	-	-
8	12:03	B	125	67.3	63.7	71.8	56.6
8	12:03	C	250	66.5	63.3	69.8	53.9
8	12:03	D	500	66.3	62.8	69.1	53.8
9	15:20	A	54	80.5	77.3	-	-
9	15:20	B	125	69.5	66.3	72.3	57.1
9	15:20	C	250	68.8	66.1	71.0	54.8
9	15:20	D	500	69.0	66.3	71.2	54.6

TABLE A-3

SUMMARY OF FIELD NOISE DATA STATISTICAL ANALYSIS RESULTS, SITE 3

MICROPHONE HEIGHT: 1.0 FOOT

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
10	8:25	A	83	73.3	69.8	77.5	65.3
10	8:25	B	125	62.3	58.9	66.2	52.1
10	8:25	C	250	63.7	60.5	66.9	51.4
10	8:25	D	500	61.1	58.1	64.3	48.7
14	11:27	A	83	72.4	69.4	76.5	61.1
14	11:27	B	125	64.5	60.0	69.3	57.6
14	11:27	C	250	64.7	61.5	68.9	52.7
14	11:27	D	500	61.1	57.4	64.2	49.2
18	7:25	A	83	75.7	72.9	79.0	62.1
18	7:25	B	125	67.2	63.9	71.1	56.5
18	7:25	C	250	67.4	64.1	70.8	55.7
18	7:25	D	500	64.8	61.6	67.7	52.0

MICROPHONE HEIGHT: 5.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
1	12:07	A	83	73.5	70.7	77.8	60.7
1	12:07	B	125	64.2	60.9	68.2	52.4
1	12:07	C	250	64.7	61.8	68.5	51.6
1	12:07	D	500	62.1	59.0	65.9	49.8
6	15:22	A	83	73.9	70.7	77.7	62.2
6	15:22	B	125	67.0	62.8	72.9	58.0
6	15:22	C	250	67.5	63.5	72.0	58.6
6	15:22	D	500	64.7	61.0	69.4	54.9
7	7:34	A	83	73.8	69.7	79.4	69.7
7	7:34	B	125	63.1	59.4	68.5	54.9
7	7:34	C	250	64.1	60.4	68.3	56.8
7	7:34	D	500	61.7	58.2	65.7	53.6
11	10:27	A	83	74.0	69.8	80.5	66.5
11	10:27	B	125	66.0	59.4	78.4	65.0
11	10:27	C	250	68.1	61.6	76.7	67.0
11	10:27	D	500	65.7	59.1	72.5	64.9
15	6:40	A	83	76.9	73.4	81.2	65.5
15	6:40	B	125	67.9	64.0	75.0	57.5
15	6:40	C	250	68.3	65.0	71.9	54.4
15	6:40	D	500	64.9	62.1	68.8	48.9

MICROPHONE HEIGHT: 15.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
2	12:19	A	83	73.0	70.2	76.3	58.7
2	12:19	B	125	64.8	61.9	68.0	49.2
2	12:19	C	250	64.3	61.5	66.2	47.0
2	12:19	D	500	61.7	59.0	63.6	44.1
5	15:09	A	83	72.4	69.7	75.6	57.4
5	15:09	B	125	65.6	62.6	68.4	51.9
5	15:09	C	250	64.8	62.3	67.6	48.9
5	15:09	D	500	61.8	59.0	64.2	47.6
8	7:53	A	83	72.8	68.7	80.8	72.6
8	7:53	B	125	64.9	59.8	72.7	64.7
8	7:53	C	250	64.8	60.6	71.5	59.7
8	7:53	D	500	61.7	57.9	66.8	54.4
12	10:55	A	83	72.8	70.3	76.7	60.3
12	10:55	B	125	64.9	61.4	70.1	55.1
12	10:55	C	250	64.8	61.7	69.4	50.9
12	10:55	D	500	62.1	59.0	67.2	49.4
16	6:55	A	83	75.6	72.8	79.3	61.0
16	6:55	B	125	69.1	65.5	73.6	57.3
16	6:55	C	250	68.8	65.7	72.5	55.5
16	6:55	D	500	65.4	63.0	68.3	49.9

MICROPHONE HEIGHT: 25.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
3	12:37	A	83	72.9	69.7	75.8	58.5
3	12:37	B	125	67.3	64.2	70.0	53.2
3	12:37	C	250	65.5	62.3	67.9	50.9
3	12:37	D	500	62.0	59.3	64.0	45.1
4	14:53	A	83	73.1	69.7	76.7	60.0
4	14:53	B	125	67.2	64.4	70.3	52.7
4	14:53	C	250	64.9	62.6	67.6	48.5
4	14:53	D	500	61.9	59.4	63.6	44.4
9	8:04	A	83	72.3	68.3	82.2	68.4
9	8:04	B	125	66.4	62.4	76.6	60.0
9	8:04	C	250	65.0	61.6	75.3	54.7
9	8:04	D	500	62.0	58.1	70.1	51.9
13	11:10	A	83	73.4	70.3	77.6	61.9
13	11:10	B	125	67.2	64.0	71.7	56.1
13	11:10	C	250	66.3	63.3	69.7	53.3
13	11:10	D	500	62.2	59.4	65.0	45.8
17	7:10	A	83	77.3	72.7	81.7	68.3
17	7:10	B	125	73.5	67.6	77.7	67.7
17	7:10	C	250	71.7	66.8	75.5	62.6
17	7:10	D	500	67.4	63.2	71.0	57.6

TABLE A-4

SUMMARY OF FIELD NOISE DATA STATISTICAL ANALYSIS RESULTS, SITE 5

MICROPHONE HEIGHT: 1.0 FOOT

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
1	12:22	A	75	79.6	76.0	82.9	69.3
1	12:22	B--H*	198	68.5	64.0	72.6	61.3
1	12:22	C--H	330	63.3	60.6	65.7	48.8
1	12:22	D--H	539	58.0	54.3	62.8	44.2
8	8:09	A	75	79.4	76.4	82.8	67.4
8	8:09	B--H	198	68.1	65.3	70.9	53.7
8	8:09	C--H	330	66.1	63.7	68.0	51.0
8	8:09	D--H	539	62.1	60.3	63.7	44.2

MICROPHONE HEIGHT: 5.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
2	12:42	A	75	79.1	75.7	82.7	68.2
2	12:42	B--H	198	69.4	66.2	73.0	58.7
2	12:42	C--H	330	64.3	61.6	66.4	47.3
2	12:42	D--H	539	58.8	56.3	61.0	42.6
7	15:00	A	75	80.2	76.9	85.2	70.2
7	15:00	B--T*	198	68.9	65.6	72.4	57.7
7	15:00	C--T	330	66.1	62.7	69.7	53.8
7	15:00	D--T	539	57.3	55.6	59.8	39.5
9	8:25	A	75	80.3	77.2	84.7	70.0
9	8:25	B--H	198	71.2	68.2	74.4	59.4
9	8:25	C--H	330	65.9	63.8	68.1	47.2
9	8:25	D--H	539	62.3	59.5	65.4	45.6
14	12:27	A	75	78.2	74.9	82.5	66.6
14	12:27	B--H	198	68.8	66.1	71.1	54.3
14	12:27	C'-H	365	66.2	63.6	69.1	51.3
14	12:27	D--H	539	61.2	58.9	62.8	43.3

MICROPHONE HEIGHT: 10.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
10	8:48	A	75	79.8	76.8	84.5	70.5
10	8:48	B--H	198	72.2	69.4	75.7	59.8
10	8:48	C--H	330	66.4	64.0	67.9	47.5
10	8:48	D--H	539	63.7	61.4	65.2	44.6
13	12:10	A	75	77.9	74.7	81.4	67.0
13	12:10	B--H	198	68.9	66.2	71.1	54.7
13	12:10	C'-H	365	66.5	64.0	68.1	48.4
13	12:10	D--H	539	62.2	60.1	64.6	45.1

MICROPHONE HEIGHT: 15.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
3	12:58	A	75	79.6	76.1	83.4	69.8
3	12:58	B--H	198	73.4	69.7	76.8	63.1
3	12:58	C--H	330	68.5	66.0	71.1	54.4
3	12:58	D--H	539	62.3	60.4	64.8	45.4
6	14:42	A	75	80.0	76.5	84.4	71.3
6	14:42	B--T	198	70.5	67.4	73.8	57.1
6	14:42	C--T	330	67.6	64.6	71.0	52.8
6	14:42	D--T	539	59.4	56.6	61.7	44.4
11	9:07	A	75	79.7	76.2	84.3	72.8
11	9:07	B--H	198	73.1	69.9	76.8	63.5
11	9:07	C--H	330	67.3	64.8	70.1	51.4
11	9:07	C--H	539	63.7	61.2	-	-
12	11:50	A	75	79.9	75.9	85.6	76.0
12	11:50	B--H	198	72.0	68.3	75.7	62.2
12	11:50	C'-H	365	68.8	65.9	71.7	55.9
12	11:50	D--H	539	64.3	61.2	67.3	52.2

MICROPHONE HEIGHT: 25.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
4	13:19	A	75	78.7	75.4	82.8	66.9
4	13:19	B--H	198	75.5	72.6	78.9	61.3
4	13:19	C--H	330	71.8	68.9	75.2	58.7
4	13:19	D--H	539	67.3	63.1	71.1	57.8
5	14:12	A	75	79.8	76.4	83.7	69.8
5	14:12	B--T	198	74.0	70.8	77.0	62.3
5	14:12	C--T	330	70.7	68.3	73.0	55.7
5	14:12	D--T	539	64.2	61.7	65.8	46.5

* Note: H stands for behind the structure and T stands for between the structures.

TABLE A-5

SUMMARY OF FIELD NOISE DATA STATISTICAL ANALYSIS RESULTS, SITE 6

MICROPHONE HEIGHT: 1.0 FOOT

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
4	14:18	A	50	79.7	73.7	89.6	88.5
4	14:18	B--H*	188	67.1	61.3	75.5	69.4
4	14:18	C--H	328	64.4	58.3	71.8	65.6
4	14:18	D--H	474	60.0	53.6	67.0	60.0
5	11:52	A	50	81.5	73.3	93.7	103.9
5	11:52	B--T*	188	65.4	59.6	74.4	70.1
5	11:52	C--T	328	60.1	55.7	66.2	57.8
5	11:52	D--T	474	58.4	54.1	63.2	51.4
7	6:50	A	50	84.3	77.2	94.8	95.6
7	6:50	B--H	188	71.1	65.7	77.3	67.3
7	6:50	C--H	328	69.0	64.7	74.4	61.8
7	6:50	D--H	474	64.7	62.0	-	-
8	7:09	A	50	84.4	76.5	93.7	95.7
8	7:09	B--T	188	70.2	63.4	77.4	69.8
8	7:09	C--T	328	65.4	61.2	70.5	57.3
8	7:09	D--T	474	64.3	60.7	69.0	54.3
15	10:28	A	50	83.0	75.7	93.3	97.1
15	10:28	B"-H	168	67.3	59.9	76.0	78.3
15	10:28	C"-H	308	62.7	56.6	69.3	66.3
15	10:28	D"-H	454	57.3	52.3	62.9	54.4

MICROPHONE HEIGHT: 5.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
1	12:19	A	50	84.5	76.7	94.1	96.1
1	12:19	B--H	188	71.5	66.3	79.0	72.0
1	12:19	C--H	328	67.7	62.9	73.9	65.4
1	12:19	D--H	474	63.7	59.1	68.7	58.8
6	12:46	A	50	79.5	71.9	92.2	95.3
6	12:46	B--T	188	67.9	61.4	76.6	70.5
6	12:46	C--T	328	64.0	58.5	71.5	61.8
6	12:46	D--T	474	65.6	58.9	77.6	69.6
9	7:27	A	50	83.0	76.2	92.2	92.0
9	7:27	B--T	188	69.5	64.1	75.4	67.0
9	7:27	C--T	328	65.6	60.4	70.4	58.9
9	7:27	D--T	474	65.5	59.4	71.4	63.4

MICROPHONE HEIGHT: 10.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
10	7:45	A	50	81.5	74.8	90.8	89.9
10	7:45	B--H	188	68.1	62.1	73.9	67.4
10	7:45	C--H	328	62.4	57.9	66.9	53.5
10	7:45	D--H	474	59.6	56.3	64.0	47.2
16	10:47	A	50	84.4	75.8	94.1	98.6
16	10:47	B"-H	168	68.8	61.8	77.5	79.4
16	10:47	C"-H	308	63.7	58.5	70.1	66.1
16	10.47	D"-H	454	58.8	54.5	63.7	53.7
18	11:36	A	50	82.0	74.4	92.1	94.2
18	11:36	B'-H	223	67.9	61.4	76.3	73.3
18	11:36	C'-H	363	64.8	58.5	71.6	68.5
18	11:36	D'-H	509	62.6	56.6	69.1	64.2

MICROPHONE HEIGHT: 15.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
2	13:06	A	50	83.8	75.0	94.8	101.2
2	13:06	B--H	188	73.2	66.4	80.9	80.5
2	13:06	C--H	328	68.5	62.5	74.7	69.7
2	13:06	D--H	474	63.0	58.7	68.4	58.8
11	8:45	A	50	84.2	75.1	95.1	97.1
11	8:45	B--H	188	72.4	65.1	81.9	77.6
11	8:45	C--H	328	68.3	62.1	75.7	68.7
11	8:45	D--H	474	64.6	59.3	71.3	61.2
12	9:03	A	50	82.0	74.3	93.0	94.1
12	9:03	B--T	188	71.9	64.2	79.7	77.5
12	9:03	C--T	328	66.8	60.6	72.9	66.2
12	9:03	D--T	474	63.4	58.7	68.3	57.2
17	11:09	A	50	82.4	74.9	93.0	95.8
17	11:09	B"-H	168	72.0	65.6	80.6	81.1
17	11:09	C"-H	308	67.1	61.4	76.0	76.2
17	11:09	D"-H	454	63.7	58.6	70.3	66.7

MICROPHONE HEIGHT: 25.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
3	13:49	A	50	83.6	76.0	95.2	98.5
3	13:49	B--H	188	77.2	71.4	86.1	82.5
3	13:49	C--H	328	72.6	67.6	80.1	72.4
3	13:49	D--H	474	69.5	63.8	75.7	69.2
13	9:25	A	50	82.5	75.3	92.8	94.5
13	9:25	B--T	188	76.7	70.7	83.6	79.3
13	9:25	C--T	328	71.9	65.5	77.8	72.6
13	9:25	D--T	474	68.4	62.1	74.1	67.9
14	9:45	A	50	85.3	75.1	95.9	103.8
14	9:45	B--H	188	78.6	70.8	86.0	87.6
14	9:45	C--H	328	72.3	65.2	79.2	77.1
14	9:45	D--H	474	67.5	61.9	73.9	67.2

* Note: H stands for behind the structure and T stands for between the structures.

TABLE A-6

SUMMARY OF FIELD NOISE DATA STATISTICAL ANALYSIS RESULTS, SITE 9

MICROPHONE HEIGHT: 1.0 FOOT

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
1	10:29	A	50	85.9	81.3	90.5	80.2
1	10:29	B	94	72.4	69.3	76.0	61.3
1	10:29	C	134	73.8	70.5	76.8	61.9
1	10:29	D	184	69.5	66.3	73.0	58.9
9	8:00	A	50	85.2	81.5	88.7	75.5
9	8:00	B	94	72.5	69.6	75.9	59.8
9	8:00	C	134	73.7	70.6	76.3	60.8
9	8:00	D	184	69.2	66.1	72.0	56.9

MICROPHONE HEIGHT: 2.5 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
2	11:47	A	50	85.5	80.6	90.3	81.4
2	11:47	B	94	74.0	69.6	78.2	67.2
2	11:47	C	134	73.3	69.5	77.1	64.3
2	11:47	D	184	68.8	64.9	72.3	57.7
10	8:10	A	50	85.6	82.0	89.3	73.2
10	8:10	B	94	74.6	71.3	78.1	63.2
10	8:10	C	134	73.5	70.3	76.5	60.1
10	8:10	D	184	69.5	66.4	72.8	57.8

MICROPHONE HEIGHT: 5.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
3	12:09	A	50	85.4	80.4	91.4	83.9
3	12:09	B	94	78.2	73.9	83.4	72.9
3	12:09	C	134	74.0	69.3	79.3	70.2
3	12:09	D	184	69.2	64.7	74.1	63.1
5	14:01	A	50	84.0	79.7	88.9	78.3
5	14:01	F	284	62.0	59.0	64.8	49.3
11	8:29	A	50	86.0	81.9	89.4	77.0
11	8:29	B	94	79.3	76.0	82.9	68.7
11	8:29	C	134	74.0	70.9	76.9	62.1
11	8:29	D	184	69.5	66.7	72.4	56.6
12	8:45	A	50	85.5	81.9	81.9	86.3
12	8:45	B	94	79.6	75.6	83.6	70.5
12	8:45	C	134	74.4	70.5	78.2	64.5
12	8:45	D	184	69.7	66.1	74.1	60.0
17	12:27	A	50	84.4	79.3	90.3	80.5
17	12:27	G	284	64.3	61.5	66.3	48.5
17	12:27	F	284	54.8	52.0	57.6	39.0

MICROPHONE HEIGHT: 7.5 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
4	12:25	A	50	84.8	79.6	-	-
4	12:25	B	94	80.0	75.9	85.6	74.8
4	12:25	C	134	73.6	69.3	77.9	66.7
4	12:25	D	184	68.5	64.4	72.4	60.9

MICROPHONE HEIGHT: 10.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
5	14:01	A	50	84.0	79.7	88.9	78.3
5	14:01	C	134	72.6	69.4	75.8	60.0
5	14:01	D	184	67.9	64.8	71.1	54.2
6	14:18	A	50	86.0	80.7	91.9	85.3
6	14:18	E	284	64.7	60.6	69.0	55.2
13	9:00	A	50	85.6	81.3	90.2	78.6
13	9:00	B	94	81.9	78.2	85.7	72.0
13	9:00	C	134	75.8	72.0	79.3	66.9
13	9:00	D	184	69.3	66.1	72.4	57.7
14	10:24	A	50	85.9	80.8	92.5	87.0
14	10:24	E	284	67.2	63.9	70.8	56.4

MICROPHONE HEIGHT: 15.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
6	14:18	A	50	86.0	80.7	91.9	85.3
6	14:18	C	134	77.2	74.2	80.9	65.7
6	14:18	D	184	70.0	67.0	74.6	58.3
7	14:50	A	50	85.4	81.1	90.6	78.5
7	14:50	E	284	64.0	61.1	66.7	50.9
14	10:24	A	50	85.9	80.8	92.5	87.0
14	10:24	C	134	79.6	75.7	84.5	74.0
14	10:24	D	184	73.2	69.3	77.8	67.1
15	10:48	A	50	86.0	80.8	-	-
15	10:48	E	284	68.4	65.5	72.3	58.8

MICROPHONE HEIGHT: 20.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
7	14:50	A	50	85.4	81.1	-	-
7	14:50	C	134	79.7	76.6	82.9	68.1
7	14:50	D	184	71.8	69.0	74.4	58.6
8	15:16	A	50	85.0	80.7	-	-
8	15:16	E	284	64.9	61.5	68.3	53.2
15	10:48	A	50	86.0	80.8	91.1	83.8
15	10:48	C	134	80.9	77.2	84.7	72.1
15	10:48	D	184	74.5	70.9	78.6	65.3
16	11:17	A	50	85.8	81.0	90.3	79.9
16	11:17	E	284	69.5	66.5	73.5	56.5

MICROPHONE HEIGHT: 25.0 FEET

Run #	Time	Station	N.L. Dist	L_{10}	L_{50}	NPL	TNI
8	15:16	A	50	85.0	80.7	89.3	77.4
8	15:16	C	134	80.4	77.1	83.4	66.6
8	15:16	D	184	74.2	71.1	76.9	61.9
16	11:17	A	50	85.8	81.0	90.3	79.9
16	11:17	C	134	81.9	78.5	85.3	71.3
16	11:17	D	184	76.7	73.1	80.1	66.1
17	12:27	A	50	84.4	79.3	90.3	80.5
17	12:27	E	284	69.1	65.8	72.3	57.3

TABLE A-7

TRAFFIC VOLUME AND AVERAGE SPEED CONDITIONS DURING NOISE MEASUREMENT PERIODS, SITE 1

MEASUREMENT RUN NUMBER	ALL LANES (6)					NEAR LANES (3)					FAR LANES (3)				
	TOTAL VOL. (VPH)	AUTO VOL. (VPH)	TRUCK VOL. (VPH)	TRUCK/AUTO (%)	AVER SPEED (MPH)	TOTAL VOL. (VPH)	AUTO VOL. (VPH)	TRUCK VOL. (VPH)	TRUCK/AUTO (%)	AVER SPEED (MPH)	TOTAL VOL. (VPH)	AUTO VOL. (VPH)	TRUCK VOL. (VPH)	TRUCK/AUTO (%)	AVER SPEED (MPH)
1	324	288	36	12.5	53.8	198	174	24	13.8	56.6	126	114	12	10.5	51.1
2	348	300	48	16.0	56.6	168	138	30	21.7	57.7	180	162	18	11.1	55.6
3															
4	432	408	24	5.8	59.0	246	240	6	2.5	54.9	186	168	18	10.7	63.1
5	492	492	0	0	56.8	240	240	0	0	57.6	252	252	0	0	56.1
6	534	516	18	3.4	58.0	240	240	0	0	57.3	294	276	18	6.5	58.8
7	624	570	54	9.4	58.0	336	300	36	12.0	58.4	288	270	18	6.6	57.6
8	492	468	24	5.1	55.1	264	252	12	4.7	54.2	228	216	12	5.5	56.1
9	612	564	48	8.5	58.4	324	312	12	3.8	57.7	288	252	36	14.2	59.1
10	456	444	12	2.7	61.5	312	312	0	0	66.1	144	132	12	9.0	57.0
11	432	420	12	2.8	60.3	276	276	0	0	61.4	156	144	12	8.3	59.2
12	618	606	12	1.9	61.6	228	216	12	5.5	59.9	390	390	0	0	63.3
13	588	576	12	2.0	59.7	372	372	0	0	58.5	216	204	12	5.8	61.0
14	564	504	60	11.9	54.5	240	180	60	33.3	55.1	324	264	60	22.7	54.0
15	496	484	12	2.4	65.1	376	376	0	0	64.9	120	108	12	11.1	65.4
16	346	334	54	16.1	60.4	190	148	42	28.3	58.7	156	144	12	8.3	62.2
17	372	324	48	14.8	59.8	150	126	24	19.0	56.1	222	198	24	12.1	63.5
18	373	331	42	12.6	57.0	186	168	18	10.7	55.9	187	163	24	14.7	58.1
19	402	362	42	11.6	55.0	216	186	30	16.1	54.5	186	144	42	29.1	55.5
20	486	438	48	10.9	57.7	312	270	42	15.5	60.0	174	168	6	3.5	55.5
21	456	420	36	8.5	57.9	258	246	12	4.8	56.7	198	174	24	13.7	59.2
22	522	492	30	6.0	59.4	264	240	24	10.0	58.0	258	252	6	2.3	60.9
23	522	450	72	16.0	62.0	222	198	24	12.1	61.7	300	252	48	19.0	62.3

TABLE A-8

TRAFFIC VOLUME AND AVERAGE SPEED CONDITIONS DURING NOISE MEASUREMENT PERIODS, SITE 2

MEASUREMENT RUN NUMBER	ALL LANES (8)					NEAR LANES (4)					FAR LANES (4)				
	TOTAL VOL. (VPH)	AUTO VOL. (VPH)	TRUCK VOL. (VPH)	TRUCK/AUTO (%)	AVER SPEED (MPH)	TOTAL VOL. (VPH)	AUTO VOL. (VPH)	TRUCK VOL. (VPH)	TRUCK/AUTO (%)	AVER SPEED (MPH)	TOTAL VOL. (VPH)	AUTO VOL. (VPH)	TRUCK VOL. (VPH)	TRUCK/AUTO (%)	AVER SPEED (MPH)
1	13,650	13,206	444	3.3	53.2	7590	7410	180	2.4	50.2	6060	5796	264	4.5	56.2
2	13,110	12,630	480	3.8	50.5	6210	6006	204	3.3	43.7	6900	6624	276	4.1	56.4
3	12,360	12,048	312	2.5	56.2	6540	6456	84	1.3	48.4	5820	5592	228	4.0	64.1
4	13,080	12,660	480	3.3	55.0	7230	7074	156	2.2	48.0	5850	5586	264	4.7	62.0
5	11,280	10,920	360	3.2	57.7	5970	5790	180	3.1	55.9	5310	5130	180	3.5	59.5
6	10,410	9,870	540	5.4	51.3	5220	4992	228	4.5	51.2	5190	4878	312	6.3	51.5
7	10,560	9,960	600	6.0	56.1	5640	5292	348	6.5	55.6	4920	4668	252	5.3	57.7
8	12,090	11,562	528	4.5	52.7	5640	5376	264	4.9	51.3	6450	6186	264	4.2	54.1
9	13,080	12,600	480	3.8	51.2	6450	6330	120	1.8	53.8	6630	6270	360	5.7	50.2
10	14,070	13,638	432	3.1	55.1	6900	6720	180	2.6	55.0	7170	6918	252	3.6	55.2
11	13,140	12,816	324	2.5	60.1	7440	7260	180	2.4	58.7	5700	5556	144	2.5	61.5
12	14,070	13,722	348	2.5	55.0	7230	7110	170	1.6	56.0	6840	6612	228	3.4	54.0
13	11,760	11,460	300	2.6	51.4	4080	3816	264	6.9	52.9	7680	7644	36	0.4	49.9
14	12,630	12,354	276	2.2	47.4	4680	4488	192	4.2	49.4	7950	7866	84	1.0	45.4
15	14,430	14,166	264	1.8	52.0	6330	6150	180	2.9	55.0	8100	8016	84	1.0	49.0
16	11,130	10,746	384	3.5	57.6	5040	4788	252	5.2	54.5	6090	5958	132	2.2	60.8
17	11,400	10,968	432	3.9	60.2	5070	4866	204	4.1	57.5	6330	6102	225	.7	63.0
18	11,910	11,478	432	3.7	58.3	5730	5526	204	3.6	57.1	6180	5952	228	3.8	59.5
19	11,370	10,962	408	3.7	59.0	5760	5544	216	3.8	58.0	5610	5418	192	3.5	60.0
20	12,450	12,030	420	3.4	56.0	5730	5502	228	4.1	54.1	6720	6528	192	2.9	58.0

TABLE A-9

TRAFFIC VOLUME AND AVERAGE SPEED CONDITIONS DURING NOISE MEASUREMENT PERIODS, SITE 3

MEASUREMENT RUN NUMBER	ALL LANES (8)					NEAR LANES (4)					FAR LANES (4)				
	TOTAL VOL. (VPH)	AUTO VOL. (VPH)	TRUCK VOL. (VPH)	TRUCK/AUTO (%)	AVER SPEED (MPH)	TOTAL VOL. (VPH)	AUTO VOL. (VPH)	TRUCK VOL. (VPH)	TRUCK/AUTO (%)	AVER SPEED (MPH)	TOTAL VOL. (VPH)	AUTO VOL. (VPH)	TRUCK VOL. (VPH)	TRUCK/AUTO (%)	AVER SPEED (MPH)
1	7440	7404	36	0.49	65.0	3540	3516	24	0.68	63.0	3900	3888	12	0.31	67.0
2	7440	7368	72	0.98	62.5	3540	3516	24	0.68	65.0	3900	3852	48	1.25	60.0
3	7440	7208	132	1.83	60.5	4290	4218	72	1.70	61.0	3150	3090	60	1.94	60.0
4	7560	7452	108	1.45	56.5	3780	3708	72	1.94	57.0	3780	3744	36	0.96	56.0
5	7350	7302	48	0.66	60.0	3840	3828	12	0.31	63.0	3510	3474	36	1.03	57.0
6	7950	7866	84	1.07	61.5	4230	4158	72	1.73	64.0	3720	3708	12	0.32	59.0
7	3090	2994	96	3.20	66.0	1380	1356	24	1.72	68.0	1710	1638	72	4.40	64.0
8	2520	2484	36	1.45	64.5	1500	1476	24	1.63	67.0	1020	1008	12	1.19	62.0
9	2580	2544	36	1.42	60.0	1500	1476	24	1.62	60.0	1080	1068	12	1.12	57.0
10	2940	2892	48	1.66	67.3	1530	1506	24	1.60	69.6	1410	1386	24	1.73	65.1
11	6000	5892	108	1.83	63.6	2940	2844	96	3.3	63.9	3060	3048	12	0.39	63.3
12	6120	6096	24	0.39	69.0	2850	2838	12	0.42	69.0	3270	3258	12	0.37	69.0
13	6090	6042	48	0.79	65.0	3210	3162	48	1.52	65.5	2880	2880	0	0	64.5
14	6870	6846	24	0.35	64.6	3510	3498	12	0.34	65.2	3360	3348	12	0.36	64.0
15	8250	7994	256	3.1	62.0	2300	2156	144	6.68	59.0	5950	5818	132	2.2	65.0
16	7950	7590	360	4.75	61.5	2400	2292	108	4.71	60.0	5550	5298	252	4.76	63.0
17	8300	8084	216	2.6	63.5	2920	2800	120	4.1	64.0	5400	5304	96	1.8	63.0
18	7750	7522	228	3.0	65.0	2560	2476	84	3.3	65.5	5190	5046	144	2.9	64.5

TABLE A-10

TRAFFIC VOLUME AND AVERAGE SPEED CONDITIONS DURING NOISE MEASUREMENT PERIODS, SITE 5

MEASUREMENT RUN NUMBER	ALL LANES (4)					NEAR LANES (2)					FAR LANES (2)				
	TOTAL VOL. (VPH)	AUTO VOL. (VPH)	TRUCK VOL. (VPH)	TRUCK/AUTO (%)	AVER SPEED (MPH)	TOTAL VOL. (VPH)	AUTO VOL. (VPH)	TRUCK VOL. (VPH)	TRUCK/AUTO (%)	AVER SPEED (MPH)	TOTAL VOL. (VPH)	AUTO VOL. (VPH)	TRUCK VOL. (VPH)	TRUCK/AUTO (%)	AVER SPEED (MPH)
1	3804	3354	450	11.8	55.7	2010	1746	264	13.1	55.2	1794	1608	186	10.3	56.3
2	3636	3246	390	10.7	53.2	1920	1722	198	10.3	52.3	1716	1524	192	11.2	54.2
3	4056	3612	444	10.9	55.6	2040	1800	240	11.8	57.8	2016	1812	204	10.1	53.4
4	3816	3378	438	11.5	61.6	1866	1668	198	10.6	63.1	1950	1710	240	12.3	60.2
5	4176	3714	462	11.1	62.5	2184	1944	240	11.0	63.8	1992	1770	222	11.1	61.3
6	4278	3786	492	11.5	56.0	2256	1986	270	12.0	55.0	2022	1800	222	11.0	57.0
7	4404	3870	534	12.1	55.0	2418	2136	282	11.7	55.5	1986	1734	252	12.7	54.5
8	5190	4792	398	7.7	54.2	2202	2002	200	9.1	57.0	2988	2790	198	6.6	51.9
9	5034	4540	494	9.8	55.7	2130	1914	216	10.1	57.1	2904	2626	278	9.6	54.3
10	4512	4032	480	10.6	57.5	1902	1662	240	12.6	60.4	2610	2370	240	9.2	54.7
11	3774	3186	588	15.6	59.1	1632	1344	288	17.6	60.9	2142	1842	300	14.0	57.3
12	3666	3222	444	12.1	60.8	1956	1740	216	11.0	60.1	1710	1482	228	13.3	61.6
13	3708	3372	336	9.1	58.9	1824	1632	192	10.5	61.5	1884	1740	144	7.6	56.4
14	3588	3270	318	8.9	59.9	1998	1824	174	8.7	60.7	1590	1446	144	9.1	59.1

TABLE A–11

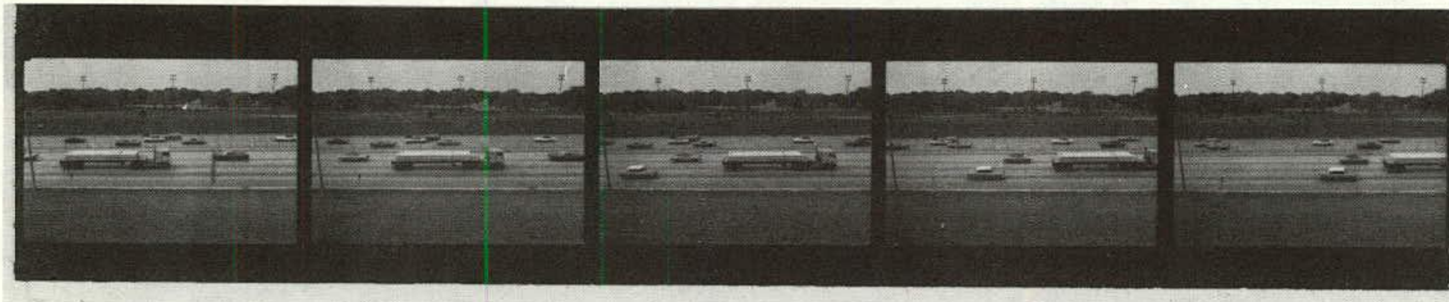
TRAFFIC VOLUME AND AVERAGE SPEED CONDITIONS DURING NOISE MEASUREMENT PERIODS, SITE 6

MEASUREMENT RUN NUMBER	ALL LANES (4) TOTAL VOL. (VPH)	AUTO VOL. (VPH)	TRUCK VOL. (VPH)	TRUCK/AUTO (%)	AVER SPEED (MPH)	NEAR LANES (2) TOTAL VOL. (VPH)	AUTO VOL. (VPH)	TRUCK VOL. (VPH)	TRUCK/AUTO (%)	AVER SPEED (MPH)	FAR LANES (2) TOTAL VOL. (VPH)	AUTO VOL. (VPH)	TRUCK VOL. (VPH)	TRUCK/AUTO (%)	AVER SPEED (MPH)
1	2184	1812	372	17.0	70.0	1104	930	174	15.8	71.0	1080	882	198	18.3	69.0
2	1944	1590	354	18.2	69.0	984	804	180	13.3	68.3	960	786	174	18.1	69.7
3	2290	1876	414	18.1	70.0	1158	924	234	20.2	70.0	1032	852	180	17.4	70.0
4	2262	1860	402	17.8	70.6	1302	1128	174	13.4	70.8	960	732	228	23.8	70.4
5	2064	1596	468	22.7	68.4	1044	786	258	24.7	66.5	1020	810	210	20.6	70.3
6	2028	1542	486	24.0	70.2	972	762	210	21.6	70.3	1056	780	276	26.1	70.2
7	2310	1956	354	15.3	66.0	1386	1230	156	11.3	71.8	924	726	198	21.4	60.3
8	2720	2450	270	9.9	73.6	1698	1548	150	8.8	73.5	1032	912	120	11.6	73.7
9	3054	2790	264	8.6	69.2	1362	1194	168	12.3	73.5	1692	1596	96	5.7	65.0
10	2382	2100	282	11.8	66.2	1182	1038	144	12.2	61.1	1200	1062	138	11.5	71.3
11	2358	1932	426	18.1	67.7	966	780	186	19.3	64.4	1392	1152	240	17.2	71.0
12	1944	1536	408	21.0	71.5	768	624	144	18.3	77.7	1176	912	264	24.6	65.4
13	2238	1800	438	19.5	73.0	852	660	192	22.6	77.3	1386	1140	246	17.7	68.8
14	2220	1782	438	19.7	73.0	924	642	282	30.5	69.5	1296	1140	156	12.0	76.5
15	2184	1788	396	18.1	71.7	996	2184	180	18.1	74.4	1188	972	216	18.2	69.1
16	1986	1566	420	21.1	70.0	846	630	216	25.5	68.0	1140	936	204	17.9	72.0
17	2052	1674	378	18.4	71.4	1026	850	174	17.0	72.8	1026	822	204	19.9	70.0
18	2296	1924	372	16.2	66.1	1142	926	216	18.9	61.2	1154	998	156	13.5	71.1

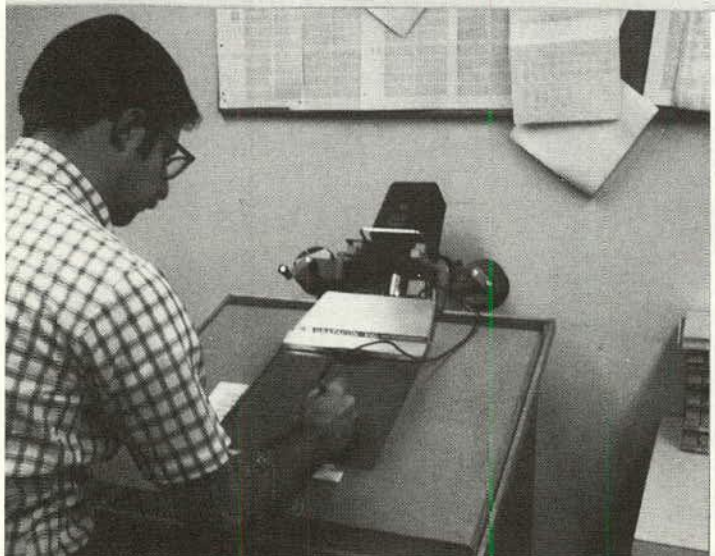
TABLE A–12

TRAFFIC VOLUME AND AVERAGE SPEED CONDITIONS DURING NOISE MEASUREMENT PERIODS, SITE 9

MEASUREMENT RUN NUMBER	ALL LANES (8) TOTAL VOL. (VPH)	AUTO VOL. (VPH)	TRUCK VOL. (VPH)	TRUCK/AUTO (%)	AVER SPEED (MPH)	NEAR LANES (4) TOTAL VOL. (VPH)	AUTO VOL. (VPH)	TRUCK VOL. (VPH)	TRUCK/AUTO (%)	AVER SPEED (MPH)	FAR LANES (4) TOTAL VOL. (VPH)	AUTO VOL. (VPH)	TRUCK VOL. (VPH)	TRUCK/AUTO (%)	AVER SPEED (MPH)
1	5484	4758	726	13.2	61.2	3012	2646	366	12.2	60.0	2472	2112	360	14.6	62.5
2	6000	5370	630	10.5	62.9	2916	2544	372	12.8	63.6	3084	2826	258	8.7	62.2
3	6303	5874	429	6.8	59.6	2961	2745	216	7.3	58.2	3402	3189	213	6.3	61.1
4	6144	5760	384	6.3	57.7	2604	2406	198	7.6	54.3	3540	3354	186	5.3	61.2
5	6318	5736	582	9.2	62.8	2820	2568	252	8.9	63.2	3498	3168	330	9.4	62.5
6	6636	6036	600	10.6	62.1	2964	2580	384	13.0	59.1	3672	3456	216	5.9	65.2
7	7236	6522	714	9.9	64.3	3168	3748	420	13.3	61.1	4068	3774	294	7.2	67.6
8	8136	7476	660	8.1	68.1	3192	2856	336	10.5	58.0	4944	4620	324	6.6	78.3
9	8772	8148	624	8.8	59.6	6108	5868	240	3.9	51.6	2664	2280	384	14.4	67.7
10	15198	14538	660	4.3	59.8	12384	12066	318	2.6	53.3	2814	2472	342	12.2	66.4
11															
12	8130	7476	654	6.5	54.4	5634	5322	312	5.5	47.9	2496	2154	342	13.7	60.9
13	6234	5686	558	9.0	59.8	4248	3990	258	6.1	59.4	1986	1686	300	15.1	60.3
14	5784	5124	660	11.4	60.6	3270	2910	360	11.0	58.8	2514	2214	300	11.9	62.5
15	5622	5016	606	10.8	60.2	2928	2628	300	10.2	58.8	2694	2388	306	11.4	61.6
16	6312	5628	684	10.8	59.5	3006	2700	306	10.2	57.4	3306	2928	378	11.4	61.6
17	5772	5274	498	8.6	60.8	2676	2448	228	8.5	63.8	3096	1826	270	8.7	57.9



(a) Sample of Average Traffic Speed Data – Time Elapsed Between Two Consecutive Exposures Equals 1/4 Second



(b) View of the Grafacon Data Reduction Pad

(c) PDP-8 Computer Used in Data Analysis

Figure A–15. Photographic traffic data reduction system.

TABLE A–13

SUMMARY OF WEATHER DATA, SITE 1

DATE AND RUN NO.	TIME	HT. (FT)	WIND SPD. (MPH)/DIR.	TEMP. (° F)	R.H. (%)
9/08/71					
1	13:16	5	5–9/W	88.5	31
2	13:31	5	—	—	—
3	13:47	5	10–12/W	—	—
9/09/71					
4	08:17	5	0–2/SW	59	87
5	08:33	5	0–2/SW	—	—
6	08:48	5	—	60.5	84
7	09:03	5	0–2/W	61	82
8	10:21	5	1–3/W	68	66
9	10:32	—	—	—	—
10	10:42	5	1–3/W	—	—
11	10:57	—	—	—	—
12	11:17	5	3–4/W	72	61
13	11:27	5	4–6/W	—	—
14	11:37	5	3–6/W	74.5	57
15	13:09	5	5–9/W	81.5	43
9/10/71					
16	09:15	5	0–2/W	67.5	72
17	09:32	5	0–2/W	—	—
18	10:06	5	1–4/W	—	—
19	10:25	5	2–5/W	74.5	58
20	11:49	5	2–6/W	79.5	45
21	12:43	5	3–7/W	—	—
22	13:14	5	3–8/W	—	—
23	13:38	5	5–9/W	87.5	34

TABLE A–14

SUMMARY OF WEATHER DATA, SITE 2

DATE AND RUN NO.	TIME	HT. (FT)	WIND SPD. (MPH)/DIR.	TEMP. (° F)	R.H. (%)
8/31/71					
1	15:26	8	4–8/E	81	49
2	15:42	—	—	—	—
3	15:56	—	—	—	—
4	16:11	8	4–8/E	82	48
9/01/71					
5	11:10	8	3–7/SE	77.5	53
6	11:27	—	4–6/SE	79	47
7	11:47	—	—	—	—
8	12:03	8	2–5/SE	81	44
9	15:20	8	3–7/SE	85.5	41
10	15:37	—	—	—	—
11	15:54	—	—	—	—
12	16:09	8	2–6/SE	84.5	39
9/02/71					
13	06:45	8	nil	63	90
14	07:20	—	—	—	—
15	07:35	8	nil	62	85
16	10:00	8	2–3/SE	72	65
17	10:20	—	—	—	—
18	10:35	8	nil	74	62
19	10:50	—	—	—	—
20	11:05	8	2–5/N	76	63

TABLE A–15

SUMMARY OF WEATHER DATA, SITE 3

DATE AND RUN NO.	TIME	HT. (FT)	WIND SPD. (MPH)/DIR.	TEMP. (° F)	R.H. (%)
8/21/71					
1	12:07	8	6–10/N	83	50
2	12:19	—	—	—	—
3	12:37	8	6–8/N	83	50
4	14:53	8	2–6/NNW	85	44
5	15:09	—	—	—	—
6	15:22	8	6–9/N	84	41
8/22/71					
7	07:34	8	nil	70	75
8	07:53	—	—	—	—
9	08:04	—	—	—	—
10	08:25	—	3–7/NW	68	—
11	10:27	8	2–7/N	77	58
12	10:55	—	—	—	—
13	11:10	—	—	—	—
14	11:27	8	2–4/NNW	84	50
8/23/71					
15	06:40	8	nil	62	90
16	06:55	8	nil	63	87
17	07:10	—	—	—	—
18	07:25	8	nil	65	85

TABLE A–16

SUMMARY OF WEATHER DATA, SITE 5

DATE AND RUN NO.	TIME	HT. (FT)	WIND SPD. (MPH)/DIR.	TEMP. (° F)	R.H. (%)
9/27/71					
1	12:22	5	4/SW	65	90
2	12:42	5	3/SW	65	90
3	12:58	5	4/SW	65	90
4	13:19	5	6/SW	65	94
5	14:10	5	4/SW	66	95
6	14:42	5	nil	66	95
7	15:00	5	nil	66	95
9/28/71					
8	08:09	5	nil	69	97
9	08:25	5	nil	69	97
10	08:48	5	4/SW	71	95
11	09:07	5	4/SW	72.5	93
12	11:50	5	8–14/SW	79	79
13	12:10	5	8/SW	80	—
14	12:27	5	6–8/SW	80	—

TABLE A–17

SUMMARY OF WEATHER DATA, SITE 6

DATE AND RUN NO.	TIME	HT. (FT)	WIND SPD. (MPH)/DIR.	TEMP. (° F)	R.H. (%)
9/27/71					
1	12:19	5	4	68	54
2	13:06	5	4	69	56
3	13:49	5	6–8	70	52
4	14:18	5	6–8	—	—
9/23/71					
5	11:52	5	8	72.5	57
6	12:46	5	12	72	53
9/24/71					
7	06:50	5	—	—	—
8	07:09	5	—	46	85
9	07:27	5	—	47.5	82
10	07:45	5	5	50	74
11	08:45	5	5	55	66
12	09:03	5	5	57.5	70
13	09:25	5	5–8	58	67
14	09:45	5	4–8	58	72
15	10:28	5	3	61	62
16	10:47	5	6	62	56
17	11:09	5	6	64	50
18	11:36	5	6	—	—

TABLE A–18

SUMMARY OF WEATHER DATA, SITE 9

DATE AND RUN NO.	TIME	HT. (FT)	WIND SPD. (MPH)/DIR.	TEMP. (° F)	R.H. (%)
9/29/71					
1	10:29	5	4	63	75
2	11:47	5	4–5	68	67
3	12:09	5	4–5	—	—
4	12:25	—	—	—	—
5	14:01	5	6/SW	70	64
6	14:18	5	6/SW	75	61
7	14:50	5	5/SW	—	—
8	15:16	5	7/SW	74	66
9/30/71					
9	08:00	5	7/SW	67	68
10	08:10	5	6/SW	68	70
11	08:29	5	6/SW	70	70
12	08:45	5	5/SW	75	75
13	09:00	5	4/SW	76	80
14	10:15	5	7/SW	77	79
15	10:24	—	—	—	—
16	10:48	5	18/SW	—	—
17	11:17	5	15/SW	79	85

APPENDIX B

TABULATIONS OF MEASURED AND PREDICTED NOISE REDUCTIONS

The measured noise reductions at the various locations for the six test sites, with corresponding Design Guide predictions, are given in Tables B-1 through B-4. The measured noise reductions at selected locations for Sites 1, 2, and 9, with corresponding line source predictions, are given in Tables B-5 through B-8. All line source noise reduction predictions were arrived at by computing an appropriate path length difference value (δ) for each location at each site, and converting this path length difference to a noise reduction using the appropriate curve in Figure D-4.

TABLE B-1

MEASURED AND DESIGN GUIDE PREDICTED NOISE REDUCTIONS, SITE 1 (ROADSIDE BARRIER CONFIGURATION)

CASE NO.**	RUN NO.	HT. FT.	NOISE REDUCTION IN dB BASED UPON L_{50} LEVELS AS MEASURED* AND PREDICTED BY THE DESIGN GUIDE AT VARIOUS DISTANCES FROM THE ROADSIDE							
			63 ft		93 ft		143 ft		243 ft	
			Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.
2	1	2	--	--	13.4	12.6	11.5	12.3	9.1	10.8
3	4	2	--	--	9.0	14.9	9.3	14.5	6.8	13.0
2	14	2	--	--	12.8	12.6	11.8	12.3	10.7	10.8
3	13	4	--	--	8.3	14.9	9.2	13.7	8.2	12.5
3	15	4	--	--	11.8	14.9	--	--	--	--
2	20	4	--	--	12.4	12.6	--	--	--	--
2	21	4	17.0	12.6	--	--	--	--	--	--
2	2	6	--	--	10.2	12.2	9.0	10.6	--	--
1	5	6	--	--	11.5	14.6	10.3	12.8	7.5	11.4
3	12	6	--	--	12.1	14.6	10.7	13.1	8.9	11.9
2	22	6	15.5	12.6	--	--	--	--	--	--
3	6	8	--	--	10.4	13.2	4.9	12.0	--	--
3	11	8	--	--	11.3	13.2	9.9	12.0	7.9	11.3
2	17	8	--	--	10.4	10.9	8.3	9.7	5.8	9.0
2	23	8	11.5	12.6	--	--	--	--	--	--
2	7	10	--	--	8.6	9.4	7.9	8.6	6.6	8.4
3	10	10	--	--	7.3	11.8	5.8	10.9	4.4	10.7
3	15	10	--	--	--	--	4.9	10.9	--	--
2	20	10	--	--	10.4	9.4	--	--	--	--
2	21	10	13.4	11.1	--	--	--	--	--	--
2	22	10	8.5	11.1	--	--	--	--	--	--
3	8	15	--	--	8.1	6.3	7.2	7.6	6.0	8.9
2	19	15	--	--	7.4	7.7	5.7	5.3	--	--
2	23	15	8.4	1.8	--	--	--	--	--	--
3	15	20	--	--	8.2	0	--	--	--	--
2	20	20	--	--	6.1	0	--	--	--	--
2	21	20	7.7	0	--	--	--	--	--	--
2	22	20	7.2	0	--	--	--	--	--	--
2	23	20	5.8	0	--	--	--	--	--	--

*Assuming a free-field propagation loss factor of 4.5 dB per doubling of distance.

**Truck mix ratios for predictions: Case No. 1 - 0%; Case No. 2 - 12.5%; Case No. 3 - 2.5%.

TABLE B-2

MEASURED AND DESIGN GUIDE PREDICTED NOISE REDUCTIONS, SITES 2 AND 3 (ELEVATED HIGHWAY CONFIGURATION)

CASE NO.**	SITE AND RUN NO.	HT. FT.	NOISE REDUCTION IN dBA BASED UPON L_{50} LEVELS AS MEASURED* AND PREDICTED BY THE DESIGN GUIDE AT VARIOUS DISTANCES FROM THE ROADSIDE.					
			125 ft		250 ft		500 ft	
			Meas.	Pred.	Meas.	Pred.	Meas.	Pred.
1	2-6	1	15.6	12.1	10.0	9.7	4.8	4.8
2	2-12	1	13.3	14.6	7.3	10.3	1.2	5.4
2	2-13	1	14.3	14.6	7.3	10.3	3.7	5.4
1	2-20	1	17.0	12.1	11.0	9.7	7.4	4.8
1	2-1	5	15.0	12.1	6.1	7.8	2.7	3.8
1	2-5	5	14.2	12.1	8.0	7.8	2.2	3.8
2	2-11	5	12.1	12.8	5.9	9.1	0.3	4.4
2	2-14	5	13.4	12.8	5.4	9.1	2.1	4.4
1	2-19	5	12.1	12.1	5.9	7.8	0.3	3.8
1	2-2	10	10.4	12.1	4.5	6.8	1.2	2.4
1	2-7	10	11.4	12.1	7.1	6.8	2.4	2.4
1	2-10	10	10.4	12.1	4.5	6.8	1.2	2.4
2	2-15	10	--	--	4.7	7.4	2.1	2.9
1	2-18	10	7.6	12.1	1.5	6.8	-1.6	2.4
2	2-3	15	9.8	10.6	4.5	5.3	2.2	2.0
1	2-17	15	4.7	10.0	-0.2	3.0	-4.2	1.6
1	3-10	1	6.9	13.4	1.7	8.2	1.2	2.8
1	3-14	1	7.4	13.4	2.3	8.2	2.5	2.8
2	3-18	1	7.0	11.2	3.2	5.7	1.8	1.6
1	3-1	5	7.4	12.2	2.5	6.8	1.2	1.6
1	3-6	5	7.4	12.2	2.5	6.8	1.2	1.6
2	3-7	5	8.3	10.6	3.7	4.3	2.0	0.9
1	3-11	5	7.4	12.2	2.5	6.8	1.2	1.6
2	3-15	5	7.4	10.6	2.8	4.3	1.8	0.9
1	3-2	15	6.9	7.2	3.5	2.3	2.4	0
1	3-5	15	6.9	7.2	3.5	2.3	2.4	0
1	3-8	15	6.9	7.2	2.5	2.3	1.3	0
1	3-12	15	6.9	7.2	3.5	2.3	2.4	0
2	3-16	15	5.3	5.0	1.5	2.2	0.3	0.1
1	3-3	25	3.6	0	1.2	0	0.8	0
1	3-4	25	3.3	0	1.5	0	0.8	0
1	3-9	25	3.9	0	1.1	0	0.7	0
1	3-13	25	3.6	0	1.2	0	0.8	0
2	3-17	25	3.6	0.1	1.2	0.2	0.8	0.2

*Assuming a free-field propagation loss factor of 4.5 dB per doubling of distance.

**Truck to Auto Ratios for Predictions: Case No. 1-1%, Case No. 2-4.7%.

TABLE B–3

MEASURED AND DESIGN GUIDE PREDICTED NOISE REDUCTIONS, SITES 5 AND 6 (ROADSIDE STRUCTURES CONFIGURATION)

CASE NO.**	LOC. ***	SITE AND RUN NO.	HT. FT.	NOISE REDUCTION IN dBA BASED UPON L_{50} LEVELS AS MEASURED* AND PREDICTED BY THE DESIGN GUIDE AT VARIOUS DISTANCES FROM THE ROADSIDE					
				1 Row of Houses 198 feet		2 Rows of Houses 330 or (365) ft		3 Rows of Houses 559 feet	
				Meas.	Pred.	Meas.	Pred.	Meas.	Pred.
1	A	5-2	5	4.5	3.0	6.2	6.0	8.6	9.0
1	A	5-9	5	3.8	3.0	4.3	6.0	6.0	9.0
1	A	5-14	5	3.8	3.0	(3.9)	6.0	6.0	9.0
1	B	5-7	5	6.3	3.0	(6.3)	6.0	10.5	9.0
				(168) or 188 ft.		(308) or 328 ft.		(454) or 474 ft.	
2	A	6-1	5	3.8	3.0	4.0	6.0	5.6	9.0
3	A	6-10	5	6.1	3.0	7.1	6.0	6.5	9.0
2	A	6-16	5	(8.0)	3.0	(7.9)	6.0	(9.6)	9.0
3	A	6-18	5	5.4	3.0	5.5	6.0	5.4	9.0
2	B	6-6	6	3.9	3.0	3.6	6.0	1.0	9.0
3	B	6-9	5	5.5	3.0	6.0	6.0	4.8	9.0

* Assuming a free-field propagation loss factor of 4.5 dB per doubling of distance.

** Truck mix ratios for predictions: Case No. 1 - 11.0%; Case No. 2 - 18.0%; Case No. 3 - 16.5%.

*** Measurement Locations: A - behind houses; B - between houses.

TABLE B–4

MEASURED AND DESIGN GUIDE PREDICTED NOISE REDUCTIONS, SITE 9 (DEPRESSED HIGHWAY CONFIGURATION)

CASE NO.**	RUN NO.	HT. FT.	NOISE REDUCTIONS IN dBA BASED UPON L_{50} LEVELS AS MEASURED* AND PREDICTED BY THE DESIGN GUIDE AT VARIOUS DISTANCES FROM THE ROADSIDE.							
			94 ft		134 ft		184 ft		284 ft	
			Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.
1	1	1	9.1	0.1	6.3	5.0	9.0	7.7	--	--
1	9	1	9.0	0.1	6.4	5.0	9.4	7.7	--	--
1	2	2.5	7.9	0.1	6.4	3.0	9.5	6.8	--	--
2	10	2.5	7.8	0.5	7.2	4.1	9.6	7.9	--	--
2	3	5	2.4	0.1	5.7	0.8	8.7	6.2	--	--
1	5A	5	0.2	0.1	--	--	--	--	12.3	8.0
2	12	5	3.4	0.1	6.7	0.8	9.7	6.2	--	--
1	17A	5	0.2	0.1	--	--	--	--	9.4	8.0
2	4	7.5	0.8	0	5.8	0.1	8.2	4.1	--	--
1	5	10	--	--	4.8	0.1	8.9	1.0	--	--
1	6A	10	--	--	--	--	--	--	11.7	6.2
1	13	10	--	--	4.8	0.1	9.2	1.0	--	--
1	14A	10	--	--	--	--	--	--	8.5	6.2
1	6	15	0.2	0.1	1.8	0.1	7.5	0	--	--
1	7A	15	0.2	0.1	--	--	--	--	11.6	4.0
1	14	15	0.2	0.1	0.6	0.1	4.5	0	--	--
1	15A	15	0.2	0.1	--	--	--	--	6.9	4.0
1	7	20	0	0	-0.2	0	5.9	0.1	--	--
1	8A	20	0	0	--	--	--	--	11.0	1.0
1	15	20	0.2	0	-0.9	0	3.9	0.1	--	--
1	16A	20	0.2	0	--	--	--	--	6.1	1.0
1	8	25	0.2	0.1	-0.9	0.1	3.6	0.1	00	00
1	16	25	0.2	0.1	-2.0	0.1	1.9	0.1	--	--
1	17	25	0.2	0.1	--	--	--	--	5.1	0.1

* Assuming a free-field propagation loss factor of 4.5 dB per doubling of distance.

**Truck to Auto ratios for predictions; Case No. 1 - 11.0%, Case No. 2 - 4.3%.

TABLE B-5

MEASURED AND LINE SOURCE PREDICTED NOISE REDUCTIONS, SITE 1 (ROADSIDE BARRIER CONFIGURATION)

RUN NO.	HT. FT.	NOISE REDUCTION IN dBA BASED UPON L_{50} LEVELS AS MEASURED* AND PREDICTED BY THE LINE SOURCE MODEL AT VARIOUS DISTANCES FROM THE ROADSIDE											
		63 feet			93 feet			143 feet			243 feet		
		Meas.	δ**	Pred.	Meas.	δ**	Pred.	Meas.	δ**	Pred.	Meas.	δ**	Pred.
1	2	-	-	-	14.4	2.31	13.1	13.2	1.44	11.7	11.7	1.02	10.8
4	2	-	-	-	10.0	2.31	13.1	11.0	1.44	11.7	9.4	1.02	10.8
14	2	-	-	-	13.8	2.31	13.1	13.5	1.44	11.7	13.3	1.02	10.8
13	4	-	-	-	9.3	1.85	12.4	10.9	1.21	11.2	10.8	0.90	10.5
15	4	-	-	-	12.8	1.85	12.4	-	-	-	-	-	-
20	4	-	-	-	13.4	1.85	12.4	-	-	-	-	-	-
21	4	17.5	3.53	14.5	-	-	-	-	-	-	-	-	-
2	6	-	-	-	11.2	1.44	11.7	10.7	1.00	10.8	-	-	-
5	6	-	-	-	12.5	1.44	11.7	12.0	1.00	10.8	10.1	0.80	10.3
12	6	-	-	-	13.1	1.44	11.7	12.4	1.00	10.8	11.5	0.80	10.3
22	6	16.0	2.60	13.4	-	-	-	-	-	-	-	-	-
3	8	-	-	-	11.4	1.08	10.9	6.6	0.81	10.3	-	-	-
6	8	-	-	-	12.3	1.08	10.9	11.6	0.81	10.3	10.5	0.70	9.9
17	8	-	-	-	11.4	1.08	10.9	10.0	0.81	10.3	8.4	0.70	9.9
23	8	12.0	1.79	12.3	-	-	-	-	-	-	-	-	-
7	10	-	-	-	9.6	0.77	10.1	9.6	0.64	9.7	9.2	0.60	9.6
10	10	-	-	-	8.3	0.77	10.1	7.5	0.64	9.7	7.0	0.60	9.6
15	10	-	-	-	-	-	-	6.6	0.64	9.7	-	-	-
20	10	-	-	-	11.4	0.77	10.1	-	-	-	-	-	-
21	10	13.9	1.11	11.0	-	-	-	-	-	-	-	-	-
22	10	9.0	1.11	11.0	-	-	-	-	-	-	-	-	-
8	15	-	-	-	9.1	0.22	7.8	8.9	0.30	8.3	8.6	0.40	8.8
19	15	-	-	-	8.4	0.22	7.8	7.4	0.30	8.3	8.6	0.40	8.8
23	15	8.9	0.11	7.0	-	-	-	-	-	-	-	-	-
15	20	-	-	-	9.2	0.0	7.0	-	-	-	-	-	-
20	20	-	-	-	7.1	0.0	7.0	-	-	-	-	-	-
21	20	8.2	0.0	7.0	-	-	-	-	-	-	-	-	-
22	20	7.7	0.0	7.0	-	-	-	-	-	-	-	-	-
23	20	6.3	0.0	7.0	-	-	-	-	-	-	-	-	-

* Assuming a free-field propagation loss factor of 3 dB per doubling of distance.

** Path length difference parameter as defined in Appendix D.

TABLE B-6

MEASURED AND LINE SOURCE PREDICTED NOISE REDUCTIONS, SITE 2 (ELEVATED HIGHWAY CONFIGURATION)

RUN NO.	HT. FT.	NOISE REDUCTION IN dBA BASED UPON L_{50} LEVELS AS MEASURED*AND PREDICTED BY THE LINE SOURCE MODEL AT VARIOUS DISTANCES FROM THE ROADSIDE					
		125 feet			250 feet		
		Meas.	δ**	Pred.	Meas.	δ**	Pred.
6	1	17.0	3.46	14.3	13.0	0.92	10.5
12	1	14.7	2.46	14.3	10.0	0.92	10.5
1	5	16.4	2.62	13.5	8.8	0.70	9.9
5	5	15.6	2.62	13.5	10.7	0.70	9.9
11	5	13.5	2.62	13.5	8.6	0.70	9.9
2	10	12.9	1.71	12.2	7.9	0.47	9.1
7	10	12.8	1.71	12.2	9.8	0.47	9.1
10	10	11.3	1.71	12.2	7.5	0.47	9.1
3	15	11.6	0.99	10.8	7.6	0.29	8.2
4	20	8.9	0.44	9.0	5.9	0.14	7.2
8	20	10.8	0.44	9.0	8.9	0.14	7.2
9	20	8.5	0.44	9.0	6.4	0.14	7.2

*Assuming a free-field propagation loss factor of 3 dB per doubling of distance.

**Path length difference parameter as defined in Appendix D.

TABLE B–7

MEASURED AND LINE SOURCE PREDICTED NOISE REDUCTIONS, SITE 9 (DEPRESSED HIGHWAY CONFIGURATION)

RUN NO.	HT. FT.	NOISE REDUCTION IN dBA BASED UPON L_{50} LEVELS AS MEASURED* AND PREDICTED BY THE LINE SOURCE MODEL AT VARIOUS DISTANCES FROM THE ROADSIDE — 134 feet			184 feet		
		Meas.	δ**	Pred.	Meas.	δ**	Pred.
1	1	7.9	0.60	8.6	11.0	1.02	11.0
9	1	8.0	0.60	8.6	11.4	1.02	11.0
2	2.5	8.2	0.42	8.9	11.7	0.87	10.4
10	2.5	8.8	0.42	8.9	11.6	0.87	10.4
3	5	8.2	0.19	7.6	11.7	0.65	9.8
11	5	7.1	0.19	7.6	11.2	0.65	9.8
12	5	8.5	0.19	7.6	11.8	0.65	9.8
4	7.5	7.4	0.05	7.0	11.2	0.46	9.1
5	10	7.4	0.0	7.0	10.9	0.30	8.3
13	10	6.4	0.0	7.0	11.2	0.30	8.3
6	15	-	-	-	9.7	0.09	7.0
14	15	-	-	-	7.5	0.09	7.0

*Assuming a free-field propagation loss factor of 3 dB per doubling of distance.

**Path length difference parameter as defined in Appendix D.

TABLE B–8

MEASURED AND LINE SOURCE PREDICTED NOISE REDUCTIONS WITH TRUCK CORRECTION, SITE 1 (ROADSIDE BARRIER CONFIGURATION)

CASE NO. ***	RUN NO.	HT. FT.	NOISE REDUCTION IN dBA BASED UPON L_{50} LEVELS AS MEASURED* AND PREDICTED BY THE LINE SOURCE MODEL WITH TRUCK CORRECTION** AT VARIOUS DISTANCES FROM THE ROADSIDE — 63 feet		93 feet		143 feet		243 feet	
			Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.
2	1	2	-	-	14.4	12.6	13.2	10.9	11.7	9.6
3	4	2	-	-	10.0	13.1	11.0	11.7	9.4	10.8
2	14	2	-	-	13.8	12.6	13.5	10.9	13.3	9.6
3	13	4	-	-	9.3	12.4	10.9	11.2	10.8	10.5
3	15	4	-	-	12.8	12.4	-	-	-	-
2	20	4	-	-	13.4	11.8	-	-	-	-
3	21	4	17.5	14.5	-	-	-	-	-	-
2	2	6	-	-	11.2	11.1	10.7	9.9	-	-
1	5	6	-	-	12.5	11.7	12.0	10.8	10.1	10.3
3	12	6	-	-	13.1	11.7	12.4	10.8	11.5	10.3
2	22	6	16.0	13.1	-	-	-	-	-	-
3	3	8	-	-	11.4	10.9	6.6	10.3	-	-
3	6	8	-	-	12.3	10.9	11.6	10.3	10.5	9.9
2	17	8	-	-	11.4	10.2	10.0	9.3	8.4	8.8
2	23	8	12.0	11.9	-	-	-	-	-	-
2	7	10	-	-	9.6	9.3	9.6	8.7	9.2	8.5
3	10	10	-	-	8.3	10.1	7.5	9.7	7.0	9.6
3	15	10	-	-	-	-	6.6	9.7	-	-
2	20	10	-	-	11.4	9.3	-	-	-	-
2	21	10	13.9	10.6	-	-	-	-	-	-
2	22	10	9.0	10.6	-	-	-	-	-	-
3	8	15	-	-	9.1	7.8	8.9	8.3	8.6	8.8
2	19	15	-	-	8.4	7.5	7.4	7.8	8.6	8.1
2	23	15	8.9	7.0	-	-	-	-	-	-
3	15	20	-	-	9.2	7.0	-	-	-	-
2	20	20	-	-	7.1	7.0	-	-	-	-
2	21	20	8.2	7.0	-	-	-	-	-	-
2	22	20	7.7	7.0	-	-	-	-	-	-
2	23	20	6.3	7.0	-	-	-	-	-	-

*Assuming a free-field propagation loss factor of 3 dB per doubling of distance.

**Assuming truck noise radiates from a line located 8 ft above the highway surface.

***Truck mix ratios for the predictions: Case No. 1 - 0%; Case No. 2 - 12.5%; Case No. 3 - 2.5%.

APPENDIX C

MODIFICATIONS TO THE DESIGN GUIDE PROCEDURES

Based on the results of this project, a number of changes were suggested in the Design Guide procedures (*NCHRP Report 117*). The modifications presented here rely, in some cases, on the procedures, figures, and tables in the Design Guide. Throughout this procedure, all references to *NCHRP Report 117* are underlined.

VERTICAL ADJUSTMENT (Δ_4)

Elevated Roadway Configuration

The following procedures supersede those in the Design Guide, p. 44, steps 6.0 through 6.10. Go to Work Sheet A (Table C-1).

1.0 WORK SHEET A: The procedure for estimating adjustment due to an elevated highway configuration is as follows for each Road Element:

1.1 Enter Road Elements defined in Work Sheet No. 1.

1.2 Enter Height of Elevated Roadway, H, in feet, in Line 1.

1.3 Enter Height of Observer, h_o, in feet, in Line 2.

Note: Height of Observer, h_o, can be positive (+) or negative (—). h_o is positive (+) when measured above the reference plane and negative (—) when measured below the reference plane, as indicated in Work Sheet A.

1.4 Enter Observer-Equivalent Lane Distance, D_E, in in Line 3 (see Line 8b of the Parameter Work Sheet).

1.5 Enter Observer-Shoulder Distance, D_S, in feet, in Line 4.

1.6 Compute Parameter $A = (D_E - D_S)$ and enter in Line 5.

1.7 Compute Parameter $B = [(H - h_o)^2 + D_S{}^2]^{\frac{1}{2}}$ and enter in Line 6.

1.8 Compute Parameter $d = [(H - h_o)^2 + D_E{}^2]^{\frac{1}{2}}$ and enter in Line 7.

1.9 Compute Parameter $\delta = A + B - d$ and enter in Line 8.

Note:

1. Parameter δ must be calculated to two significant figures.
2. If Parameter δ is negative (—), the Elevated Roadway Adjustment is zero. If Parameter δ is positive (+) proceed to step 1.10.

1.10 Using Parameter δ, enter Figure C-1 and read the proper Adjustment for Elevated Roadway. Enter in Line 9a.

1.11 To obtain the Adjustment for Trucks, add +3 dBA to Line 9a and enter in Line 9b. (Note: the numerical value of truck adjustment is smaller than that for autos but it can never be positive.)

1.12 Enter the Elevated Roadway Adjustment for each Road Element calculated above in Line 5 of the Noise Prediction Work Sheet.

Depressed Roadway Adjustment

The following procedures supersede those in the Design Guide, p. 44, steps 6.0, 6.1, and 6.11 through 6.17. Go to Work Sheet B (Table C-2).

2.0 WORK SHEET B: The procedure for estimating the Adjustment due to a depressed highway configuration is as follows for each Road Element:

2.1 Enter Road Elements defined in Work Sheet No. 1.

2.2 Enter Depth of Depressed Roadway, H, in feet, in Line 1.

2.3 Enter Height of Observer, h_o, in feet, in Line 2.

Note: Height of Observer, h_o, can be positive (+) or negative (—). h_o is positive (+) when measured above the reference plane and negative (—) when measured below the reference plane as indicated in Work Sheet B.

2.4 Enter Observer-Equivalent Lane Distance, D_E, in Line 3 (see Line 8b of the Parameter Work Sheet).

2.5 Enter Observer-Cut Distance, D_C, in feet, in Line 4.

2.6 Compute Parameter $A = [H^2 + (D_E - D_C)^2]^{\frac{1}{2}}$ and enter in Line 5.

2.7 Compute Parameter $B = [h_o{}^2 + D_C{}^2]^{\frac{1}{2}}$ and enter in Line 6.

2.8 Compute Parameter $d = [(H + h_o)^2 + D_E{}^2]^{\frac{1}{2}}$ and enter in Line 7.

2.9 Compute Parameter $\delta = A + B - d$ and enter in Line 8.

Note:

1. Parameter δ must be calculated to two significant figures.
2. If Parameter δ is negative (—), the Depressed Roadway Adjustment is zero. If Parameter δ is positive (+) proceed to step 2.10.

2.10 Using Parameter δ, enter Figure C-1 and read the proper Adjustment for Depressed Roadway. Enter in Line 9a.

2.11 To obtain the Adjustment for Trucks, add +3 dB to Line 9a and enter in Line 9b. (Note: the numerical value of truck adjustment is smaller than for autos but it can never be positive.)

2.12 Enter the Depressed Roadway Adjustment (Δ_4) for each Road Element calculated above in Line 4 of the Noise Prediction Work Sheet.

SHIELDING ADJUSTMENT (Δ_6 AND Δ_7)

The procedures for estimating shielding adjustments due to roadside barriers and roadside structures are as follows.

Roadside Barriers

The following procedures supersede those in the Design Guide, p. 45, steps 9.0 through 9.10. Go to Work Sheet C (Table C-3).

3.0 WORK SHEET C: The procedure for estimating the Adjustment for barriers is as follows for each Road Element.

3.1 Enter Road Elements defined in Work Sheet No. 1.

TABLE C–1

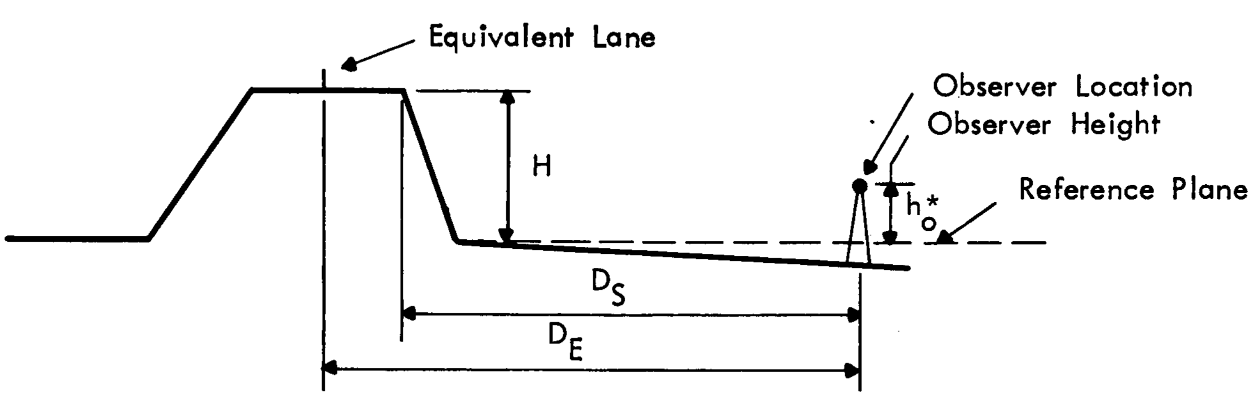
WORK SHEET A: ELEVATED HIGHWAY ADJUSTMENT

Line	Symbol	Ref.	ROADWAY ELEMENT					
				Number				
				Type				
			TIME INTERVAL					
1	H		Height of Barrier					
2	$\pm h_o^*$		Height of Observer *					
3	D_E		Observer - Equivalent Lane Distance					
4	D_S		Observer - Shoulder Distance					
5	A		$A = (D_E - D_S)$					
6	B		$B = \left[(H - h_o)^2 + D_S^2\right]^{1/2}$					
7	d		$d = \left[(H - h_o)^2 + D_E^2\right]^{1/2}$					
8	δ^{**}		$\delta = A + B - d^{**}$					
9		Fig C-1	Elevated Freeway Adjustment***	(a) Autos (b) Trucks				

* Observer height is measured from the reference plane: position (+) above the plane and negative (-) below the plane.

** The path length difference δ must be calculated to two significant figures. If path length difference δ is negative (-), adjustment is equal to zero.

*** For Trucks add +3 dB to value given by Figure C-1.



3.2 If Line 9a of the Parameter Work Sheet is checked, proceed to steps 3.3 through 3.13.

3.3 Enter Height of Barrier, H, in feet, in Line 1.

3.4 Enter Height of Observer, h_o, in feet, in Line 2.

Note: Height of Observer, h_o, can be positive (+) or negative (—). h_o is positive (+) when measured above the reference plane and negative (—) when measured below the reference plane, as indicated in Work Sheet C.

TABLE C-2

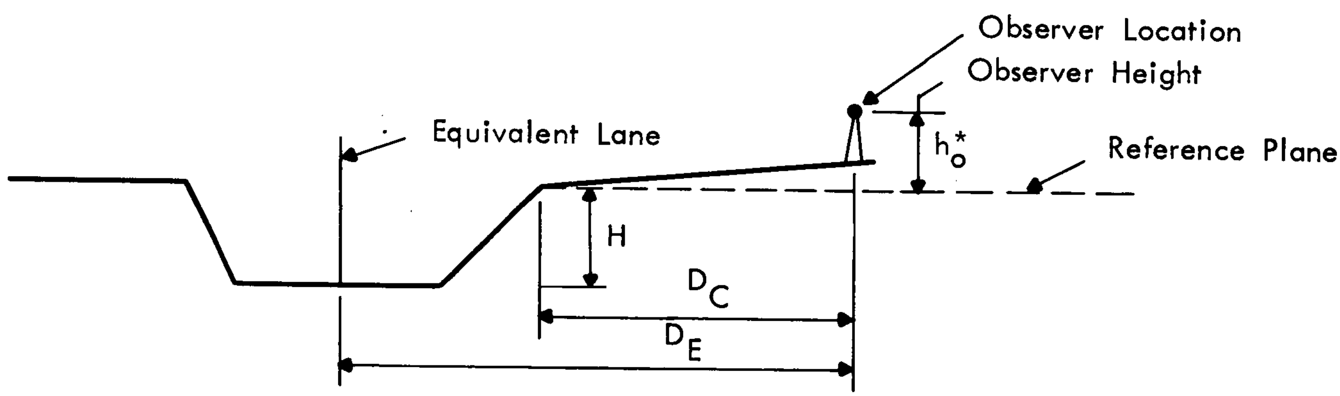
WORK SHEET B: DEPRESSED HIGHWAY ADJUSTMENT

Line	Symbol	Ref.	ROADWAY ELEMENT					
				Number				
				Type				
			TIME INTERVAL					
1	H		Depth of Depressed Freeway					
2	$\pm h_o^*$		Height of Observer *					
3	D_E		Observer - Equivalent Lane Distance					
4	D_C		Observer - Cut Distance					
5	A		$A = \left[H^2 + (D_E - D_C)^2\right]^{1/2}$					
6	B		$B = \left[h_o^2 + D_C^2\right]^{1/2}$					
7	d		$d = \left[(H + h_o)^2 + D_E^2\right]^{1/2}$					
8	δ^{**}		$\delta = A + B - d$ **					
9		Fig C-1	Depression Freeway Adjustment ***	(a) Autos				
				(b) Trucks				

* Observer height is measured from the reference plane: position (+) above the plane and negative (-) below the plane

** The path length difference δ must be calculated to two significant figures. If path length difference δ is negative (-), adjustment is equal to zero.

*** For Trucks add +3 dB to value given by Figure C-1.



3.5 Enter Equivalent Lane Distance, D_E, in Line 3.

3.6 Enter Observer-Barrier Distance, D_B, in feet, in Line 4.

3.7 Calculate Parameter $A = [H^2 + (D_E - D_B)^2]^{\frac{1}{2}}$ and enter in Line 5.

3.8 Calculate Parameter $B = [(H - h_o)^2 + D_B]^{\frac{1}{2}}$ and enter in Line 6.

3.9 Compute Parameter $d = [h_o^2 + D_E^2]^{\frac{1}{2}}$ and enter in Line 7.

3.10 Compute Parameter $\delta = A + B - d$ and enter in Line 8.

Note:

1. Parameter δ must be calculated to two significant figures.

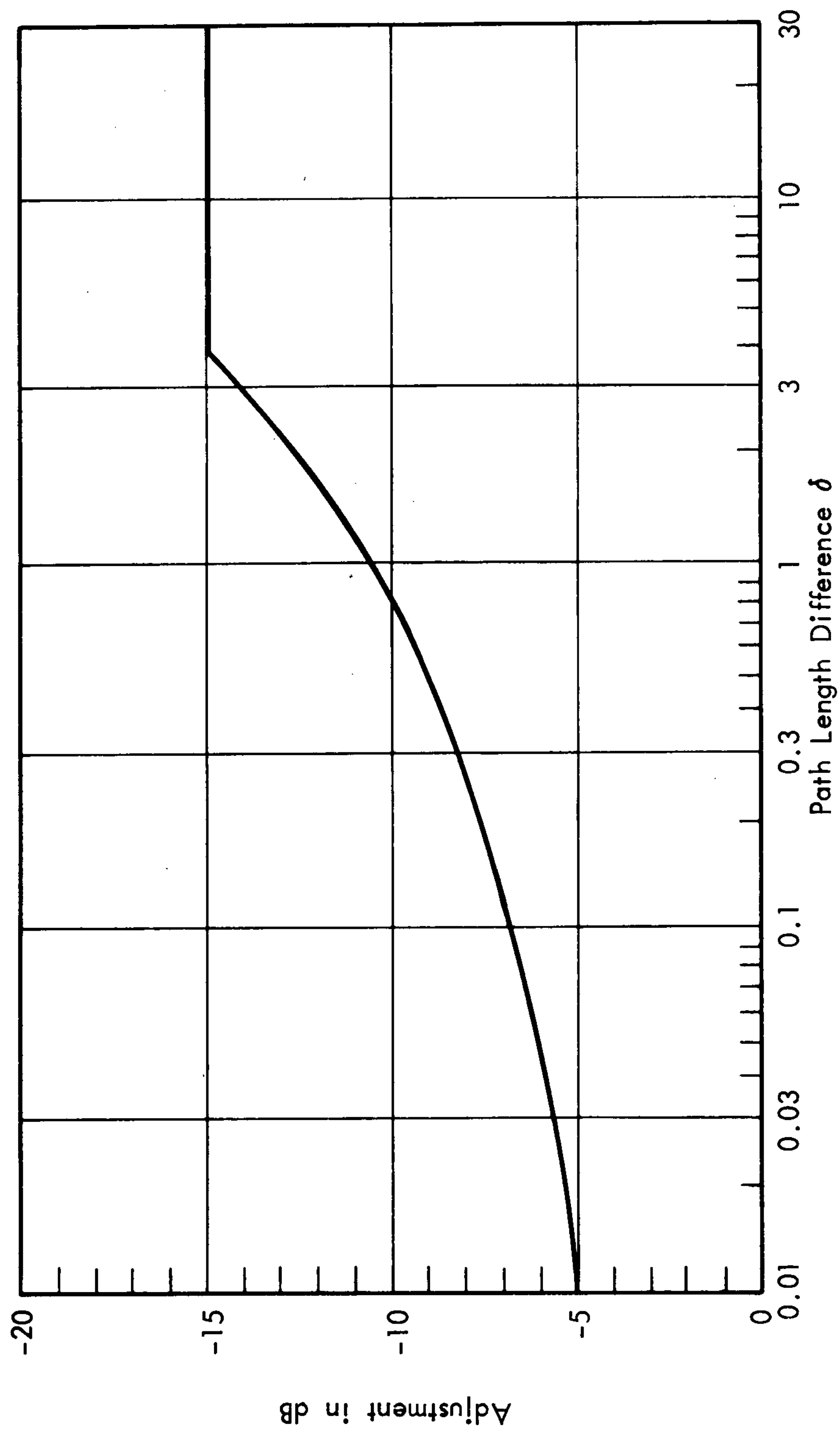


Figure C–1. Adjustment for elevated and depressed roadway configurations.

TABLE C-3

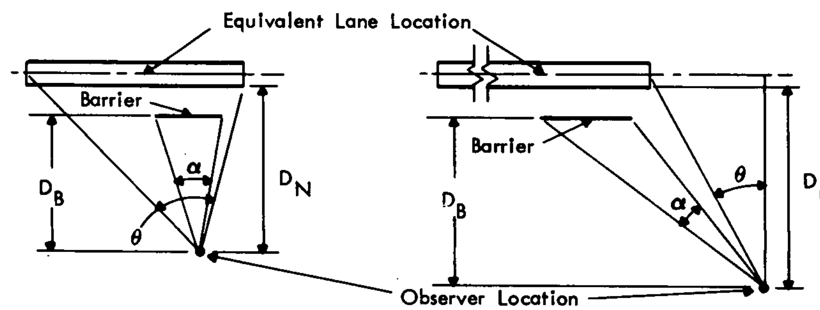
WORK SHEET C: ROADSIDE BARRIER ADJUSTMENT

Line	Symbol	Ref.			ROADWAY ELEMENT		Number / Type			
					TIME INTERVAL					
1	H				Height of Barrier					
2	$\pm h_o^*$				Height of Observer*					
3	D_E				Equivalent Lane - Barrier Distance					
4	D_B				Observer - Barrier Distance					
5	A				$A = \left[H^2 + (D_E - D_B)^2\right]^{1/2}$					
6	B				$B = \left[(H - h_o)^2 + D_B^2\right]^{1/2}$					
7	d				$d = \left[h_o^2 + D_E^2\right]^{1/2}$					
8	δ^{**}				$\delta = A + B - d^{**}$					
9		Fig C-2			Adjustment for Infinite Barrier***	(a) Autos / (b) Trucks				
10	θ		ADJUSTMENT FOR FINITE BARRIER	Finite Element	Included Element Angle					
11	α				Included Barrier Angle					
12					$A = \alpha/\theta$					
13		Fig C-2			Adjustment in dB***	(a) Autos / (b) Trucks				
14	θ			Semi-Infinite Element	Comp. Barrier Angle					
15	α				Included Barrier Angle					
16					$A = \alpha/(90 - \theta)$					
17		Fig C-2			Adjustment in dB***	(a) Autos / (b) Trucks				
18				Infinite Element	Included Barrier Angle					
19					$A = \alpha/180$					
20		Fig C-2			Adjustment in dB***	(a) Autos / (b) Trucks				

* Observer height is measured from the reference plane: position (+) above the plane and negative (-) below the plane.

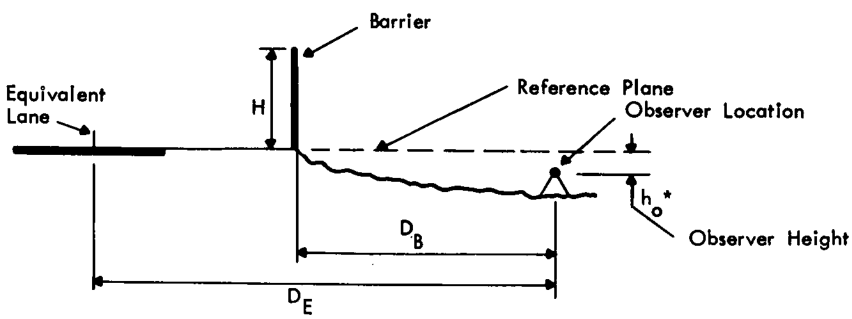
** The path length difference δ must be calculated to two significant figures. If path length difference δ is negative (-), adjustment is equal to zero.

*** For Trucks add +3 dB to value given by Figure C-2.



Finite Roadway Element

Semi Infinite Roadway Element

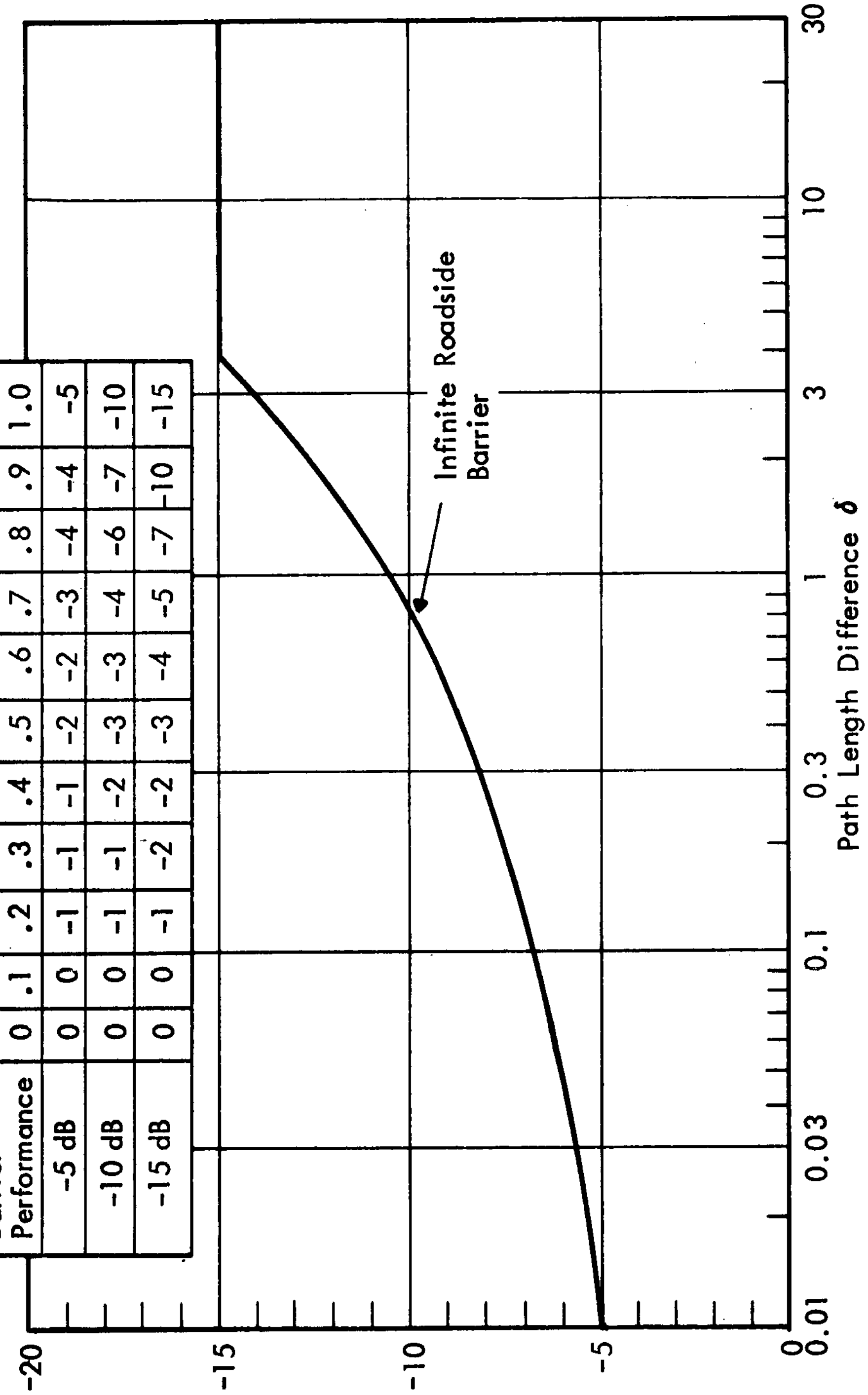


2. If Parameter δ is negative (—), the Roadside Barrier Adjustment is zero. If Parameter δ is positive (+) proceed to step 3.11.

3.11 Using Parameter δ, enter Figure C-2 and read the proper Adjustment for an Infinite Roadside Barrier. Enter in Line 9a.

Note: To obtain the Adjustment for Trucks add +3 dB to Line 9a and enter in Line 9b. (Note: the numerical value of truck adjustment is smaller than that for autos but it can never be positive.)

- For a Finite Roadway Element proceed to steps 3.12.1 through 3.12.5.
- For Semi-Infinite Roadway Element proceed to steps 3.12.6 through 3.12.10.



ADJUSTMENT FOR FINITE BARRIER IN dB

Infinite Barrier Performance	Parameter A										
	0	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
-5 dB	0	0	-1	-1	-1	-2	-2	-3	-4	-4	-5
-10 dB	0	0	-1	-1	-2	-3	-3	-4	-6	-7	-10
-15 dB	0	0	-1	-2	-2	-3	-4	-5	-7	-10	-15

Figure C-2. Adjustment for roadside barriers.

• For Infinite Roadway Element proceed to steps 3.12.11 through 3.12.14.

3.12 Depending on the Road Element Type considered, do one of the following:

3.12.1 Enter Included Element Angle, θ, in Line 10. This is obtained from Line 8d of the Parameter Work Sheet.

3.12.2 Enter Included Barrier Angle, *a*, in Line 11. This angle represents the included angle between the observer and the barrier (see sketch).

3.12.3 Compute the Parameter $A = (a/\theta)$ and enter in Line 12.

3.12.4 Using Parameter A and the Infinite Barrier Adjustment (Line 9a) enter Figure C-2 and read the appropriate adjustment for a finite barrier. Note that the adjustments are given for only three values of the Infinite Barrier. Select the closest value to the one calculated in Line 9a. Enter this adjustment in Line 13a. Go to step 3.13.

3.12.5 To obtain the Adjustment for Trucks, proceed as in step 3.12.4, but use the Infinite Line Adjustment on Line 9b. Enter the calculated adjustment in Line 13b.

3.12.6 Enter Complementary Element Angle, θ, in Line 14. This is obtained from Line 8d of the Parameter Work Sheet.

3.12.7 Enter Included Barrier Angle, *a*, in Line 15. This angle represents the included angle between the observer and the barrier (see sketch).

3.12.8 Compute the Parameter $A = (a/90 - \theta)$ and enter in Line 16.

3.12.9 Using Parameter A and the Infinite Barrier Adjustment (Line 9a) enter Figure C-2 and read the appropriate adjustment for a finite barrier. Note that the adjustments are given for only three values of the Infinite Barrier. Select the closest value to the one calculated in Line 9a. Enter this adjustment in Line 17a.

3.12.10 To obtain the Adjustment for Trucks, proceed as in step 3.12.9, but use the Infinite Line Adjustment on Line 9b. Enter the calculated adjustment on Line 17b.

3.12.11 Enter Included Barrier Angle, *a*, in Line 18. This angle represents the included angle between the observer and the barrier.

3.12.12 Compute the Parameter $A = a/180$ and enter in Line 19.

3.12.13 Using Parameter A and the Infinite Barrier Adjustment (Line 9a) enter Figure C-2 and read the appropriate adjustment for a finite barrier. Note that the adjustments are given for only three values of Infinite Barrier. Select the closest value to the one calculated in Line 9a. Enter this adjustment in Line 20a.

3.12.14 To obtain the Adjustment for Trucks, proceed as in step 3.12.13 but use the Infinite Line Adjustment on Line 9b. Enter the calculated adjustment on Line 20b.

3.13 Enter the Finite Barrier Adjustment in Line 7a of the Noise Prediction Work Sheet. Note that the algebraic addition to the Vertical Adjustment (Δ_4) Line 5 and the Barrier Adjustment (Δ_6) Line 7a should not exceed −20 dB ($\Delta_4 + \Delta_6 > -20$ dB).

Roadside Structures and Planting

The following procedures supersede those in the Design Guide, p. 45, steps 9.11 and 9.12.

4.0 Multiple rows of intervening buildings and structures such as houses or apartments can reduce noise levels by up to 10 dB, depending on the degree of shielding provided. The following rule should be followed:

• First row of structures equals a −4.5-dB adjustment.
• Every subsequent row of structures equals an additional −1.5-dB adjustment up to a maximum of 10 dB.

4.1 A design value of 5 dB noise reduction for every 100 ft of foliage between the observer and the roadway element may be used if the trees are at least 15 ft tall and sufficiently dense so that no visual path exists between them and the roadway. The total adjustment should not exceed 10 dB. Note that this adjustment is always negative.

4.2 Add the adjustments of lines 4.0 (Roadside Structures) and 4.1 (Planting) and enter total adjustment in Line 7b of the Noise Prediction Work Sheet. Note that this adjustment is always negative.

APPENDIX D

REVIEW OF ANALYTIC AND EMPIRICAL MODELS

The theoretical and experimental performance of acoustic shields or barriers has been discussed by several authors (*2, 3, 4, 5, 6, 7, 8*). Assuming that the shield or barrier has sufficient mass to make sound transmitted through the barrier negligible, and further that no line-of-sight exists between source and observer, then sound can reach the observer only by diffraction. In other words, an acoustic barrier does not create an absolute acoustic "shadow" on the side of the barrier remote from the source. On the contrary, sound diffracted over the barrier edge "spills"

sound energy into the shadow zone. An additional inherent assumption is that the barrier is long enough to make sound diffracted around its ends negligible.

Consider the generalized geometry shown in Figure D-1b. The top edge of the plane may represent any one of the four types of noise reduction configurations evaluated in this study. In the case of a roadside barrier, the top edge represents the top of the wall or earthmound. In the case of an elevated highway section, the edge corresponds to the outer edge of the shoulder. For the depressed highway section, the edge is the intersection of the cut-slope with the terrain. In the case of roadside structures, the top edge of the structure corresponds to the top edge of the plane. Thus, in the context of this discussion, "barrier or shield" applies to all four of the geometries. In the following paragraphs, four models for barrier noise reduction are discussed briefly.

In recent papers by Maekawa (*2, 3*) the performance of semi-infinite acoustic shields is discussed and validated in the laboratory. The performance is shown to be a function of the acoustic wavelength, λ, and the path length difference, δ, where

$$\delta \equiv \pm(A + B - d) \tag{D-1}$$

as shown in Figure D-1. The distance $(A + B)$ corresponds to the shortest path over the shield's edge between source and receiver; d is the direct path distance between source and receiver. Note that δ is defined as positive when the shield blocks line-of-sight between source and receiver.

The Maekawa results predict excess noise reduction by a shield as a function of the Fresnel number, N:

$$N = (2/\lambda)\delta \tag{D-2}$$

Figure D-2 shows this relationship. However, the results apply only to a single-source receiver distance. To obtain data for practical use in highway design, Galloway (*9*) performed a limited measurement program of noise produced by traffic under conditions of elevated and depressed grade. Based on these measurements, Maekawa's curve was modified to be linear, as shown in Figure D-2. This curve formed the basis for the calculations for elevated, depressed, and roadside barrier adjustments used in the Design Guide (*NCHRP Report 117*, Figs. 9, 10, and 11). Maekawa's curve was further modified by limiting the maximum attenuation predicted to 15 dBA due to refraction and environmental factors.

The refracted sound field from an infinite coherent line source parallel to an infinite barrier was calculated by Keller (*18*) for large Fresnel numbers, N. These results were modified by Kurze and Anderson (*8*) to be valid for the incoherent line source. This formulation corresponds more closely to the automotive traffic situation where the noise reduction provided by a barrier is calculated by integrating over a string of point sources. The resulting noise reduction is shown in Figure D-3, in which N_{max} is the maximum Fresnel number, N, obtained when the source receiver line is perpendicular to the barrier.

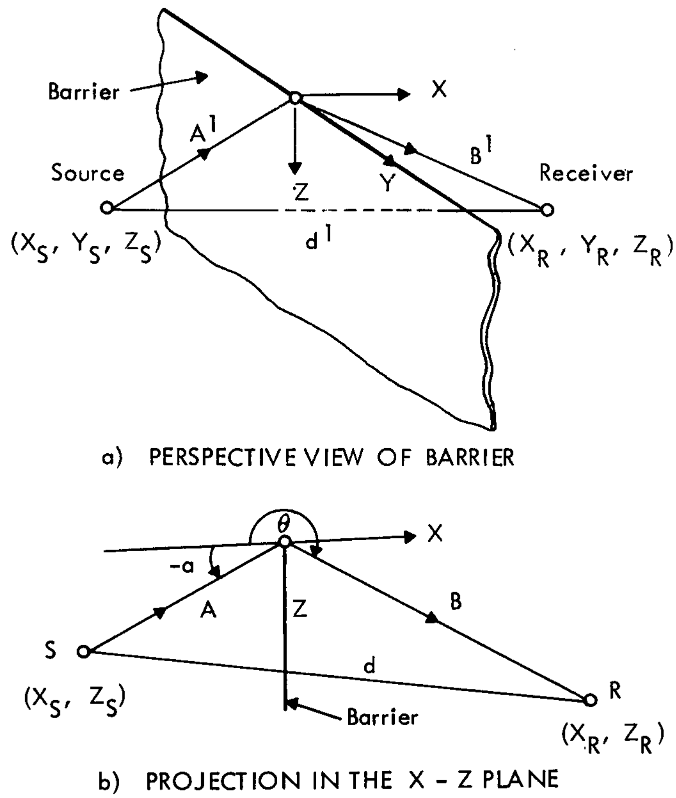


Figure D–1. Generalized acoustic barrier geometry.

The effective wavelength of traffic noise is about 2 or 3 ft; i.e., the numerical reduction of the dBA traffic noise lies close to the noise reduction provided at a frequency of about 500 Hz. Therefore, the excess attenuation (ΔL) due to an infinite barrier can be written as a function of the path length difference (δ) only. Using this assumption a "linearized" form of the Line Source Model was computerized as shown in Figure D-4. This Modified Line Source Model (MLSM) is linearized for small path length differences, as was the case in the Design Guide model, and is also restricted to a maximum excess attenuation of 15 dBA. In addition to the MLSM, Figure D-4 shows the model used in the Design Guide, a model using Maekawa's measurements, and the Line Source Model (LSM) derived by Kurze and Anderson.

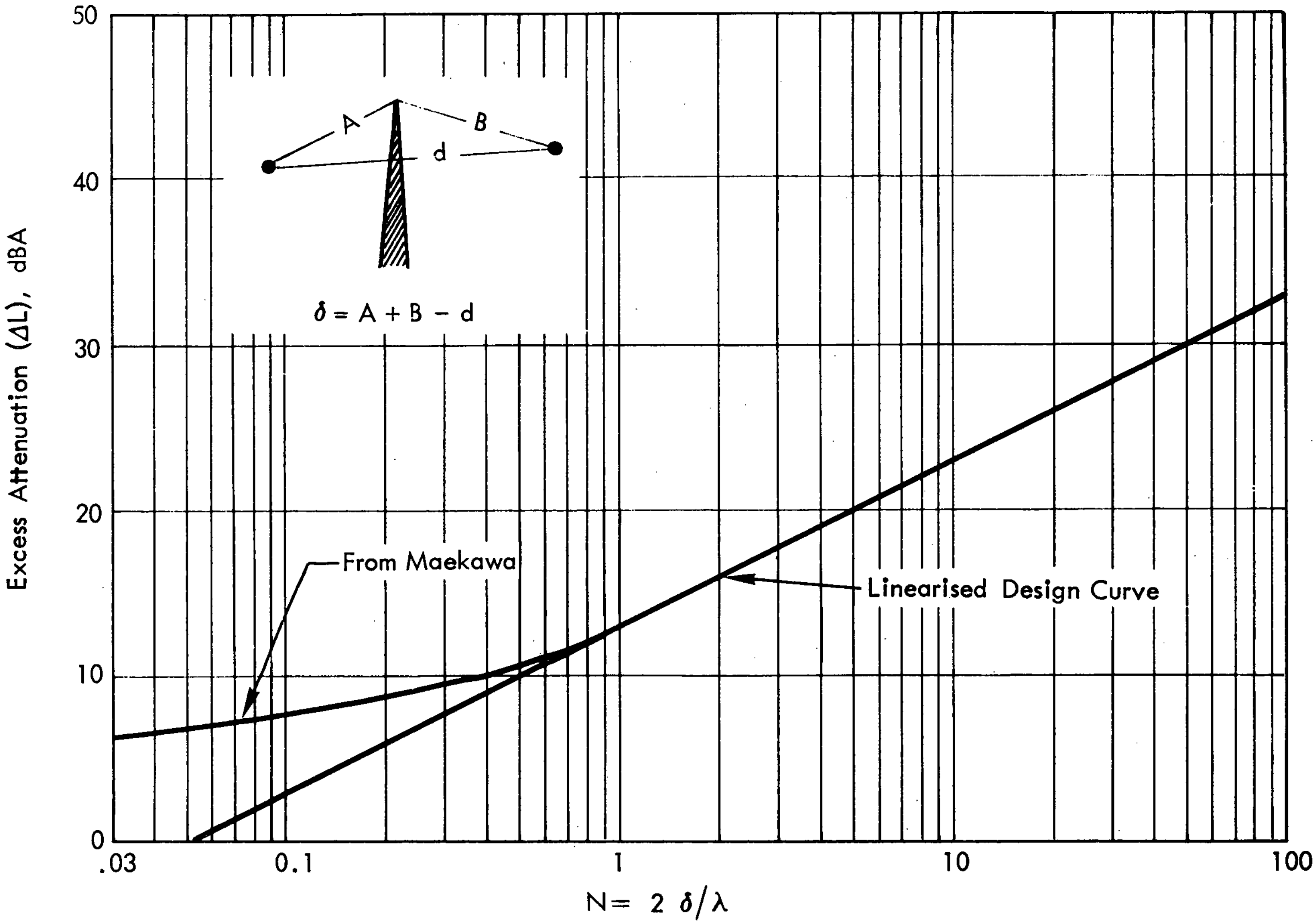


Figure D–2. Excess attenuation of infinite acoustic barrier.

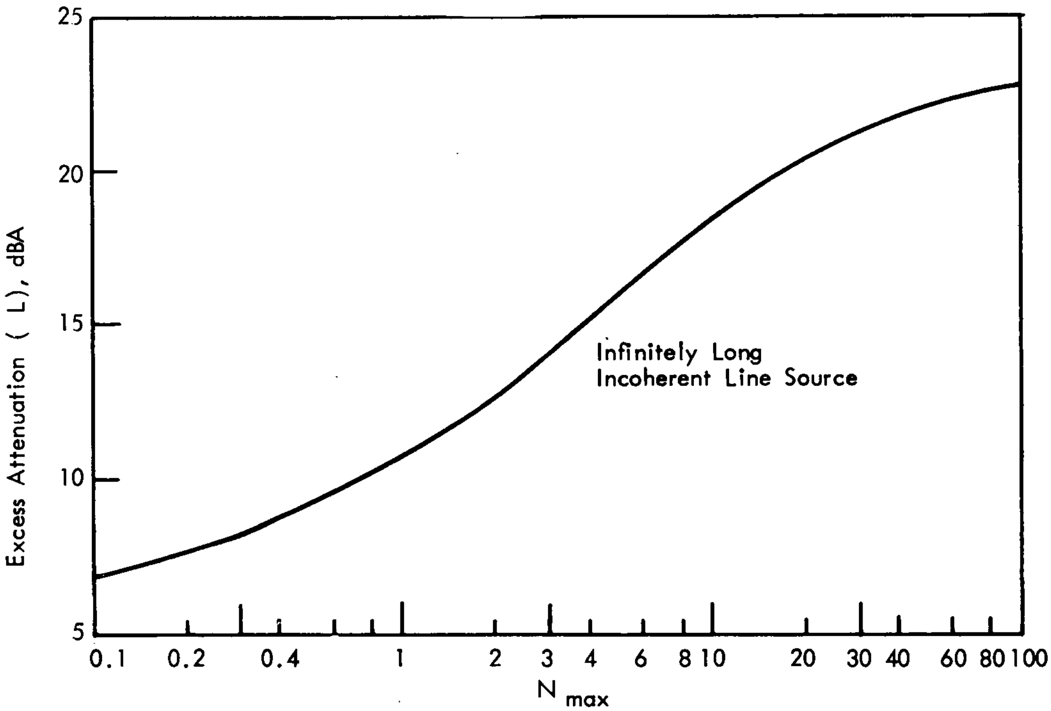


Figure D–3. Excess attenuation by a rigid barrier vs Fresnel number, N_{max}, for an infinitely long, incoherent line source parallel to the edge of a rigid barrier.

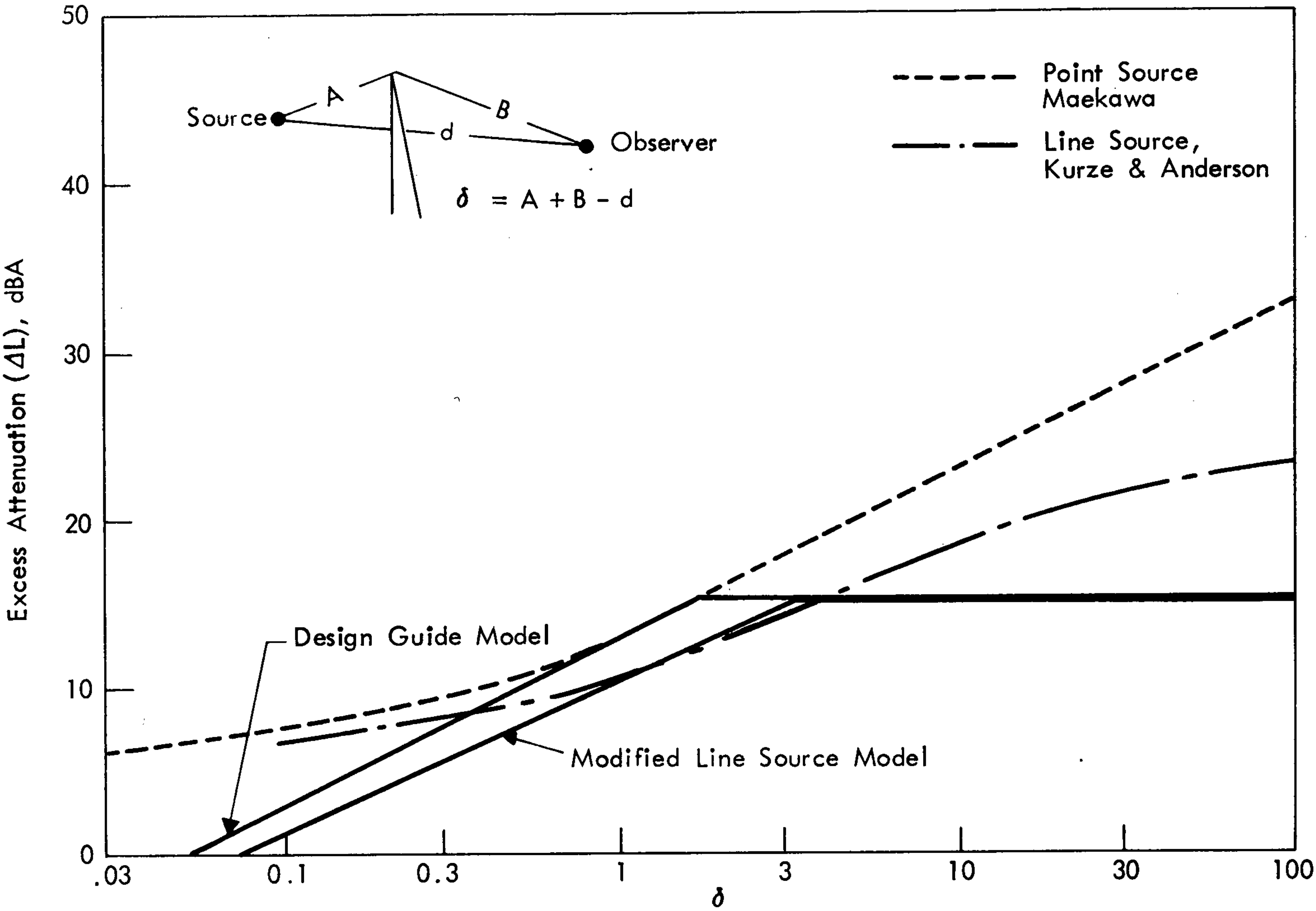


Figure D–4. Attenuation of infinite acoustic barrier for point source and infinite line source.

APPENDIX E

TEST FIELD SITE REQUIREMENTS

A number of geometrical and traffic requirements were imposed during the test field site location and selection procedure. This was necessary in order to simplify the description of the noise field and limit the number of variables that must be considered.

This appendix contains a copy of a memorandum (Fig. E-1) sent to 30 state highway departments requesting assistance in the identification and location of suitable test sites. Each test site configuration was described in detail and the minimum requirements were specified. A number of inquiry forms were provided to facilitate the selection and reply to the survey.

MEMORANDUM

To: State Highway Officials
From: Bolt Beranek and Newman Inc. - Acoustical Consultants
Subject: Survey to Identify Suitable Highway Geometries for the Field Evaluation of Noise Reduction Measures
Date: 11 May 1971

I. INTRODUCTION

As mentioned in the cover letter, the objective of this study is the field evaluation of the acoustical performance of various noise abatement measures. To that effect we are requesting the cooperation of your department in the identification and location of suitable highway sections in your state that might serve as sites for our measurements.

This memorandum provides a description of the highway and traffic condition we are trying to locate in terms of various parameters of interest. The specific type of highway geometries we are seeking can be divided into four main categories, these are:

- Depressed Highway Configuration
- Elevated Highway Configuration
- Roadside Barriers or Earthmounds
- Roadside Structures

In the following paragraphs we discuss these four categories individually and list the minimum requirements we must locate for a successful field program.

II. DEPRESSED HIGHWAY CONFIGURATION

The first of these categories is a depressed highway geometry. The intent is to evaluate the noise reduction afforded by various depressed geometries on the surrounding area relative to the at grade highway configuration. Listed below are the minimum requirements we must find. Figure 1 shows a plan view and crosssection of a typical depressed configuration. The minimum requirements are:

1. The section of highway should be uniformly depressed over a length of no less than 3500 feet.
2. The depth of cut should be no less than 10 feet and vary no more than ±10% over the entire section length.
3. The section of highway must be straight (±15% from centerline) and level over the entire length (maximum grade 1%).
4. The section of highway must be void of off-ramps or on-ramps over the entire length and be of constant cross-section (highway width must not vary more than 20%).
5. The surrounding terrain should be level (at least on one side of the highway) for 300 feet from the highway shoulder.
6. Preferably, no other major sources of noise should be present in the immediate area such as heavy street traffic, aircraft landing or takeoff operations, or a large industrial center.

The enclosed form for the depressed highway configuration lists again these minimum parameters. Please fill in the information requested, one form for each section of highway identified.

Figure E-1. Memorandum to state highway officials.

III. ELEVATED HIGHWAY CONFIGURATION

The second category, elevated highway geometry includes both the fill and viaduct type cross sections. Figure 2 shows a plan view and cross section of a typical elevated configuration. The minimum requirements are:

1. The section of highway should be uniformly elevated over a length of no less than 3500 feet.
2. The height of the fill of structure should be no less than 10 feet and vary no more than ±10% over the entire section length.
3. The section should be straight (±15% from centerline) and level (maximum grade 1%).
4. The section must be void of on-ramp and off-ramps over the entire length and be of constant cross section (highway width must not vary more than 20%).
5. The surrounding terrain should be level (at least on one side of the highway) for 300 feet from the highway shoulder.
6. Preferably, no other major sources of noise should be present in the immediate area such as heavy street traffic, aircraft landing or takeoff operations, or a large industrial center.

The enclosed form for the elevated highway configuration lists again these minimum parameters. Please fill in the information requested, one form for each highway section identified.

IV. ROADSIDE BARRIERS OR EARTHMOUNDS

The use of roadside walls of earthmounds for the basic purpose of highway noise control has not yet been widely accepted to date. However, in many instances, these devices have been used for design, landscaping or other reasons throughout the country. Here again we are searching for a section of highway where such a measure is present as shown on Figure 3. The ideal situation is an at-grade, straight and level roadway with a barrier or earthmound on one or both sides of the highway. The minimum requirements in terms of the basic parameters are consistent with the first two categories as defined below:

1. The barrier or earthmound should be uniformly elevated over a length of no less than 3500 feet.
2. The height of the barrier or earthmound should be no less than 10 feet and vary no more than ±10% over the entire section length.
3. The section of highway should be straight (±15% from centerline) and level (maximum grade 1%), and preferably at-grade.
4. The section of highway should be void of on-ramps and off-ramps over the entire length and be of constant cross section (highway width must not vary more than 20%).
5. The surrounding terrain (at least on the side of the barrier) should be level for 300 feet from the barrier or earthmound.
6. Preferably, no other major sources of noise should be present in the immediate area such as heavy street traffic, aircraft takeoff or landing operations, or large industrial operations.

The enclosed form for the barrier or earthmound configuration lists again these minimum parameters. Please fill in the information requested, one form for each section of highway identified.

V. ROADSIDE STRUCTURE

The first few rows of roadside structures, be it residential dwellings or commercial-industrial facilities, can be considered as partial acoustical barriers between the highway generated noise and the rest of the community. The degree of noise reduction depends not only on the structures height but also on their linear density, location with respect to the highway, etc. In this case the ideal situation for which we are searching is a section of highway which is straight, level, preferably at-grade and which is surrounded at least on one side by a development of constant characteristics. For example a housing track with equal size lots and dwellings. The typical plan view and cross section of the desired geometry is shown on Figure 4. The minimum requirements in terms of the highway parameters are listed below:

1. The section of highway should be straight (±15% from centerline) and level, preferably at-grade, (maximum grade 1%) for at least 3500 feet.
2. At least on one side of the highway, structures of constant linear density and three rows deep should be present over the entire section of highway.
3. The terrain next to the highway should be level, preferably at-grade with the highway, for at least 300 feet from the highway edge.
4. Preferably, no other major sources of noise should be present in the immediate area such as heavy street traffic, aircraft landing or takeoff operations, or large industrial operations.

The enclosed form for the roadside structure case lists again these minimum parameters. Please fill in the information requested, one form for each section of highway identified.

In the above discussion, we have identified four general categories of highway noise control measures. Our intent is to use the form information supplied by your department for a preliminary screening of the most favorable sites to perform our measurements. On-the-spot inspection and more detailed analysis of these selected sites will be conducted by members of our staff.

We would like to take this opportunity to thank you again for your cooperation in this matter. If you find any questions as to the description we provided or the objectives of this study please feel free to call collect Mr. B. Andrew Kugler or Mr. Richard Horonjeff at (213) 347-8360.

Figure E-1 (continued).

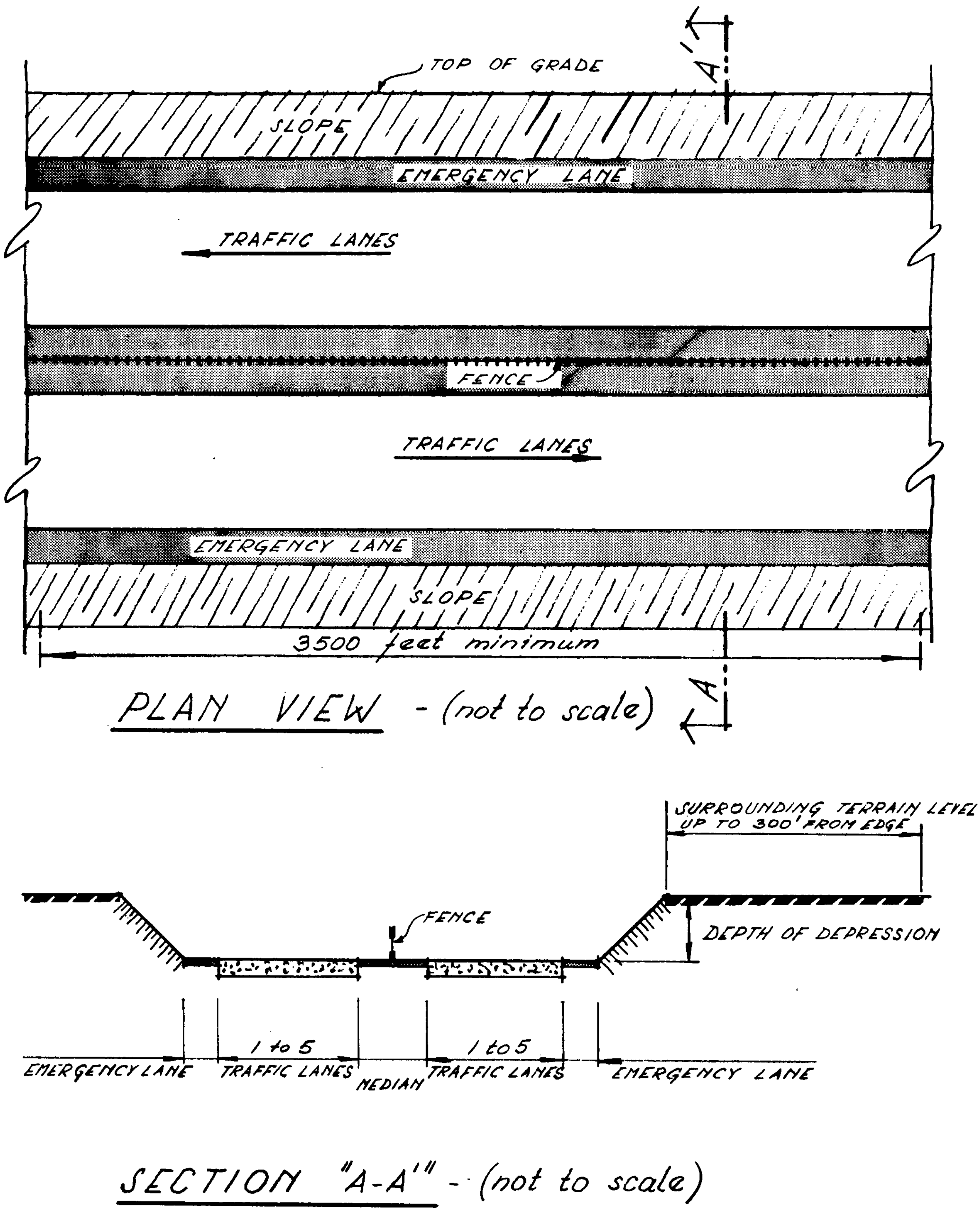


FIGURE 1 - DEPRESSED CONFIGURATION

Figure E–1 (continued).

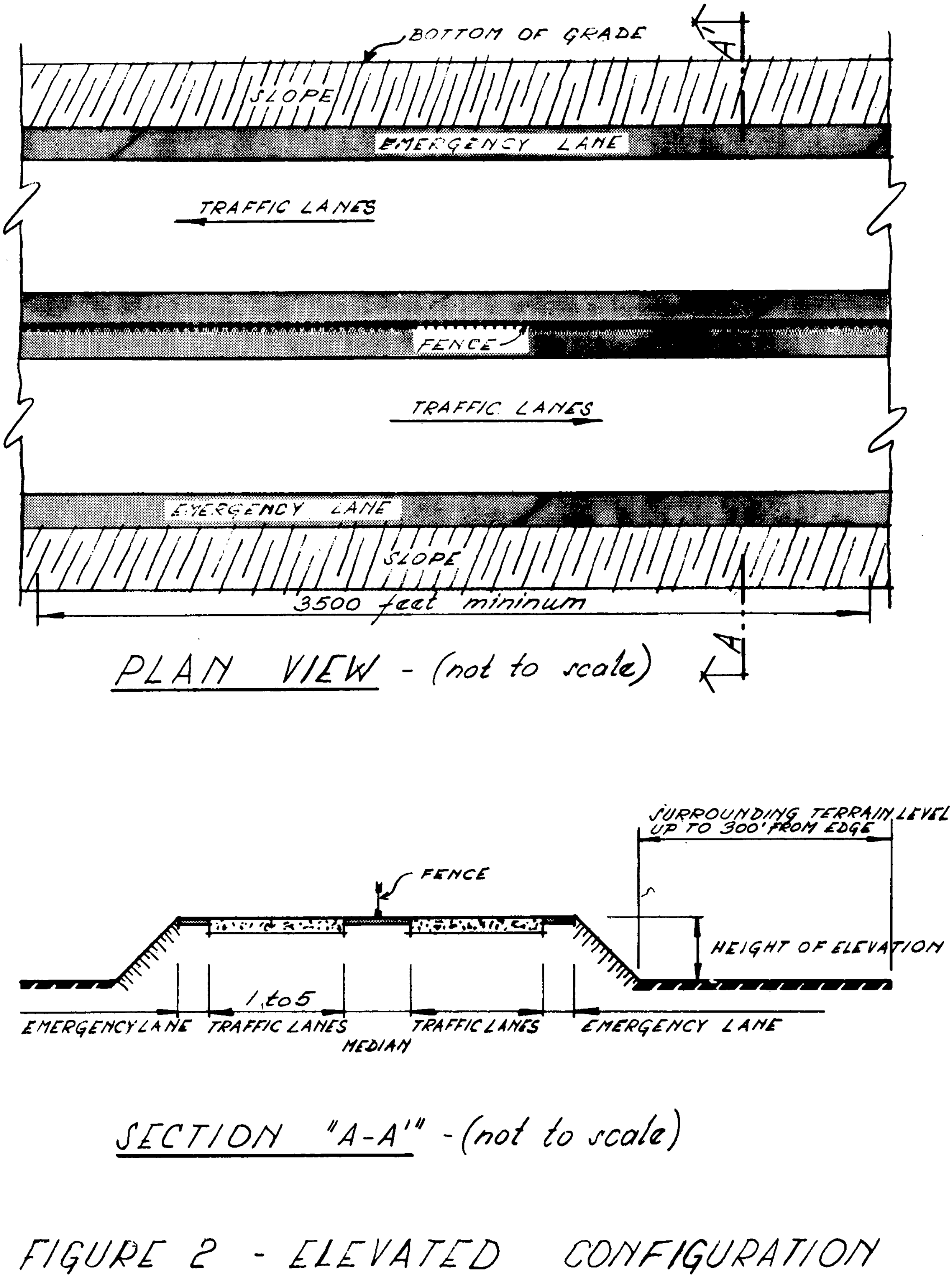


Figure E-1 (continued).

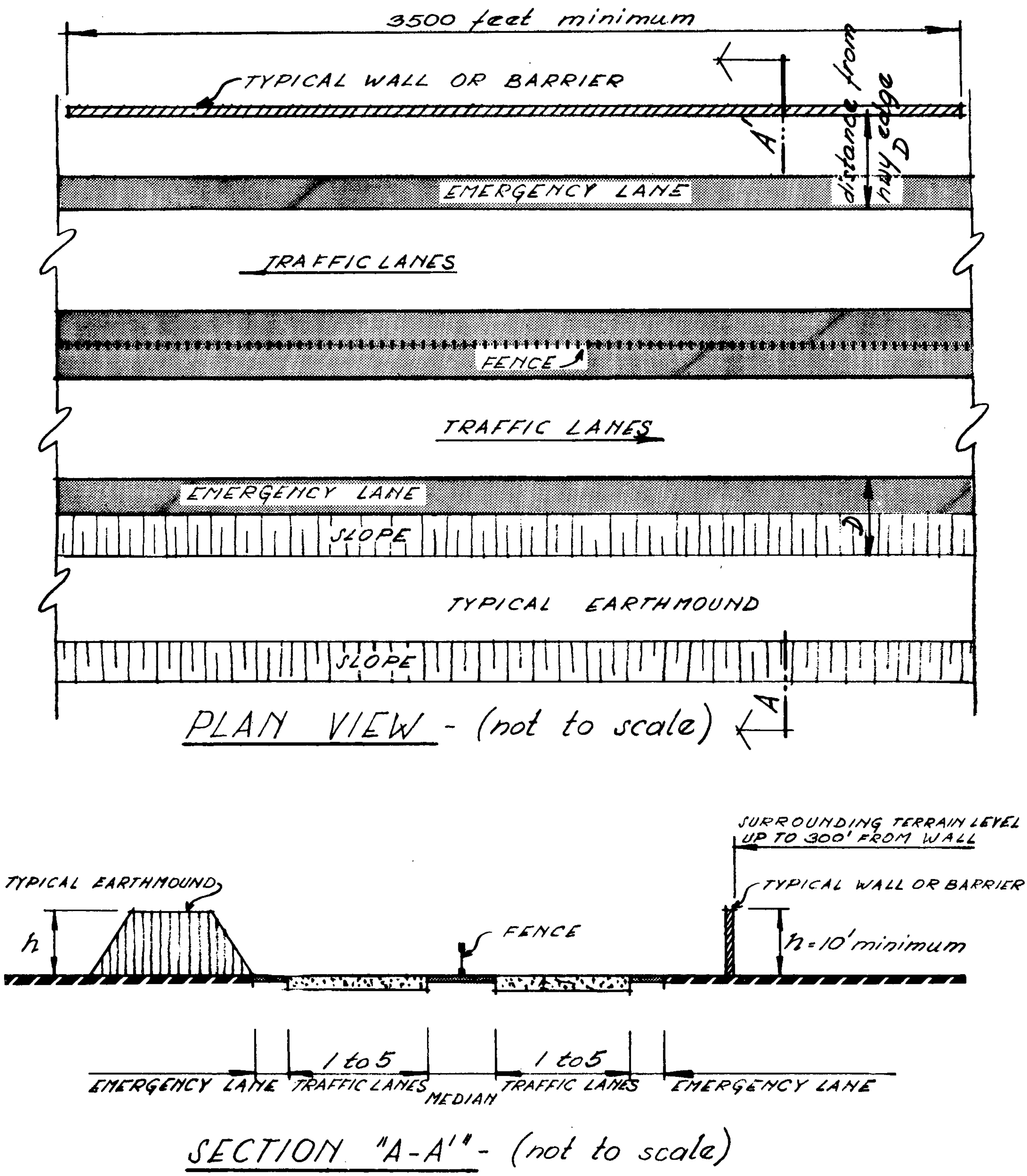
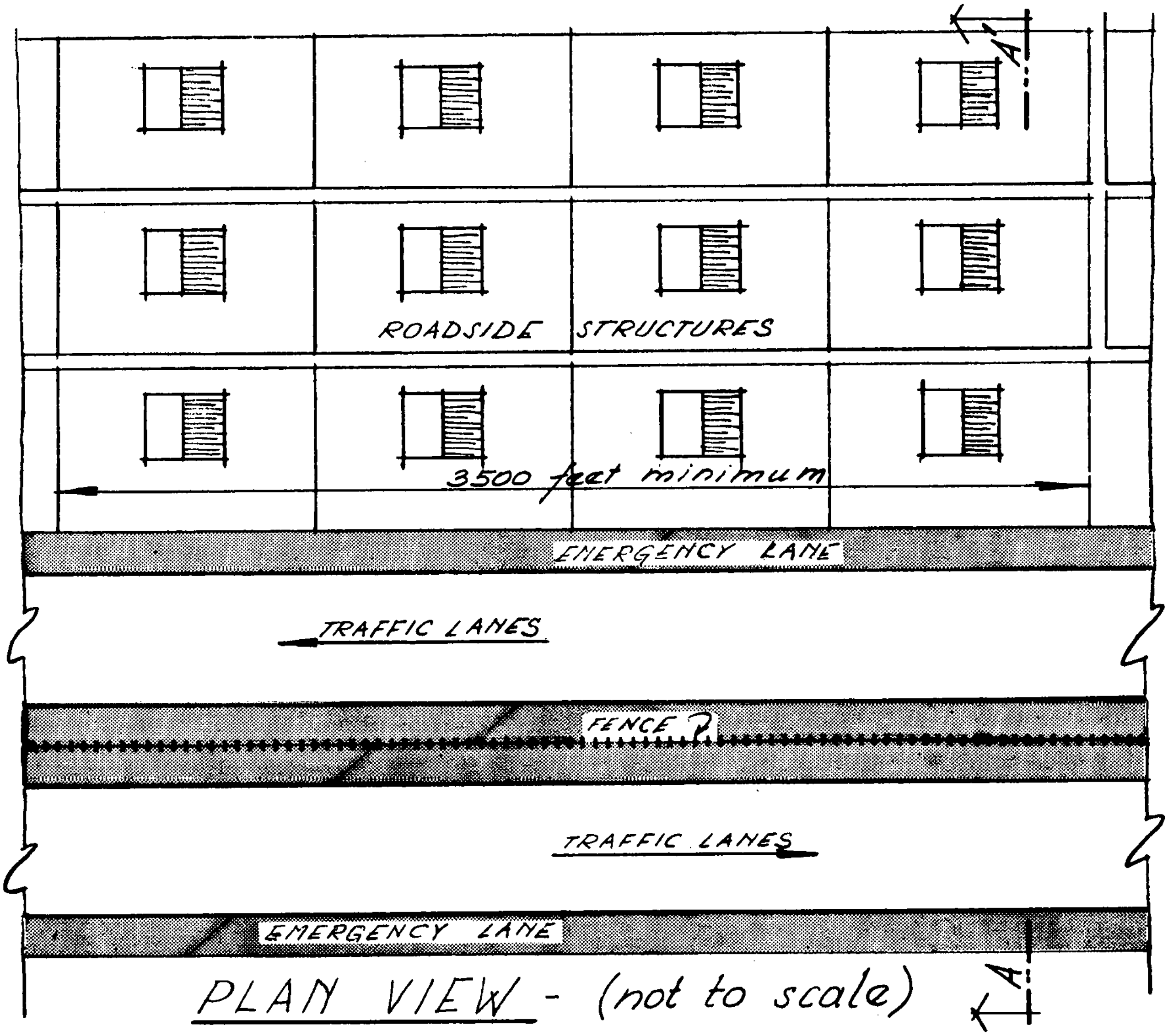


FIGURE 3 - ROADSIDE BARRIERS & EARTHMOUNDS

Figure E–1 (continued).



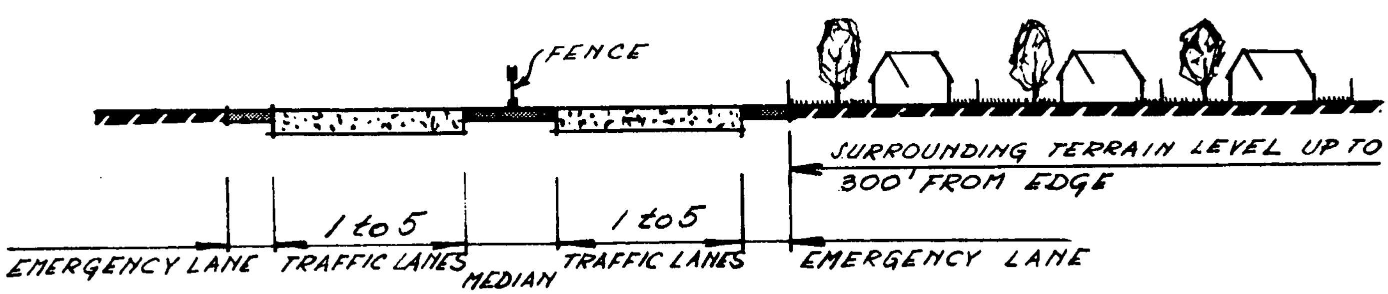


FIGURE 4 - ROADSIDE STRUCTURES

Figure E–1 (continued).

INQUIRY FORM NO. 1
DEPRESSED HIGHWAY CONFIGURATION

I. GENERAL INFORMATION

A. State: ____________________

B. Highway Route Designation: ____________________

C. Highway Section Location: ____________________

____

____

II. GEOMETRICAL HIGHWAY PARAMETERS

	Minimum Reqd.	Available
A. Length of Section	3500 feet	______
B. Depth of Section	10 feet ± 10%	______
C. No. of Traffic Lanes		______
D. Lane Width		______
E. Width of Section (Average)		______
F. Width of Median if any		______
G. Grade of Embankment		______

Note: the section whose parameters are listed above must be straight (± 15%) and level (maximum grade 1%) with constant surface roughness.

III. TRAFFIC CONDITIONS

A. Average Daily Traffic (ADT) over section length: ______

B. Average Design Speed: ____________________ mph.

C. Maximum Truck/Auto Ratio: ____________________ %

IV. SURROUNDING TERRAIN CHARACTERISTICS

Please describe in a few words the topography and utility of the terrain up to 300 feet from the edge of the highway: ________

____

____

Please return to: Bolt Beranek and Newman Inc.
21120 Vanowen Street
Canoga Park, California 91303
Attention: Mr. B. Andrew Kugler

INQUIRY FORM NO. 2
ELEVATED HIGHWAY CONFIGURATION

I. GENERAL INFORMATION

A. State: ____________________

B. Highway Route Designation: ____________________

C. Highway Section Location: ____________________

____

____

II. GEOMETRICAL HIGHWAY PARAMETERS

	Minimum Reqd.	Available
A. Length of Section	3500 feet	______
B. Height of Section	10 feet ± 10%	______
C. No. of Traffic Lanes		______
D. Lane Width		______
E. Width of Section (Average)		______
F. Width of Median if any		______
G. Grade of Fill		______

Note: the section whose parameters are listed above must be straight (15%) and level (maximum grade 1%) with constant surface roughness.

III. TRAFFIC CONDITIONS

A. Average Daily Traffic (ADT) over section length: ______

B. Average Design Speed: ____________________ mph.

C. Maximum Truck/Auto Ratio: ____________________ %

IV. SURROUNDING TERRAIN CHARACTERISTICS

Please describe in a few words te topography and utility of the terrain up to 300 feet from the edge of the highway: ________

____

____

Please return to: Bolt Beranek and Newman Inc.
21120 Vanowen Street
Canoga Park, California 91303
Attention: Mr. B. Andrew Kugler

INQUIRY FORM NO. 3
ROADSIDE BARRIERS OR EARTHMOUNDS

I. GENERAL INFORMATION

A. State: ____________________

B. Highway Route Designation: ____________________

C. Highway Section Location: ____________________

____

____

II. GEOMETRICAL HIGHWAY PARAMETERS

	Minimum Reqd.	Available
A. Length of Section	3500 feet	______
B. Height of Barrier or Earthmound	10 feet ± 10%	______
C. No. of Traffic Lanes		______
D. Lane Width		______
E. Width of Section (Average)		______
F. Width of Median if any		______
G. Distance from Barrier to Near Lane		______

Note: the section whose parameters are listed above must be straight (± 15%) and level (maximum grade 1%) with constant surface roughness.

III. TRAFFIC CONDITIONS

A. Average Daily Traffic (ADT) over section length: ______

B. Average Design Speed: ____________________ mph.

C. Maximum Truck/Auto Ratio: ____________________ %

IV. SURROUNDING TERRAIN CHARACTERISTICS

Please describe in a few words the topography and utility of the terrain up to 300 feet from the edge of the highway: ________

____

____

Please return to: Bolt Beranek and Newman Inc.
21120 Vanowen Street
Canoga Park, California 91303
Attention: Mr. B. Andrew Kugler

INQUIRY FORM NO. 4
ROADSIDE STRUCTURES

I. GENERAL INFORMATION

A. State: ____________________

B. Highway Route Designation: ____________________

C. Highway Section Location: ____________________

____

____

II. GEOMETRICAL HIGHWAY PARAMETERS

	Minimum Reqd.	Available
A. Length of Section	3500 feet	______
B. No. of Traffic Lanes		______
C. Lane Width		______
D. Width of Section (Average)		______
E. Width of Median if any		______

Note: the section whose parameters are listed above must be straight (± 15%) and level (maximum grade 1%) with constant surface roughness.

III. TRAFFIC CONDITIONS

A. Average Daily Traffic (ADT) over section length: ______

B. Average Design Speed: ____________________ mph.

C. Maximum Truck/Auto Ratio: ____________________ %

IV. SURROUNDING TERRAIN CHARACTERISTICS

Please describe in a few words the topography and utility of the terrain up to 300 feet from the edge of the highway: ________

____

____

Please return to: Bolt Beranek and Newman Inc.
21120 Vanowen Street
Canoga Park, California 91303
Attention: Mr. B. Andrew Kugler

Figure E-1 (continued).

APPENDIX F

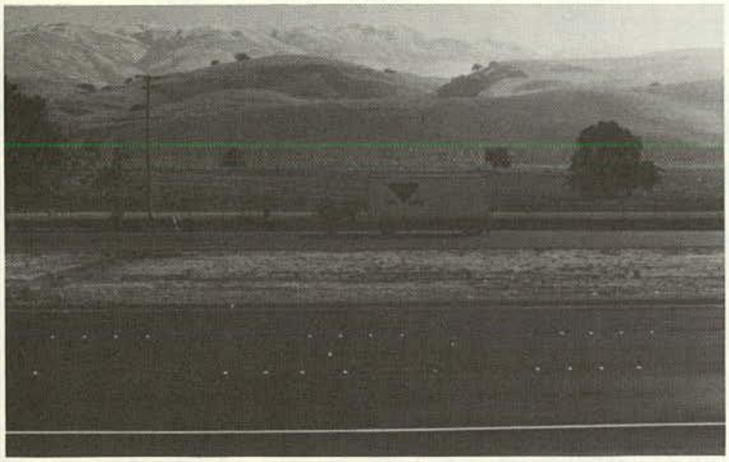
TEST SITE DESCRIPTIONS

SITE 1—ROADSIDE BARRIER

Test Site Description

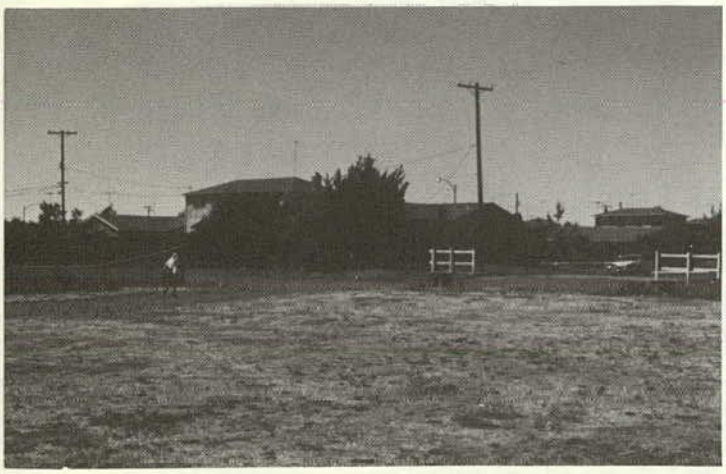
Site 1 is located along I-680 in Milpitas, Calif. The noise reduction measure consists of a combination earthmound-masonry block wall 11 ft high. The barrier, constructed as an experimental project sponsored by the FHWA, extends a total length of one mile and parallels the highway at a distance of approximately 50 ft from the near lane.

Figure F-1 shows four views of the barrier and surrounding terrain. The highway is a six-lane divided roadway with the surface falling in the normal roughness category. On the far side of the barrier is a residential area. As Figure F-1 shows, there was an open area without intervening structures where measurements were made. The ground at the site was packed dirt. Other than local street traffic, no major noise sources were present in the vicinity.



(a) Overview of test site from top of berm-wall barrier combination.

(b) Microphone station "A" (reference station) on top of barrier.



(c) Area behind barrier where measurements were taken.

(d) Overview of measurement station from behind wall.

Figure F–1. Scenes from Site 1.

Traffic Characteristics

One goal of the field measurement program was to evaluate each site under a variety of traffic conditions. The variables of greatest interest were total volume, truck mix ratio, and average speed. Another variable that could influence barrier performance is highly disparate flow in the two traffic directions.

Unfortunately, at the Milpitas site, measurements were restricted to somewhat low total volumes. This section of I-680 was new at the time and not yet heavily traveled. As a result, the total volume never exceeded 650 vehicles per hour. The truck mix ratio did vary substantially, between 0 and 16 percent. However, because of the very low total volume, the average speed did not vary substantially.

Measurement Locations

Figure F-2 shows a cross-section of the test site. The microphone locations are indicated by Stations A through E. Station A, used as the reference microphone, was located on top of the barrier to obtain a clear line-of-sight to the highway. This location thus represents a measure of the free-field noise levels from the highway at a distance of 43 ft from the near lane. The microphones at the other stations were located at various heights above the ground to provide a spatial description of the noise field. Microphone heights of 2, 4, 6, 8, 10, 12, 15, and 20 ft above a horizontal from the barrier were used. Note that because the terrain slopes downward from the edge of the barrier, all microphone heights were established relative to a horizontal identified as the "microphone height reference line" in Figure F-2. Thus, the 2-ft microphone height really corresponds to a location 13 ft below the top of the barrier.

The camera used to acquire the average speed data was also located on top of the barrier, with a flat, unobstructed view of the traffic lanes. In all, 37 locations were sampled at distances ranging from 20 to 200 ft behind the barrier.

The choice of measurement locations in this as well as all subsequent test sites was based on an incremental difference criterion. In other words, measurement locations were chosen at all points where a significant difference in noise levels was expected.

Data Acquisition

Data were acquired over a three-day period (8 to 10 Sept. 1971). A total of 23 measurement runs were performed, each a 10-min tape recording of the traffic noise at four different measurement locations. Care was taken to ensure that a free-flow condition was present at all times during the data acquisition period. A run was terminated and rerun if traffic conditions changed substantially during its progress.

As described in Appendix A, traffic volume and mix information were continuously acquired during the 10-min tape-recording periods. Speed information also was recorded by the camera system. At the end of each run, weather information was collected to describe atmospheric conditions throughout the run.

Because only four recording systems were used, noise data were acquired at only four locations at any one time, including the reference location. After each run, the microphone heights were changed at the three shielded locations. For example, after a measurement was performed with Stations B, C, and D (Fig. F-2) at a height of 2 ft above the ground, these microphones were changed to 4 ft, and so on. Note that this site also shows a Station E; this corresponds to the equipment used at Station D, relocated in late runs to provide an additional measurement station.

SITE 2—ELEVATED HIGHWAY CONFIGURATION

Test Site Description

Site 2 is located along a straight and level section of US 101 (Ventura Freeway) in Encino, Calif. The section of interest is bounded by Hayvenhurst Avenue on the west and Haskell Avenue on the east. The highway is elevated approximately 29 ft above the surrounding terrain. It is an eight-lane divided roadway (Fig. F-3).

The community to the south of the highway is comprised of single-story residential dwellings. To the north, where the measurements were made, the terrain is flat, level farmland without structures or substantial noise sources other than freeway traffic, except for occasional interference from nearby Van Nuys Airport.

The area in which the measurements were made is part

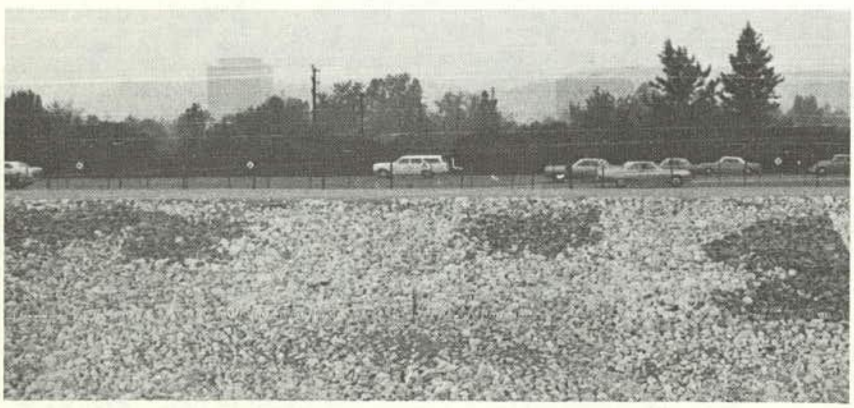


Figure F–3. Scene from Site 2.

of the Sepulveda Dam Flood Control Basin administered by the U.S. Army Corps of Engineers. The terrain is sublet as farmland, and, during the evaluation period, was recently plowed.

Traffic Characteristics

Traffic on this section of highway is extremely heavy, becoming choked regularly during morning and evening rush hours. Therefore, measurements were possible only during the very early hours and from approximately 10:00 AM to 3:00 PM, when free-flowing conditions existed. Volumes of as high as 14,500 vph were recorded during measurement periods.

The truck mix ratio was almost constant, ranging from about 1.8 to 4.5 percent, with an occasional 5.0 percent being recorded. The very heavy automobile volumes were the basic source of the low ratio.

Measurement Locations

Figure F-4 shows a cross-section of the test site. The microphone locations are indicated by Stations A through D. Station A, used as a reference location, was located on top of the shoulder of the fill. The other three stations were located at 125, 250, and 500 ft from the nearest lane. Five different microphone heights were used; 1, 5, 10, 15, and 20 ft above the surrounding terrain. The terrain slopes gently away from the roadway, necessitating determination of the exact height of the stations relative to the roadway before the measurements were acquired. The camera was located approximately 125 ft from the near lane. Because the roadway is elevated, it was necessary to use a lift and ladder arrangement similar to the one shown in Figure F-5. The camera was elevated approximately 13 ft above the roadway and about 40 ft above the ground level in this fashion, affording a full view of all traffic lanes.

Data Acquisition

Data were acquired over a three-day period (31 Aug. to 2 Sept. 1971). A total of 20 measurement runs were recorded, each run of 10-min duration. Traffic and speed data and weather information were collected coincident with noise measurements.

SITE 3—ELEVATED HIGHWAY CONFIGURATION

Test Site Description

Site 3 is located along a straight section of I-405 (San Diego Freeway) between Saticoy Street and Roscoe Boulevard in Van Nuys, Calif. The highway is elevated approximately 28 ft above the surrounding level terrain. It is an eight-lane divided roadway (Fig. F-5). Land use on both sides of the freeway is primarily for light-industrial purposes. The combination of a very large unused parking lot and an adjacent open field affords a good measurement site. The highway sideslope is landscaped with bushes and trees. Fortunately, little interruption of line-of-sight exists to interfere with acoustic measurements. The closest structure to the freeway is an industrial building located approximately 500 ft from the near lane. No other noise sources were found in the vicinity except for an occasional

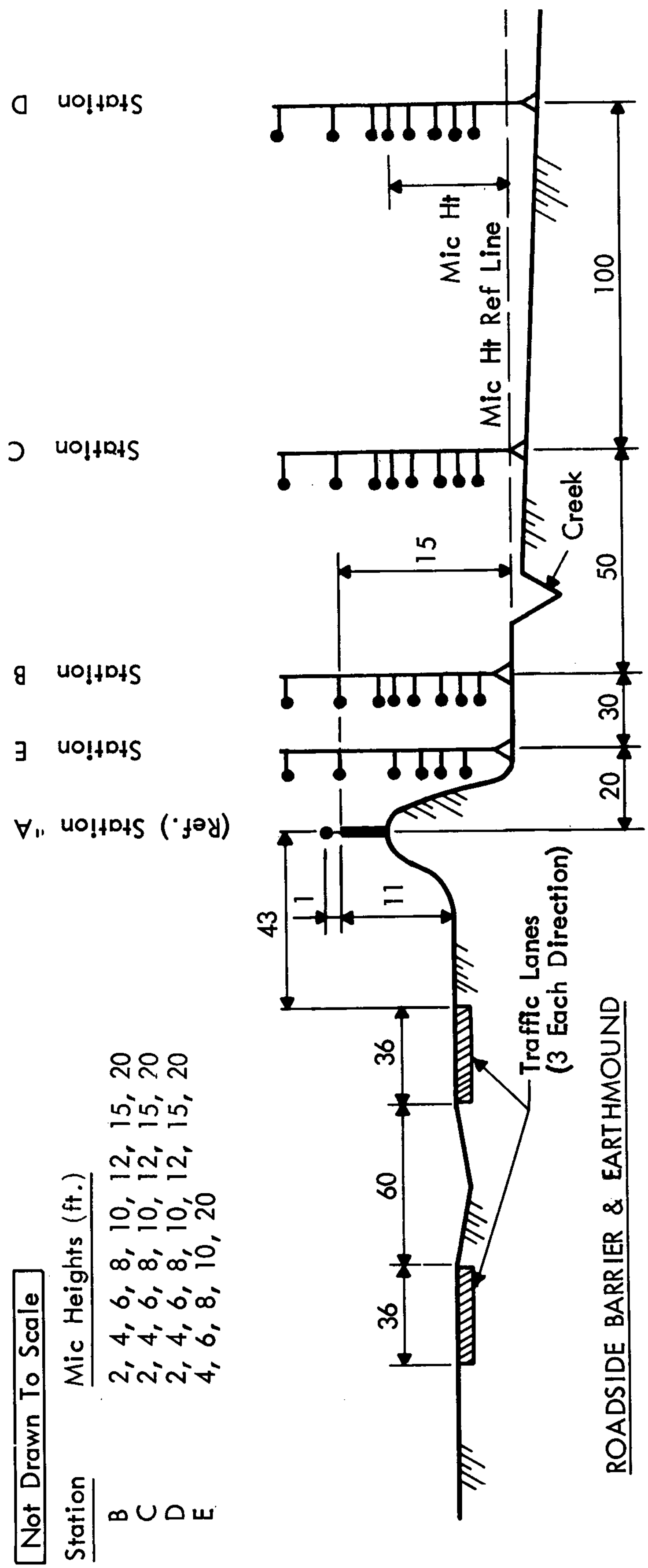


Figure F-2. Site cross-section and acoustic measurement stations, Site 1.

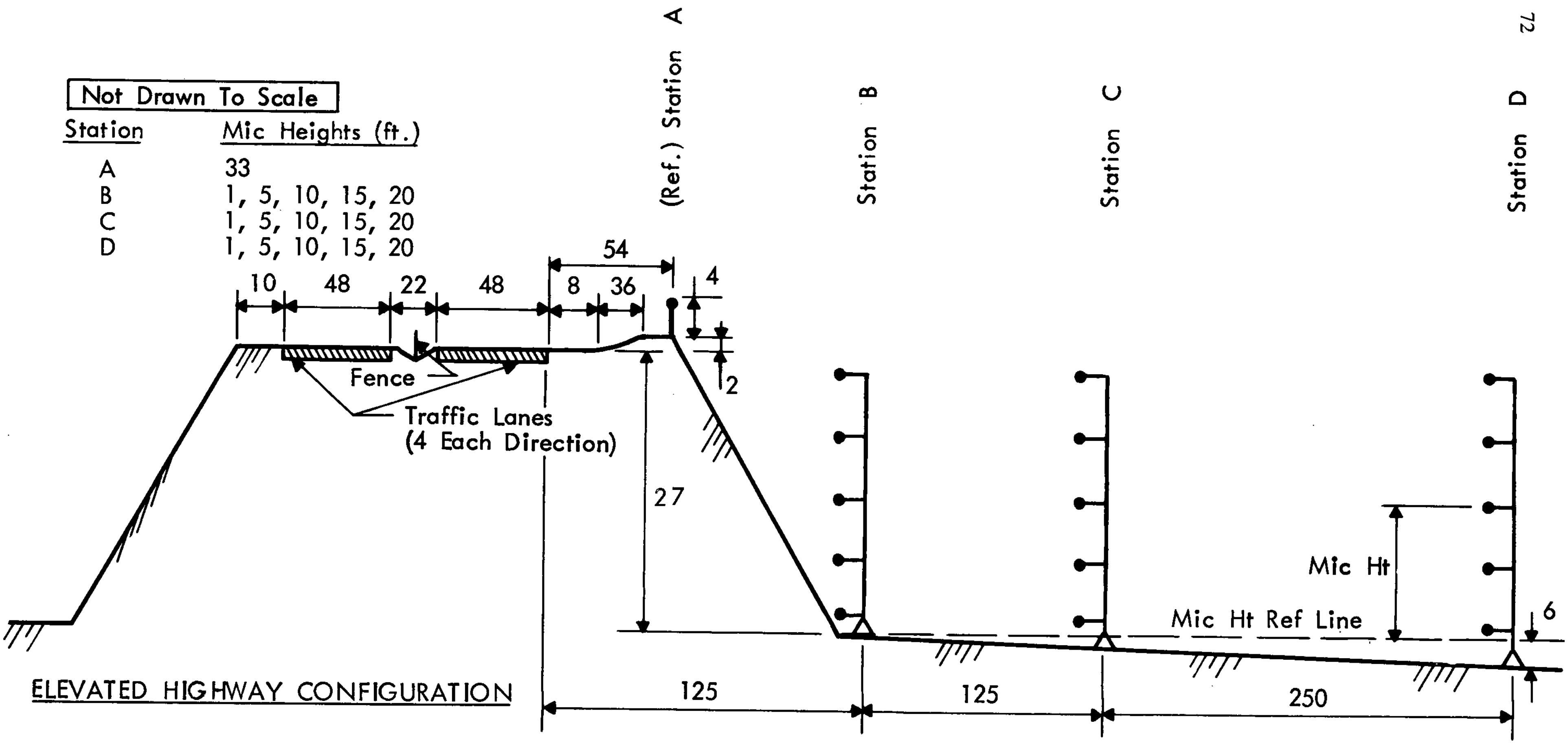


Figure F–4. Site cross-section and acoustic measurement stations, Site 2.

(a) Overview of test site showing reference targets on median.

(b) Parking lot area next to test site.

(c) Camera equipment and scissor lift arrangement.

(d) Location of "B", "C" and "D". Microphones at 25 feet.

Figure F–5. Scenes from Site 3.

aircraft overflight from nearby Van Nuys Airport. During the measurement sequence, care was taken to exclude this occasional source of noise from the data. The ground condition for this site was the hard paved surface of the parking lot.

Traffic Characteristics

During normal weekday operating conditions, traffic on this section of highway is extremely heavy, especially during morning and evening rush hours. Unfortunately, the parking lot that was the site of the measurements was available only over the weekend, so only moderate traffic flows were encountered. Traffic volume varied between a high of 8,200 vph and a low of 2,500 vph. The truck mix ratio remained low, with only one measurement run exceeding 4.0 percent, due to weekend conditions. In general, the ratio varied from 0.5 to 1.5 percent.

Measurement Locations

Figure F-6 shows a cross-section of the test site. The microphone locations (Stations A through D) were located at 83, 125, 250, and 500 ft, respectively, from the near

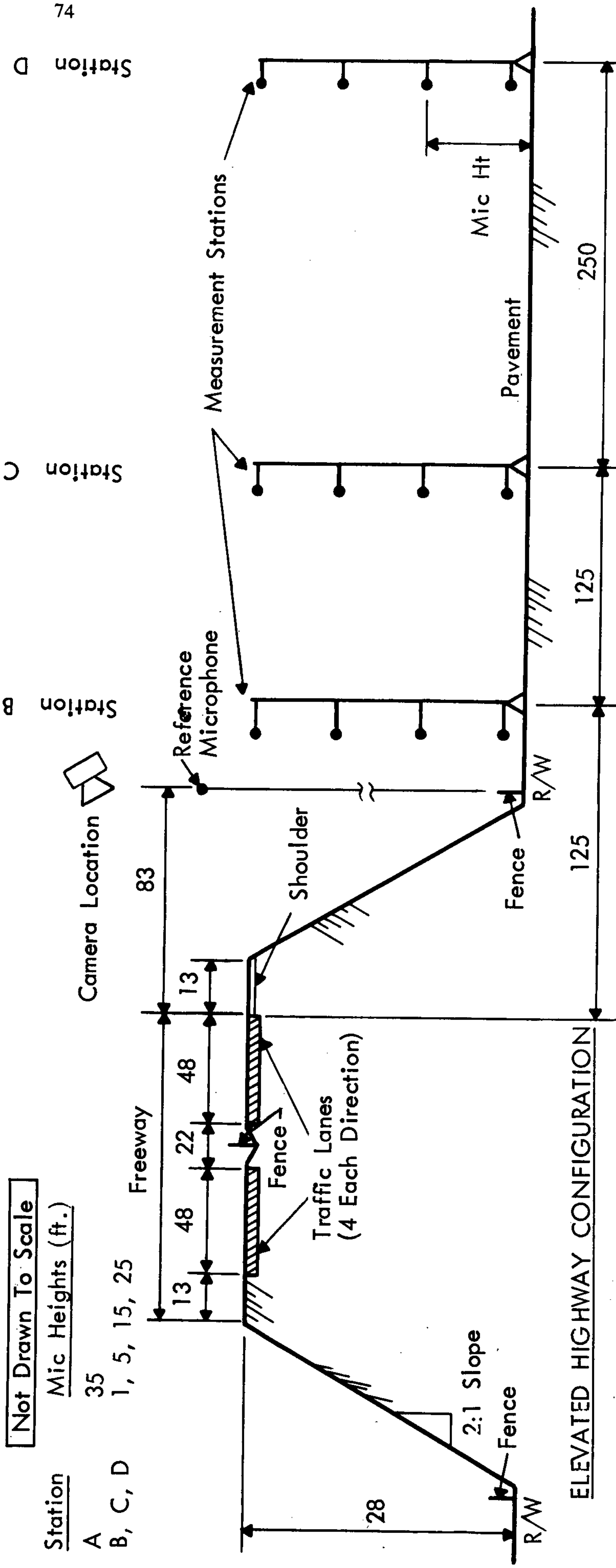


Figure F–6 Site cross-section and acoustic measurement stations, Site 3.

lane. Because the elevated configuration extends 28 ft above the surrounding terrain, it was necessary to elevate the camera to approximately 40 ft to obtain an unobstructed view of all lanes. This was accomplished by using the 25-ft scissor lift and a 15-ft ladder (Fig. F-5). The reference microphone, also located on the platform, was fixed at a 35-ft elevation.

Four different microphone heights over the surrounding terrain were used: 1, 5, 15, and 25 ft.

Data Acquisition

Data were acquired over a three-day period (14 to 16 Aug. 1971). A total of 18 measurement runs were recorded, each run of 10-min duration. Traffic and speed data and weather information were collected together with noise measurements.

SITE 4—DEPRESSED HIGHWAY CONFIGURATION

Test Site Description

Site 4, a 25-ft depressed section of highway, is located along I-494 in Bloomington, Minn. Because the original geometric configuration of this site had been changed substantially since the researchers' initial inspection, and the new geometry no longer satisfied the site selection criteria, an alternate site of the same configuration was selected and evaluated instead (Site 9 in Minneapolis, Minn.).

SITE 5—Roadside Structures

Test Site Description

Site 5 is located along I-35W in Richfield, Minn. It is bounded by 66th Street on the north and 76th Street on the south. A residential community on the west side of the highway extends along the roadway, which is at grade level for the entire length of the site. The homes are equally spaced and are of similar construction and shape (mainly one story). The roadway is a four-lane divided highway (Fig. F-7).

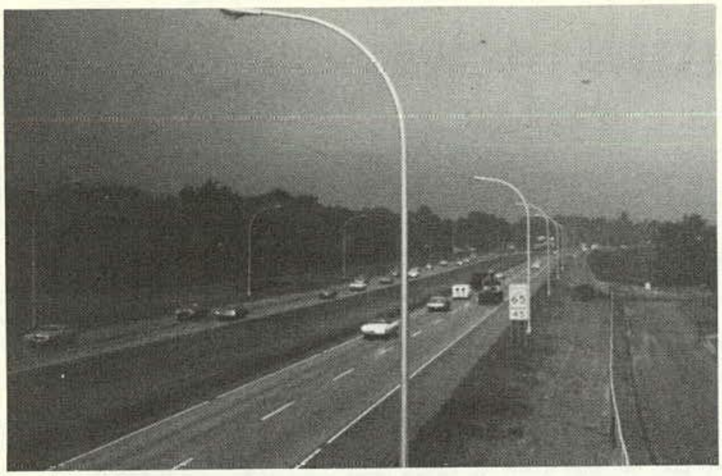
The community to the west of the highway is comprised of one- and two-story residential dwellings. To the east and directly across the test site is open terrain. No other major noise sources were present in the vicinity except occasional local traffic.

The pavement surface at this site was extremely rough as a result of the use of studded tires for a number of years. The contribution of tire noise to the over-all noise environment was therefore substantially more severe than at the California site.

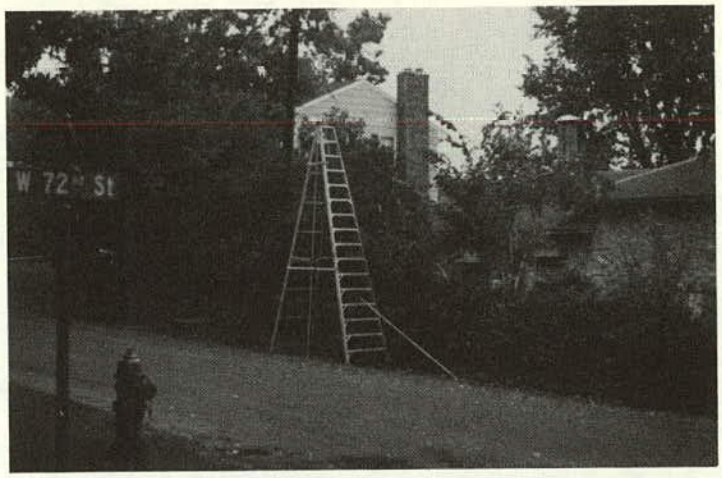
Traffic Characteristics

Traffic on this section of highway was moderately to extremely heavy, becoming occasionally choked during rush hours. However, during most of the day traffic conditions were acceptable for noise measurement purposes. Volumes as high as 4,400 vph per hour were recorded.

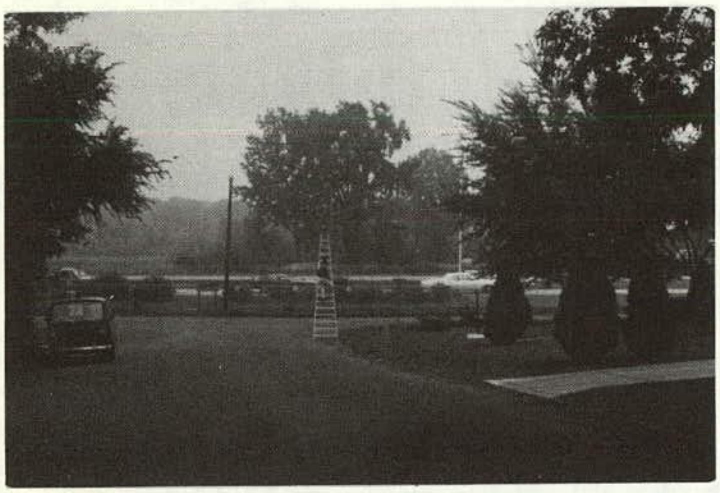
The truck mix ratio was high and did not vary substantially during data acquisition. The ratio varied from a low of 7.7 percent to a high of 15.6 percent. Truck noise was thus a significant contributor to over-all noise levels in all cases.



(a) Overview of highway test site from pedestrian overpass. Measurement locations to the left of roadway.



(b) Location of station "B" behind first row of houses



(c) Camera equipment position and reference marker on fence line

Figure F–7. Scenes from Site 5.

Measurement Locations

Figure F-8 shows a cross-section of the test site. The microphone locations are indicated by Stations A through D. Station A was located in front of the structures and was used as the reference station. The other three stations were located at 198, 330, and 539 ft from the near lane. Station C was moved to a distance of 365 ft (Station C′) from the near lane for certain selected runs. In addition, measurements were taken with the microphones positioned both between two adjacent houses and directly behind the structures.

Data were collected at five different microphone heights: 1, 5, 10, 15, and 25 ft above the surrounding terrain. The terrain in this area slopes gradually upward away from the roadway. Because the object was to determine the noise reduction provided by each row of houses, the microphone heights are referred to the rear of each house instead of to the height of the highway. The camera equipment was located near the reference microphone at a height of 15 ft to provide an unobstructed view of all traffic lanes.

Data Acquisition

Data were acquired over a two-day period (27 to 28 Sept. 1971). A total of 14 measurement runs were recorded, each of 10-min duration. The measurements on 28 September were only partially completed, and a scheduled third day of measurements was canceled because of inclement weather. Traffic and speed data and weather information were collected together with noise measurements.

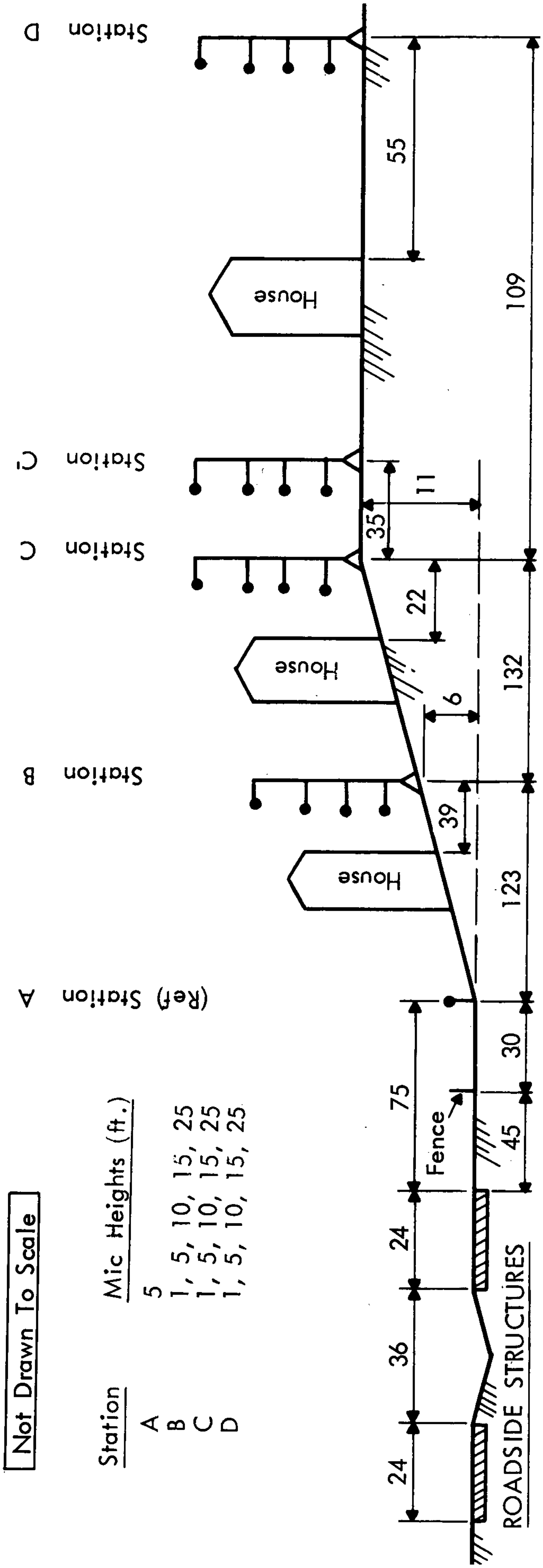


Figure F-8. Site cross-section and acoustic measurement stations, Site 5.

SITE 6—ROADSIDE STRUCTURES

Test Site Description

Site 6 is located along I-94 in Ypsilanti, Mich. It is bounded on the west by Grove Street and on the east by Harris Road. A residential community on the south side of the highway presented the desired roadway-structures configuration. This location represented an ideal condition for the field evaluation of this category of noise reduction measure because the entire community is a single development composed of identical rows of structures along the roadway.

The roadway is a four-lane divided highway (Fig. F-9). Its surface was very rough as a result of extensive use of studded tires during winter. Thus, tire noise contributed largely to the over-all highway noise levels in this area.

The houses are one-family residential dwellings, all approximately 40 ft by 24 ft, and 15 ft high. The highway is separated by a chain-link fence from the individual backyards and is level with the surrounding terrain.

No major noise sources other than the highway were present in the area, except for occasional local traffic and some interference from Detroit Metropolitan Airport.

Traffic Characteristics

Traffic on this section of highway was moderate to light, with a heavy concentration of truck traffic at all times. Michigan allows up to 16 axles on trucks; therefore, noise levels associated with these trucks were considerably higher than expected from a "typical" truck. It follows that truck traffic was instrumental in determining the associated highway noise levels.

Total traffic volume varied from 3,100 to 1,900 vph. The truck mix ratio was relatively high, varying between 9 and 24 percent.

Measurement Locations

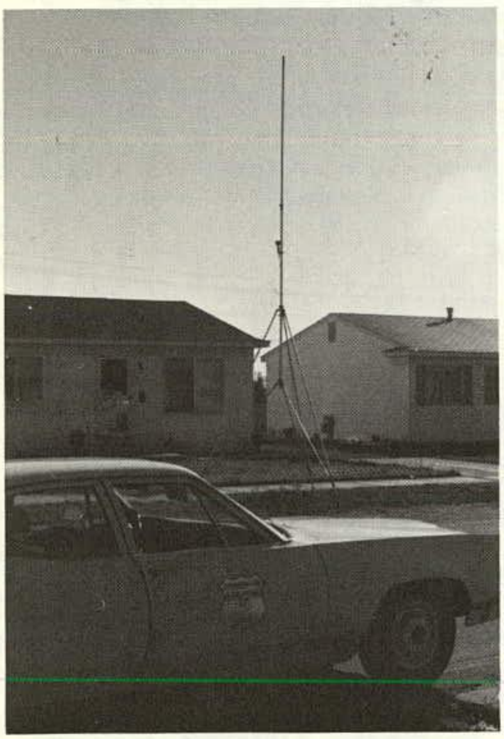
Figure F-10 shows a cross-section of the test site. The microphone locations are indicated by Stations A through D. Station A, used as the reference station, was located 50 ft from the near lane, with an unobstructed view of the entire highway segment. The other measurement stations were located behind each row of houses. Thus, Station B was located behind the first row, Station C behind the second row, etc. Three different distances were sampled behind each row of houses to provide a better description of the sound field. Distances of 15, 35, and 70 ft behind each house were used. Furthermore, the microphone locations were moved from behind the houses to between the houses to evaluate this difference in the sound field. Four microphone heights were used: 1, 5, 15, and 25 ft above the ground, referred to the nearest house. This procedure resulted in 16 spatial measurements behind each row of houses.

Data Acquisition

Data were acquired over a three-day period (22 to 24 Sept. 1971). A total of 18 measurement runs were recorded, each of 10-min duration. The number of runs acquired was limited because of high winds and unfavorable weather

(a) View of test site section showing station "A" and reference marker on median.

(b) First and second row of roadside structures being evaluated.



(c) Location of station "B" at the test site.

(d) Camera equipment position at the test site

Figure F–9. Scenes from Site 6.

conditions throughout the site evaluation period. Traffic and speed information were acquired concurrently with noise data.

SITE 9—DEPRESSED HIGHWAY CONFIGURATION

Test Site Description

Site 9 is located on I-35W in Minneapolis, Minn. The section of interest is a 23-ft depressed configuration extending for approximately one-half mile (Fig. F-11). It is bounded by 38th Street on the north and 46th Street on the south. The only disadvantage of this location was the proximity of houses to the cut. The closest house was approximately 200 ft from the near lane and 110 ft from the cut.

With the cooperation of the City of Minneapolis, the frontage road (2nd Avenue South) next to the cut was closed for the duration of the measurements. This was

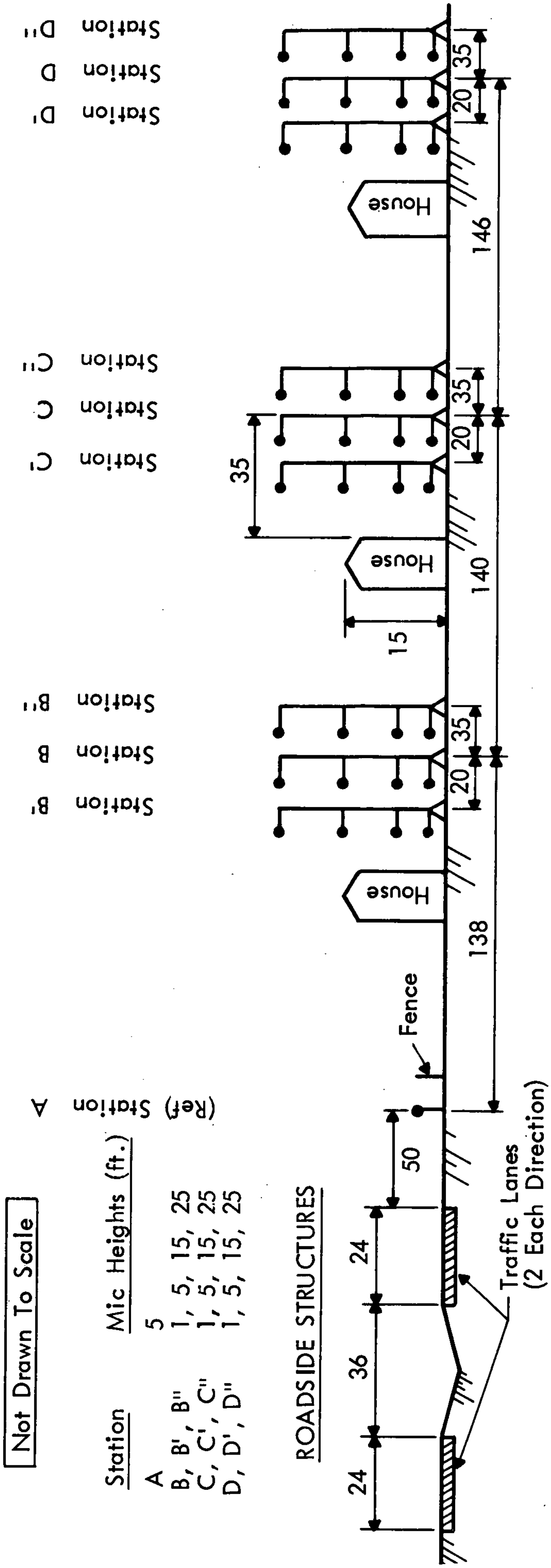


Figure F–10. Site cross-section and acoustic measurement stations, Site 6.

necessary to eliminate the contribution of traffic on this street from the highway noise data. No other major noise sources were present in the vicinity except for occasional interference from aircraft overflights. The pavement characteristics fell in the rough category because of the use of studded tires.

Traffic Characteristics

Traffic on this section of highway was extremely heavy, especially during rush hours when one of the flow directions normally becomes choked. During the measurement period, total traffic varied from a low of 5,400 vph to a high of 8,700 vph, with the exception of one measurement run when 15,200 vph were recorded just before a choked condition was attained. The truck mix ratio was generally high, varying between 6.5 and 13.2 percent.

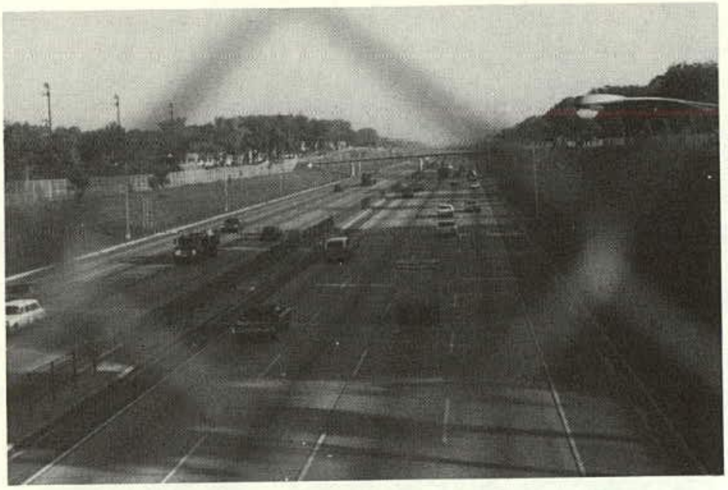
Measurement Locations

Figure F-12 shows a cross-section of the test site. The microphone locations are indicated by Stations A through G. Station A, used as the reference location, was situated half-way down the bank. Stations B, C, and D were located at 94, 134, and 184 ft from the nearest lane. These positions correspond to distances of 10, 50, and 100 ft from the edge of cut. Station B was moved along 34th Street to location E (200 ft from the edge of cut) later in the measurement program to provide a more complete spatial description of the test site. Stations F and G, located at the same distance from the highway as E, represent two locations behind the first row of houses.

The camera equipment was located at the edge of the cut (Fig. F-11).

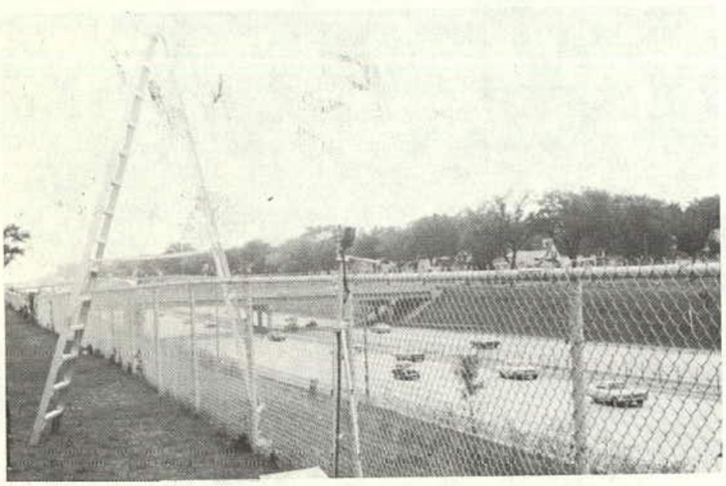
Data Acquisition

Data were acquired over a three-day period (29 Sept. to 1 Oct. 1971). A total of 17 measurement runs were performed, each of 10-min duration. Traffic volume, mix, and speed data, as well as weather information, were collected concurrently with noise data.



(a) Overview of the highway test site from pedestrian bridge. Measurement stations are to the right commencing at ladder location

(b) Views of service road parallel to to highway. Service road was closed during measurement period.



(c) Camera equipment position next to highway section.

(d) Location of stations "D" and "E" at the test site

Figure F–11. Scenes from Site 9.

DEPRESSED HIGHWAY CONFIGURATION

Not Drawn To Scale

Station	Mic Heights (ft.)
A	-6
B	1, 2.5, 5, 7.5, 10, 15
C	1, 2.5, 5, 7.5, 10, 15, 20, 25
D	1, 2.5, 5, 7.5, 10, 15, 20, 25
E	1, 2.5, 5, 7.5, 10, 15, 20, 25
F	5
G	5

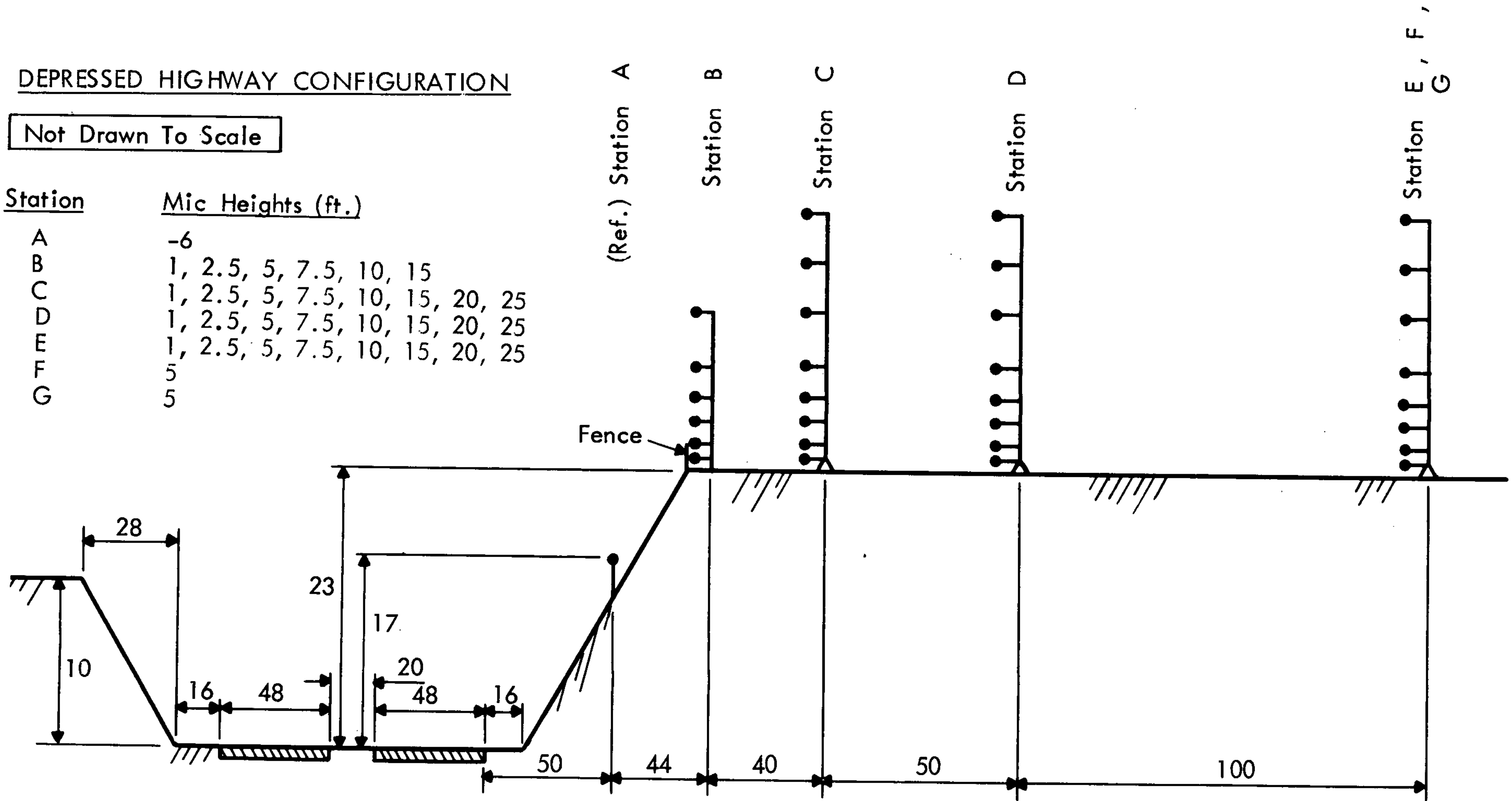


Figure F–12. Site cross-section and acoustic measurement stations, Site 9.

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* Highway Research Board Special Report 80.

Rep. No.	*Title*
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