Report No. FHWA-RD-76-54

NOISE BARRIER ATTENUATION: FIELD EXPERIENCE

DEPARTMENT OF TRANSPORTATION
UNITED STATES OF AMERICA

February 1976
Final Report

Prepared for
FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Washington, D. C. 20590

Technical Report Documentation Page

1. Report No. FHWA-RD-76-54	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Noise Barrier Attenuation: Field Experience		5. Report Date February 1976 6. Performing Organization Code
7. Author(s) Myles A. Simpson		8. Performing Organization Report No. 3200
9. Performing Organization Name and Address Bolt, Beranek and Newman Inc. 1701 North Fort Myer Drive Arlington, Virginia 22209		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DOT-FH-11-8287
12. Sponsoring Agency Name and Address Department of Transportation Federal Highway Administration Office of Research Washington, D.C. 20590		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

FHWA contract manager T. M. Barry (HRS-42)

16. Abstract

A noise measurement program was undertaken at ten field sites at which a variety of noise barriers have been constructed, in order to compare measured values of barrier attenuation with analytical projections. Barrier types included in the study were concrete, masonry and wooden walls, and berms of various shapes.

The measured attenuation values were compared with attenuations predicted by the Kurze-Anderson Infinite Line Source Model of barrier atttenuation. The analysis indicated that the model predicts barrier attenuation equally well at all locations behind the barrier. On the average, the model underpredicts the measured attenuation by 1 to 2 dB. The model works best for thin vertical walls, while the largest underpredictions generally occur for berms.

17. Key Words Highway noise, noise attenuation, noise barriers, noise measurements	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 95	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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TABLE OF CONTENTS

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1. INTRODUCTION

The impact of the noise produced by roadway traffic on adjacent communities may conceptually be reduced by a variety of measures: the relocation of highway corridors, proper land-use planning, restricting vehicle use, controlling vehicle speed, and using noise abatement barriers, to name a few. In most cases, however, and particularly for already-existing highways, practical constraints limit the choices to the use of noise abatement barriers. It is not surprising, then, that construction of such barriers has increased dramatically in recent years.

Noise abatement barriers are generally either vertical, solid walls; earth berms; or a combination of the two. By placing such structures between the roadway (noise source) and the community, traffic noise levels are attenuated by the diffraction of sound waves over the top of the barrier. Several prediction methods have been developed for estimating the amount of attenuation provided by a barrier as a function of the source-barrier-observer geometry. The highway engineer may use one of these methods to determine the physical dimensions and the location of the barrier required to achieve a needed noise reduction.

These various estimation procedures are based either on theoretical consideration of diffraction effects, or on measurements made using scale models employing point sources. Verification of the predictive procedures by actual measurements of barrier attenuation of highway noise in the field has been limited. Further, in most instances the attenuation provided by barriers constructed along highways has not been measured, once the barrier has been built (Appendix G reviews the limited state measurement data available).

The increasing need for highway noise barriers, coupled with the desirability of obtaining field evaluation of the performance of these barriers in terms of highway noise reduction, prompted Bolt Beranek and Newman Inc. to undertake a measurement program involving ten structures that have been built along highways in the United States specifically to abate roadway noise.

The field study included concrete, stucco, and wooden walls, earth berms, and wall and earth berm combinations. The ten sites were located within five states: California, Connecticut, Michigan, Minnesota and Wisconsin.

At each site, "shielded" highway noise levels were measured at typically 18 locations of varying heights and distances behind the barrier. Measurements were also obtained at a "free-field" location, i.e., at a location with unobstructed view of the highway. These measurements were used to determine the levels that would have been measured if the barrier were not constructed. The difference between the free-field and shielded levels represents the measured barrier attenuation.

Our primary goal was to compare this measured attenuation with the attenuation that would be predicted, based on theoretical considerations. We chose the infinite line source model of Kurze and Anderson (Ref. 1) as the basis for our prediction of barrier attenuation. This attenuation model has been incorporated within the current TRB Design Guide (Ref. 2).

For barriers of "infinite" length, the infinite line source model provides the attenuation as a function of the path length difference over the top of the barrier. On this basis, all barriers which meet minimal surface weight requirements should perform in a similar manner, regardless of minor differences in material or shape. If the measured and predicted attenuations do not agree within acceptable limits, the secondary goals of the program were to determine whether one particular type of noise barrier works better than another, and if there are available theories of barrier attenuation which would better predict the measured results.

The next two sections of this volume discuss the measurement procedures and measurement sites, respectively. Details of the data processing are described in Section 4, while analysis of the measured and predicted attenuations is described in Section 5. A summary of the results of this measurement program is provided in the last section. The several appendices provide details of the measurements, including presentation of the highway, traffic and noise level data, and comparisons of measured and predicted attenuation values. Also provided is an analysis of the frequency characteristics of the measured attenuation values. Finally, the last appendix compares predicted attenuations with attenuations measured by various state highway departments.

2. MEASUREMENT APPROACH

In order to measure the noise reduction of a barrier, one would ideally measure free-field levels before the barrier is installed, and shielded levels after the barrier is installed. Since the current study is concerned with already-existing barriers, this approach is clearly not feasible. The approach adopted in this study was to measure shielded levels behind the barrier, and estimate free-field levels by projections from a single reference measurement location in free-field.

The advantage of this approach is that when free-field and shielded measurements are made simultaneously, the measured noise reduction (obtained by subtracting the shielded levels from the projected free-field levels) would be based upon identical source and transmission conditions, so that errors resulting from variations in the traffic flow and meteorological conditions from one set of measurements to the next would be eliminated. The disadvantage to this approach is that knowledge of the propagation loss factor for the terrain is required. This factor may range from 3 to 4.5 dBA per doubling of distance; by restricting the shielded measurement locations to distances from the roadway that are within three times the distance of the free-field location, potential errors in the selection of the propagation loss factor can be minimized.

Another difficulty in using a free-field measurement as a reference arises from selection of an appropriate measurement location. For this study two approaches were taken: wherever possible, the free-field reference measurements were obtained at a reference station located along the roadway beyond the barrier, and set back a distance comparable to the location of the closest shielded measurements. Since this was not always possible, due to changes in traffic flow along the roadway, terrain changes, etc., the alternate approach was to use a reference station on the highway side of the barrier. Such a measurement, of course, is not truly "free-field", since the barrier itself behind the measurement location may influence the level being measured. In order to minimize these effects, a cardioid microphone was used for these measurements. This type of microphone has the characteristic that it is omnidirectional over the frequency range of interest for highway noise for a range of angles of nearly ± 90 degrees relative to the microphone axis, but is extremely insensitive to noise signals from behind the microphone. To illustrate this, Figure 1 shows a typical directionality plot for a representative cardioid microphone for sound signals of 250, 500 and 1,000 Hz (left side of figure), and 2,000, 4,000 and 8,000 Hz (right side of figure). The effect of this microphone, then, is to receive the acoustic energy in the forwared plane of the microphone, but to suppress the signal coming from behind it; the net result should be measurements which closely approximate free-field measurements.

The shielded measurements, i.e., measurements obtained behind the barrier, consisted of three measurement stations in a plane perpendicular to the barrier and roadway. During a particular measurement run, simultaneous measurements were obtained at the reference station, and at each of the three shielded measurement stations. At each shielded station, measurements were obtained for typically six different heights above the ground. Assuming that the noise reduction of the barrier is a function of the path length difference over the top of the barrier (see Section 4 for further discussion), the locations of the three shielded measurement stations, and the

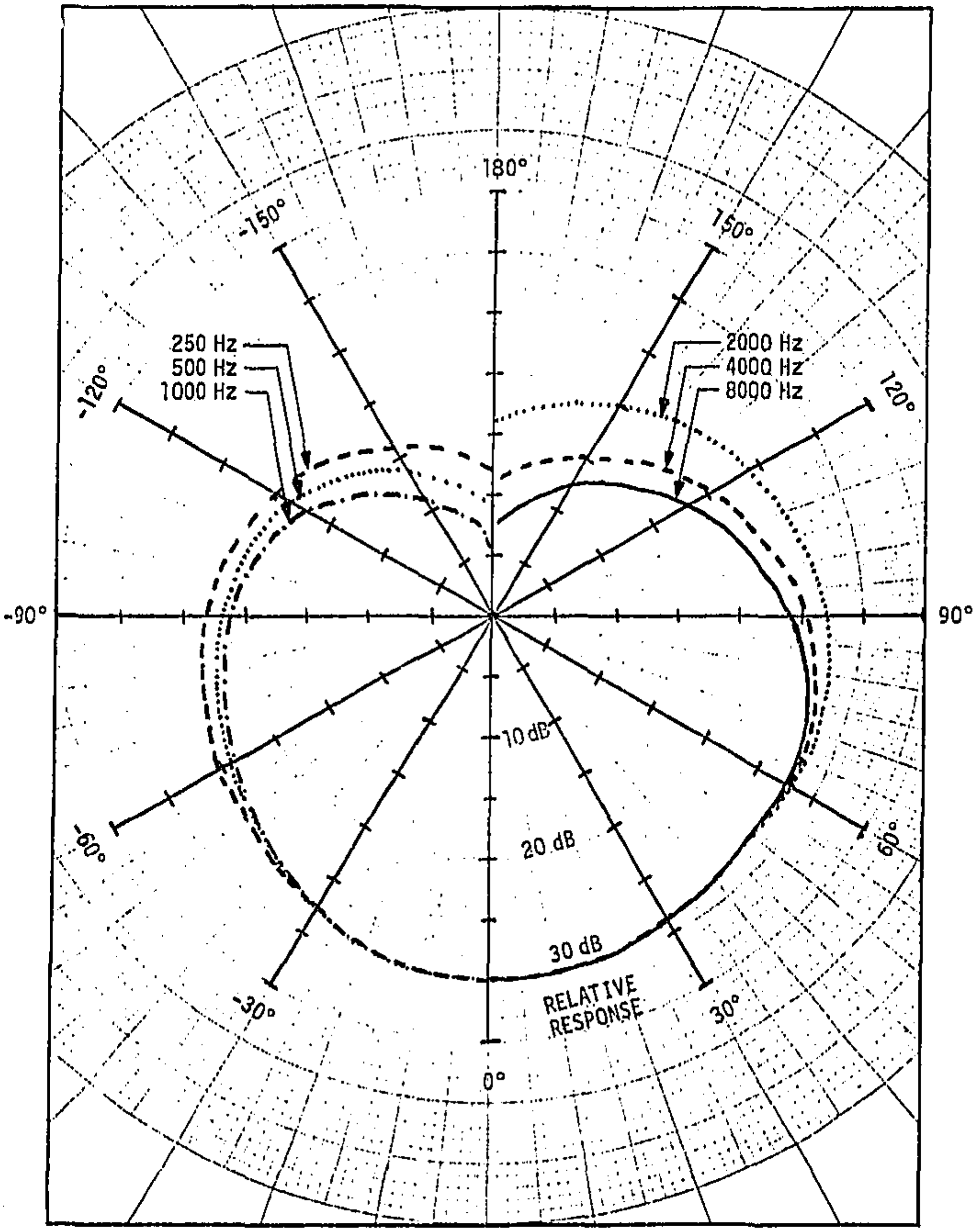


FIGURE 1 REPRESENTATIVE DIRECTIONALITY CHARACTERISTICS OF A CARDIOID MICROPHONE.

six heights at each measurement station were chosen so that at each station there would be a range of expected noise reductions, and the full range of expected noise reductions would be uniformly represented among all measurement points. This approach permits a definitive evaluation of the barrier noise reduction potential, and further permits comparisons of measured reductions with predicted reductions to be made as a function of distance from the roadway as well as height above ground.

Certain restrictions were placed upon selection of the measurement heights and distances. As mentioned before, the distance to the roadway from the farthest measurement station was kept to within three times the distance of the reference location to the roadway. Secondly, the length of the barrier placed constraints on the measurement distances. In order to approximate an "infinite" barrier, the distance from the farthest measurement station to the barrier was kept to within one-third the length of the barrier on either side of the plane of the measurement stations. (As will be discussed in Section 5, it was still necessary to take into account the sound energy diffracting around the edges of the barrier, despite this distance restriction.) Finally, concern over possible ground effects placed constraints upon measurement height. Previous studies of the variation of noise level with height above ground are contradictory. Reference 3, for example, suggests that the propagation loss falls dramatically as the measurement height increases above five feet. Reference 4, on the other hand, found no significant change for measurement heights from 5 to 15 feet. In this study, measurements were generally restricted to 15 feet above the ground.

The noise levels were monitored continuously for ten minutes during each run, using noise monitoring systems developed by BBN. These systems sample the noise environment eight times per second, and construct a statistical distribution of the noise levels occuring over this period. At the end of each data sample, the distribution of levels is recorded in digital format on a magnetic tape cassette for later processing in the laboratory. From the statistical distribution, various percentile levels such as the L_{10} and L_{50} may be determined, as well as the equivalent level, L_{eq}. (Appendix A describes in detail the data acquisition and reduction techniques.) The measured noise levels (L_{10}, L_{50} and L_{eq}) determined in this matter should have a 95% confidence interval of less than ± 0.5 dB, for the range of traffic volumes and measurement distances experienced in this study.

During each measurement run, the number of vehicles traveling in each direction was counted, as well as the number of heavy trucks in each traffic lane. The times of travel for several vehicles between two points of known distance were also tabulated, for later use in determining average speed of travel during the measurement run.

3. MEASUREMENT SITES

Based upon a review of noise abatement structures existing along highways in this country, 10 sites were selected for field evaluation under this measurement program. Several criteria were applied for the site selection process. Barrier requirements included a minimum length of 700 feet, and minimum height of 10 feet above roadway surface. The barrier was to be parallel to the roadway, with uniform height along its length.

The roadway itself was to be straight and of constant cross section and traffic flow characteristics along the length of the section shielded by the barrier. The roadway was to be level, with a maximum gradient of 2%.

The measurement stations were to be at least 350 feet from each end of the barrier; at each station (up to a distance of 100 feet behind the barrier), there was to be unobstructed view of the barrier. The site was to be free of interfering ambient noise sources such as local traffic, aircraft overflights, and industrial equipment.

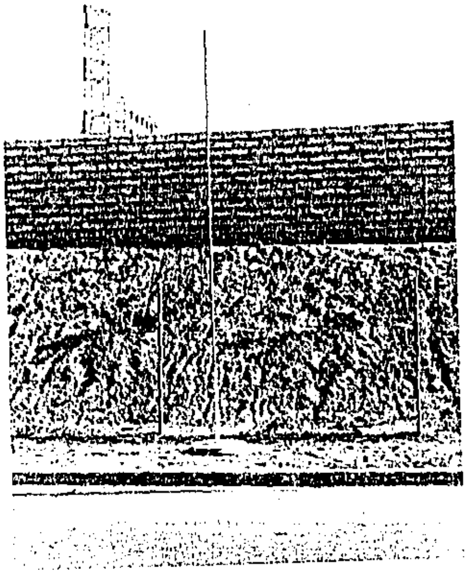
The final requirement was that a location be available for free-field measurements, either beyond the extent of the barrier at a location exposed to similar traffic flow, or in front of the barrier at a location with reasonable access.

Table I lists the 10 sites at which measurements were obtained. Included among the sites are concrete, wooden and stucco walls, concrete walls on earth berms, and earth berms alone. Pictures of each site are shown in Figure 2. Appendix B provides cross sections of each measurement site,

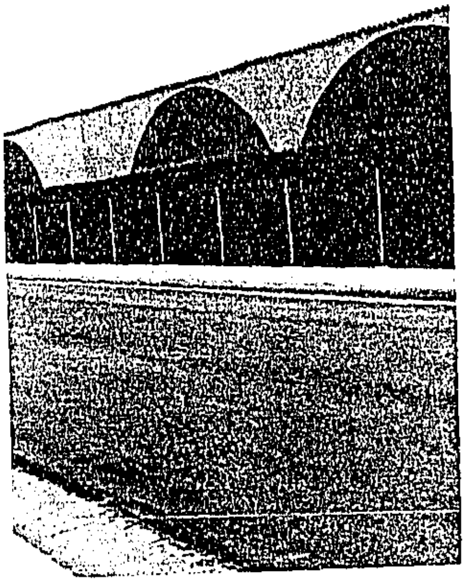
Table I Description of Barrier Sites

Site	Highway	Location	Barrier Description	Height Above Road, Ft.	Length, Ft.	Average Traffic Volume, VPH*	Average Truck Mix, %*
01	SR-7	Long Beach, Cal.	Concrete Masonry Wall on Earth Berm	12	2124	7418	9.3
02	I-605	Long Beach, Cal.	Concrete Masonry Wall on Earth Berm	15	1100	8882	1.7
03	I-10	San Gabriel, Cal.	Concrete Masonry Wall	13	1900	11397	3.4
04	I-75	Allen Park, Mich.	Wooden Wall	13.5	2700	4503	7.3
05	I-94	Kalamazoo Mich.	Earth Berm	10	1850	1341	16.6
06	I-94	Milwaukee, Wisc.	Earth Berm	6-9	800	1335	22.8
07	I-94	Minneapolis, Minn.	Precast Concrete Wall	10-23	4000	6038	4.5
08	I-210	Arcadia, Cal.	Stucco Wall	10	2750	2821	2.9
09	I-80	Sacramento, Cal.	Concrete Masonry Wall on Earth Berm	15	2272	2445	5.1
10	I-84	West Hartford, Conn.	Earth Berm	20	1800	3777	7.0

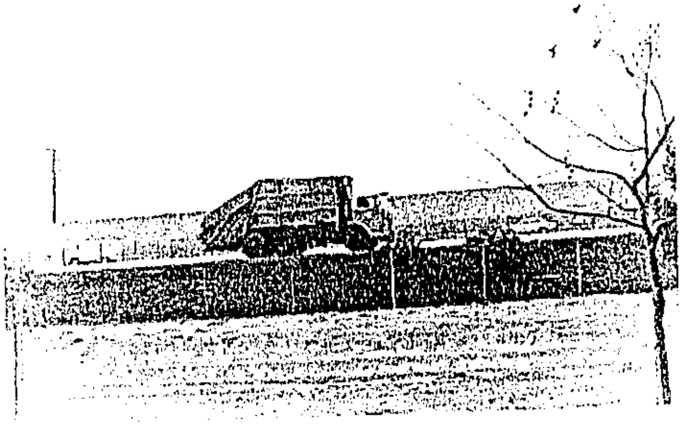
*During field measurements.



SITE 01



SITE 03



SITE 02

Figure 2

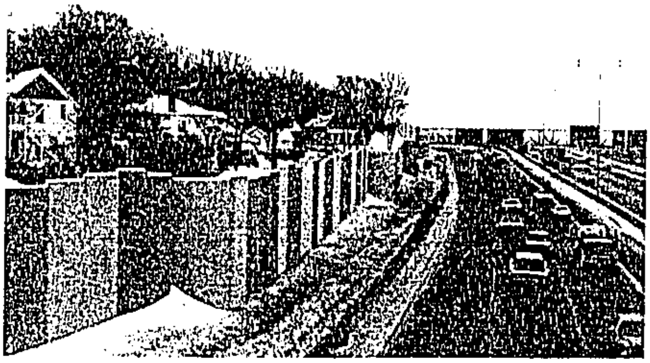
Photographs of Measurement Sites

SITE 04

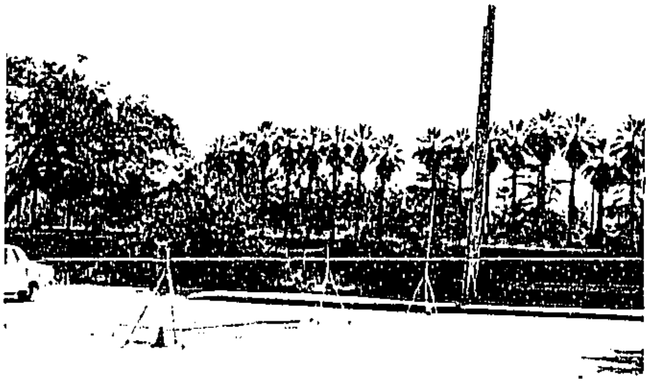
SITE 05

Figure 2
(Continued)

SITE 06

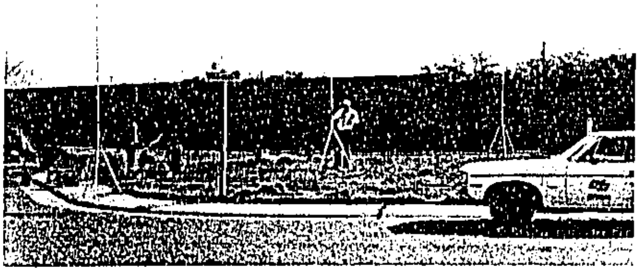


SITE 07



SITE 08

Figure 2
(Continued)



SITE 09

SITE 10
(Photo Courtesy of Connecticut
Dept. of Transportation)

Figure 2

(Continued)

illustrating the relationship between the roadway and barrier, and the location of the noise measurement stations. Tabulated in Appendix C are the traffic flow characteristics during the measurement sessions at each site.

Both Sites 01 and 02 are concrete masonry walls on earth berms. The concrete blocks at Site 01 have a slump surface to improve visual effects; the concrete blocks at Site 02 were selected to match those used in adjoining residential walls. The barrier wall at Site 02 was constructed to provide shielding for an elementary school.

The concrete block wall at Site 03 has an architectural facing on the community side of colored Spanish plaster applied over metal lath to form a Spanish archway design. Mission tile has been applied along the top of the wall; the net result is a very attractive effect (see Figure 2). The barrier at Site 04 is a wooden wall, constructed of 2-inch by 8-inch tongue and grove wooden planks.

Both Sites 05 and 06 are landscaped earth berms, whose construction costs were minimized by the availability of construction material locally. Site 05, constructed to provide shielding for an adjacent schoolyard, was built from surplus earth work in the area. Similarly, waste earthen material from safety improvement project sites in the area was used in the construction of the barrier at Site 06.

The concrete barrier at Site 07 was constructed using 4 to 7 inch thick precast concrete panels. To enhance the physical appearance of the barrier the heights were stepped, and the raked finish of the concrete slabs was oriented randomly toward the highway or toward the community. The barrier is also stepped horizontally to follow the gently curving edge of the roadway.

The barrier wall at Site 08 was constructed by attaching metal lath to an existing chain link fence and covering with stucco in successive layers. The stucco provides a Spanish style texture and color on the community side for purposes of appearance.

At Site 09 there is another concrete block wall on an earth berm. For a visual effect the wall is constructed with alternating patterns of 5-score block and random 3-score block, with a 2-inch veneer cap atop the wall.

The earth berm at Site 10 was constructed with a 1.5:1 slope, with flat top 5 feet wide, and 5 foot wide shelves on each side to allow for planting. It is constructed of earth borrow material, and covered with 4-inch wood chips.

4. DATA PROCESSING PROCEDURES

For each behind-the-barrier measurement point, the measured noise level was processed in conjunction with the measured reference level to yield a value of measured barrier attenuation. This measured attenuation was then compared with a corresponding value of predicted attenuation, based upon the barrier geometry and traffic characteristics. The determination of measured and predicted attenuations is detailed in the following, and the methodology for comparing measured versus predicted values is also described.

It should be noted that the attenuation values were based upon an analysis in which the roadway was considered to be a single infinite line source. Additional analyses were performed in which the roadway was composed of two infinite line sources, one for each direction of travel. In all cases, both the measured and predicted values of barrier attenuation based upon the two line source analysis were within 0.5 dB of the attenuation values based upon the single line analysis. This result is not surprising, since the traffic flow at each of the 10 sites was generally evenly split between the two sets of lanes.

4.1 Determination of Measured Attenuation

Appendix D provides tabulations of the measured L_{10}, L_{50} and L_{eq} values at the reference station and at each shielded measurement station, for each of the 10 sites.

Based upon the roadway configuration, equivalent lane distances were determined for each of the shielded measurement stations and the reference station, using equation (1).

$$d_E = \sqrt{d_N \times d_F} \qquad (1)$$

where d_E = Equivalent lane distance

d_N = Distance to near edge of near lane

d_F = Distance to far edge of far lane

In order to estimate the noise levels that would have been measured at each of the behind-the-barrier measurement points if the barrier were not constructed, the noise levels measured at the free-field station were projected back to the measurement stations, using either a 3 or 4.5 dB per doubling of distance propagation loss factor, as shown in equation (2).

$$L_i = L_o - a \log \frac{d_i}{d_o} \qquad (2)$$

where L_i = Noise level at station i

L_o = Noise level at reference station

d_i = Equivalent lane distance to station i

d_o = Equivalent lane distance to reference station

$$a = \begin{cases} 10 \text{ for propagation over clear, hard ground} \\ \quad \text{(corresponds to 3.0 dB/doubling of distance)} \\ \\ 15 \text{ for propagation over softer ground} \\ \quad \text{(corresponds to 4.5 dB/doubling of distance)} \end{cases}$$

For all measurement sites except site 02, the propagation loss factor was assumed to be 4.5 dB per doubling of distance, based upon field observation of terrain conditions. At site 02, with measurements obtained over a hard surface (a paved schoolyard), a propagation loss factor of 3 dB per doubling of distance was selected as being appropriate.

At each measurement point, then, the value of measured attenuation was obtained by subtracting the noise level measured at that location from the appropriate projected free-field level. This procedure was performed for each of three measures of the noise level, L_{10}, L_{50} and L_{eq}.

4.2 Determination of Predicted Attenuation

As discussed in Volume I, the Kurze-Anderson model for barrier noise reduction should provide reasonable predictions for the attenuation of traffic noise levels by roadside barriers. This model assumes that the traffic noise is an incoherent line source, and that noise reaches a shielded receiver only by diffraction over the barrier. The attenuation provided by the barrier depends upon the Fresnel number, N, which is defined in Figure 3 as a function of the wavelength of the sound source and the path length difference δ over the barrier versus through the barrier. For highway applications, the usual procedure is to assume an effective frequency of 550 Hz, corresponding to a wavelength of 2 feet. Under these conditions, the barrier attenuation can be read directly from Figure 3 with $N = \delta$.

On a typical highway with both cars and trucks, the usual procedure is to assume that the automobile noise sources are located at ground level, while the noise sources for trucks are located at a nominal height of 8 feet above grade. The path length difference for car and truck sources will thus be different, resulting in different expected values of attenuation for cars and trucks.

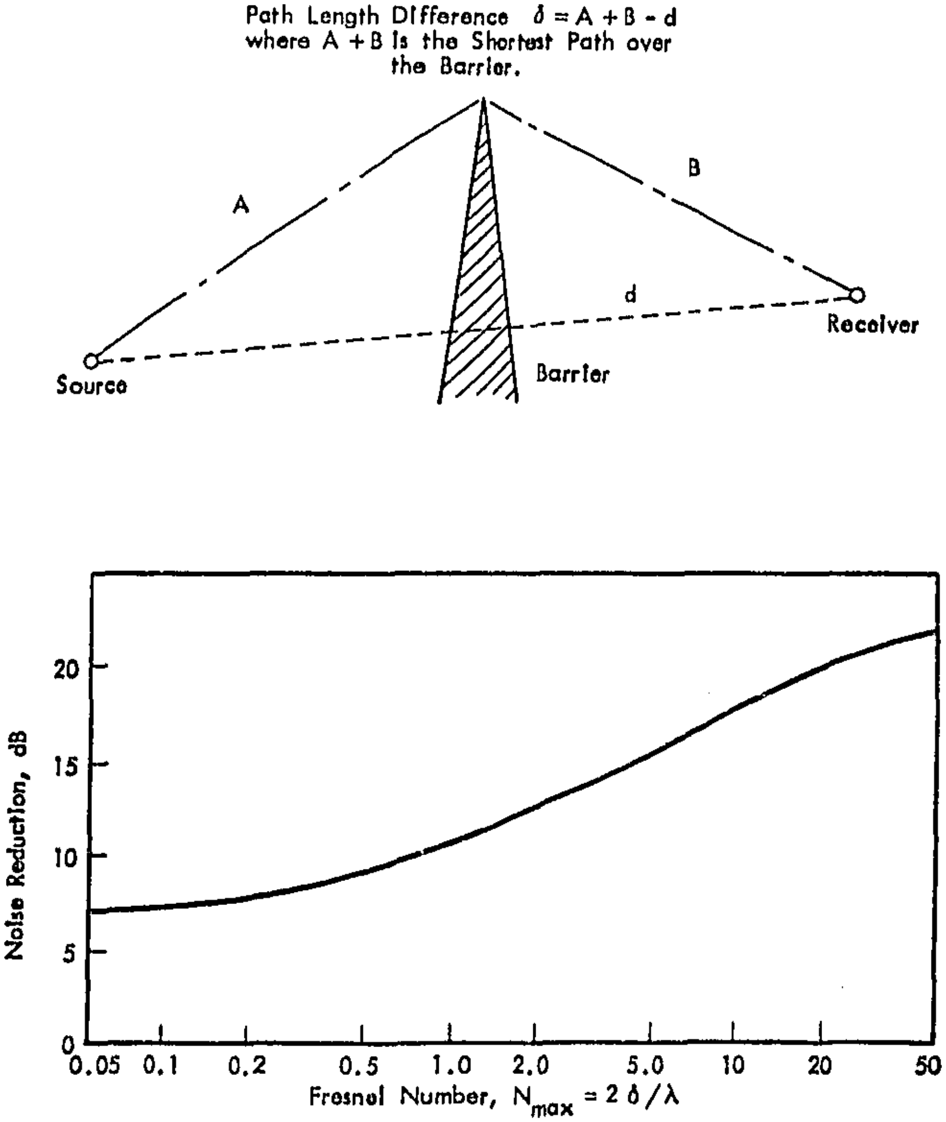


FIGURE 3 NOISE REDUCTIONS FOR INFINITY LONG BARRIER RUNNING PARALLEL TO AN INCOHERENT LINE SOURCE

Determination of the expected attenuation of the total traffic flow on the roadway therefore requires knowledge of the relative composition of cars and trucks.

Reference 4 provides an analytical model for estimating traffic noise levels. From this reference, the basic equations for the equivalent levels of car and truck populations are given in equations (3) and (4), for a 4.5 dB per doubling of distance propagation loss factor. (For a 3 dB loss factor, add 5 log (d/50) to each equation.)

$$L_{eq}\ (\text{cars}) = 10 \log VS^2 - 15 \log d + 28 \qquad (3)$$

$$L_{eq}\ (\text{trucks}) = 10 \log \frac{V}{S} - 15 \log d + 96 \qquad (4)$$

where V = Hourly volume of cars or trucks

S = Average speed of cars or trucks

These equations were applied to the car and truck flows measured on each roadway to yield the relative equivalent level contributions of cars and trucks for any particular measurement run.

For a particular site, the noise source was assumed to be an infinitely long line source, located at a distance from the barrier equal to the equivalent lane distance between the barrier and the roadway. For each measurement point behind the barrier, the expected attenuation for both cars and trucks was determined by computing the path length difference between the measurement point and the assumed infinite line source, and then determining the attenuation from Figure 3. The car and truck attenuations were then applied to the equivalent level contributions of cars and trucks as determined from equations (3) and (4). The barrier attenuation of the entire roadway was determined by subtracting the summed attenuated car and truck contributions from the summed car and truck contributions without attenuation applied.

4.3 Measured Versus Predicted Attenuation

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 points. The discrepancy at a particular measurement point is simply the difference between the measured noise reduction at that point and the corresponding value of predicted noise reduction. The average discrepancy, computed over all measurement points at a particular site, describes the overall bias in the predicted noise reductions relative to the measured noise reductions. The standard deviation of this average describes the scatter in the predictions relative to the measurements. Ideally, if there were perfect agreement between measured and predicted results, both of these terms would be zero. In practice, there will always be some random error due to measurement system variabilities, if not prediction inaccuracies. For this reason it is necessary to test the computed average discrepancy to determine if it represents a statistically significant difference from zero. For each site, individual discrepancies among measurement points were determined, and the average discrepancy was computed; a conventional null hypothesis test using the Student t variable (Reference 5) was performed, to test the difference of the average discrepancy from zero.

Even if the average discrepancy between the 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 the measured and predicted results. One method of evaluating this possibility is to fit a least-squares' regression line to the measured versus predicted noise reduction data, and then compare this line to the results expected for an ideal relationship. For the ideal case, the slope of the regression line would be unity, with an intercept of zero. Again it is necessary to test the slope and intercept of the computed regression line to determine any statistically significant difference between the computed slope and intercept from unity and zero respectively. If either the slope and/or the intercept do not pass these tests, the discrepancies between measured and predicted results would be considered statistically significant. Note that a significant difference from zero in the intercept, along with a slope which is equivalent to one, would suggest the predictions include a constant bias error at all locations. On the other hand, a significant difference from unity in the slope would indicate the prediction procedure does not properly account for changes in location.

A final procedure to assess the agreement between measured and predicted noise reductions at each site is to evaluate the average discrepancies at various distances from the roadway (computed by averaging over all heights at each distance), as well as the average discrepancies at various heights above ground (computed by averaging over all distances at each height). Consequently, a conventional analysis of variance was performed for each site, to evaluate the variation in discrepancy with either height or distance.

5. ANALYSIS OF RESULTS

As described in the preceeding section, at each site measured and predicted values of barrier reduction were determined for each measurement point. These values were compared by examining the average discrepancy for the entire site, the linear regression of measured versus predicted values, and the variance of the discrepancies as a function of height and distance. This section reports the results of these analyses.

A preliminary examination of the data was made based upon measured attenuations determined from L_{eq} values of free-field and shielded noise levels. The highway and barrier were assumed to be infinite in length for all sites. Table II lists the results of the analysis. Tabulated for each site are the average discrepancy and standard deviation, the slope and intercept of the computed least-square's regression line, and an indication of whether or not these factors are significantly different from their ideal values. Also indicated is whether or not the discrepancy varies with height or distance at each site.

The table reveals rather poor agreement between measured and predicted values of attenuation for almost all sites. Only at Site 08 is the average discrepancy statistically equivalent to zero, with the other statistical tests indicating no variation with height or distance.

A detailed examination of the individual discrepancies among measurement points at each site reveals that the variation of discrepancy with height and distance could more meaningfully be expressed as a variation of discrepancy with path length difference, δ. The general trend throughout all sites in which there was variation with location is that the discrepancy increases for decreasing δ. Expressed another way, the attenuation

Table II Results of Preliminary Discrepancy Analysis for "Infinite" Barriers

Site	Average Discrepancy, dBA	Different From 0?	Standard Deviation, dBA	Number of Samples	Varies with Height?	Varies with Distance?	Regression Line Intercept, dBA	Different From 0?	Regression Line Slope	Different from 1?
01	-1.2	Yes	0.9	18	Yes	Yes	1.6	No	0.7	No
02	-0.7	No	1.2	18	Yes	Yes	4.4	No	0.6	Yes
03	1.3	Yes	0.9	14	No	No	4.8	Yes	0.7	No
04	-1.7	Yes	1.3	18	No	No	-1.2	No	1.0	No
05	3.2	Yes	2.0	18	No	Yes	2.1	No	1.2	No
06	1.6	Yes	1.3	18	No	No	0.5	No	1.2	No
07	-1.5	Yes	1.0	18	No	No	-1.1	No	1.0	No
08	-0.1	No	1.9	18	No	No	-0.4	No	1.1	No
09	3.0	Yes	1.3	18	Yes	No	5.9	Yes	0.6	Yes
10	1.4	No	2.0	15	No	No	5.3	Yes	0.6	No

NOTE: Discrepancy is measured attenuation minus predicted attenuation.
All statistical tests performed at 1% level of significance.

is underpredicted more for low path length differences than for high path length differences. It should be noted that any defect in the barrier itself, such as flanking around the ends, transmission through the barrier, or propagation through openings in the barrier, will have the effect of degrading the barrier performance. Moreover, this degradation will be worse for the higher predicted values of attenuation than for the lower values. This type of an effect, then, would balance out the variation in discrepancy observed in the data reflected in Table II. With this in mind the data were re-evaluated, taking into consideration the contribution to the shielded noise levels resulting from unshielded sections of highway beyond the ends of the barrier. Depending upon the length of the barrier and the expected noise reduction, this resulted in a decrease in predicted barrier attenuation ranging from a few tenths of a decibel to 1.5 dB, and increasing with increasing path length difference δ.

The results of the re-analysis of the discrepancies at each site for the "finite" length barriers are shown in Table II. (See Appendix E for plots of measured versus predicted attenuation for each site.) As expected, the discrepancies have all increased, reflecting the decrease in predicted attenuation. However, note that for most sites, the discrepancy now does not vary significantly with height or distance. Also at most sites, the slope of the regression line is not significantly different from one although the intercept may or may not be significantly different from zero. These factors indicate that the model of barrier attenuation used to obtain the predicted reductions does properly account for changes in location, however there is a constant bias at all locations. Further, this constant bias is not uniform from site to site.

Table III Results of Discrepancy Analysis for Finite Length Barriers

Site	Average Discrepancy, dBA	Different From 0?	Standard Deviation, dBA	Number of Samples	Varies with Height?	Varies with Distance?	Regression Line Intercept, dBA	Different From 0?	Regression Line Slope	Different from 1?
01	-0.8	Yes	0.9	18	No	Yes	2.0	No	0.7	Yes
02	1.2	Yes	0.9	18	No	No	4.3	Yes	0.7	No
03	1.8	Yes	0.8	14	No	No	5.1	Yes	0.7	No
04	-1.4	Yes	1.3	18	No	No	-0.7	No	0.9	No
05	3.5	Yes	1.9	18	No	Yes	1.9	No	1.2	No
06	2.0	Yes	1.5	18	No	No	0.9	No	1.2	No
07	-0.8	No	1.2	18	No	No	0.5	No	0.9	No
08	0.4	No	1.8	18	No	No	-0.5	No	1.2	No
09	3.4	Yes	1.2	18	No	No	5.8	Yes	0.7	Yes
10	1.6	Yes	1.9	15	No	No	5.1	Yes	0.6	No

NOTE: Discrepancy is measured attenuation minus predicted attenuation.
All statistical tests performed at 1% level of significance.

The various factors upon which the determination of measured and predicted attenuation values depend were examined to identify possible sources of discrepancies. With regard to the measured attenuation values, discrepancies may have arisen from improper selection of propagation loss factors, or errors in measured free-field levels due to the location of the reference free-field station. Review of the discrepancies, however, reveals that at the one site in which a propagation loss factor of 3 dB per doubling of distance was used (Site 02), results agreed quite well. There is no physical reason for changing the loss factor at this site. At the other sites, switching from 4.5 to 3 dB would generally tend to make the average discrepancies larger than at present. Further, a change in the propagation loss factor could easily result in a variation of discrepancy with distance.

With regard to the free-field measurements, at half of the sites measurements were acquired on the highway side of the noise barrier, while the remaining free-field stations were located beyond the barrier and set back at a distance comparable to the shielded measurement locations. Grouping the data into two sets, depending upon location of the free-field station, revealed no discernable trends between the two sets of data.

Attention was then directed towards the predicted attenuations. Since the general trend in the discrepancies is for underprediction of the barrier attenuation, it was hypothesized that the lower attenuation of truck noise relative to automobile noise may somehow account for this underprediction. The percentage truck mix was correlated with the discrepancy at each measurement point; no significant relationship resulted from this correlation, however.

Further analysis considered the relative location of car and truck sources. One way of assessing the importance of the use of different source heights is to assume no difference, that is, to determine attenuations assuming all noise sources are located at ground level. Of course this should result in higher predicted attenuations, particularly at those sites with high truck mix. Re-analysis of the data showed increases in predicted attenuation ranging from 0.1 dB for Site 02 with truck mix of 1.7%, to only 1.7 dB for Site 06 with a 22.8% truck mix. Thus the predicted attenuations are not very sensitive to truck source height. The resulting average discrepancies are all within ± 2 dB, which is not a significant improvement in agreement considering that the assumption of a single source location is physically unreasonable.

The predicted attenuations are all based on a "thin screen" approximation to the barrier configuration. Barrier attenuation theories for thick barriers (References 6 and 7) indicate lower attenuations for berms than for walls of equal height when the berms are non-absorbing. For berms with absorptive surfaces, however, higher attenuation may result. Unfortunately, at the present time, these concepts are not well quantified, and practical methods to take berm shape and absorption into account have not yet been developed.

These effects would, however, help explain some of the measurement results, since the data of Table III generally indicate a larger average discrepancy for the earth berms than for the vertical walls, or berm and wall combinations. Figures 4, 5, and 6 show the individual measured versus predicted attenuations for wall, wall and berm, and berm sites, respectively. Shown on the figures are the ideal and computed least squares' regression lines. The average discrepancies are 0 dB for the wall sites, 1.3 dB for the wall and berm sites, and 2.4 dB for the berm sites.

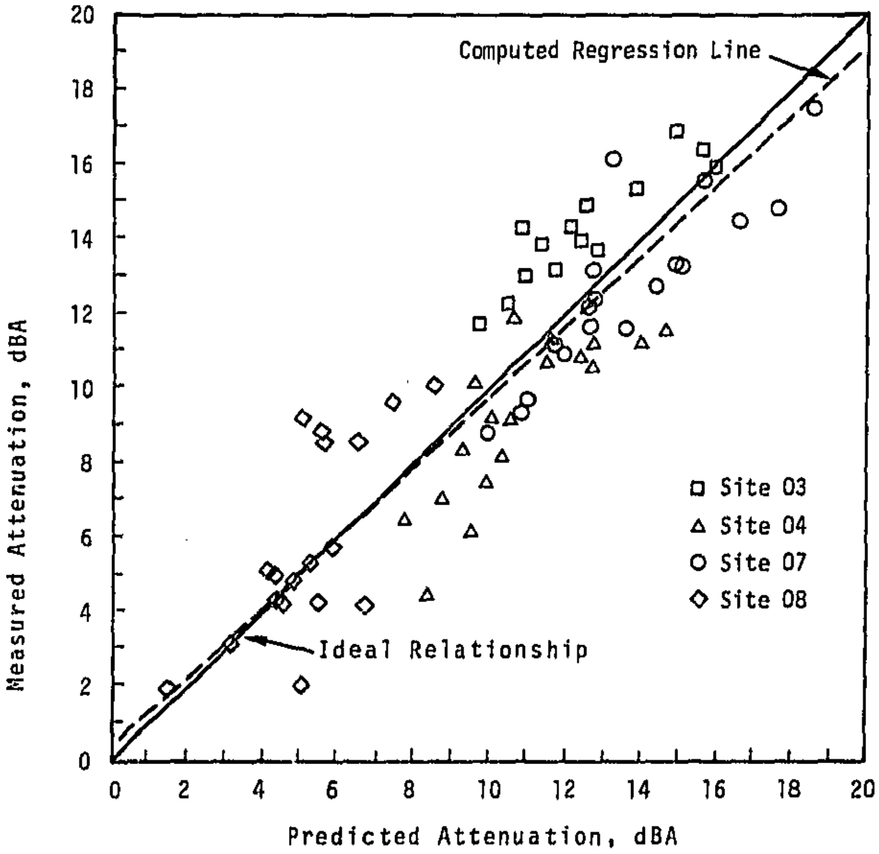


FIGURE 4 Measured versus Predicted Attenuation for Wall Sites.

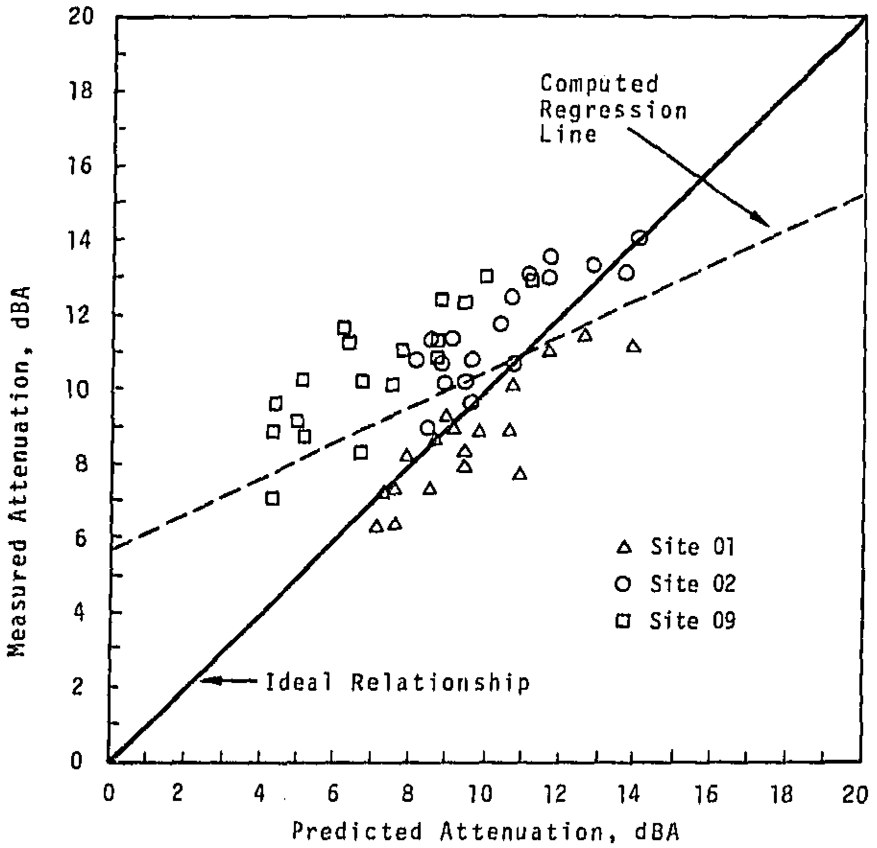


FIGURE 5 Measured Versus Predicted Attenuation for Wall Berm Sites.

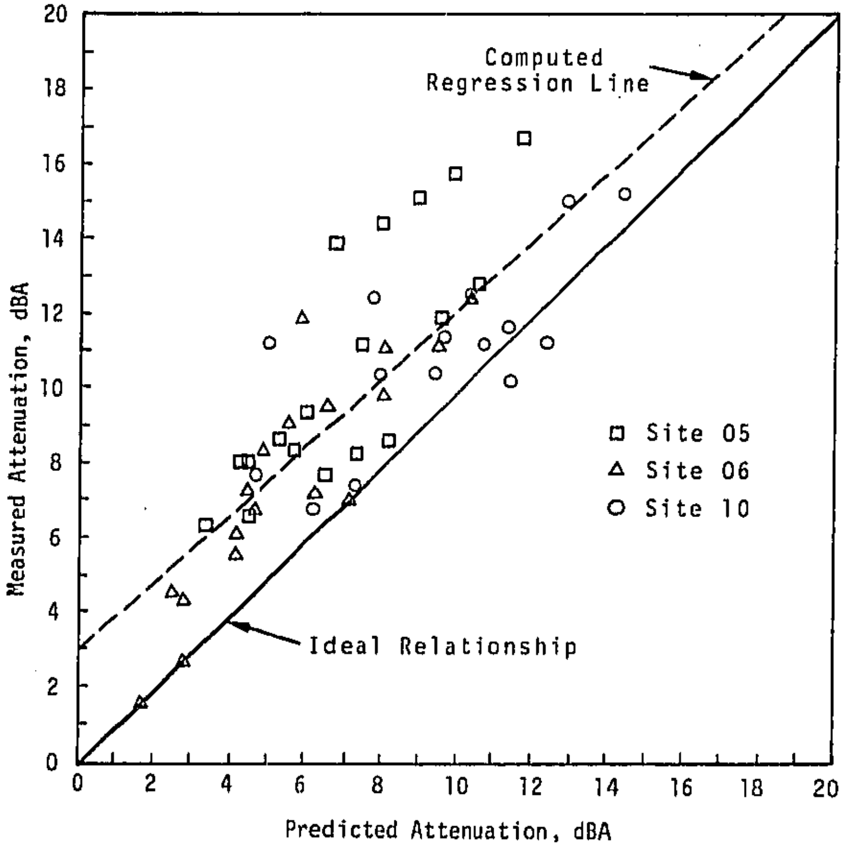


FIGURE 6 Measured versus Predicted Attenuation for Berm Sites.

A final evaluation of the predicted attenuations (based on ground level and eight foot high sources) was conducted using measured attenuation levels in terms of L_{10} and L_{50} values. Table IV compares the average discrepancies at each site as determined using L_{10}, L_{50} and L_{eq} values of measured reference and shielded levels. The table shows that the L_{10} discrepancy is generally higher than the L_{eq} discrepancy, while the L_{50} discrepancy is generally lower. (Note that the Kurze-Anderson line source model, upon which the predicted attenuations are based, was derived for L_{eq} attenuation.) Stated another way, the measured attenuations are highest for L_{10}, lower for L_{eq}, and lower still for L_{50}. These results are reasonable, since the attenuation provided by a barrier is highest for those sections of roadway closest to the observer, and decreases for sections farther up and down the roadway. Since the L_{10}, L_{eq} and L_{50} levels are influenced by respectively larger and larger sections of the road, the L_{10} level should be attenuated most, and the L_{50} level attenuated least. As an indication of the relative magnitude of the attenuation differences, the discrepancy averaged over all sites is zero dB for L_{50}, 1.1 dB for L_{eq}, and 1.8 dB for L_{10}.

Table IV Comparison of Average Discrepancies

Site	Average Discrepancy in dBA Determined from Different Noise Measures		
	L_{10}	L_{eq}	L_{50}
01	-0.5	-0.8	-1.2
02	1.8	1.2	0.2
03	2.2	1.8	1.3
04	-0.5	-1.4	-1.9
05	3.0	3.5	3.0
06	3.1	2.0	0.1
07	-0.1	-0.8	-2.7
08	1.2	0.4	-1.5
09	4.0	3.4	2.3
10	2.4	1.6	0.2

6. SUMMARY OF RESULTS AND CONCLUSIONS

Use of the Kurze-Anderson infinite line source model of barrier attenuation provides predictions of attenuation which agree with measured attenuations equally well at all locations behind the barrier. Averaged over all sites with similar barrier configurations, the average difference between measured and predicted attenuations in terms of L_{eq} values is 0 dB for vertical walls, 1.3 dB for walls on berms and 2.4 dB for berms.

At any one site, there is an average discrepancy which appears to be site-dependent (The discrepancies are within ± 2 dB for all but two sites.) The range of individual discrepancies has a standard deviation of 1 to 2 dB.

The model provides attenuation predictions which are about 1 dB higher than attenuations measured in terms of L_{50} values, and less than 1 dB below attenuations measured in terms of L_{10} values.

Based on these results, it is concluded that the Kurze-Anderson model predicts the attenuation of vertical barrier walls with reasonable accuracy, when noise levels are expressed in terms of L_{eq}. For vertical walls on berms and particularly for berms alone, the attenuation may be underpredicted. Finally, when noise levels are expressed in terms of L_{10}, the predictions may slightly underestimate measured barrier attenuations (by less than one dB).

It is recommended that the model be modified to properly take into account wide barriers, and the absorptive characteristics of the surface of these barrier configurations.

REFERENCES

1. U.J. Kurze and G.S. Anderson, "Sound Attenuation by Barriers," Applied Acoustics 4, 35-53 (1971).

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3. M.E. Delany, "A Practical Scheme for Predicting Noise Levels Arising from Road Traffic," NPL Acoustic Report Ac 57, National Physical Laboratory, England (1972).

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5. I. Guttman, et al, "Introductory Engineering Statistics," Wiley, New York (1965).

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APPENDIX A
NOISE DATA ACQUISITION AND REDUCTION TECHNIQUES

At each shielded measurement location (behind the barrier), noise levels were monitored using instrumentation systems specially developed by BBN. These systems were also used at the free-field reference stations located beyond the barrier.

Each monitoring system consists, basically, of a microphone and preamplifier, a special noise monitoring unit and a digital tape recorder. This instrumentation is illustrated in block diagram form in Figure A.1. As can be seen in the diagram, the noise signal is A-weighted, converted to a digital format, and the output distributed to one of 64 contours, each 1.25 decibels wide. The noise environment is sampled at a rate of eight times per second.

During each measurement run, noise levels were monitored for ten minutes. At the end of this period the contents of the 64 counters, as well as the time of day, are recorded onto a digital tape cassette. Each tape cassette was processed later by computer as shown in Figure A.2 to yield an output listing of noise level statistics and noise exposure levels.

Measurements at the free-field stations located on the highway side of the barrier were made with a conventional analog recording system, which included a cardioid microphone (see block diagram in Figure A.3). The noise recordings were analyzed by a real time spectral analysis system, illustrated in block diagram form in Figure A.4. The primary elements of this system are a real time spectrum analyzer under control of a digital computer. During analysis the computer samples the contents of the one-third octave band filters at the rate of five times per second. A statistical distribution is produced for each spectral value, and the various statistics of interest are listed. From the spectral data the statistics of the A-weighted levels are computed and also displayed.

In the field, calibration signals were recorded on the data tapes (both digital and analog) at intervals during the recordings using an acoustic calibrator. The calibration signals were later analyzed during data reduction as a check on system performance and as a calibration standard for the noise recordings.

During selected measurement runs, in addition to the digital monitoring units, analog systems were used at the reference station and at one of the shielded stations. The analog records were processed using the spectral analysis system of Figure A.4. The resulting data were used to evaluate the frequency dependence of the measured barrier attenuation, as described in Appendix F.

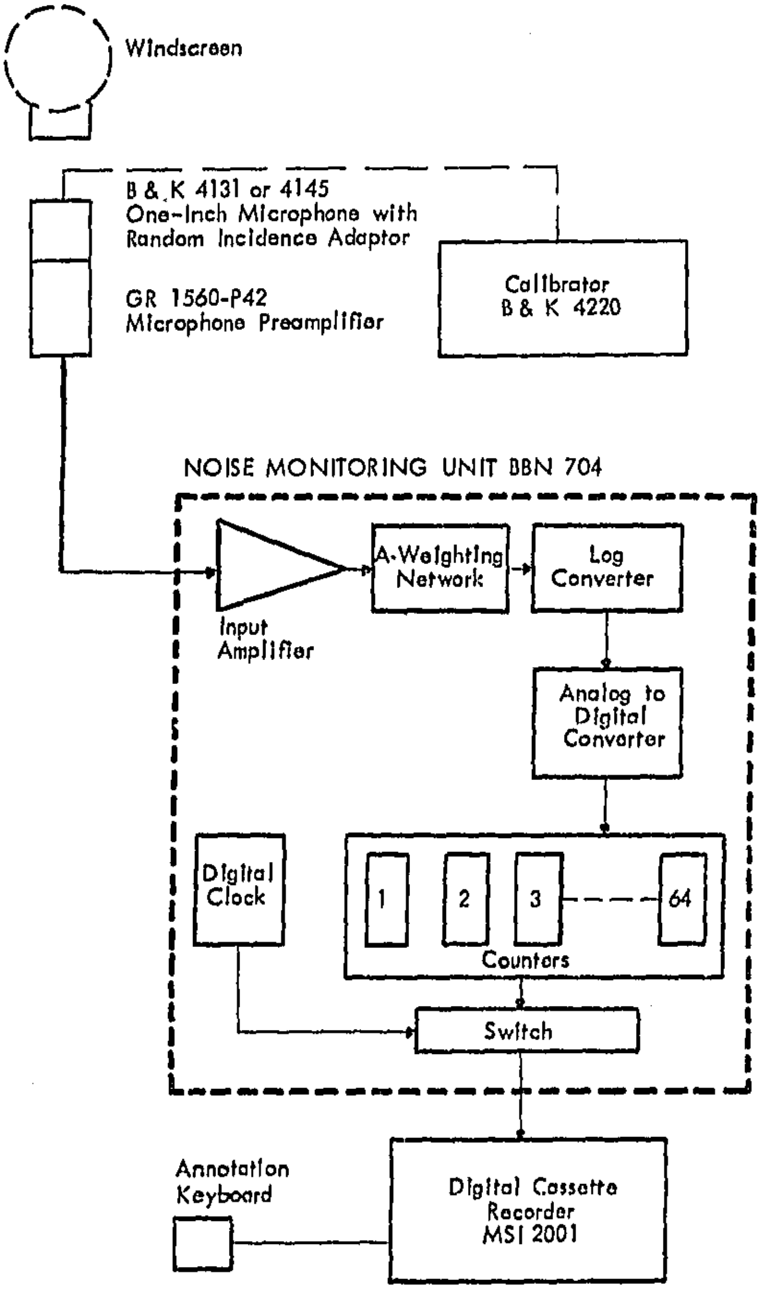


FIGURE A.1. BLOCK DIAGRAM OF DIGITAL NOISE MONITORING INSTRUMENTATION

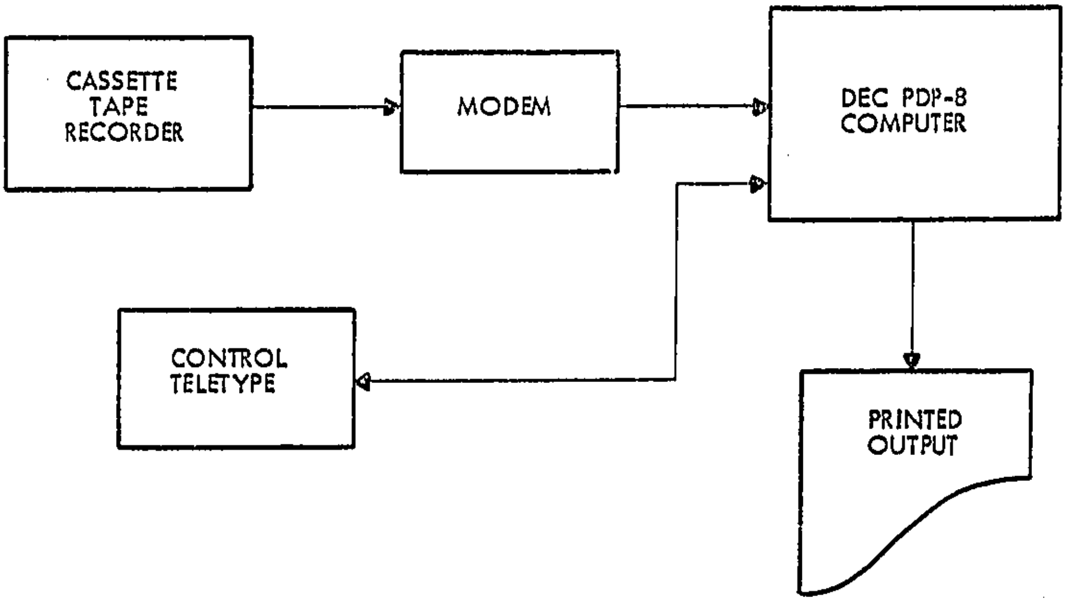


FIGURE A.2. BLOCK DIAGRAM OF DIGITAL DATA ANALYSIS SYSTEM

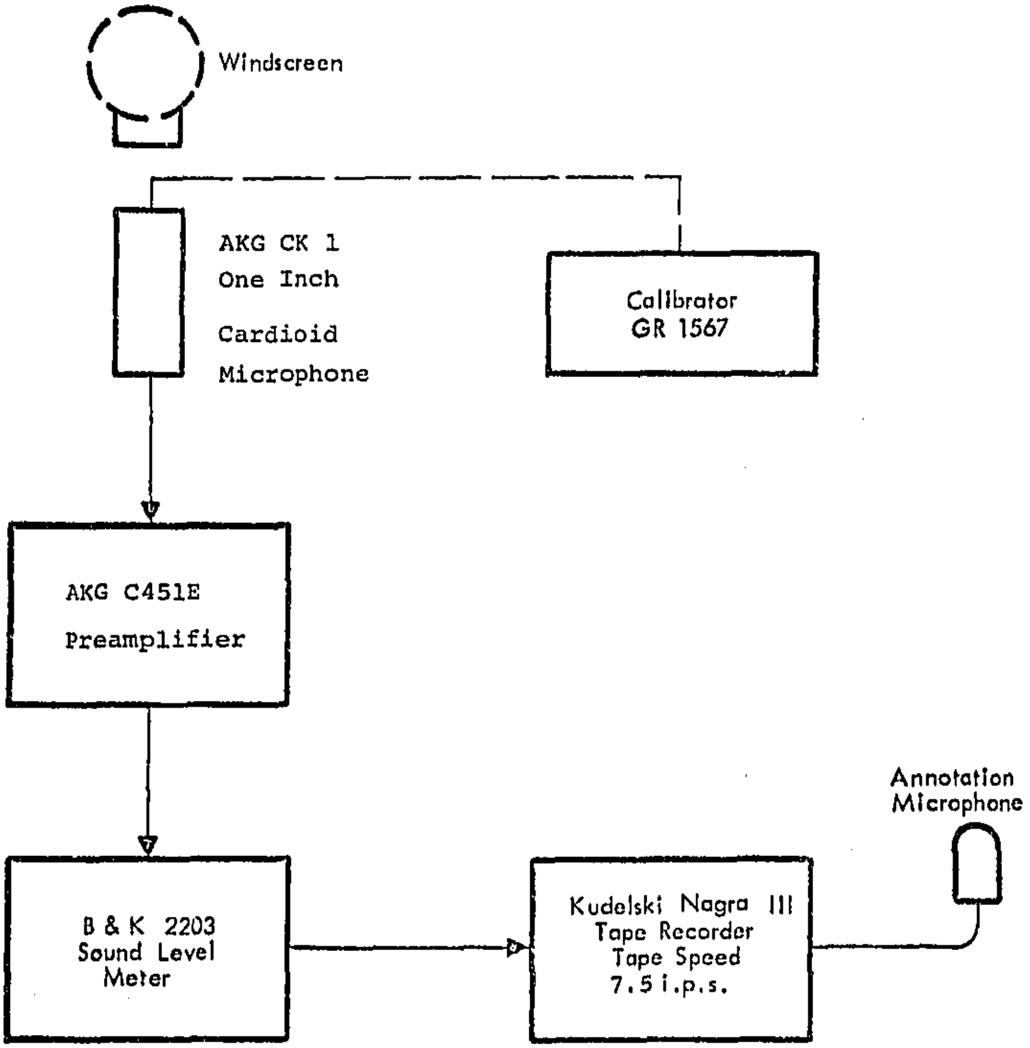


FIGURE A.3. BLOCK DIAGRAM OF ACOUSTICAL INSTRUMENTATION

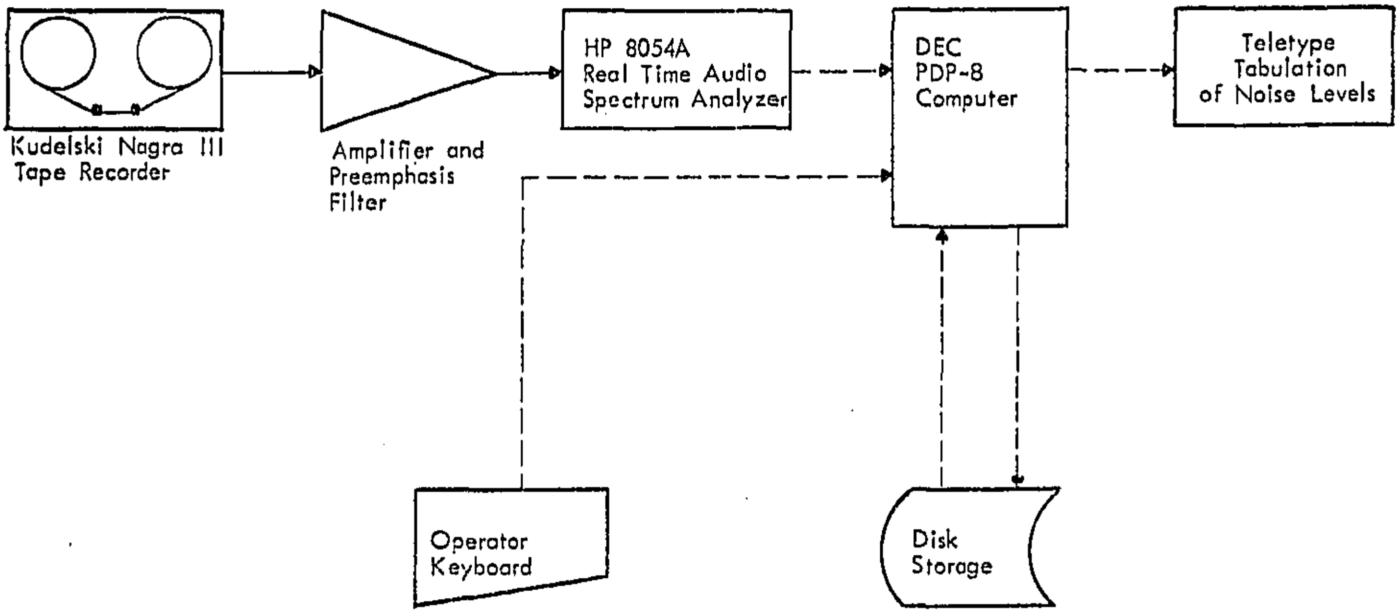


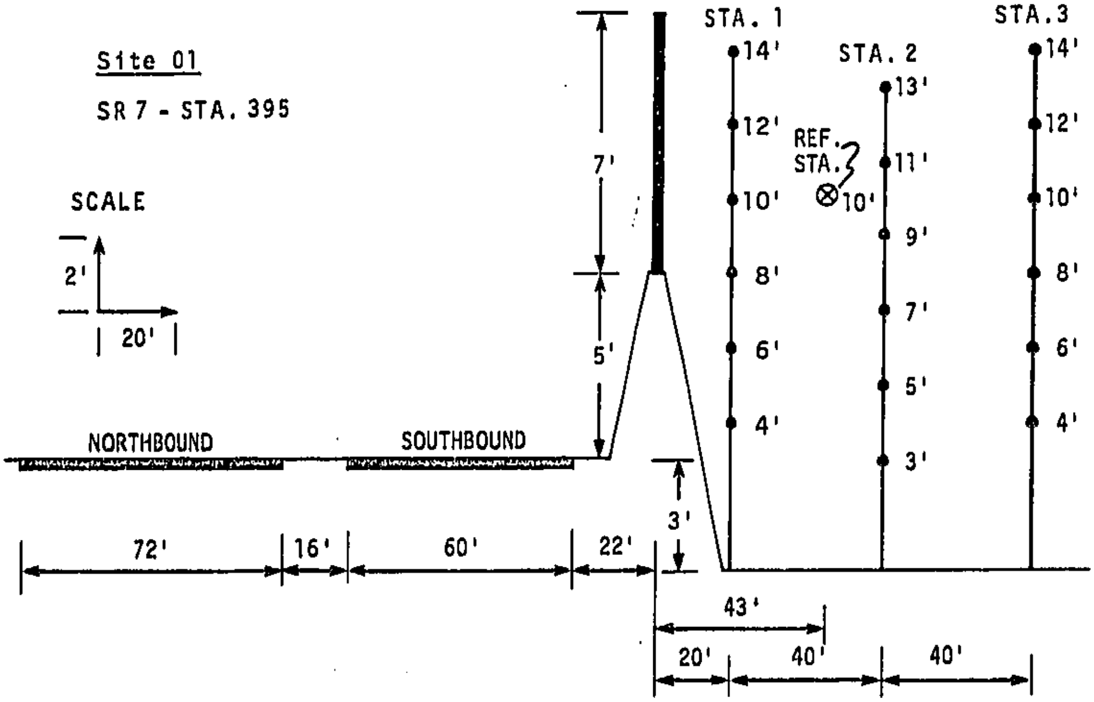
FIGURE A.4. BLOCK DIAGRAM OF LABORATORY ANALYSIS EQUIPMENT

APPENDIX B

MEASUREMENT SITE CROSS SECTIONS

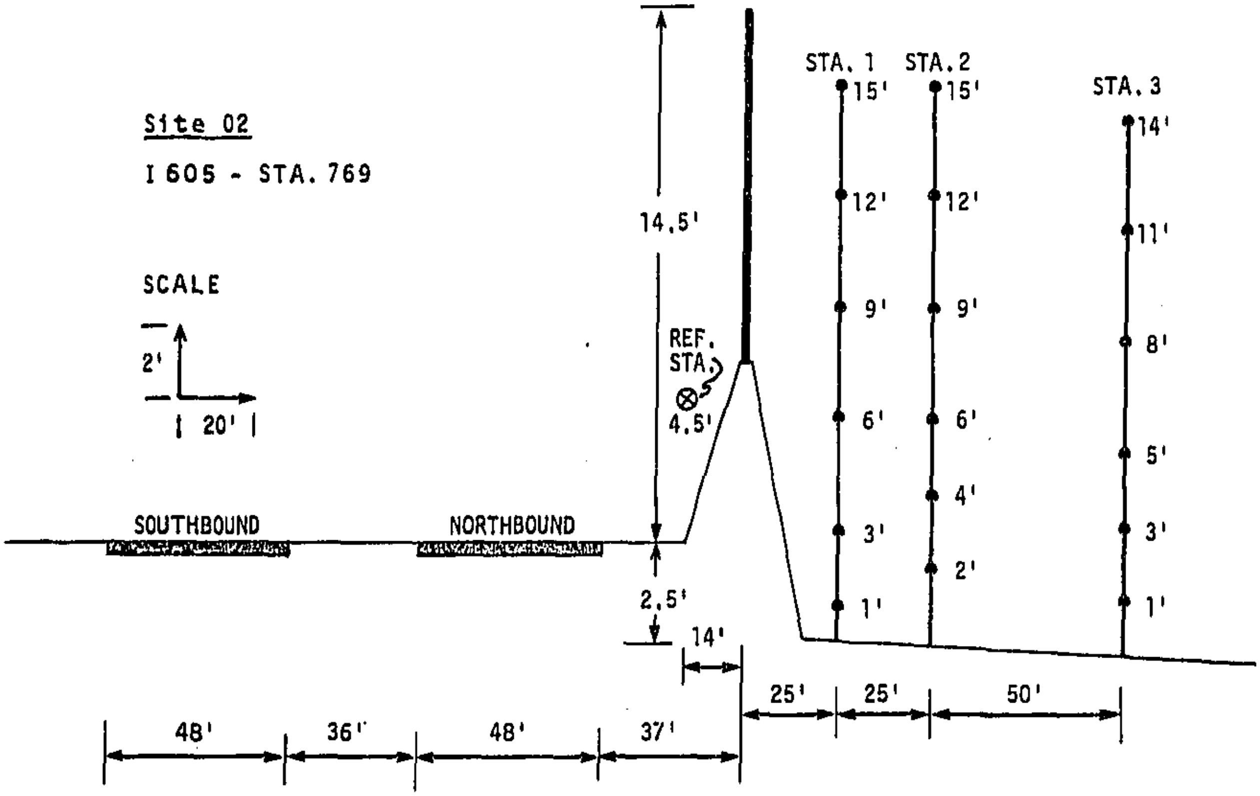
This appendix contains cross sections of the highway-barrier-measurement station geometry for each of the 10 measurement sites. For those sites where the free-field reference station was located beyond the barrier, the projection of the reference location onto the cross section is shown.

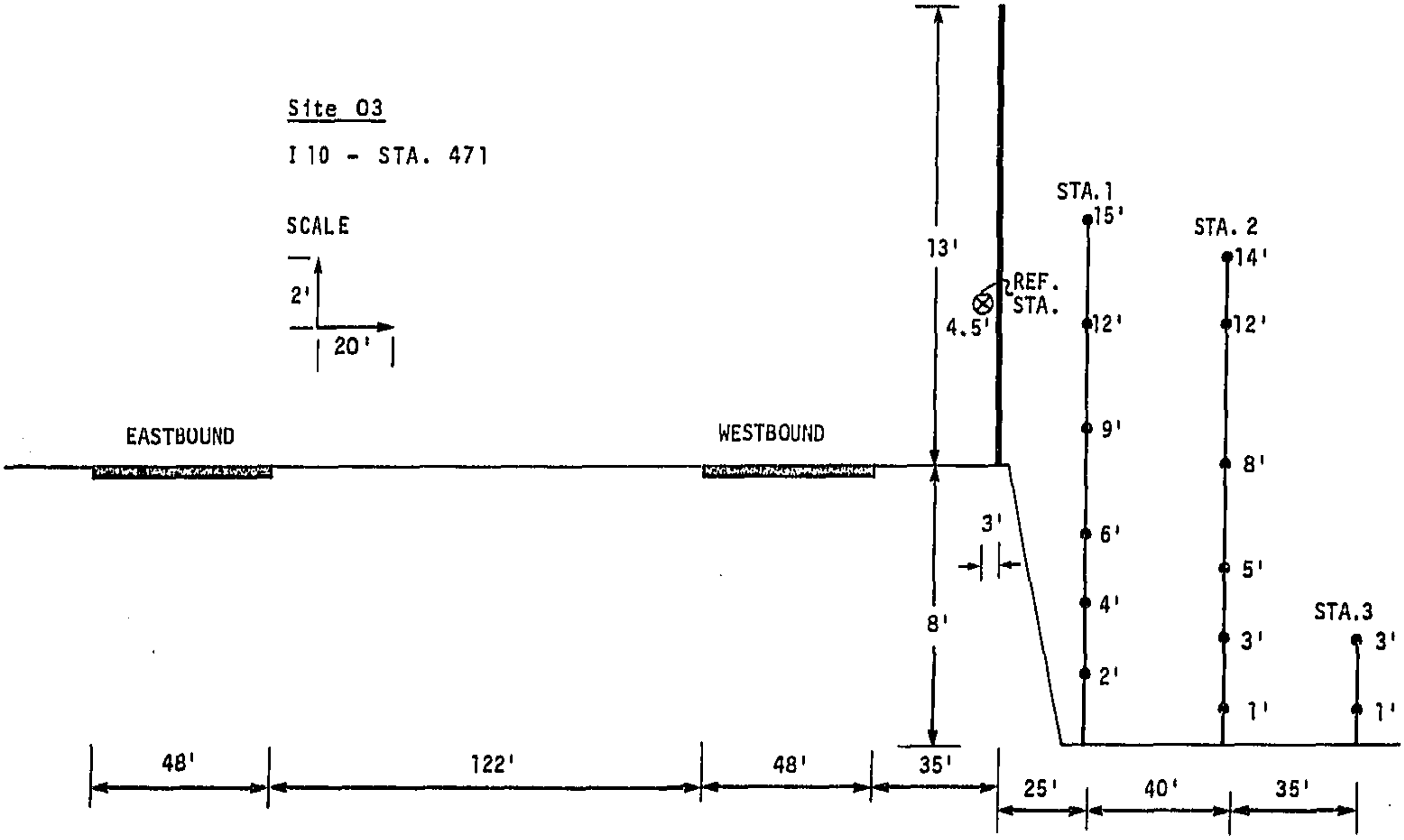
Note that a distorted scale is used on the drawings; the vertical dimension is expanded ten times that of the horizontal.

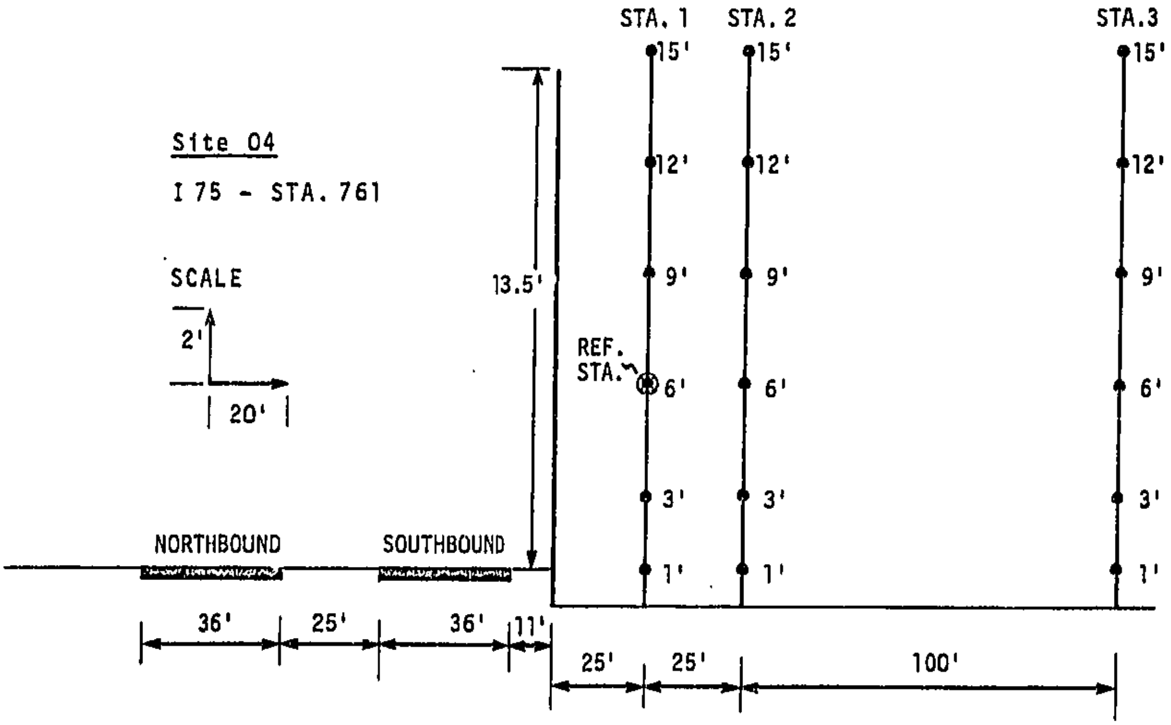

Site 01
SR 7 - STA. 395
SCALE
2'
20'
NORTHBOUND
SOUTHBOUND
7'
5'
3'
72'
16'
60'
22'
43'
20'
40'
40'
STA. 1
14'
12'
10'
8'
6'
4'
STA. 2
13'
11'
9'
7'
5'
3'
REF.
STA.
10'
STA.3
14'
12'
10'
8'
6'
4'

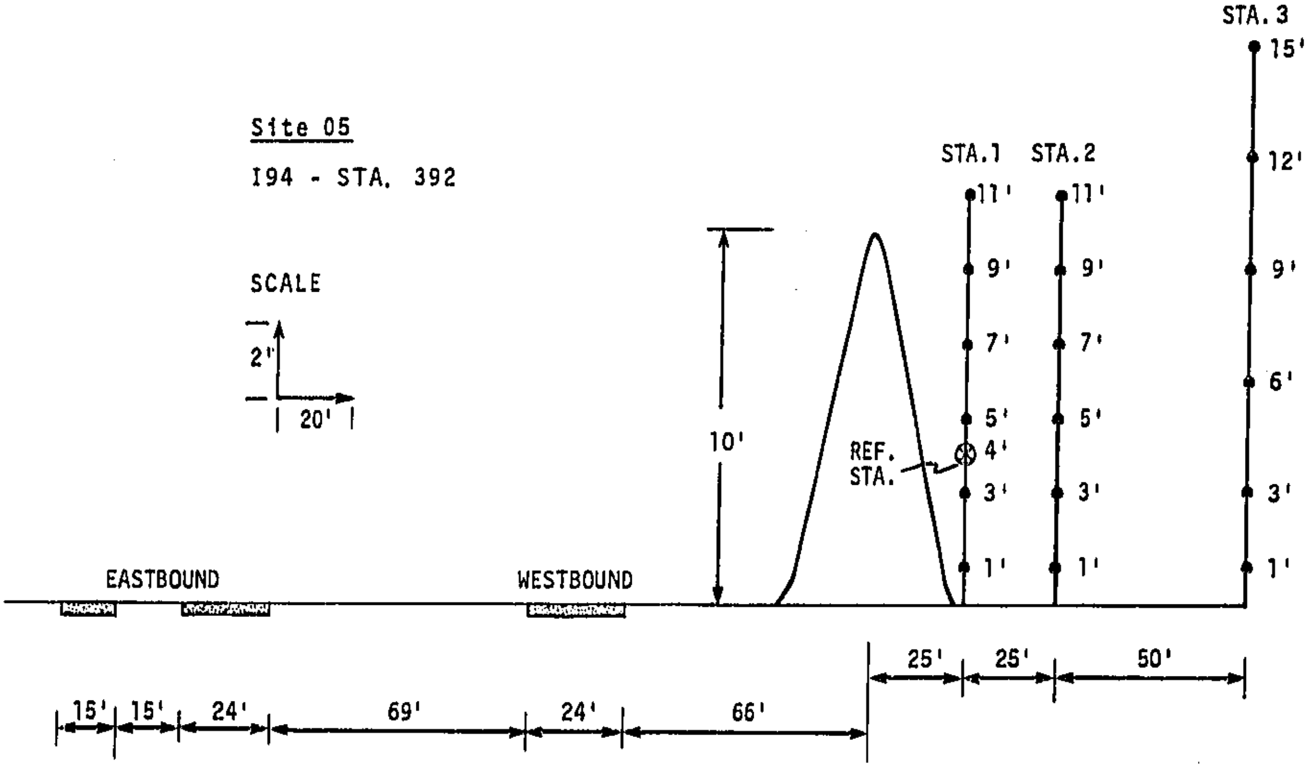
Site 02

I 605 - STA. 769




Site 03
I 10 - STA. 471
SCALE
2'
20'
EASTBOUND
WESTBOUND
13'
REF. STA.
4.5'
3'
8'
STA. 1
15'
12'
9'
6'
4'
2'
STA. 2
14'
12'
8'
5'
3'
1'
STA. 3
3'
1'
48'
122'
48'
35'
25'
40'
35'

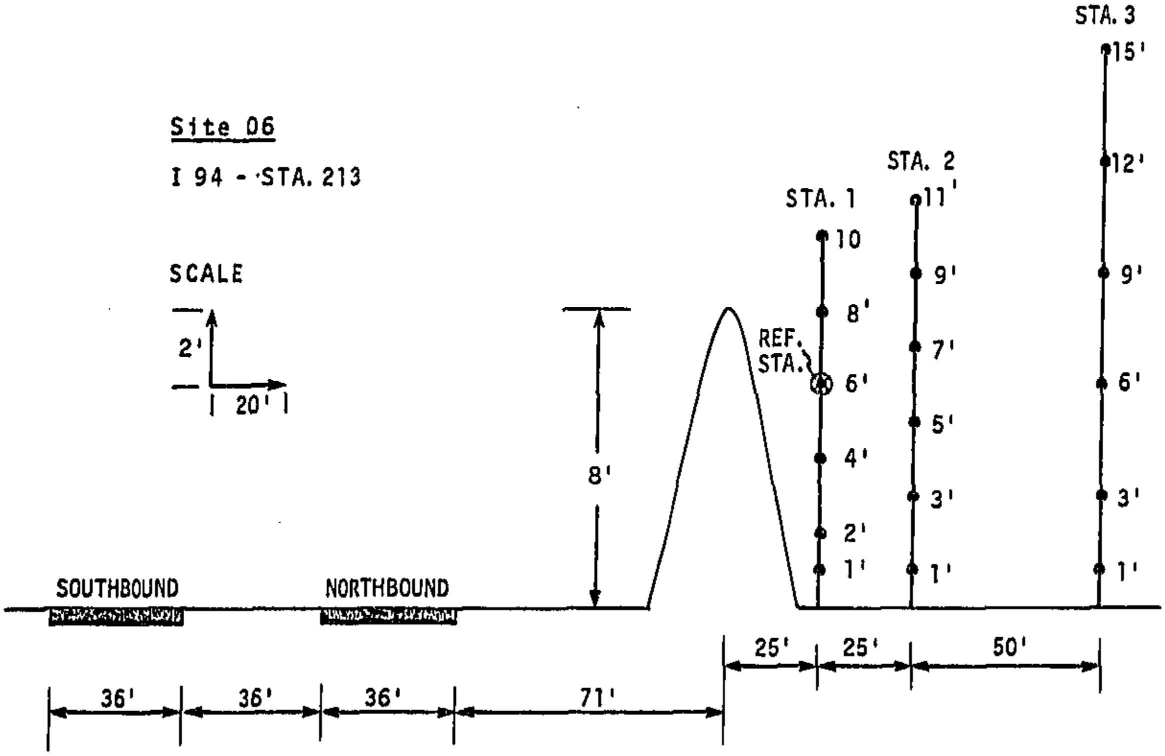

Site 04
I 75 - STA. 761
SCALE
2'
20'
STA. 1
STA. 2
STA.3
15'
12'
9'
6'
3'
1'
REF. STA.
13.5'
NORTHBOUND
SOUTHBOUND
36'
25'
36'
11'
25'
25'
100'



Site 05
I94 - STA. 392
SCALE
2'
20'
10'
REF. STA.
STA.1
STA.2
STA.3
11'
9'
7'
5'
4'
3'
1'
11'
9'
7'
5'
3'
1'
15'
12'
9'
6'
3'
1'
EASTBOUND
WESTBOUND
25'
25'
50'
15'
15'
24'
69'
24'
66'

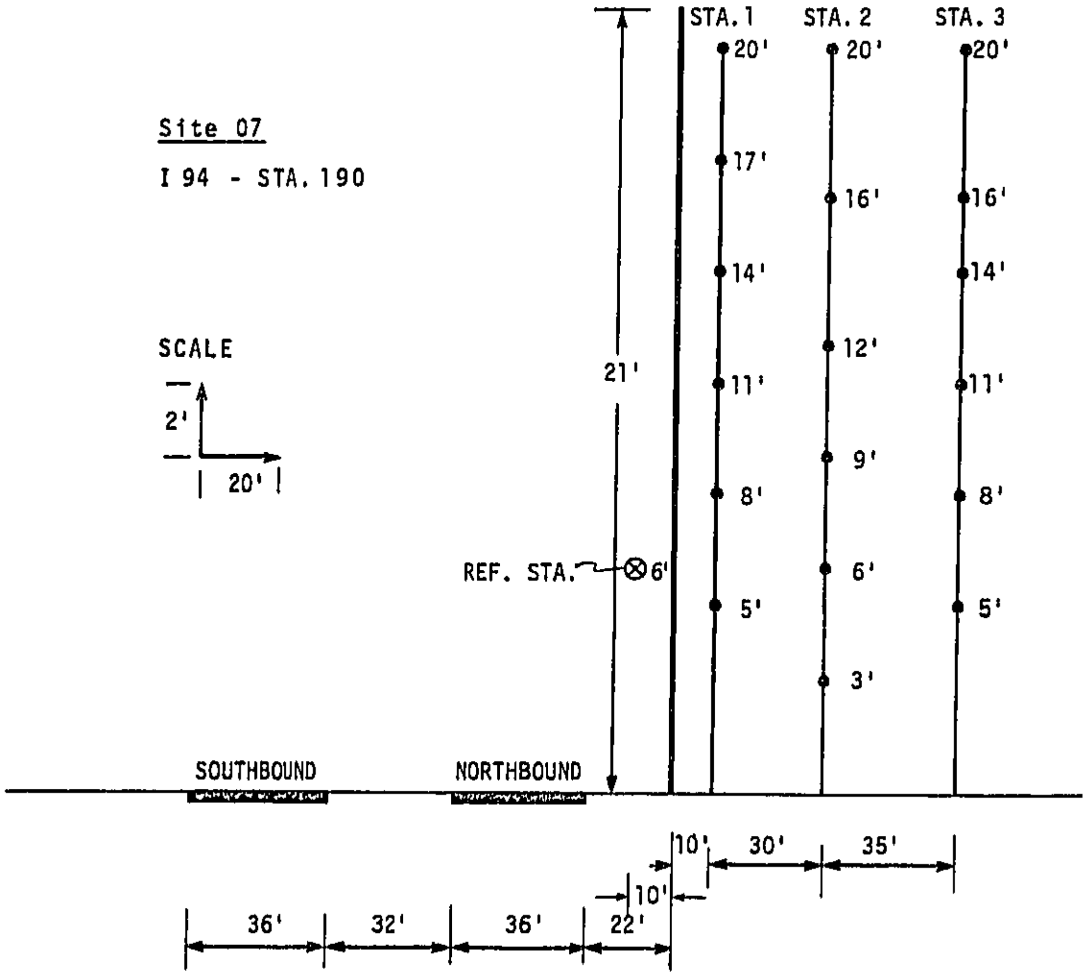
Site 06

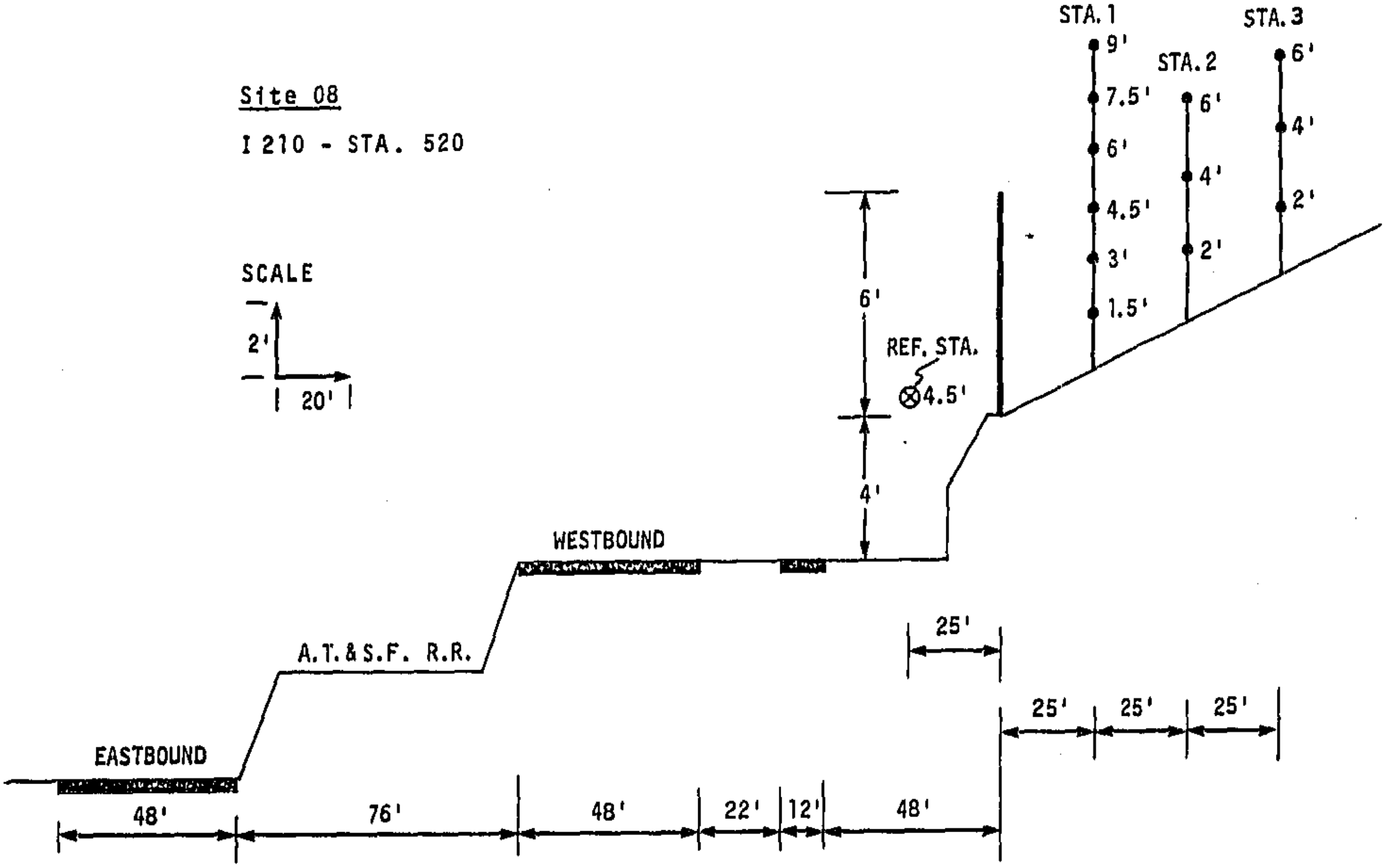
I 94 - STA. 213



Site 07

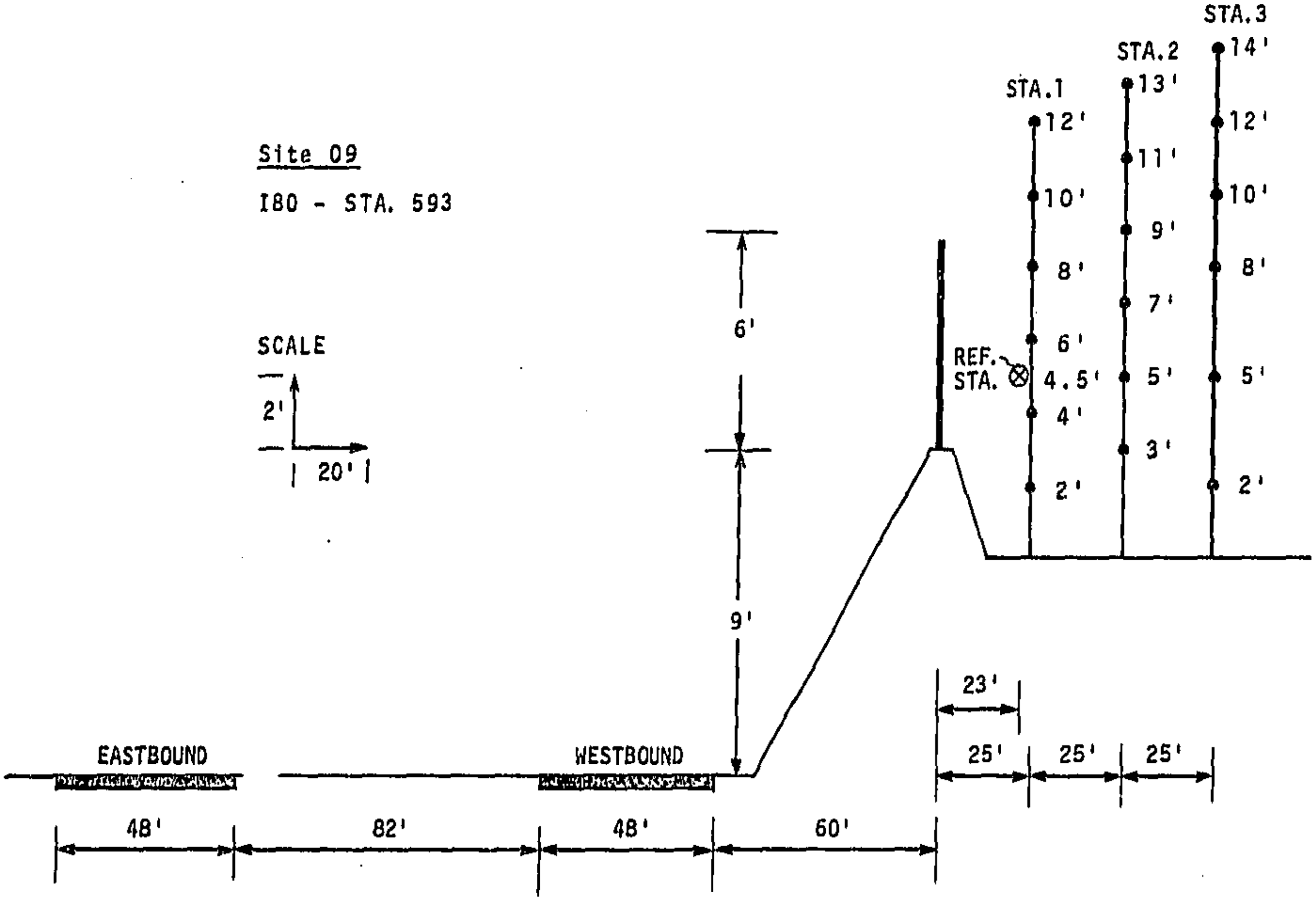
I 94 - STA. 190



Site 08
I 210 - STA. 520
SCALE
2'
20'
STA. 1
9'
7.5'
6'
4.5'
3'
1.5'
STA. 2
6'
4'
2'
STA. 3
6'
4'
2'
6'
REF. STA.
4.5'
4'
WESTBOUND
A.T.&S.F. R.R.
EASTBOUND
25'
25'
25'
25'
48'
76'
48'
22'
12'
48'

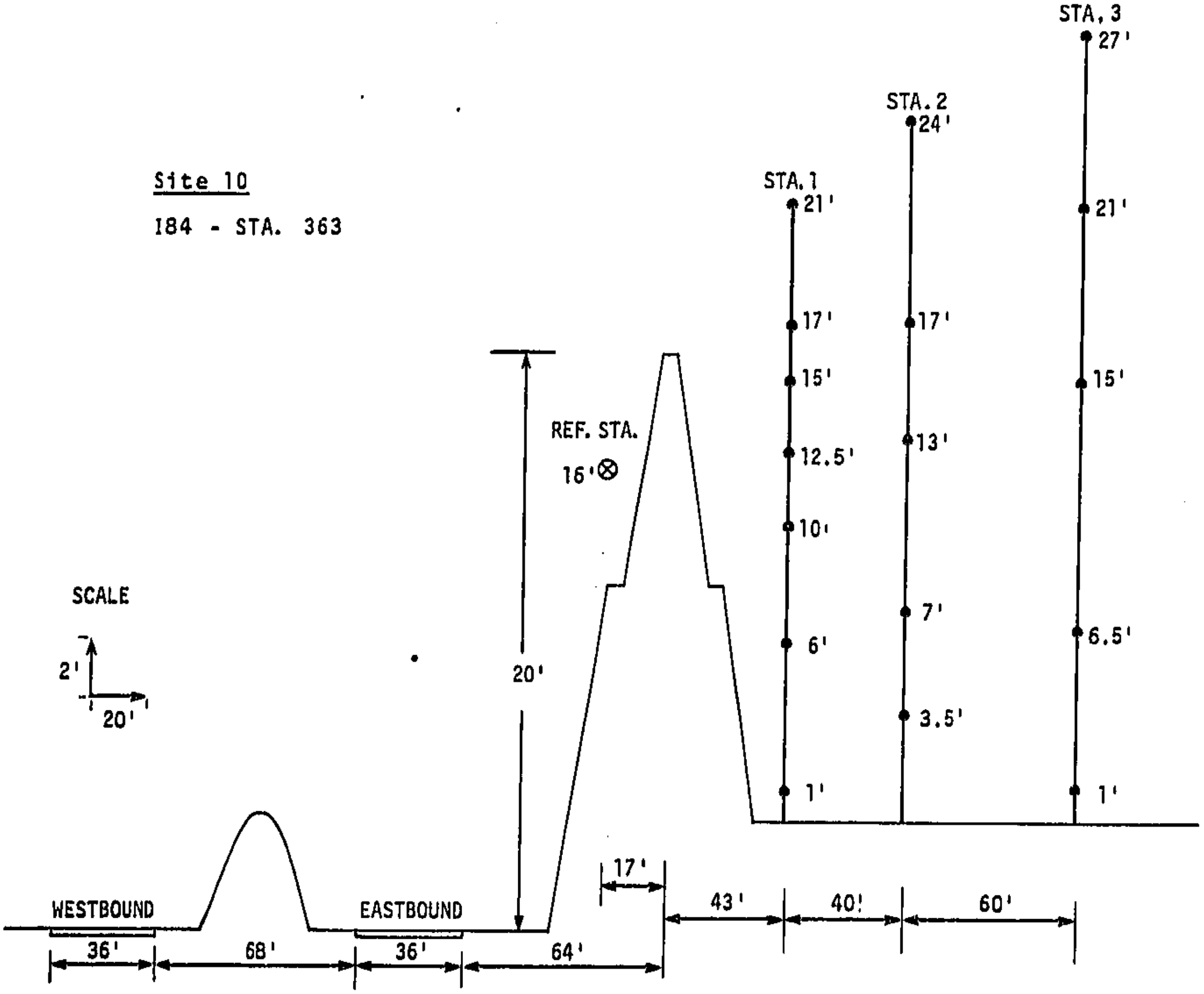
Site 09

I80 - STA. 593



Site 10

I84 - STA. 363



APPENDIX C

MEASUREMENT SITE TRAFFIC CHARACTERISTICS

For each measurement site, the traffic flow characteristics observed during each measurement run are tabulated on the following pages. The truck mix refers to the percentage of heavy trucks (trucks with three axles or more) out of the total vehicle flow. Although each run lasted for ten minutes, the counted volumes were multiplied by six to give hourly values.

SITE 01 - 23 Jan 1975

RUN	TIME	NEAR LANES		FAR LANES		AVERAGE SPEED (MPH)
		TOTAL VOLUME (VPH)	TRUCK MIX (%)	TOTAL VOLUME (VPH)	TRUCK MIX (%)	
1	1142	(3528)	12.6	3504	12.0	54
2	1208	(3048)	11.4	3036	11.1	51
3	1241	3030	10.9	3216	9.1	52
4	1428	3630	10.4	3546	8.6	53
5	1453	4344	6.5	3480	7.4	55
6	1512	4326	7.6	4098	8.8	53
7	1532	4686	7.7	4476	6.2	49

(xx) Indicates volumes estimated from Far Lane traffic

SITE 02 - 28 Jan 1975

RUN	TIME	NEAR LANES		FAR LANES		AVERAGE SPEED (MPH)
		TOTAL VOLUME (VPH)	TRUCK MIX (%)	TOTAL VOLUME (VPH)	TRUCK MIX (%)	
1	1417	3282	3.1	3102	2.3	65
2	1500	3588	1.7	4122	1.6	64
3	1527	3744	3.0	4668	1.7	60
4	1543	4590	1.8	5562	1.6	54
5	1604	4722	1.9	5616	1.3	56
6	1622	4290	2.0	6066	0.4	56

SITE 03 - 20 Feb 1975

RUN	TIME	NEAR LANES		FAR LANES		AVERAGE SPEED (MPH)
		TOTAL VOLUME (VPH)	TRUCK MIX (%)	TOTAL VOLUME (VPH)	TRUCK MIX (%)	
1	1441	4818	4.1	5388	5.9	47
2	1454	4890	5.6	5754	3.5	51
3	1511	4512	3.7	5508	3.6	50
4	1525	4794	2.4	6462	2.2	51
5	1543	5370	2.5	7182	1.8	51
6	1559	5700	4.1	8004	1.9	50

SITE 04 - 3 Feb 1975

RUN	TIME	NEAR LANES		FAR LANES		AVERAGE SPEED (MPH)
		TOTAL VOLUME (VPH)	TRUCK MIX (%)	TOTAL VOLUME (VPH)	TRUCK MIX (%)	
1	1518	2346	9.0	9102	7.3	52
2	1542	2496	8.2	1392	9.9	52
3	1610	2202	6.5	1728	9.0	50
4	1630	2790	9.5	1980	5.2	48
5	1650	3426	5.3	2178	8.8	50
6	1726	3540	5.3	1800	6.3	52
7	1743	2316	7.0	1422	6.3	51

SITE 05 - 7 Feb 1975

RUN	TIME	NEAR LANES		FAR LANES		AVERAGE SPEED (MPH)
		TOTAL VOLUME (VPH)	TRUCK MIX (%)	TOTAL VOLUME (VPH)	TRUCK MIX (%)	
1	0955	678	16.8	690	15.7	53
2	1010	654	14.7	612	14.7	53
3	1030	660	18.2	564	18.1	53
4	1044	672	15.2	600	17.0	53
5	1058	804	18.7	702	20.5	64
6	1119	756	16.7	654	12.8	64

SITE 06 - 11 Feb 1975

RUN	TIME	NEAR LANES		FAR LANES		AVERAGE SPEED (MPH)
		TOTAL VOLUME (VPH)	TRUCK MIX (%)	TOTAL VOLUME (VPH)	TRUCK MIX (%)	
1	1212	750	21.6	588	23.5	62
2	1229	606	23.8	636	25.5	62
3	1247	690	27.8	654	14.7	62
4	1301	672	24.1	744	15.3	66
5	1317	582	27.8	750	22.4	64
6	1333	672	21.4	702	25.6	66

SITE 07 - 13 Feb 1975

		NEAR LANES		FAR LANES		
RUN	TIME	TOTAL VOLUME (VPH)	TRUCK MIX (%)	TOTAL VOLUME (VPH)	TRUCK MIX (%)	AVERAGE SPEED (MPH)
1	1403	2502	6.7	2658	4.5	66
2	1421	2940	4.7	3066	4.7	64
3	1440	2856	4.8	2928	4.9	63
4	1500	2790	4.1	2994	4.4	60
5	1522	2952	5.3	3522	3.1	56
6	1539	3678	2.8	3342	4.3	54

SITE 08 - 21 Feb 1975

RUN	TIME	NEAR LANES		FAR LANES		AVERAGE SPEED (MPH)
		TOTAL VOLUME (VPH)	TRUCK MIX (%)	TOTAL VOLUME (VPH)	TRUCK MIX (%)	
1	1254	1158	2.6	1488	4.0	53
2	1309	1182	2.5	1530	5.1	58
3	1326	1038	1.2	1464	2.5	58
4	1340	1320	3.2	1704	2.5	54
5	1403	1410	2.1	1614	2.2	58
6	1416	1380	4.3	1630	1.8	59

SITE 09 - 26 Feb 1975

RUN	TIME	NEAR LANES		FAR LANES		AVERAGE SPEED (MPH)
		TOTAL VOLUME (VPH)	TRUCK MIX (%)	TOTAL VOLUME (VPH)	TRUCK MIX (%)	
1	1141	1044	2.3	1110	5.4	53
2	1154	1230	4.9	1338	5.4	56
3	1208	1038	4.0	1134	5.3	56
4	1246	1380	4.3	1410	4.3	55
5	1258	1176	8.2	1200	4.0	55
6	1317	1296	6.0	1314	7.3	57

SITE 10 - 12 March 1975

RUN	TIME	NEAR LANES		FAR LANES		AVERAGE SPEED (MPH)
		TOTAL VOLUME (VPH)	TRUCK MIX (%)	TOTAL VOLUME (VPH)	TRUCK MIX (%)	
1	1011	2016	7.4	2028	5.3	58
2	1031	1734	4.8	1596	9.0	59
3	1058	2004	3.9	1860	12.6	58
4	1118	1866	5.8	1824	7.9	58
5	1156	1884	8.3	1884	4.5	59
6	1215	1770	5.8	2160	9.4	59

APPENDIX D
MEASURED NOISE LEVELS

Presented in this appendix are the noise levels measured at each free-field and shielded measurement location. The distances listed are equivalent lane distances to the roadway; heights are relative to grade level at the measurement station (for reference stations on the highway side of a barrier, height is relative to roadway grade).

SITE 01

RUN	REF. STATION, DIST = 118				STATION 1, DIST = 89				STATION 2, DIST = 137				STATION 3, DIST = 181			
	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}
	DISTANCE AND HEIGHT IN FEET; L_{eq}, L_{10}, L_{50} IN dBA															
1	10	76.1	79.3	74.3	4	66.6	69.1	65.7	3	66.8	69.4	65.1				
2	10	75.3	78.2	73.5	6	65.8	68.4	64.9	5	65.5	68.3	64.0	6	63.4	65.9	62.5
3	10	75.1	78.6	73.2	8	66.0	68.7	64.9	7	65.5	68.4	63.7	8	63.7	66.2	63.0
4	10	75.9	78.8	74.1	10	67.6	70.2	66.4	9	67.0	69.3	65.2	10	65.0	67.4	63.9
5	10	75.1	77.5	74.1	12	68.0	70.4	67.0	11	66.7	69.2	65.4	12	65.1	67.4	64.3
6	10	75.5	78.1	74.5	14	69.9	72.2	69.0	13	68.1	70.4	66.8	14	66.4	68.5	65.6
7	10	75.9	78.6	74.3	4	67.3	70.0	66.1	3	67.5	70.3	65.6	4	64.9	67.3	63.7

SITE 02

RUN	REF. STATION, DIST = 60				STATION 1, DIST = 110				STATION 2, DIST = 138				STATION 3, DIST = 192			
	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}
	DISTANCE AND HEIGHT IN FEET; L_{eq}, L_{10}, L_{50} IN dBA															
1	4	79.2	81.9	76.8	12	66.1	68.4	64.4	12	65.9	68.3	64.2	13	65.4	67.4	63.8
2	4	78.5	81.2	77.0	9	63.2	65.1	62.7	9	63.2	65.0	62.7	10	62.8	64.6	62.3
3	4	79.5	81.9	77.5	6	63.8	66.0	62.8	6	63.7	66.0	62.7	7	64.4	66.9	63.3
4	4	80.4	82.9	78.6	3	64.9	66.9	64.2	4	64.0	66.0	63.2	4	65.3	67.3	64.3
5	4	80.3	82.9	78.8	1	64.0	65.9	63.4	2	63.4	65.1	62.7	1	64.7	66.4	64.0
6	4	80.3	82.9	78.6	15	66.5	68.4	65.9	15	65.5	67.3	64.9	16	64.5	66.2	63.9

SITE 03

RUN	REF. STATION, DIST = 89				STATION 1, DIST = 129				STATION 2, DIST = 178				STATION 3, DIST = 218			
	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}
	DISTANCE AND HEIGHT IN FEET; L_{eq}, L_{10}, L_{50} IN dBA															
1	4.5	80.9	83.8	79.2	2	62.7	65.4	61.6	1	62.7	65.5	61.3	1	61.3	64.2	59.9
2	4.5	81.8	84.8	79.7	4	63.0	66.0	61.3	3	63.0	65.8	61.6	3	62.6	65.3	61.3
3	4.5	81.5	84.5	79.7	6	62.2	64.7	60.9	5	62.6	64.9	61.6				
4	4.5	81.3	84.1	79.8	9	63.4	65.8	62.3	8	63.7	65.9	63.1				
5	4.5	81.7	84.1	80.0	12	64.3	66.4	63.3	12	64.8	66.7	64.2				
6	4.5	82.0	84.6	80.2	15	65.3	67.5	64.5	14	65.5	67.4	64.9				

SITE 04

DISTANCE AND HEIGHT IN FEET; L_{eq}, L_{10}, L_{50} IN dBA

RUN	REF. STATION, DIST = 69				STATION 1, DIST = 69				STATION 2, DIST = 98				STATION 3, DIST = 204			
	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}
1	6	79.3	82.8	76.7												
2					15	72.7	75.7	70.3	15	72.4	75.6	70.5	15	65.1	67.5	62.9
3					12	71.1	73.8	68.1	12	70.2	70.7	65.5	12	63.5	66.1	61.7
4					9	69.6	73.0	67.4	9	65.8	68.7	64.4	9	62.8	65.8	61.2
5					6	69.2	71.7	66.9	6	66.1	68.2	64.7	6	63.6	66.5	61.9
6					3	68.2	71.1	66.0	3	66.2	68.8	64.8	3	64.0	67.1	61.8
7	6	78.6	82.4	76.0	1	66.9	70.2	64.9	1	64.9	67.7	63.4	1	62.2	65.0	59.8

SITE 05

RUN	REF. STATION, DIST = 147				STATION 1, DIST = 147				STATION 2, DIST = 175				STATION 3, DIST = 228			
	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}
	DISTANCE AND HEIGHT IN FEET; L_{eq}, L_{10}, L_{50} IN dBA															
1	4	76.1	79.9	72.0	11	68.1	72.0	64.6	11	66.8	70.6	63.6	15	66.6	70.1	63.7
2					9	65.9	69.3	61.1	9	65.7	68.9	60.8	12	65.7	69.2	61.0
3					7	64.8	68.3	62.1	7	61.0	64.3	58.5	9	64.4	67.6	62.3
4					5	63.5	67.7	59.7	5	59.9	63.7	56.7	6	64.7	68.5	61.0
5					3	62.7	65.9	59.3	3	59.3	62.4	56.6	3	64.2	67.7	60.8
6	4	74.4	78.4	71.2	1	57.7	61.0	54.8	1	57.5	60.3	55.9	1	62.7	66.1	59.8

SITE 06

RUN	REF. STATION, DIST = 140				STATION 1, DIST = 140				STATION 2, DIST = 166				STATION 3, DIST = 218			
	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}
	DISTANCE AND HEIGHT IN FEET; L_{eq}, L_{10}, L_{50} IN dBA															
1	6	73.1	77.8	68.4	1	60.8	64.8	56.3	1	62.2	64.8	60.8	1	58.3	62.2	55.4
2	6	71.5	76.0	66.8	2	60.2	64.3	55.1	3	63.4	65.7	62.7	3	59.5	63.7	55.9
3	6	71.8	76.2	67.6	4	60.5	64.1	58.5	5	63.4	65.4	63.1	6	61.6	65.0	60.3
4	6	74.3	77.9	68.5	6	64.7	67.5	60.7	7	64.9	67.2	62.8	9	66.0	68.5	61.8
5	6	72.9	77.3	68.9	8	66.2	70.0	63.2	9	65.5	68.1	64.2	12	65.7	69.1	63.1
6	6	73.4	76.7	69.8	10	70.6	73.4	67.1	11	68.0	70.2	66.2	15	68.7	71.9	66.0

SITE 07

	REF. STATION, DIST = 37				STATION 1, DIST = 66				STATION 2, DIST = 101				STATION 3, DIST = 140			
RUN	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}
	DISTANCE AND HEIGHT IN FEET; L_{eq}, L_{10}, L_{50} IN dBA															
1	6	79.7	83.0	76.8	20	67.1	70.2	65.4	20	64.1	67.0	62.3	20	61.8	64.9	59.9
2	6	80.9	84.2	77.8	17	64.9	67.4	63.7	16	63.1	65.5	61.8	16	61.5	63.8	60.2
3	6	80.6	83.9	77.6	14	63.7	66.5	62.7	12	62.7	65.5	61.7	14	61.4	64.5	60.3
4	6	80.0	83.0	76.2	11	61.9	64.2	61.0	9	61.1	63.5	60.1	11	59.8	62.4	58.5
5	6	79.8	83.0	77.1	8	61.3	63.5	60.6	6	60.2	62.3	59.2	8	58.4	60.9	57.5
6	6	79.8	82.7	77.6	5	59.0	61.1	58.5	3	58.3	60.5	57.6	5	56.0	58.5	55.0

SITE 08

RUN	REF. STATION, DIST = 114				STATION 1, DIST = 173				STATION 2, DIST = 200				STATION 3, DIST = 227			
	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}
	DISTANCE AND HEIGHT IN FEET; L_{eq}, L_{10}, L_{50} IN dBA															
1	4.5	70.4	73.8	66.7	9	64.9	67.9	63.3	6	62.2	64.8	61.0	6	61.3	63.7	60.2
2	4.5	71.3	73.7	67.3	7.5	65.3	67.1	62.0	4	62.6	64.7	60.2	2	62.9	63.9	59.3
3	4.5	69.7	72.9	66.2	6	62.4	64.6	60.6	2	62.3	64.1	60.2	4	63.6	63.7	59.9
4	4.5	71.7	74.3	67.8	4.5	63.2	65.6	60.4	6	63.9	66.2	61.5	6	63.0	65.0	61.0
5	4.5	71.9	75.3	67.2	3	59.7	62.7	58.3	4	59.6	62.4	58.3	4	58.4	61.1	56.9
6	4.5	73.4	76.9	68.7	1.5	60.8	64.3	59.0	2	61.2	64.7	59.2	2	60.5	64.0	58.3

SITE 09

RUN	REF. STATION, DIST = 147				STATION 1, DIST = 150				STATION 2, DIST = 178				STATION 3, DIST = 206			
	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}
	DISTANCE AND HEIGHT IN FEET; L_{eq}, L_{10}, L_{50} IN dBA															
1	4.5	70.2	73.3	67.9	2	57.6	60.6	63.3	3	56.9	59.8	55.7	2	55.7	58.7	54.3
2	4.5	72.7	75.7	69.5	6	61.9	64.8	59.1	5	60.2	63.0	57.7	5	59.6	61.7	56.5
3	4.5	71.4	74.2	68.2	8	61.2	64.0	58.8	7	60.3	62.6	57.4	8	61.0	61.9	56.4
4	4.5	73.3	75.5	68.7	10	63.1	66.0	60.1	9	60.8	63.6	58.2	10	59.5	62.4	57.3
5	4.5	72.5	75.9	68.5	12	65.5	69.0	63.1	11	62.5	65.8	60.7	12	61.2	64.6	59.5
6	4.5	72.2	76.0	69.1	4	59.4	62.4	57.8	13	62.2	65.6	60.3	14	60.6	63.7	59.0

SITE 10

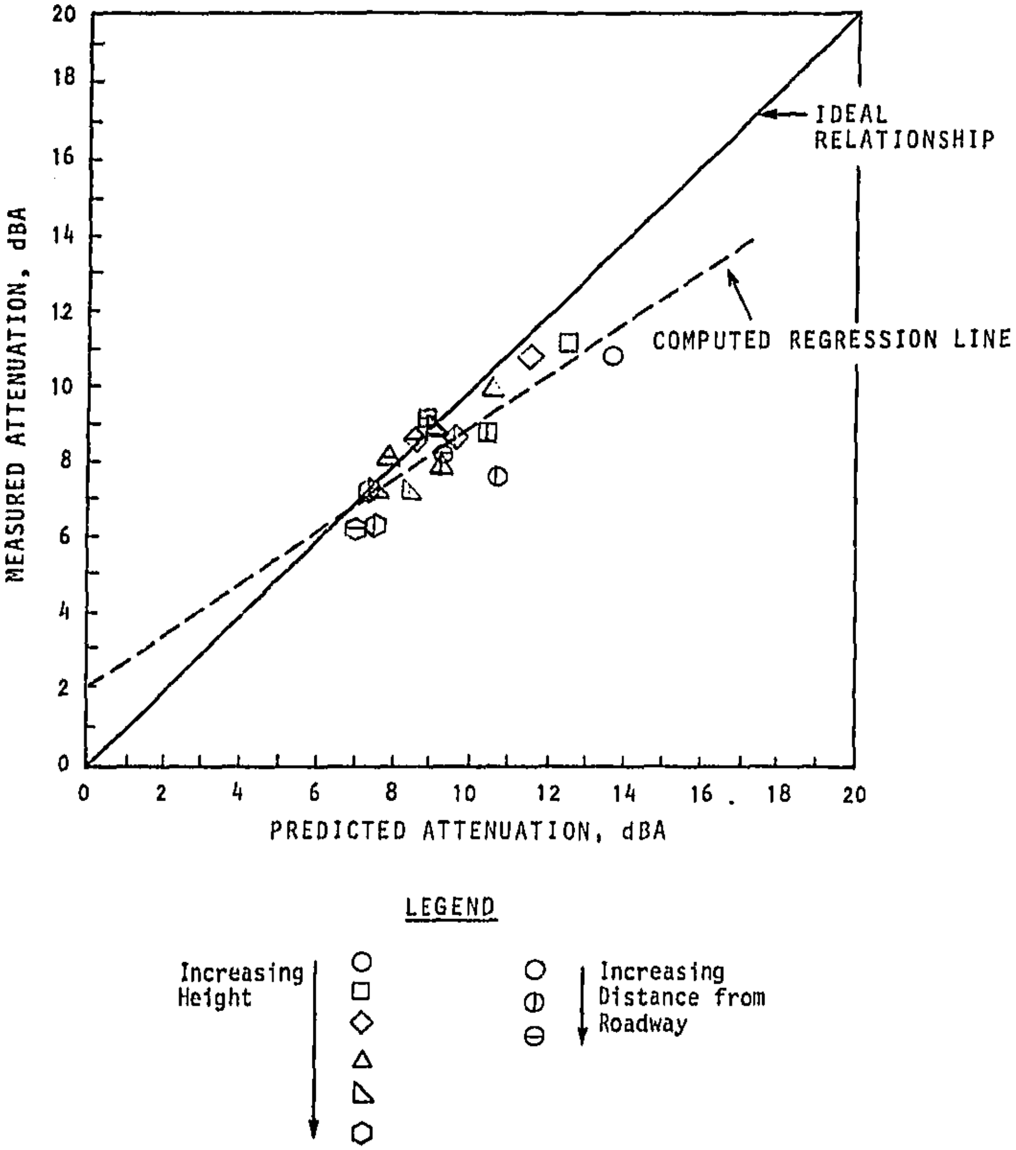
DISTANCE AND HEIGHT IN FEET; L_{eq}, L_{10}, L_{50} IN dBA

RUN	REF. STATION, DIST = 94				STATION 1, DIST = 163				STATION 2, DIST = 205				STATION 3, DIST = 268			
	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}	HT.	L_{eq}	L_{10}	L_{50}
1	16	77.8	80.8	75.9	15	62.6	65.1	61.7	3.5	61.3	63.3	59.6	27	63.9	66.1	63.2
2	16	78.3	81.3	75.6	12.5	63.2	65.1	61.8	7	63.3	64.7	61.3	21	64.1	66.3	62.7
3	16	78.4	81.3	76.2	10	61.9	64.2	61.4	24	65.9	68.3	65.2	1	60.5	62.8	59.7
4	16	78.7	81.4	75.7	6	60.7	62.7	59.6	17	63.4	65.2	62.4	6.5	60.8	62.9	60.1
5	16	80.2	83.3	77.5	21	65.1	67.7	64.1	13	63.4	65.5	62.4	15	62.7	64.9	62.0
6	16	79.1	82.1	76.6	17	62.6	64.3	60.9								
					1	60.6	62.1	58.3								
					4	60.5	61.9	58.6								

APPENDIX E
COMPARISONS OF MEASURED AND PREDICTED ATTENUATIONS

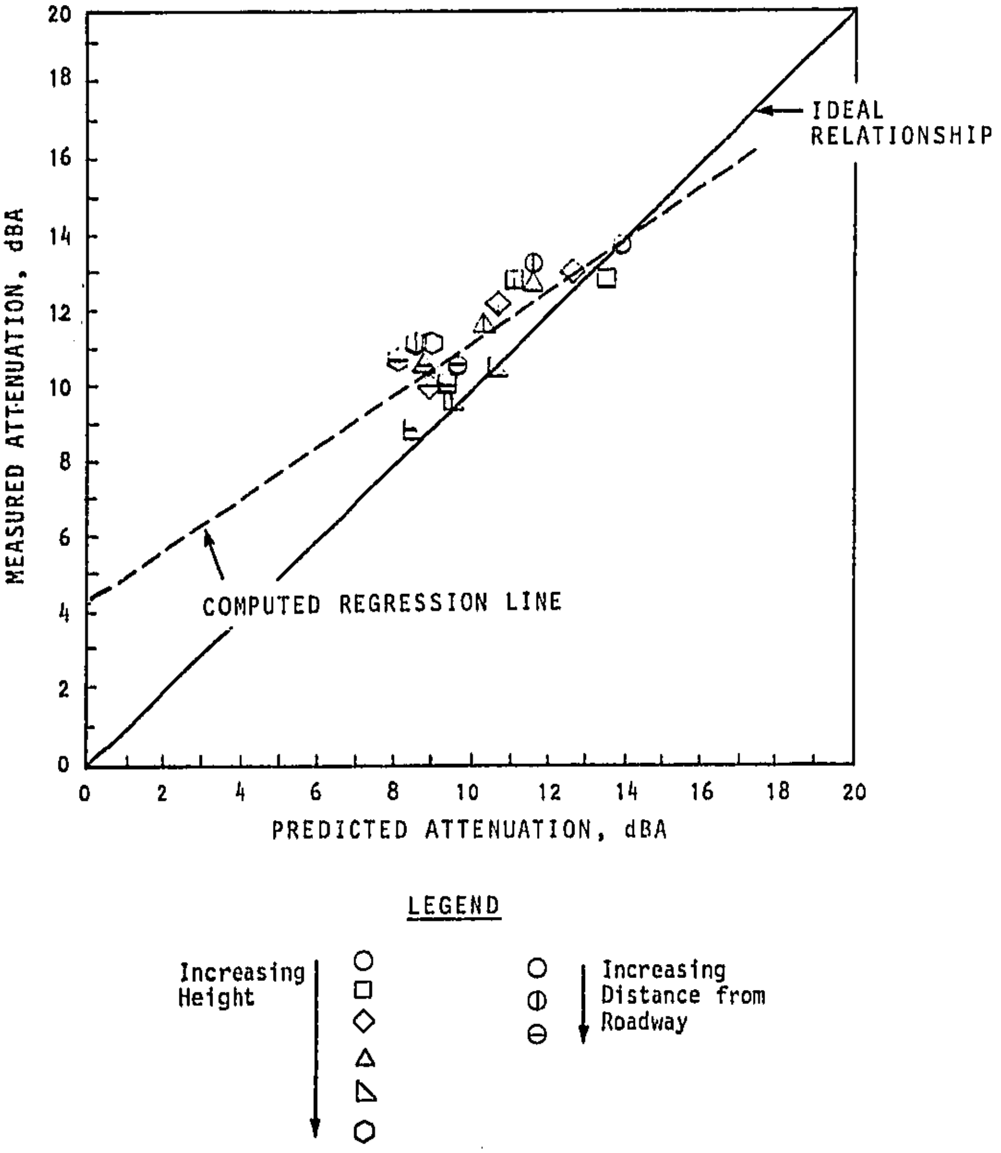
This appendix contains plots of the measured versus the predicted attenuations at each measurement site. Measured attenuations are based upon L_{eq} data; predicted attenuations assume both car and truck noise sources (0 and 8 feet high, respectively), and take into account the finite length of each barrier. Shown on the plots are both the ideal line, and the computed least-squares' regression line. Note that the plotted attenuations are coded for both height above ground and distance from roadway. See Table III for a summary of the statistical tests performed for the data at each site.

SITE 01

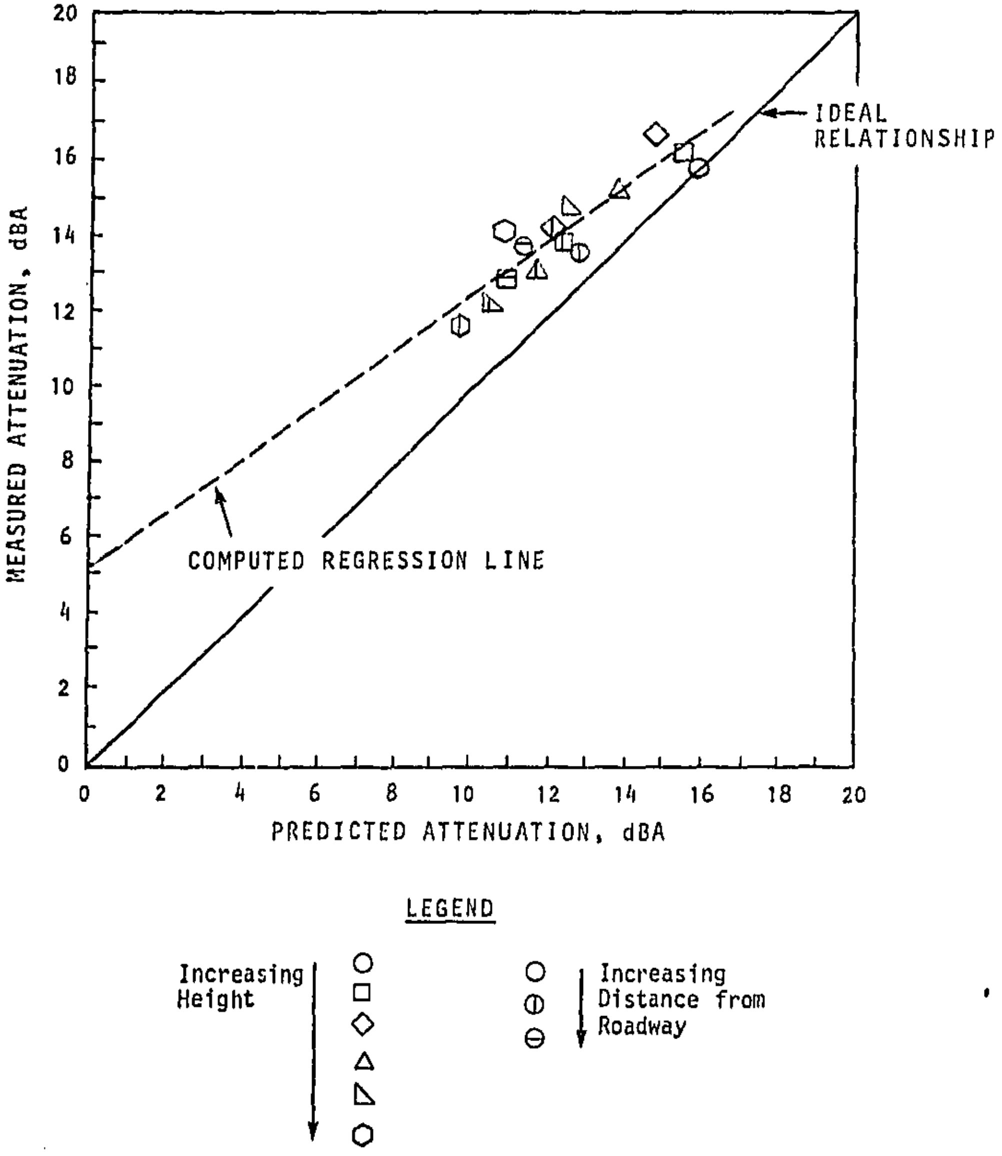


MEASURED ATTENUATION, dBA
0
2
4
6
8
10
12
14
16
18
20
PREDICTED ATTENUATION, dBA
IDEAL RELATIONSHIP
COMPUTED REGRESSION LINE
LEGEND
Increasing Height
Increasing Distance from Roadway

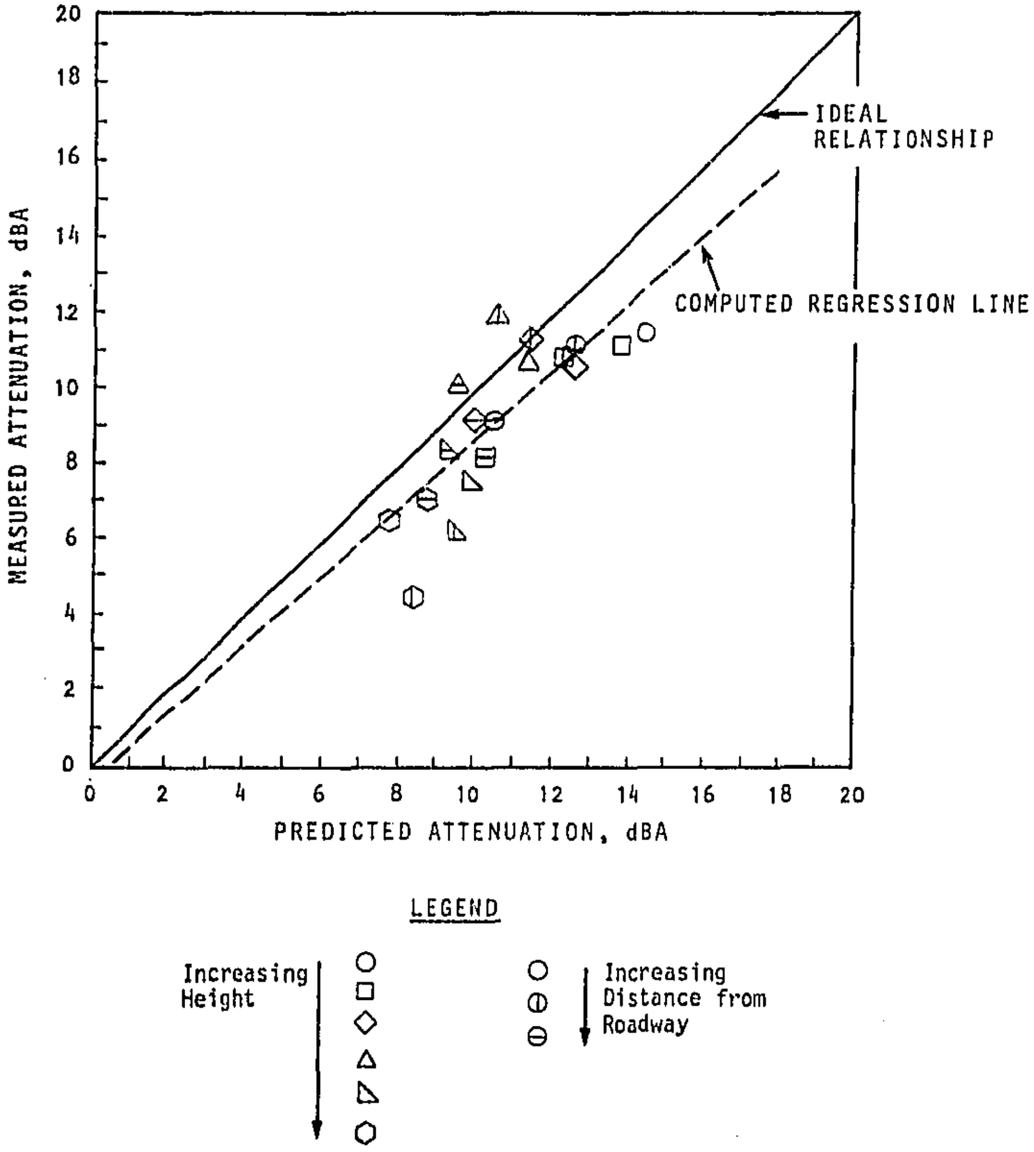
SITE 02


MEASURED ATTENUATION, dBA
20
18
16
14
12
10
8
6
4
2
0
0
2
4
6
8
10
12
14
16
18
20
PREDICTED ATTENUATION, dBA
IDEAL RELATIONSHIP
COMPUTED REGRESSION LINE
LEGEND
Increasing Height
Increasing Distance from Roadway

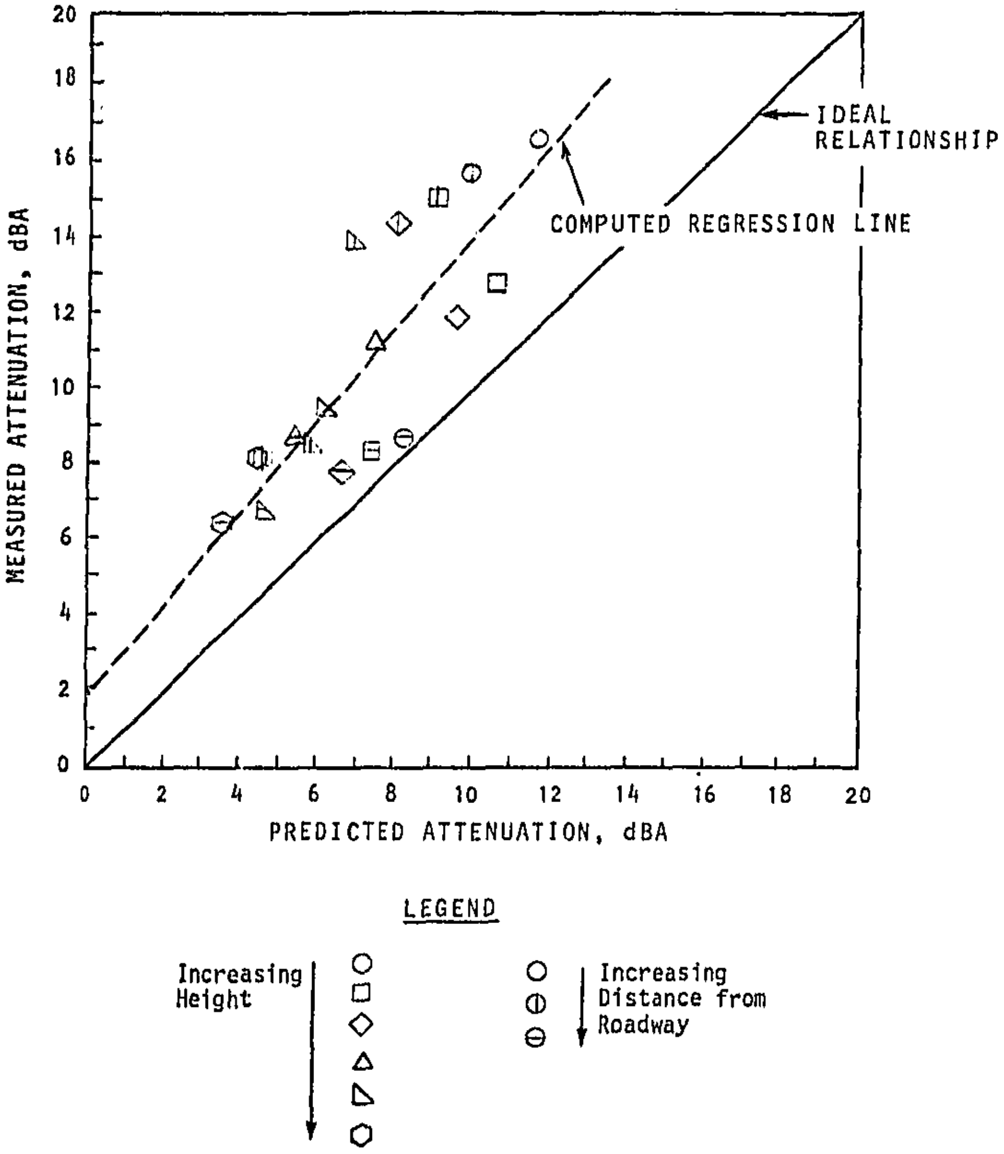
SITE 03


20
18
16
14
12
10
8
6
4
2
0
MEASURED ATTENUATION, dBA
0
2
4
6
8
10
12
14
16
18
20
PREDICTED ATTENUATION, dBA
IDEAL RELATIONSHIP
COMPUTED REGRESSION LINE
LEGEND
Increasing Height
Increasing Distance from Roadway

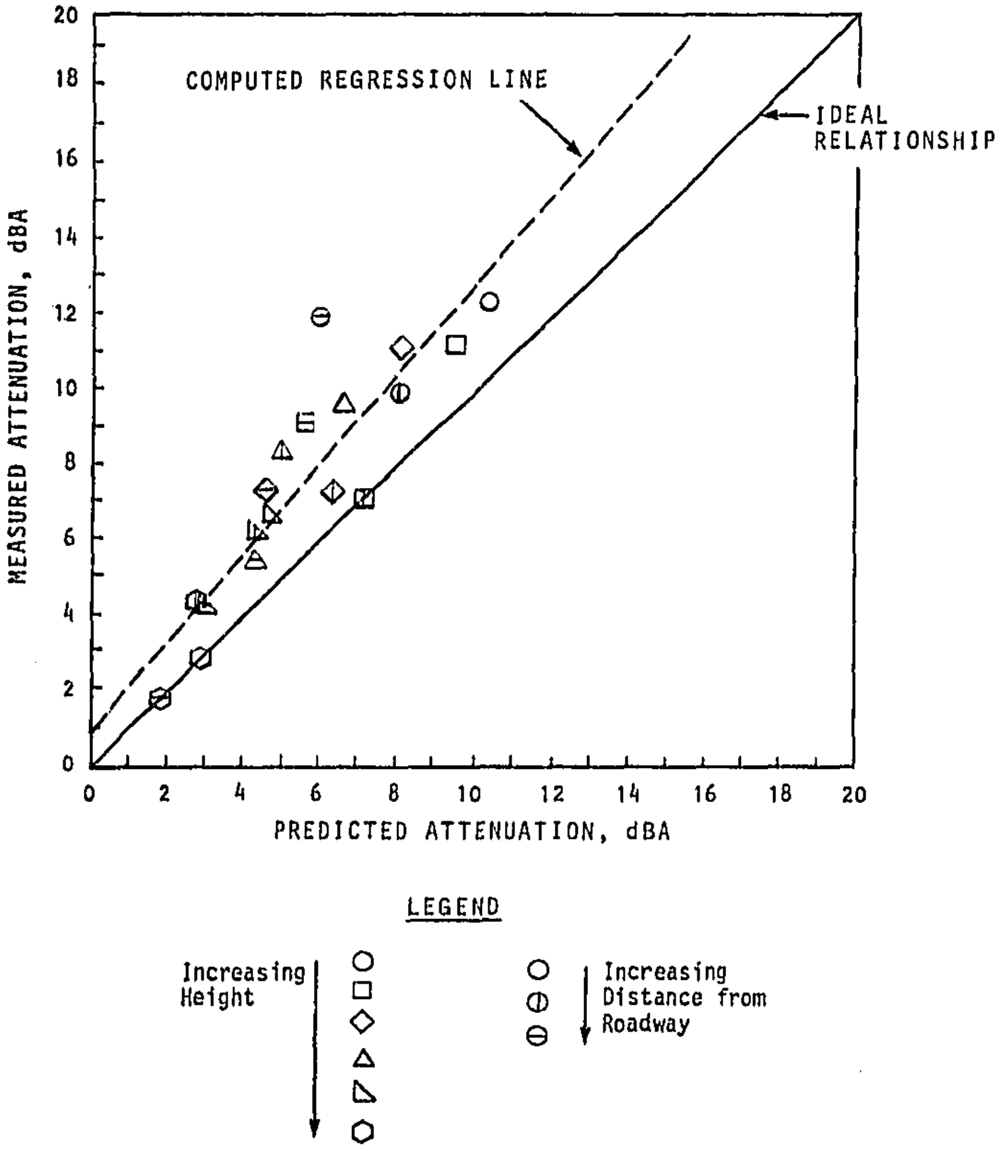
SITE 04


IDEAL RELATIONSHIP
COMPUTED REGRESSION LINE
MEASURED ATTENUATION, dBA
0
2
4
6
8
10
12
14
16
18
20
PREDICTED ATTENUATION, dBA
0
2
4
6
8
10
12
14
16
18
20
LEGEND
Increasing Height
○
□
◇
△
◺
⬡
○
⦶
⊖
Increasing Distance from Roadway

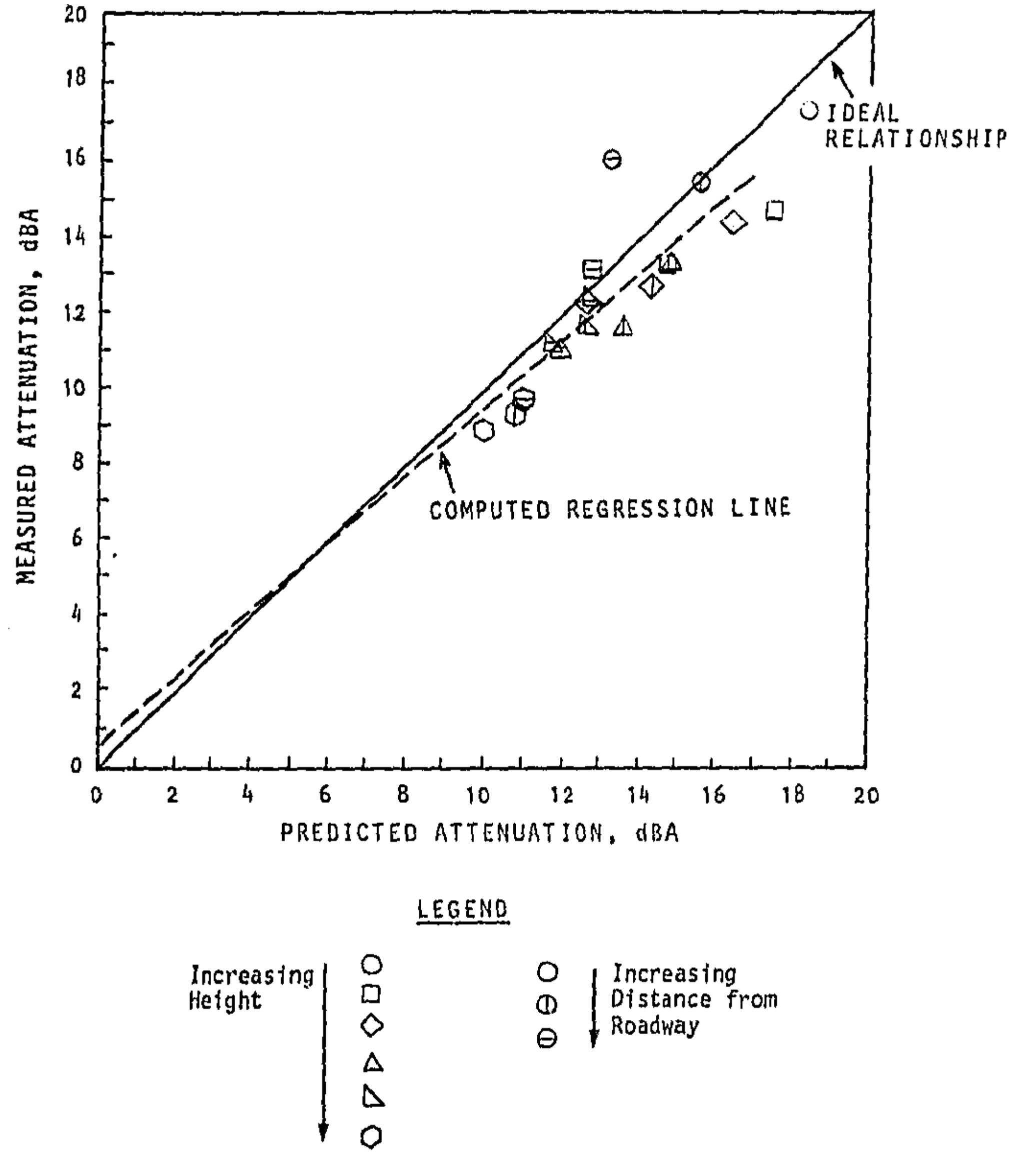
SITE 05


20
18
16
14
12
10
8
6
4
2
0
MEASURED ATTENUATION, dBA
0
2
4
6
8
10
12
14
16
18
20
PREDICTED ATTENUATION, dBA
IDEAL RELATIONSHIP
COMPUTED REGRESSION LINE
LEGEND
Increasing Height
Increasing Distance from Roadway

SITE 06

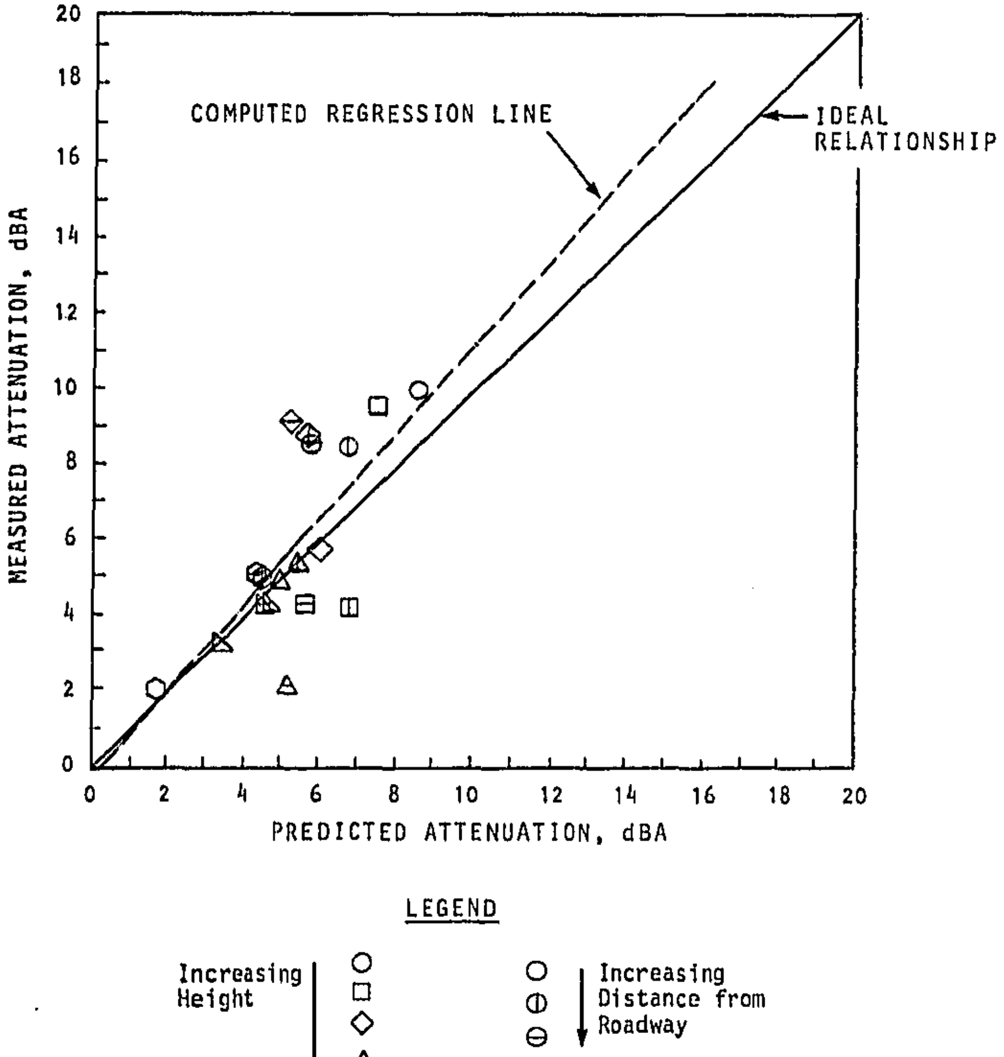

COMPUTED REGRESSION LINE
IDEAL RELATIONSHIP
MEASURED ATTENUATION, dBA
0
2
4
6
8
10
12
14
16
18
20
PREDICTED ATTENUATION, dBA
0
2
4
6
8
10
12
14
16
18
20
LEGEND
Increasing Height
○
□
◇
△
◺
⬡
○
⦶
⊖
Increasing Distance from Roadway

SITE 07

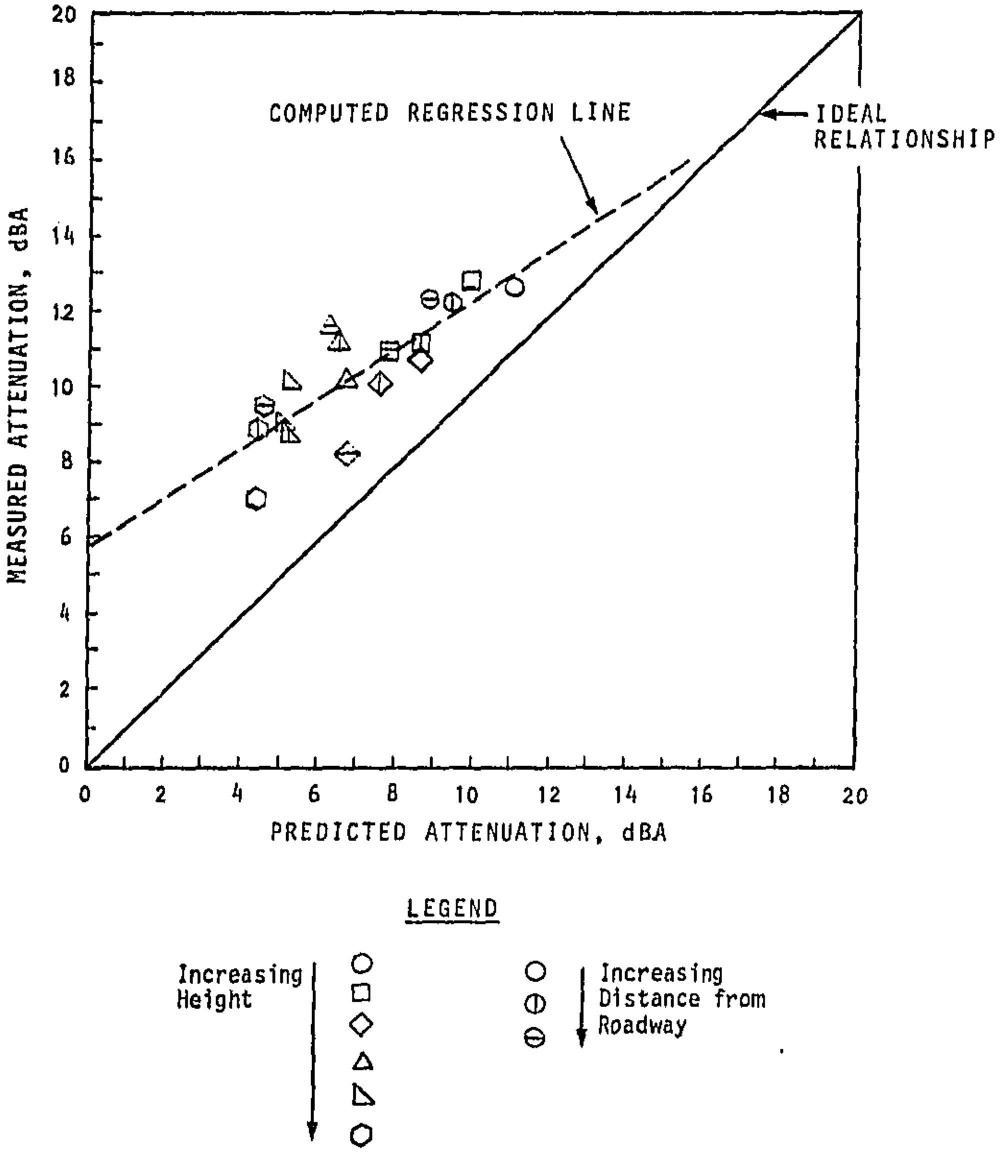


MEASURED ATTENUATION, dBA
0
2
4
6
8
10
12
14
16
18
20
PREDICTED ATTENUATION, dBA
IDEAL RELATIONSHIP
COMPUTED REGRESSION LINE
LEGEND
Increasing Height
○
□
◇
△
◺
⬡
○
⦶
⊖
Increasing Distance from Roadway

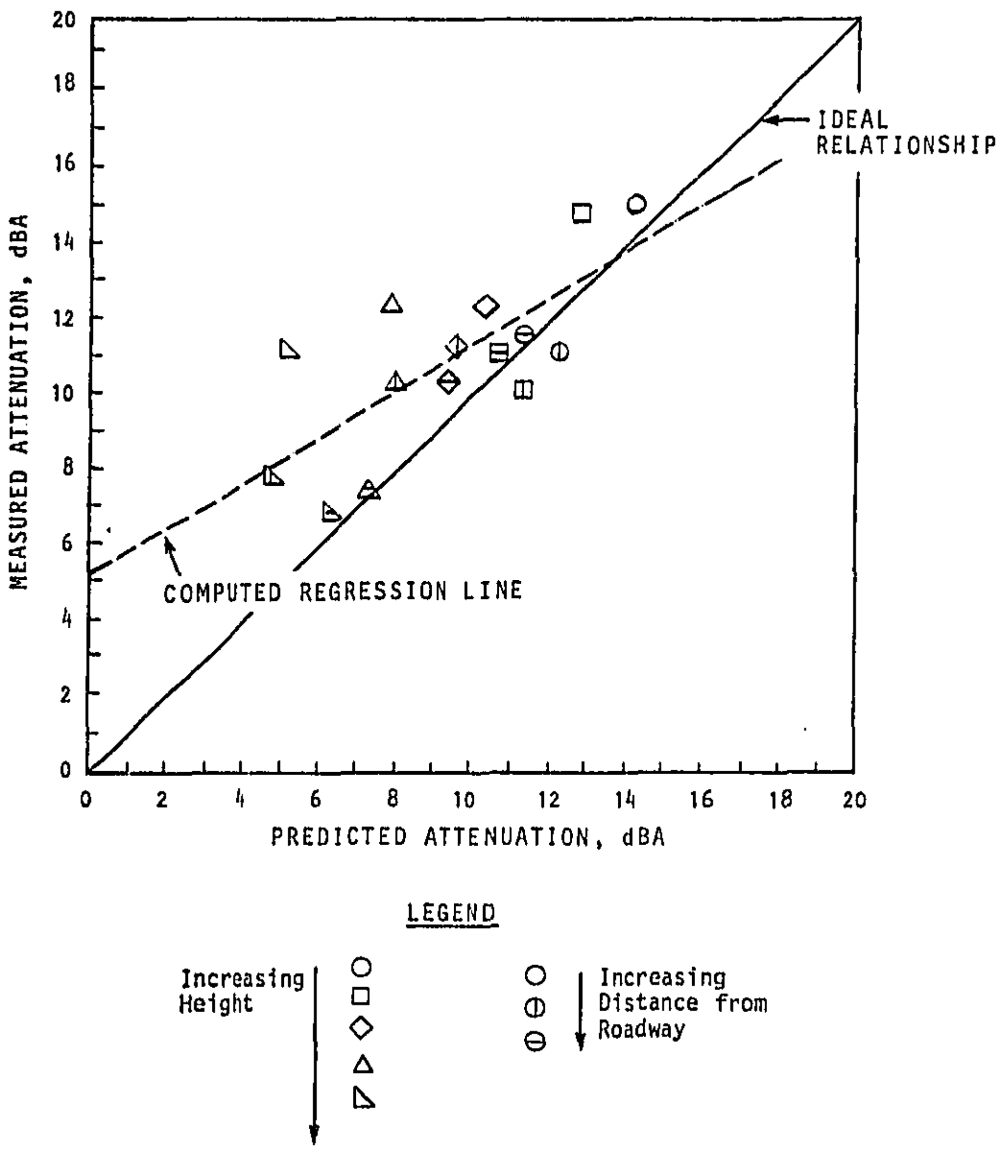
SITE 08


20
18
16
14
12
10
8
6
4
2
0
MEASURED ATTENUATION, dBA
0
2
4
6
8
10
12
14
16
18
20
PREDICTED ATTENUATION, dBA
COMPUTED REGRESSION LINE
IDEAL RELATIONSHIP
LEGEND
Increasing Height
Increasing Distance from Roadway

SITE 09


COMPUTED REGRESSION LINE
IDEAL RELATIONSHIP
MEASURED ATTENUATION, dBA
PREDICTED ATTENUATION, dBA
0
2
4
6
8
10
12
14
16
18
20
LEGEND
Increasing Height
Increasing Distance from Roadway

SITE 10


MEASURED ATTENUATION, dBA
0
2
4
6
8
10
12
14
16
18
20
PREDICTED ATTENUATION, dBA
IDEAL RELATIONSHIP
COMPUTED REGRESSION LINE
LEGEND
Increasing Height
Increasing Distance from Roadway

APPENDIX F

FREQUENCY ANALYSIS OF MEASURED BARRIER ATTENUATION

Most practical methods for estimating barrier attenuation rely upon the assumption that the A-weighted noise reduction of the barrier is identical to the noise reduction determined from diffraction theory for a 550 Hz signal. Because of the spectral content of automobile and truck noise sources, and the spectral shape of the A-weighting filter, the acoustic energy in the region around 500 Hz is a major contributor to the A-weighted noise level of traffic noise. Thus, the use of the 550 Hz noise reduction for the A-weighted noise reduction seems reasonable.

In order to validate this assumption, the measured A-weighted attenuation was compared with the attenuation measured in the 500 Hz octave band for twenty-two samples obtained at nine of the barrier sites.

The average difference between the A-weighted and 500 Hz octave band measured attenuations for these twenty-two samples was 0.5 dB, which was not significantly different from 0. Figure F.1 shows the measured A-weighted attenuations plotted versus the measured attenuations in the 500 Hz octave band. The computed least squares' regression line through these data points is shown on the figure; it has a correlation coefficient of .94. This comparison indicates that the A-weighted attenuation is nearly identical to the attenuation of the 500 Hz octave band. Thus, the use of a predictive method based on a frequency of 550 Hz appears to be a valid approach to predicting the A-weighted attenuation of a barrier.

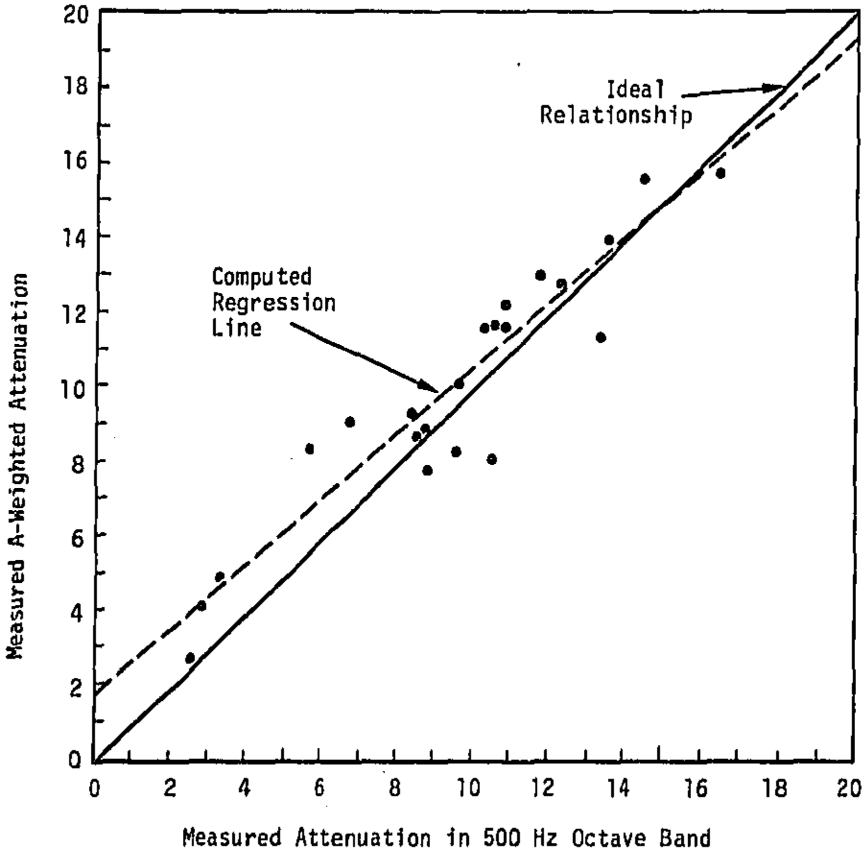


FIGURE F.1 Comparison of Measured A-Weighted and 500 Hz Attenuation.

APPENDIX G

COMPARISON OF MEASURED AND PREDICTED ATTENUATIONS FOR STATE HIGHWAY DEPARTMENT DATA

In Reference 8, information is provided concerning fifty barriers that have been built along roadways in this country to reduce traffic noise. For thirteen of these barriers, measurements of the resulting attenuation have been reported by the various State Highway Departments.

The reported measured attenuations have been compared with predicted values of attenuation based upon the barrier attenuation nomograph in Reference 2. (Note that this nomograph incorporates the Kurze-Anderson infinite line source model of attenuation.)

Table G-1 presents the predicted versus measured attenuations for the various barriers, along with the geometric and traffic parameters used in the prediction calculations. Note that for several of the sites, more than one observer location is considered. As shown on the table, complete, well-defined information concerning the noise measurements was available for only three of the barriers.

A lack of information concerning many of the details of the measurements and highway configurations precludes an extremely accurate assessment of agreement between measured and predicted results. However, as a rough measure of the agreement between measured and predicted values, the average discrepancy may be determined. For the thirteen barriers (incorporating 18 measurement/prediction comparisons), the average discrepancy is -0.5 dB, with a standard deviation of 4 dB. This small average discrepancy between measured and predicted values indicates relatively good agreement. The large standard deviation is not unexpected, based upon the lack of detailed information from which to base predictions.

Perhaps more important than the good agreement between measured and predicted results indicated by this rough comparison is the conclusion that barrier attenuation be evaluated after construction, and that uniform reporting standards and procedures be adopted by the various state highway departments in this evaluation. This approach could lead to the development of a data base for the purpose of evaluating barrier effectiveness. It is therefore recommended that all reported attenuation data include the following minimum information:

1. Source-barrier distance
2. Barrier-observer distance
3. Source height
4. Observer height
5. Barrier height
6. Barrier length
7. Location of measurement position
8. Traffic volume
9. Heavy truck mix
10. Average vehicle speed
11. Measured attenuation values (including clear definition of noise level descriptor used)
12. Brief description of measurement procedure

Table G-1

PREDICTED VS. MEASURED HIGHWAY NOISE BARRIER ATTENUATION

Barrier Location and Description	Source-Barrier Distance (ft.)	Observer-Barrier Distance (ft.)	Height (ft.)	Length (ft.)	Traffic Volume (VPH)/ Truck Mix (%)	Speed (MPH)	Predicted Attenuation (dBA)			Measured Attenuation (dBA)
							Autos	Trucks	Total	
Fresno, Ca. SR-41 Concrete Wall	46 46	24 74	7 7	860 860	500/5 500/5	55 55	9.5 7.5	6 0	7 2	10-13
Montebello, Ca. SR-60 Concrete Wall	14	41	12.5	2300	4833/5	55	14.5	11	12	10-12
Ontario, Ca. I-10 Metal Wall	80 80	15 80	8.5 8.5	304 304	2792/5 2792/5	55 55	9.5 5	8.5 3.5	9 4	6
Pacoima, Ca. I-5 Concrete Wall	31	110	14	1164	4208/5	55	10	9	10	13
Sacramento, Ca. I-80 Concrete Wall	50 60	70 95	7 7	8310 8310	2445/5 2445/5	55 55	9.5 9	0 0	3 3	13
Boulder, Co. SR-157 Earth Berm	30 40	50 75	6.5 6.5	1550 1550	3000/5 3000/5	55 55	10 9	0 0	2 2	0-8
W.Hartford, Ct. I-84 Earth Berm*	110 128	40 130	20 20	1800 1800	3777/7 3777/7	59 59	14 10	13 9	13 9	11 11

* Predicted attenuations for these sites are based on complete, well-defined measurement information.

Table G-1

PREDICTED VS. MEASURED HIGHWAY NOISE BARRIER ATTENUATION (Cont'd)

Barrier Location and Description	Source-Barrier Distance (ft.)	Observer-Barrier Distance (ft.)	Height (ft.)	Length (ft.)	Traffic Volume (VPH)/ Truck Mix (%)	Speed (MPH)	Predicted Attenuation (dBA)			Measured Attenuation (dBA)
							Autos	Trucks	Total	
Kalamazoo, Mi. I-94 Earth Berm	72	25	10	1850	1341/16.5	57	11	9	10	7-9
Minneapolis, Mn. I-35W Wooden Wall*	98 104 106	35 185 335	17 17 17	1880 1880 1880	8000/5 8000/5 8000/5	60 60 60	16.5 9.5 6.5	15.5 8.5 6	16 9 6	10 6 7
Minneapolis, Mn. I-94 Concrete Wall*	64	68	21	(See below)†	6000/4.5	60	15	13	14	12
St. Paul, Mn. I-94 Earth Berm	40	55	12.5	1050	6000/4	60	11.5	10	11	2.5-5
Bellevue, Wa. I-405 Wooden Wall	40 120	60 170	12 12	735 735	3000/5 3000/5	55 55	10 5.5	8.5 4.5	9 4	4
Oak Creek, Wi. I-94 Earth Berm	90 90 90	25 125 300	7.5 7.5 7.5	800 800 800	1335/2.5 1335/2.5 1335/2.5	64 64 64	8.5 4 2.5	6.5 2.5 1.5	7 4 2	9 6 4

* Predicted attenuations for these sites are based on complete, well-defined measurement information

† Section of continuous wall

GPO 912-683

* U.S. GOVERNMENT PRINTING OFFICE: 1977—728-336/1209