URBAN TRAFFIC NOISE REDUCTION: FINAL REPORT

By

Donald L. Woods

and

Murray F. Young

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The opinions, findings and conclusions expressed or implied in this report are those of the research agency and not necessarily those of the Texas Highway Department or of the Federal Highway Administration.

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ABSTRACT

This report presents the findings of Project 2-8-71-166 and documents the execution of the research program in accordance with the project objectives. The project activity was divided into three major segments and reported accordingly. In Research Report 166-1 the human tolerance to traffic noise was examined and recommendations made dealing with the maximum noise levels for individual vehicles and for the acceptable noise levels for various land uses.

Research Report 166-2 examined the problem of the evaluation of highway noise complaints and recommended a procedure for estimating the noise levels from existing facilities for engineering decision making. The recommended procedure involves the use of an inexpensive hand-held sound pressure level meter and periodic sampling of the sound pressure level. A detailed procedures manual on the concept has been provided.

Research Report 166-3 served a two-fold purpose. The first was to examine the utility of several theoretical methods of estimating the magnitude of the noise reduction resulting from a barrier wall, and the second was to evaluate the relative accuracy of the design guide procedure (NCHRP Report 117) for estimating noise levels on existing and proposed freeway facilities. It was concluded that the use of Fehr's equations to predict the noise reduction is both practical and accurate within acceptable engineering limits, and that the side slope of a depressed freeway can be considered as a barrier wall for practical application. Further, it was concluded that the design guide procedure yields valid estimates of the traffic noise, at least for the cases considered in this study.

IMPLEMENTATION STATEMENT

The results of this research have been and are being utilized at the present time by the Texas Highway Department and several other agencies. This final report documents the research accomplishments, and specific implementation of the findings reported herein is not expected. The implementation has been and should be the result of the more detailed project reports previously transmitted to the sponsor.

RECOMMENDATIONS FOR FURTHER RESEARCH

The findings of this project indicate a need for further research in the following areas:

1. Establishment of maximum noise levels from urban freeways during nighttime hours
2. Means of decreasing noise from trucks and construction equipment
3. Evaluation of the optimum longitudinal profiles, cross-sections and grades for new freeways to reduce the effects of urban noise
4. Cost-effectiveness of traffic noise reduction measures
5. Aesthetic treatment of traffic noise barriers

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

BASIC STUDY OBJECTIVES

The five basic objectives of this research study were as follows:

1. To evaluate and recommend threshold noise levels for various types of land use activities;
2. To evaluate and recommend equipment for the measurement of traffic noise;
3. To recommend a procedure for the evaluation of traffic noise potential associated with a new highway location with a specific design configuration;
4. To establish the degree of traffic noise near urban highways in Texas; and
5. To recommend traffic noise reduction techniques for use on existing traffic facilities.

The original work plan called for these objectives to be completed over a 24-month period, but due to a re-evaluation of the Texas Highway Department's current need for research, this project was not renewed for the fiscal year 1971-72. Consequently, objective numbers 4 and 5 were not covered in the depth that they deserved.

Three research reports, Numbers 166-1, 166-2 and 166-3, were submitted to the Department during the length of the contract. Research Report Number 166-1 basically considered the objective of evaluating and recommending threshold noise levels for various types of land use activities. The report reviewed and evaluated much of the existing state-of-the-art of highway noise measurement, sources of highway noise, and individuals affected by highway noise.

Objective number 2, evaluation and recommendation of equipment for the measurement of traffic noise for the Austin office, was undertaken during the initial library review and reported in correspondence to the Department. This recommendation outlined noise measuring equipment necessary for the Austin office which included a recorder, microphone, inverter, octave-band analyzer, graphic level recorder, and sound level recorder. Noise measuring equipment for use in district offices was reported in the second report (Number 166-2) and was included with Objective 3.

Objective number 3 was to recommend a procedure for the evaluation of traffic noise near a new highway. The results of this effort are reported in Research Report Number 166-3. This research utilized field data gathered in Houston, Texas, and compared these values with those estimated using the procedure outlined by Galloway, et al. (1). The field-measured and the theoretically-calculated traffic noise values showed an exceptionally close correlation. Research Report Number 166-2 described a procedure that could be used in estimating highway noise from an existing facility. A hand-held sound level meter is used to measure the sound pressure every 15 seconds for a period of five minutes. The average of these readings yields a mean value that can be used to evaluate highway noise problems for engineering decisions. In addition, a method of estimating the peak traffic noises associated with a mean sound pressure level was developed.

Objective number 4, establishment of the degree of traffic noise near urban highways in Texas, was only partially met. Due to the reduced contract time, the only noise levels actually measured in the field were those on sections of the Katy Freeway (IH-10) and State Highway 59, as well as ambient noise levels in several residential areas. All sites were located in Houston, Texas.

Objective number 5 was the basis for Research Report Number 166-3. This report described the use of barrier walls to reduce noise from existing affect highway noise and used Fehr's (2) equations to calculate the noise attenuation from a barrier wall or side slope. A brief summary of each project report is presented in the following paragraphs.

THRESHOLD NOISE LEVELS

The title of Research Report Number 166-1, "Threshold Noise Levels," introduces the basic problem faced by the highway engineer today. What should be the maximum sound pressure level (in units dBA) from cars and trucks? In attempting to answer this question, the authors have reviewed the state-of-the-art and have suggested that the daytime maximum noise level, measured 50 feet from the source, should be 85 dBA for trucks and 77 dBA for cars.

The above maximum values were derived after a review of the magnitude of the problem involving the sources of highway noise, the methods by which it can be measured, and the individuals who are affected by the noise.

It is generally accepted that the physical effect of noise can be measured in units of decibels. These units are usually measured on the "A" weighted network of a precision sound level meter (3). It must be noted that the decibel is not a direct measure of loudness, but when applied to highway noise it correlates closely to that noise which is heard by the human ear. The psychological impact of highway noise cannot be measured in quantitative units since it is a subjective value. Galloway, et al., (3), found that the higher socio-economic groups tend to have a lower noise tolerance level than other groups, whereas Colony (4) developed an acceptability index for residential property in which values over 72 dBA were classed as "annoying."

The physiological effects of highway noise are less clear. Botsford (5) considers 90 dBA to be the beginning of dangerous noise, but, even then, only when one is exposed for prolonged periods of time. Young (6) suggests that 85 dBA heard for prolonged periods could induce hearing impairment in a very small percentage of people. Since automobiles traveling at 65 mph on an 8-lane freeway produce a maximum noise level of about 75 dBA (measured 100 feet from the source), it is unlikely that such traffic could impair one's hearing.

The sources of highway noise were reviewed, and it was found that the engine-exhaust noises of trucks and the tire-roadway interaction of cars were the primary sources of highway noise pollution. Colony (4) found that the majority of people living near a freeway considered trucks the primary source of the problem. This noise is mainly caused by the air intake, the exhaust system, and the engine itself.

In recommending threshold noise levels, the authors considered the above problems, i.e. the physical quantitative factors, the subjective psychological effects, and the physiological effects of prolonged extreme noise exposure. The threshold noise level values suggested by the authors were compared with those recommended by other authors or agencies, and it was decided that these values were realistic at this particular time. As traffic increases, however, these values should be lowered, especially for trucks, since it is these vehicles that create the troublesome peak values. Using these values the authors recommended noise levels for various land use activities measured at the property line, as well as inside the structure, for both day (7 a.m.-10 p.m.) and night (10 p.m.-7 a.m.) hours (Table 1).

Based on the review of many studies undertaken in this and other countries, it is recommended that consideration be given to the adoption of a maximum sound level of 85 dBA for trucks and 77 dBA for automobiles, measured 50 feet from the source and under full acceleration. These values are recommended for daytime hours, and further research is necessary to determine night maximum vehicle noise values. Maximum noise legislation is the long term solution of the control of noise levels from vehicles; but for immediate action acoustic barrier walls appear to be necessary for noise reduction in problem areas.

TRAFFIC NOISE MEASUREMENT EQUIPMENT

(a) Austin Office

In reviewing the types of sound pressure level measurement and recording equipment needed in the Austin Division Office of the Texas Highway Department, two primary factors were considered. Most importantly, the head office needed equipment capable of analyzing traffic-associated noise, recording this noise for a permanent record, and obtaining sufficient accuracy to meet all legal requirements for acceptance in a court of law. Secondly, the equipment must be portable.

TABLE 1

SUMMARY OF RECOMMENDED NOISE LEVELS
FOR VARIOUS LAND USES (7)

Land Use Activity	Time of Day	Recommended Maximum Mean Sound Pressure Level (dBA) At Property Line	Inside a Structure
Residential (single and multiple family)	Day (7a.m.-10p.m.)	70	65
	Night (10p.m.-7a.m.)	65	55*
Business, Commercial and Industrial	All	75	65
Educational Institutions	All	70	60
Hospitals and Rest Homes	Day	60**	55
	Night	50**	45
Public Parks	All	70	55

*Air conditioning systems commonly operate at 55 dBA. For non-air-conditioned residential structures it may be desirable to reduce this value by 5 dBA.

**Expected ambient noise level.

At the present time, these requirements can probably best be met with the following components:

Item	Source	Type	Approx. Coat
Acoustical Data Recorder	General Radio	1525-A	$3,000
Acoustical Microphone Set	General Radio	1560-P6	300
175 watt, 12 volt D.C. to 120 volt, 60 Hz AC power Inverter	--	--	300
Octave-band Noise Analyzer	General Radio	1558	1,100
Graphic Level Recorder	General Radio	1521-B	1,600
Sound Level Calibrator	General Radio	1562-A	300
		TOTAL	$6,600

The recommended equipment, or its equal, will provide precision noise recording and analysis capability for meeting the needs of the Texas Highway Department. The recommended equipment was not tested relative to other brands and types, but was successfully used during the project. Due to the continued improvement in acoustical equipment, it would be advisable that contact be made with the General Radio Company to ensure that there have not been any improved models marketed since early 1971.

(b) Field Offices

The traffic noise measurement equipment needed by the district offices of the Texas Highway Department varies singificantly from that required by the Austin office. The costly data recorders and acoustic noise analyzers are too expensive to provide this capability in each district. Not only would the complex equipment be unused for a large percentage of the time, but the acoustically-trained personnel necessary to operate such equipment would be unproductive. It is unlikely that there would be sufficient demand to justify a full-time position in this capacity.

Research Report Number 166-2 recommends that each Highway Department district office have the capability to evaluate highway noise using the periodic sampling procedure (8). This would provide a means of estimating the seriousness of any reported highway noise problem in the district. Such a procedure allows the District Engineer to have inexpensive equipment on hand which can be operated by his own personnel. Upon receipt of traffic noise complaints, a technician can be sent into the field, and, in a matter of hours, the mean noise level of the traffic, measured at various distances from the highway, can be determined.

The following equipment, or its equivalent, is recommended. The use of a particular brand of equipment does not necessarily mean that this product is endorsed, but means instead that this particular make of equipment was successfully used during the project.

a) General Radio Sound-Level Meter, Type 1565-A, with carrying case and replacement battery.

b) General Radio Sound-Level Calibrator, Type 1562-A.

This product is available on the market today, but periodic checks should be made before purchasing equipment to ensure that new or improved models have not been released.

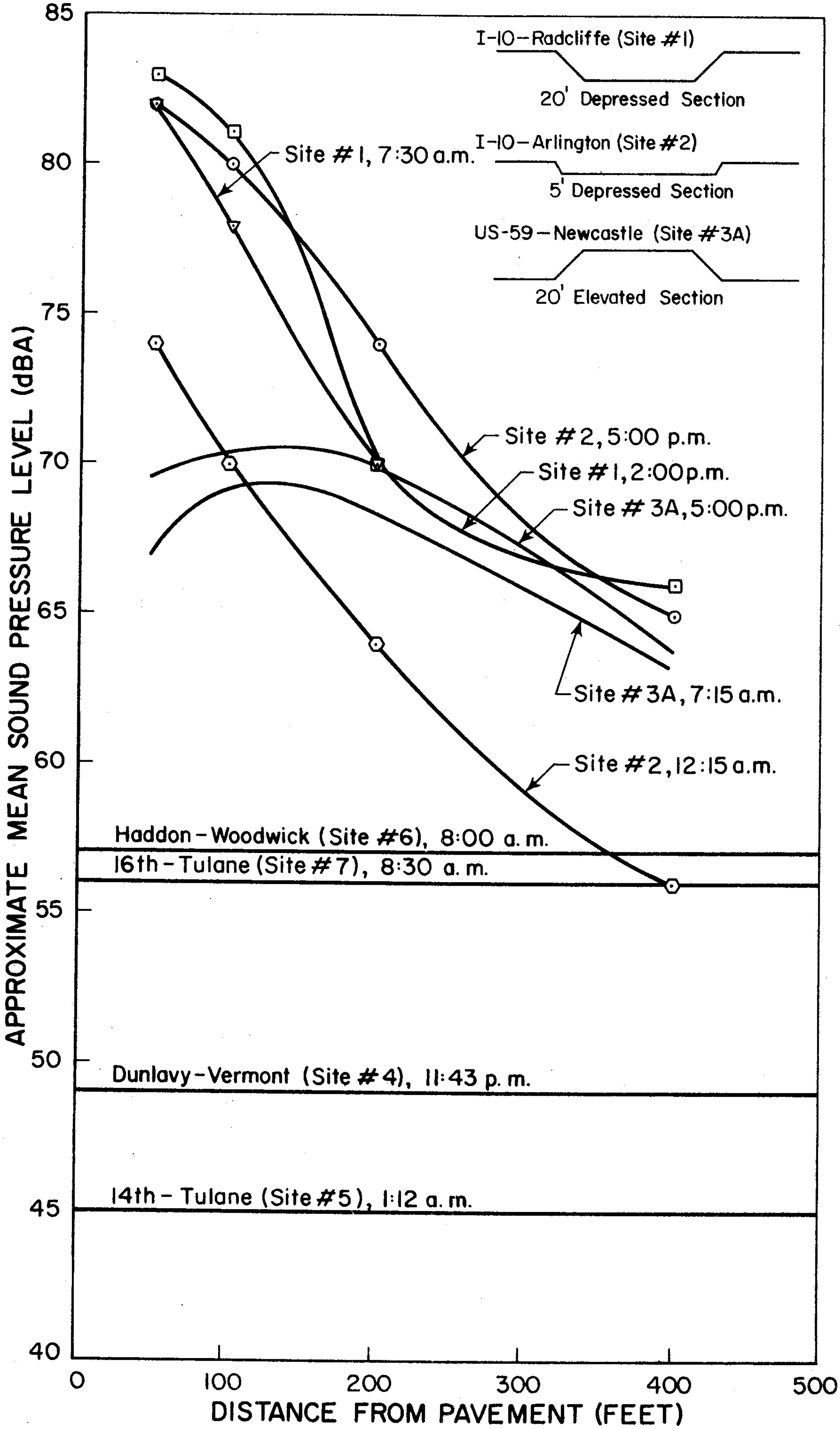
FIELD MEASUREMENTS

The field measurement of traffic noise was deemed desirable to provide basic data for comparison with the design guide estimates, to evaluate the use of the hand-held sound pressure meter, and to establish a data pool which would permit the evaluation of the periodic sampling concept. Field recordings of the sound measure level were made adjacent to three freeway sections in Houston, Texas, on January 12, 13, and 14, 1971.

Figure 1 summarized typical values recorded in the field. Site number 1 was a depressed section (see Figure 2 in the next section) of the Katy Freeway (IH-10) at Radcliffe Street, with recordings made at distances of from 50 feet to 400 feet from the traveled lane. Site number 2 was on IH-10 at Arlington Street, where the depressed section was about 3 to 5 feet deep. Sites number 3 and number 3A were adjacent to State Highway 59 near Newcastle Street. Ambient noise levels were recorded at four locations in surrounding residential areas, far enough away from any major arterial street or freeway to ensure minimal interaction.

The ambient levels shown in Figure 1 compare favorably with the values found by Thiessen (9) in his research on factors influencing background noise levels. He found night ambient levels just over 50 dBA and daytime ambient levels just over 60 dBA.

The ambient noise levels recorded in residential areas and those recorded 400 feet from a freeway are presented in Table 2. Ambient noise levels in residential areas late at night generally were double those recorded during early morning hours (i.e., a 10-dBA increase). For morning noise levels in residential areas when compared to those measured 400 feet from a freeway



MEAN dBA VALUES AT HOUSTON SITES
Figure 1

Table 2

MEAN AMBIENT NOISE RECORDED IN HOUSTON, TEXAS

Locations	Time of Recording	Approximate Mean dBA
Dunlavy-Vermont (Site 4)	11:43 p.m.	49
14th - Tulane (Site 5)	1:12 a.m.	45
Haddon-Woodwick (Site 6)	8:00 a.m.	57
16th - Tulane (Site 7)	8:30 a.m.	56
400' Arlington* (Site 2)	12:46 a.m.	53
400' Arlington* (Site 2)	5:50 p.m.	64
400' Newcastle (Site 3A)	11:15 p.m.	58
400' Newcastle (Site 3A)	2:45 p.m.	64
400' Radcliffe (Site 1)	3:30 p.m.	63

*Indicate 400 feet from the freeway on Arlington Street during the day, there is about an 8-dBA difference. However, it is interesting to note that the morning noise level in residential areas is as high as that measured 400 feet from the freeway during night hours. While this level does not appear to be excessive (56 ± dBA), it could be significant to adjacent residents during sleeping hours. More importantly, however, are the 90th percentile values. These are the sound pressure levels which occur for 10 percent of the time and are usually associated with truck exhausts, motor bikes, sports cars, or automobiles in hard acceleration. Using the 90th percentile graph (Figure 9), a mean value of 56 dBA would give a 90th percentile value of 59 dBA. This indicates that noise levels above 59 dBA occur for 10 percent of the time, which during nighttime hours is likely to be even more objectionable than the mean value.

It is interesting to note that the embankment of elevated freeways provides good protection from traffic noise within 200 feet of the traveled way. Noise levels at Site 3A between 50 feet and 200 feet are as much as 15 dBA lower than the values at Sites 1 and 2 without any "barrier wall" to reduce the sound. As the observer goes farther from the source, the height of the embankment "barrier wall" is reduced in height, and the noise levels at all freeway sites become similar.

HIGHWAY NOISE REDUCTION BY BARRIER WALLS

(a) Acoustical Materials for Barrier Walls

Before a discussion of the various types of acoustical materials can be presented, one must understand their function. Porous materials are efficient in reducing traffic noise because their surfaces have the two components necessary to attenuate sound energy: 1) a surface capable of absorbing sound waves, as opposed to a surface which reflects sound; and, 2) a surface that transforms wave energy into heat energy by friction (10).

The difference between sound transmission loss and sound absorption also should be defined. Light weight barrier walls made of porous concrete, wood, mineral-wool fibers, etc., absorb most of the incident sound but transmit this sound with little attenuation. However, a barrier wall constructed of dense concrete or brick absorbs little sound and prevents its passage to the other side; thus, a larger degree of attenuation results (11).

Both cost and noise energy attenuation must be considered when selecting acoustical materials. No one material can be generally recommended, since some of those which reduce the sound to a predetermined level might be too expensive and/or not applicable to every situation. Waller (12) compared the performance and economics of noise reduction materials in the construction industry and noted that not only the cost of the wall itself must be considered, but also costs for foundations, erection of the barrier, and attachment of the acoustical material to the wall. He notes that the engineer should seek a balance, an optimization, between sound-absorbing and sound-insulating materials.

Sabine, et al. (13), in their study of transmission losses in lightweight concrete, found that there was an increased transmission loss (17dB) between an unplastered and a plastered four-inch cinder block. They concluded that a porous masonary wall which is painted heavily enough to seal the surface porosity has a transmission loss equal to that of a solid masonary wall of the same weight and stiffness. Future research is needed to determine the feasibility of a barrier wall constructed of a lightweight material (such as vermiculite concrete), plastered or heavily painted on one side.

Another lightweight barrier wall material is polystyrene foam. If polystyrene foam has an open cell wall, there exists an increased resistance to the transmission of sound and absorption due to the many branch channels (14). Sheets of polystyrene foam have the advantages of good shear and bending strengths, easy application and good sound-deadening properties. Softer and more flexible polystyrene foams have been developed for use as sound absorbing barriers. The sound absorption properties of hard polystyrene foam are greatly improved by needle puncturing and support of the sheet away from the wall. The use of hard polystyrene foam sheeting directly on a wall does not reduce the absorption significantly.

Care must be taken in the selection of barrier wall materials from the vast array of products available on the market today since the majority of these products has been manufactured for use inside buildings rather than for walls exposed to the environment. Such practical aspects as space limitations, weight limitations, and weather exposure must be considered when selecting an acoustical material. Some materials rapidly disintegrate when exposed to the weather (wood and cellulose fibers, wool, felt, etc.), whereas others recommended for outside use (fiber-glass blankets, rockwool, or steel wool) perform well (10).

In summary, the highway engineer must recognize the trade-off that must be made between the cost of the acoustical materials and the resulting noise attenuation. Noise control is a systems problem in which the goal is to obtain an acceptable reduction of noise at a reasonable cost. Future research is necessary to find barrier wall materials that will give an acceptable noise attenuation at reasonable costs. Research is also needed to investigate the possibility of using lightweight concrete barrier walls on bridges.

(b) Noise Level Reduction by Barrier Walls

One method of reducing traffic noise is to construct acoustically opaque barrier walls that will reduce the noise to acceptable levels. One objective of this research was to review the methods of reducing traffic noise and the types of barrier walls that might be used for this purpose.

Two sites were evaluated; one site had data already available (Sacramento Cummunity Drive-In Church, California), and the other required the measurement of traffic noise in the field (on Radcliffe Street, adjacent to the Katy Freeway (IH-10), Houston, Texas). The basic aim of this study was to correlate noise values recorded in the field with those calculated using Fehr's equations (2).

A detailed description of the methods and equipment used at the Houston sites was previously reported by the authors (8,15), and only a brief description of the site and other supporting details will be included here.

The general dimensions of the Houston test site are shown in Figure 2. Measurements taken at 200 feet and 400 feet from the traveled way resulted in a variation in the effective height of the side slope barrier.

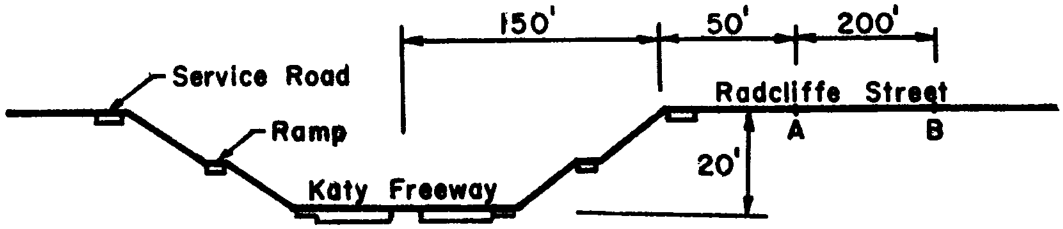


Figure 2. Cross section of Katy Freeway and Radcliffe Street.

The top of the side slope represented the top of the theoretical barrier wall, with the sound source located 20 feet below. The effective barrier heights for the Radcliffe Street sites are shown in Figure 3, where HA = 5 feet and H_B = 13 feet.

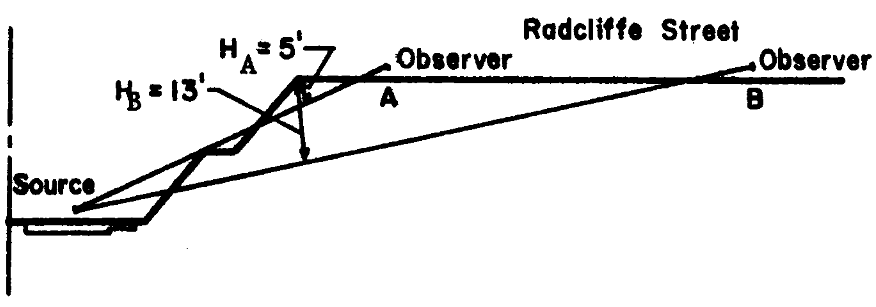


Figure 3. Effective barrier heights for Radcliffe Street sites.

A vertical 20-foot cut section gives greater attenuation than a sloping 20-foot section, especially within 200 feet of the traveled way. This results because the effective height of the vertical side (H_v) is greater and closer to the noise source than is the sloping side section (H_s), as seen in Figure 4. As the receiver moves farther away from the noise source, the difference in the effective heights rapidly decreases. This can be seen in Figure 5, where the difference in the effective heights due to vertical and sloping sides of a depressed freeway rapidly decrease when the receiver moves from 100 feet to 300 feet from the noise source.

The Sacramento Community Drive-In Church was located adjacent to Route 99, a heavily traveled route with a high percentage of trucks. Due to excessive traffic noise, the church decided to construct a 10-foot high earth barrier, about 350 feet long, between the drive-in area and Route 99.

Analysis of field data was described in a previous report by the authors (15) and will not be detailed in this summary report. However, a brief description of the computer and nomograph solutions using Fehr's equations (2) has been included to emphasize their use in highway noise investigations. Noise level reduction graphs developed from the computer output have been included in Appendix A. Appendix B shows the nomograph solution of Fehr's equations (2) with a worked example.

Table 3 below compares the values found using the sound level estimation method (8), the design guide method (1), the complete analysis using the data recorder (8), and the method for consideration of the side slopes

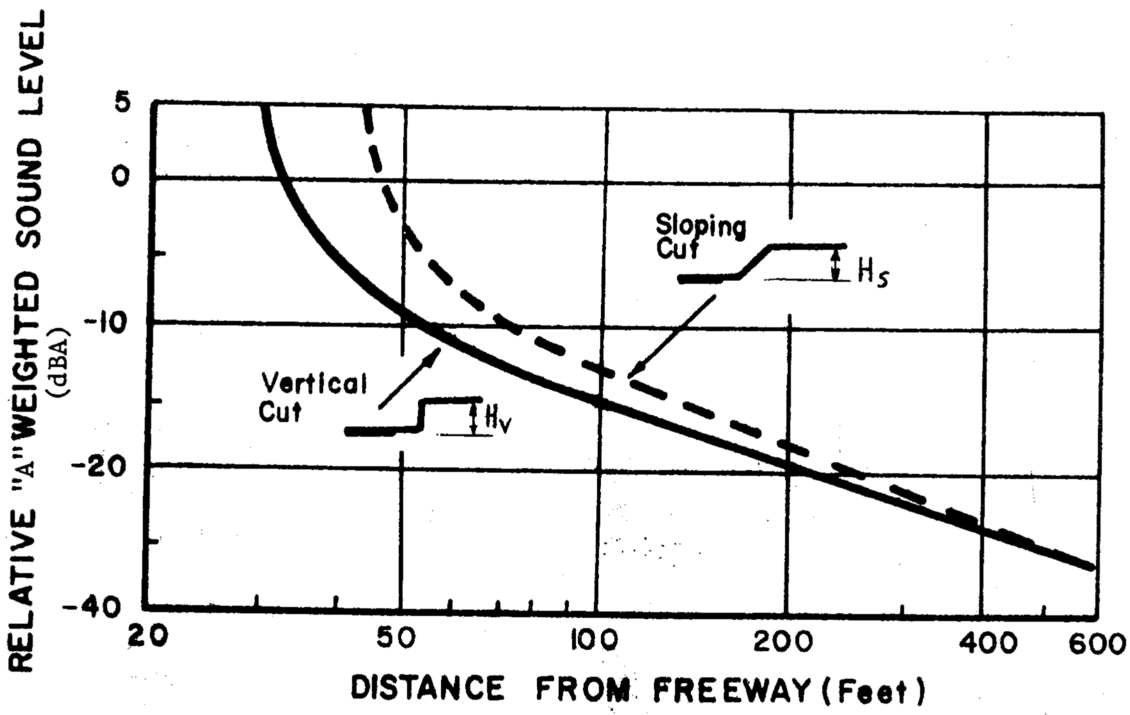


Figure 4 . Noise reduction due to vertical and sloped sides. (3)

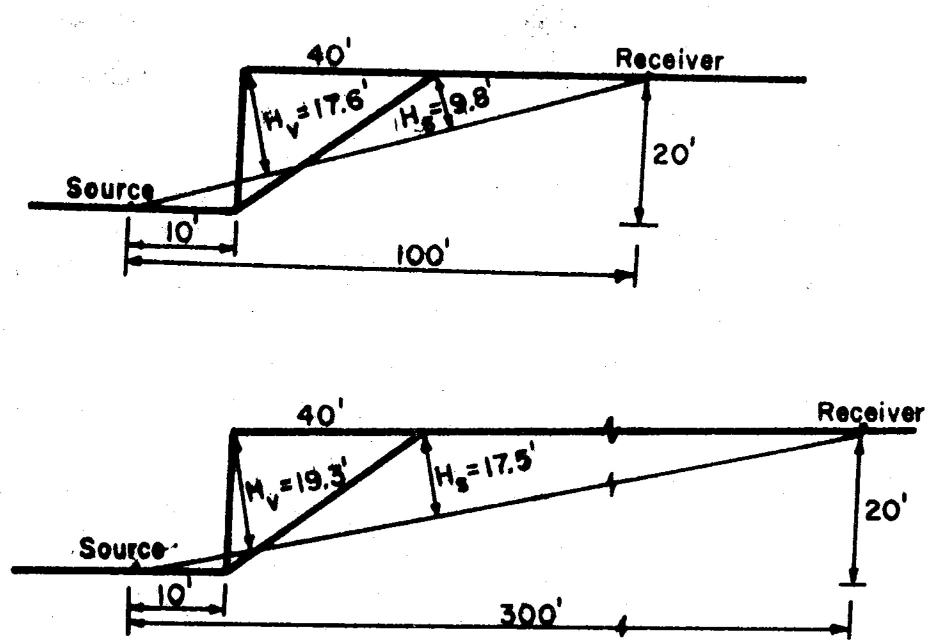


Figure 5 . Effective heights of vertical and sloped sides.

of a depressed freeway as a barrier (15), for the Radcliffe Street sites in Houston.

TABLE 3

COMPARISON OF MEAN SOUND PRESSURE LEVELS ON RADCLIFFE STREET

Location	Sound Pressure Level Estimation Method (dBA)	Design Guide Method (dBA)	Complete Analysis with Data Recorder (dBA)	Sideslope as a Barrier (dBA)
A (200')	67, 68	67	68	67
A (400')	61	61	63	59

These results show such close correlation that the side slope of a depressed section can be considered a barrier wall. It was found that, as the effective height of the barrier wall increases and the distance from the source increases, the attenuation of the sound increases. Fehr's barrier wall equations (2) for noise attenuation appear valid for freeway locations in cut sections where the effective barrier wall height is used.

Further research is necessary in the field of barrier wall costs, cost-effectiveness of noise reduction, and the aesthetics of barrier wall design.

ENVIRONMENTAL CONSIDERATIONS IN DESIGN

Gradient Adjustments

Galloway, et al. (1), noted that while adjustments are necessary for trucks on grades, no adjustment is necessary for automobile traffic. Table 4 below can be applied to the stream, regardless of whether the near side or far side is on an upgrade or downgrade. Gradients of less than 2 percent are considered neglibible.

TABLE 4

ADJUSTMENTS FOR TRUCKS ON GRADES

% Gradient	≤ 2	3-4	5-6	≤ 7
Adjustment in dBA	0	+2	+3	+5

Shielding by Structures

Only limited work has been done in this field, but measurements taken by Galloway, et al. (1), suggest that values of 3-5 dB per row of houses can be used. A maximum value of 10 dB can be applied when the line of sight between the source and the sound is entirely blocked. A spot evaluation by the authors did not confirm reductions of this magnitude for single family residential areas, and it is suggested that no reduction due to houses be used in practice.

Landscaping

Contrary to popular belief, bushes and trees provide very little sound attenuation. It would require a 100-foot wide band of trees 15 feet high to decrease the sound by 5 dB, with the trees dense enough so that the line of sight from source to receiver would be entirely blocked (15). Galloway, et al. (1), note that a depth of trees of less than 50 to 100 feet provides little actual attenuation, although such a belt may improve the psychological impact of the highway on adjacent residents.

Changes in vegetation and ground cover can cause varying noise levels during different seasons. More attenuation occurs when grass, snow, or some other absorbent material is on the ground. For traffic noise propagated across grassland to a receiver about 4 feet high, the ground effect reduces the received level by approximately 3 dBA per 350 feet (17).

Wind

Wind will distort sound waves near the ground, and moderate winds will cause sound levels to fluctuate ± 5 dB over a few hundred feet (15). For distances of more than 100 feet, turbulence due to temperature and wind gradients can cause a bending of the sound waves. Differences in the level of traffic noise due to a wind of 10 mph blowing from a receiver to the road are 2 dBA at 150 feet and 7 dBA at 650 feet. Wind reduces noise markedly when blowing from the hearer to the source but only increases the noise slightly when blowing toward the hearer. This is due primarily to the refraction of the sound transmitted by the wind gradient (17).

Temperature and Humidity

Temperature can only affect the transmission of sound over large distances and only then by a temperature inversion. This could occur if the temperature of the upper air layers varies sufficiently to refract the sound back to an observer some distance from the source (15).

Humidity has virtually no effect on noise attenuation and can be eliminated when considering factors that affect highway noise.

Roadway Surface

Galloway, et al. (1), have suggested that the roughness of the road surface can cause a 10-dBA variation in highway noise. Table 5 below shows the classification of road surfaces as they relate to surface influence on vehicle noise. However, tests in England (15) have failed to verify this large variation due to surface coarseness; in one test a difference of only 1 dBA was found between a Portland-cement and an asphaltic-concrete surface.

TABLE 5

SURFACE INFLUENCE ON VEHICLE NOISE (1)

Road Surface Classification	Description	Adjustment in dB
Smooth	Very Smooth, Seal Coated Asphaltic Pavement	-5
Normal	Moderately Rough Asphalt and Concrete Surface	0
Rough	Rough Asphalt Pavement with Large Voids ½" or Larger in Diameter, or Grooved Concrete	+5

The above factors are especially pertinent to the highway engineer when assessing the traffic noise from a new highway. These factors are included in Galloway's design guide method (1) presented in a later section.

HIGHWAY NOISE MEASUREMENT FOR ENGINEERING DECISIONS

When complaints of highway noise are received by the Highway Department, the highway engineer must have some tool to assist him in assessing their validity. The periodic sampling procedure presented in Research Report Number 166-2 describes how a district office can undertake preliminary surveys to assess problem locations. If in the opinion of the engineer a problem does exist, the headquarters office can then respond to the district's request for a detailed assessment of the problem.

The procedure developed in this project was the use of a hand-held sound level meter to measure highway noise values at 15-second intervals for a period of five minutes. The mean of these recordings will have 95 percent probability of being within $\pm$ 0.5 dBA of the true mean value. Figure 6 shows that the relative error associated with increased sampling duration is exponential in nature. The graphs represent the 95th confidence intervals for the average difference from the mean value for a particular known sampling interval and for a duration of recording. It can be seen in all the graphs that the range of the 95 percent probability curve decreases very rapidly in the first four minutes of recordings but thereafter decreases very slowly. There is little advantage in increasing the recording duration to 8 or 10 minutes since only a slight decrease in the relative error for the estimation of the mean value can be expected.

SUMMARY OF 95 PERCENTILE CONFIDENCE INTERVALS

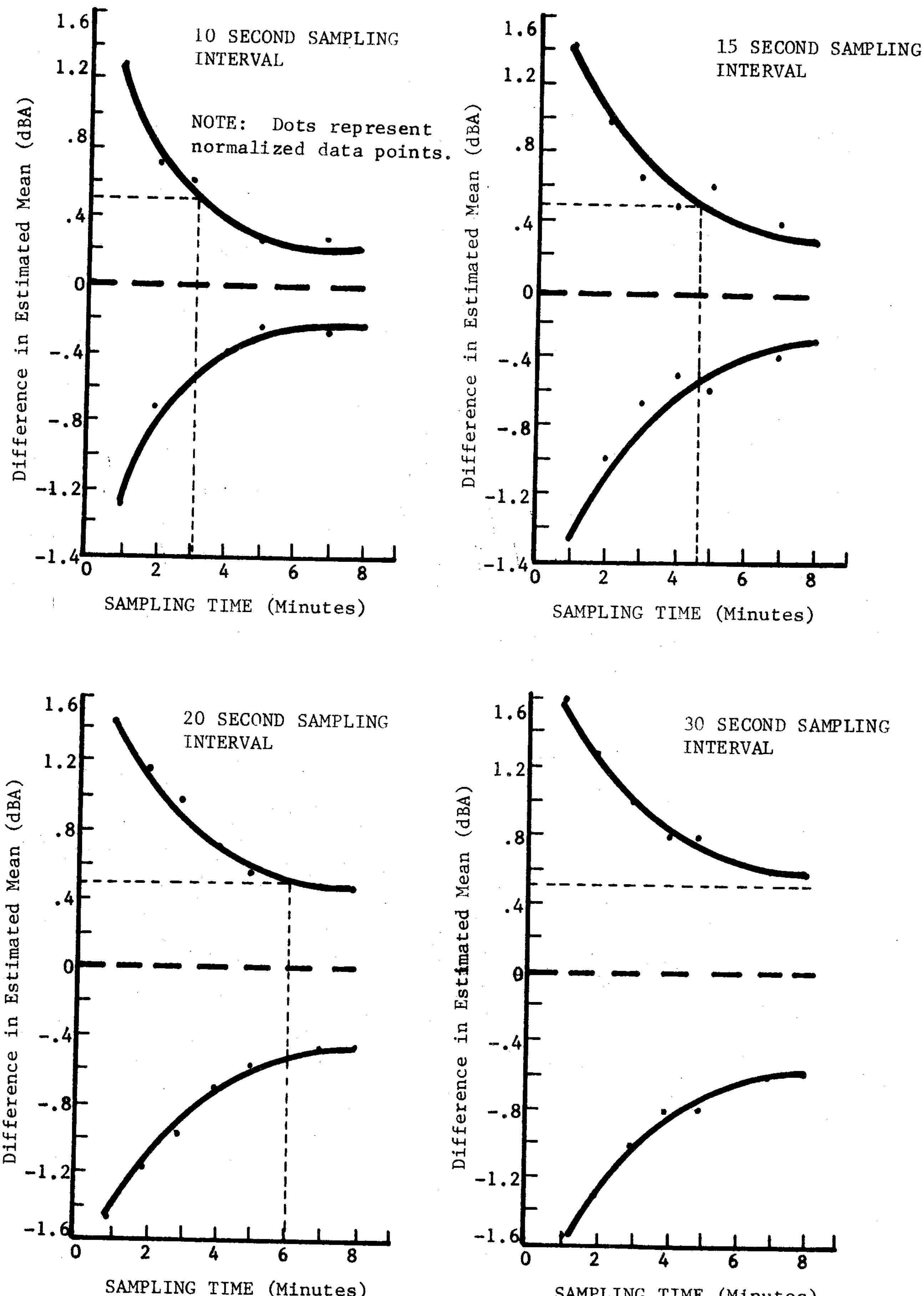


FIGURE 6

The use of a 15-second sampling rate for five minutes would permit a technician to complete his recording at any location in one hour, assuming a 10-minute setup time, plus five minutes recording time at each location. This is also assuming that the selected distances of 50 feet, 100 feet, 200 feet, and 400 feet are readily accessible at each site. Field tests revealed that 15 minutes per location was more than generous.

The mean value at each of the Houston, Texas, recording sites was obtained and plotted on a strip chart plotter. With the mean plotted on the graph, the total time (in seconds) was determined for which the sound pressure level exceeded the mean value. Similarly, for increments of 2 dBA above the mean, the time that the sound pressure level exceeded the specific value was accumulated. These time values were converted to a percentage of the total sampling time. An accumulative curve was then plotted for each data set (run), with the percentage of the time that the sound pressure level was exceeded versus that particular sound pressure level (dBA). Using these graphs, the 80th, 85th, 90th, and 95th percentile values were determined and plotted against the mean sound pressure level in dBA units (Figures 7-10). These plots are, in fact, point estimates of the percentile values. This means that by using the 90th percentile graph and knowing the mean sound pressure level (dBA) of a run, the 90th percentile value can be estimated quite simply (see Figure 9). For example, if the mean sound pressure level is estimated at 72 dBA, the 90th percentile would be estimated at 74 dBA.

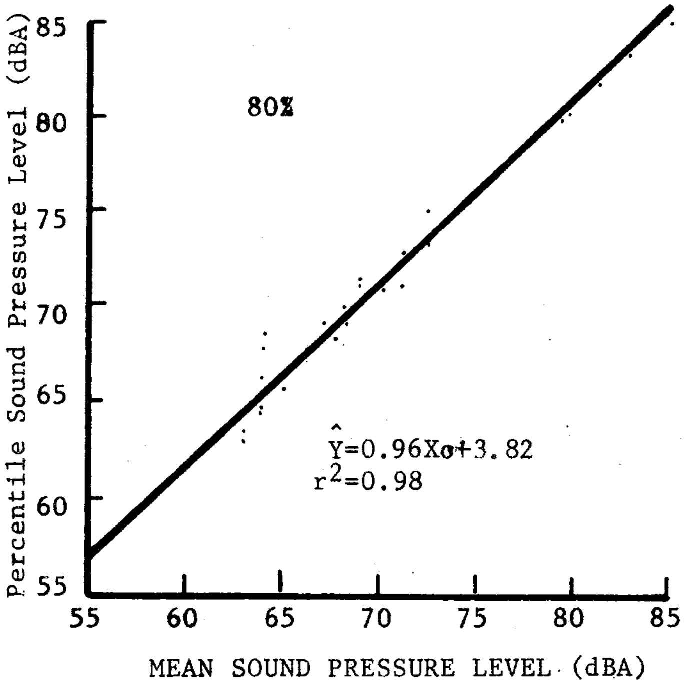


FIGURE 7

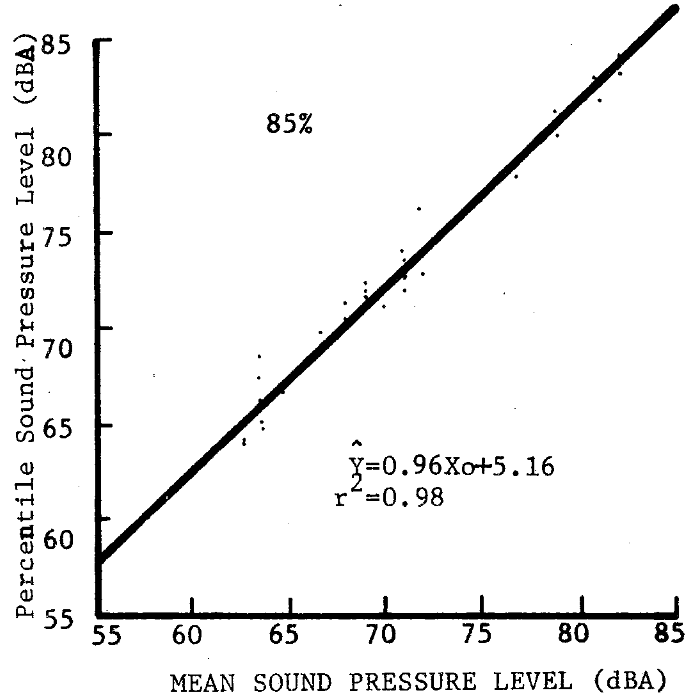


FIGURE 8

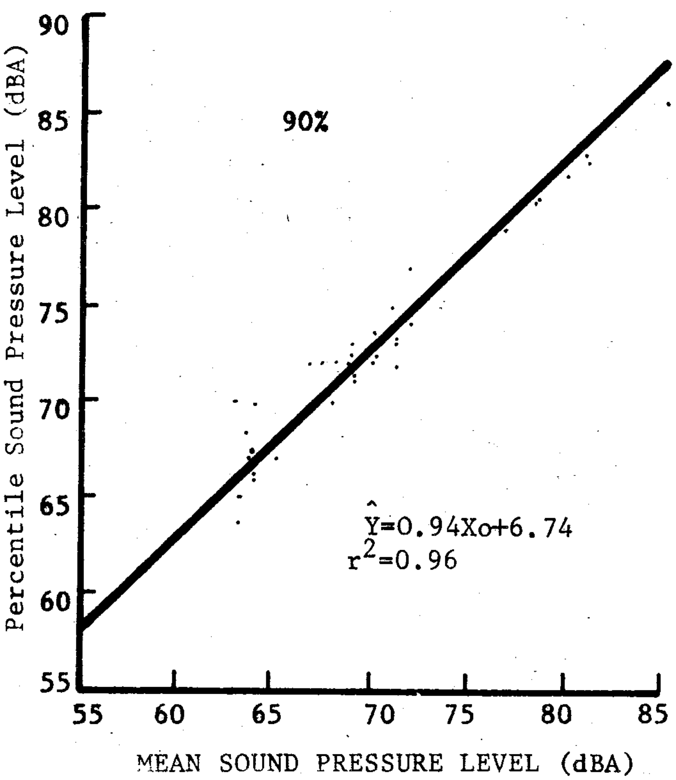


FIGURE 9

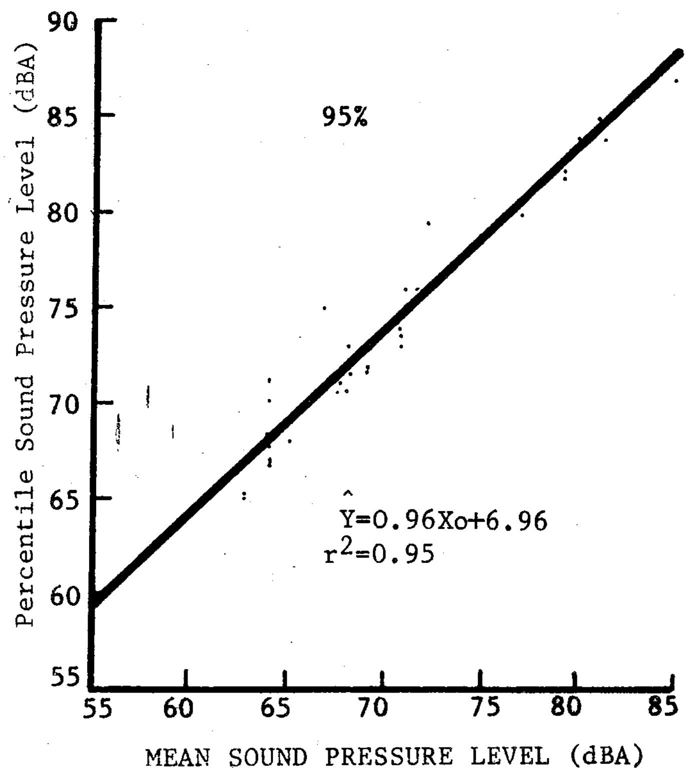


FIGURE 10

LEAST SQUARES LINEAR REGRESSION LINES FOR VARIOUS PERENTILE LEVELS AND THE MEAN SOUND PRESSURE LEVEL

Analysis of the results revealed that the field recordings compared favorably with those found by using the short periodic sampling procedure. There was close correlation between each reading, showing that the periodic sampling procedure yielded relatively accurate results. This procedure permits adequate evaluation of highway noise problems for engineering decision making but cannot replace the more complex equipment and specially trained personnel needed for possible legal cases. A typical procedures manual has been included in Appendix C of this report.

TRAFFIC NOISE EVALUATION FOR NEW HIGHWAYS

(a) Bolt, Beranek and Newman Noise Simulation Program

A copy of the traffic noise simulation program developed as a part of the National Cooperative Highway Research Program research study and reported in NCHRP Report 78 was obtained from the Automation Division of the Texas Highway Department. This program was written in the Fortran IV programming language and was compatible with the computer facility available at the Texas A&M University Data Processing Center. The initial attempts to compile the program revealed that the program, at least in the version provided to the Texas Highway Department, had never been successfully used. Several of the subroutines had common variables dimensioned with a value of one (1), and the calling program had the variables dimensioned with a value of eight (8). In addition, several "undefined variable" source deck errors occurred, and, upon detailed examination of the variable involved, it was found that the variable had been misspelled in the defining statement just preceding the statement in which the error occurred. These and similar programming problems convinced the authors that the program was not an operative version of the simulation program developed in the NCHRP project.

In the hope that the program was a late version of the final product, the research staff carefully corrected the programming errors. An example set of output from the program was obtained from the original author and used for comparative purposes. The initial run with the data used in the example program was very encouraging. The resulting average noise values appeared to reproduce reasonably well the example output furnished by the program author, certainly well within the limits of variation expected for simulation programs. The flows in the example were very light, and when the flow rates were increased to more reasonable levels (i.e., 1000 to 1500 VPH/lane) the program produced average noise levels well above any that could be expected from vehicular traffic (i.e., 100 + dBA). A detailed examination of the output revealed that individual lanes were carrying far too many vehicles - an indication that too many vehicles were being generated. An examination of the intervehicular gap subroutine did not reveal the source of the problem, and it became apparent that the problem was in the basic logic of the original program.

Since basic logic problems existed in the program, and since the possible uses of the simulation program were somewhat vague, the authors suggested that work on the simulation be discontinued. Discussion with representatives of the Texas Highway Department indicated that the program was of considerable interest to the Department. Accordingly, the effort to make the program functional was renewed. A "flow-charting" program developed by the staff of the Texas Transportation Institute was utilized to obtain a flow chart of the simulation program. This flow chart was examined in detail for evidence of logic errors which could produce the types of problems uncovered in the program runs. After several hours of detailed study of the flow chart, no problems were identified that logically could be expected to correct those in the program.

Since there was no apparent use for the program and since the logic changes would entail an undetermined amount of time and money, work on the simulation program was terminated. This material, including a copy of the output from a run illustrating the problem and a copy of the program flow chart, was informally forwarded to the Texas Highway Department with a recommendation that no further work on the simulation program be undertaken. Should the Texas Highway Department desire an operating copy of the program, it was recommended that this copy be obtained through the National Cooperative Highway Research Program Office.

(b) Design Guide Method

The design guide method (1) for the analysis of the sound pressure level on Radcliffe Street sites in Houston was used in a field study that was documented in a previous report (15). Exceptionally close correlation was obtained for the two sites selected, and preliminary investigations by the authors suggest that this theoretical method would yield close correlation to the actual field values in other locations.

Further research is necessary to verify the above method as satisfactory for all freeway geometric configurations, but this method appears to be satisfactory for preliminary engineering decisions.

SUMMARY OF FINDINGS

1. The State needs to implement maximum vehicle noise legislation. Sound pressure levels of 85 dBA for trucks and motorcycles and 77 dBA for automobiles are suggested as reasonable noise level limits at the present time (June, 1972).
2. As a general policy, the state should attempt to maintain the mean traffic noise level at or below the values presented in Table 1 (page 6).
3. There is need for a less complicated method of evaluating the validity of traffic noise complaints. The periodic sampling approach using a 15-second sampling interval of five minutes duration is recommended.
4. Peak traffic noise levels can be estimated with a degree of accuracy acceptable for engineering decisions based on the mean sound pressure level (See Figures 7 thru 10, page 26).
5. As the effective height of an impermeable (acoustically opaque) wall increases, the distance from the wall to the receiver and the distance from the wall to the sound source decreases; the attenuation of the sound increases.
6. Fehr's barrier wall equations for noise attenuation appear valid for freeways located in cut sections where the effective barrier height is the perpendicular distance from the line of sight between the source and observer to the top of the side slope.
7. Noise reduction due to barrier walls is related to the weight of the wall (exposed surface) and the frequency of the sound. At lower frequencies, most materials have a lower transmission loss than at the middle and high frequencies.

8. Lightweight, porous materials increase their transmission losses when painted or plastered on at least one side. This phenomenon might be employed in the future design of barrier walls on bridges; however, future research in this area is suggested.

9. All four methods (Periodic Sampling, Design Guide (DCHRP 117), Data Recorder, and Side Slope as a barrier) gave similar results, but, due to its simplicity in use, Fehr's equation for noise reduction due to a barrier wall is recommended for purposes of engineering evaluations.

10. In general, there is no simple solution to traffic noise problems. From an engineering point of view, the use of barrier walls on existing freeways, careful design and location of new freeways, and legal limitations on maximum noise emitted by individual vehicles appear to be the most practical means of traffic noise control at this time.

CONCLUSION

Noise control is a systems problem in which the goal is to obtain an acceptable reduction in noise at a reasonable cost; therefore, trade-offs are necessary between the many subsystems that create and affect traffic noise. The engineer must attempt to obtain an optimization of these factors to produce a result that is socially, aesthetically, and financially acceptable.

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APPENDIX A - NOISE LEVEL REDUCTION GRAPHS FROM THE COMPUTER OUTPUT

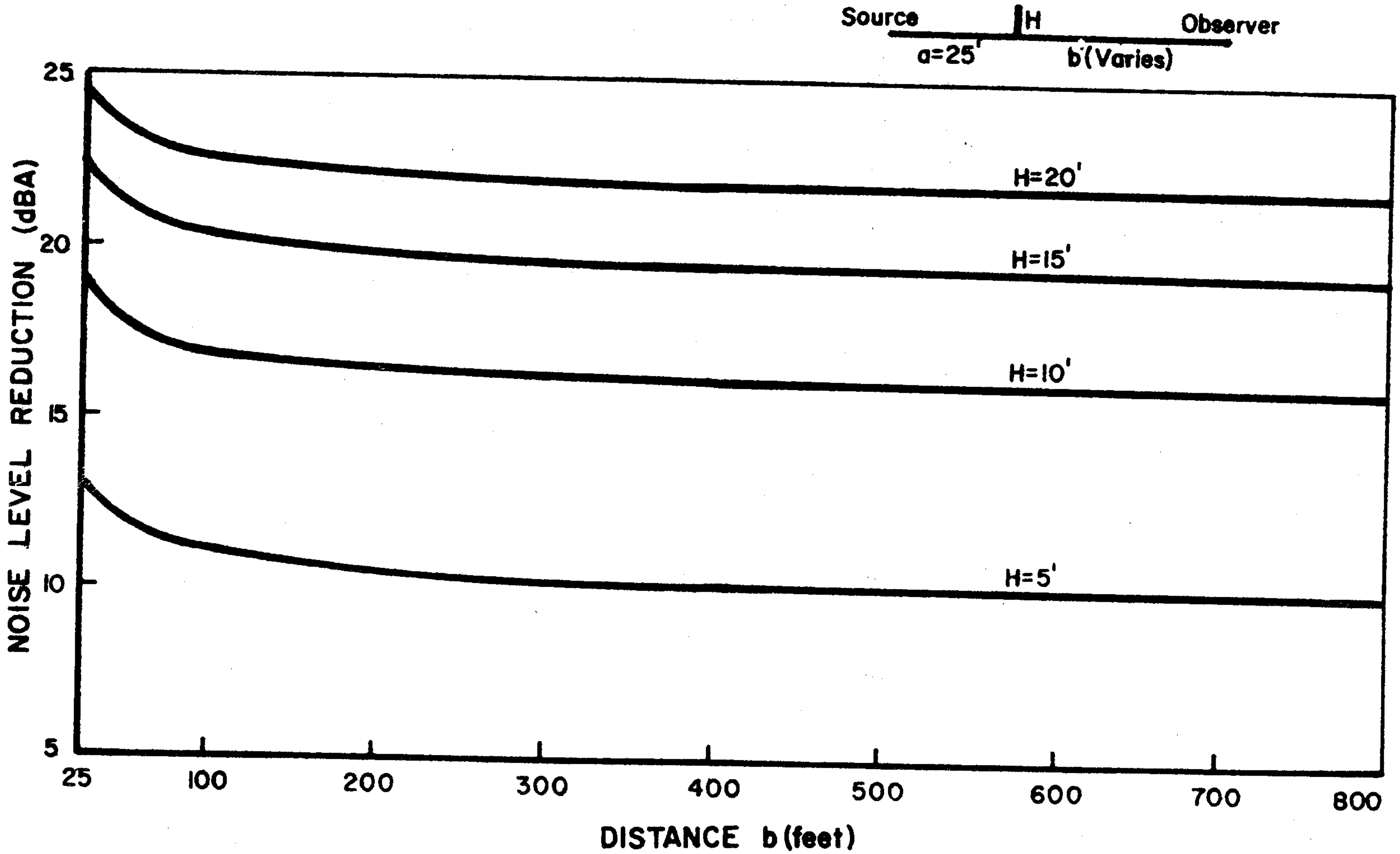


Figure A-1 Noise reduction - source to wall distance 25 feet.

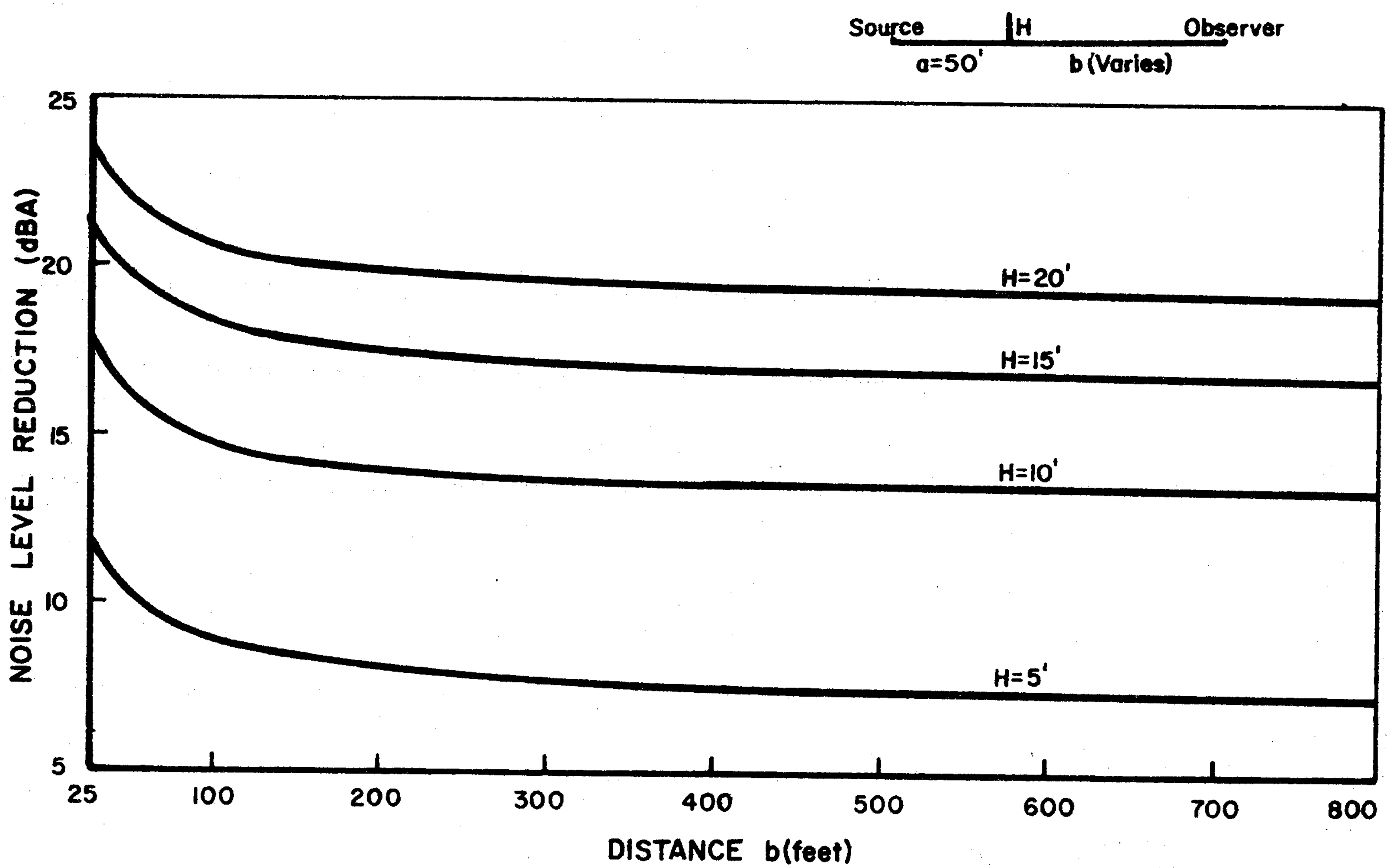


Figure A-2 Noise reduction - source to wall distance 50 feet.

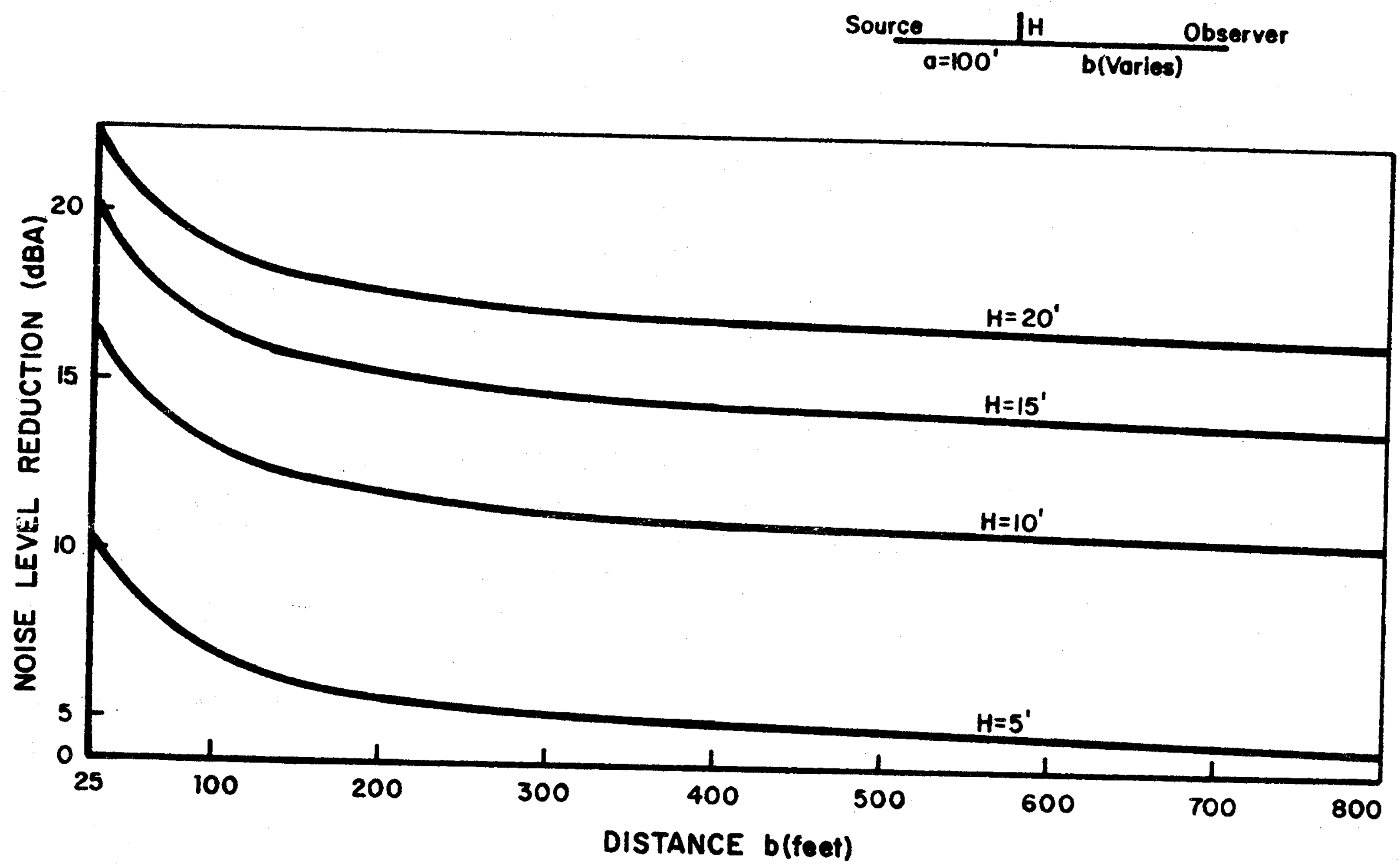


Figure A-3 Noise reduction - source to wall distance 100 feet.

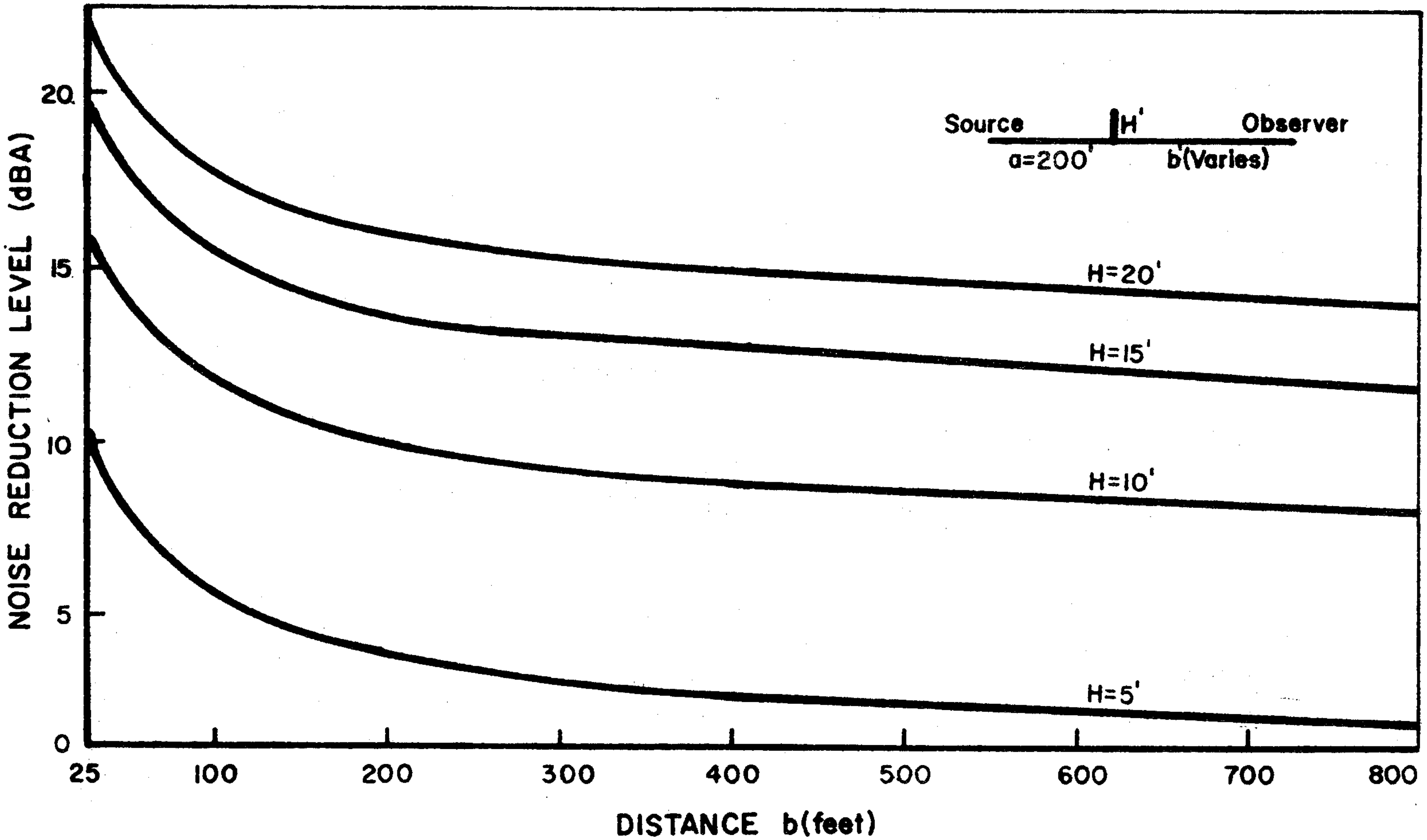


Figure A-4 Noise reduction - source to wall distance 200 feet.

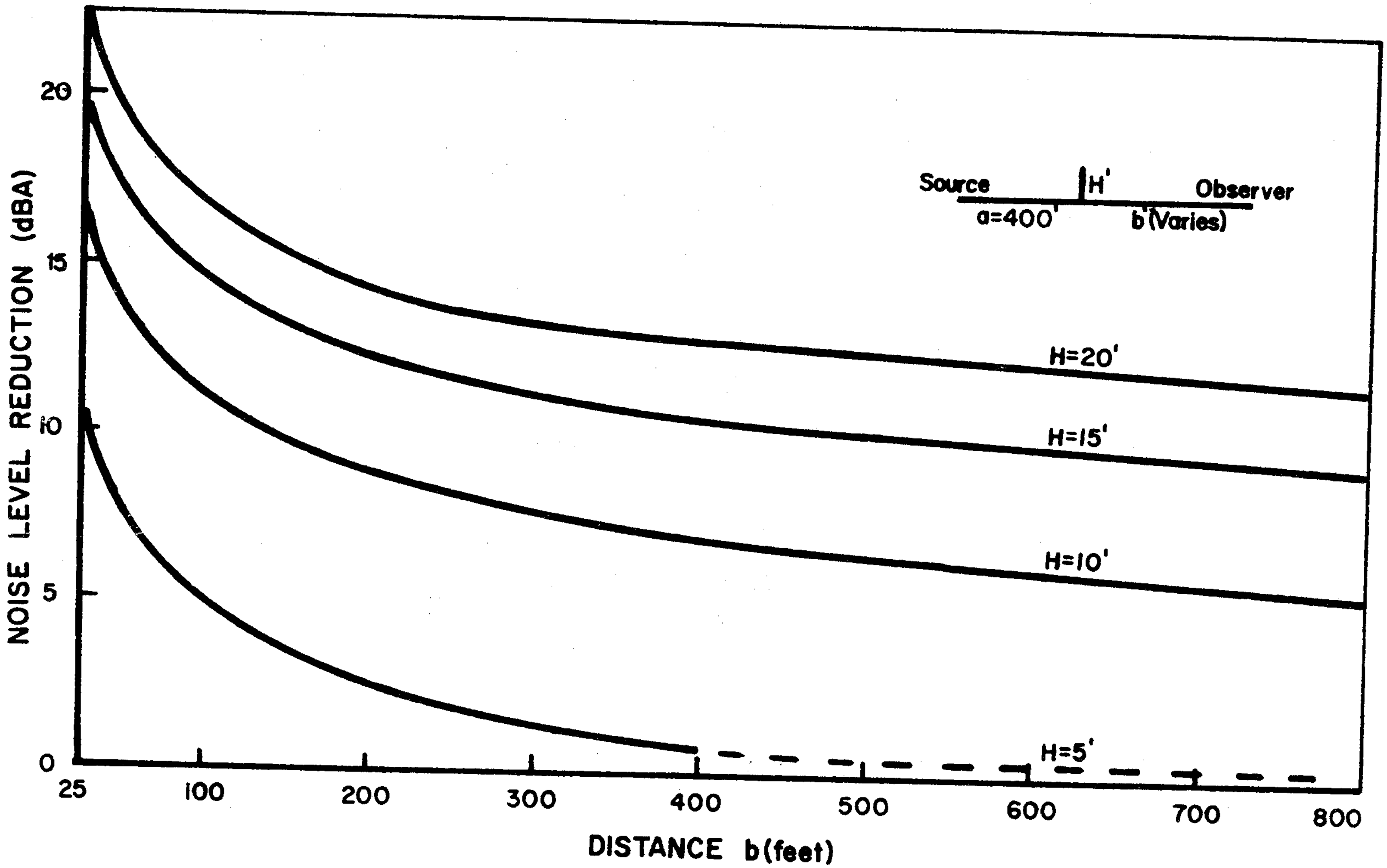


Figure A-5 Noise reduction - source to wall distance 400 feet.

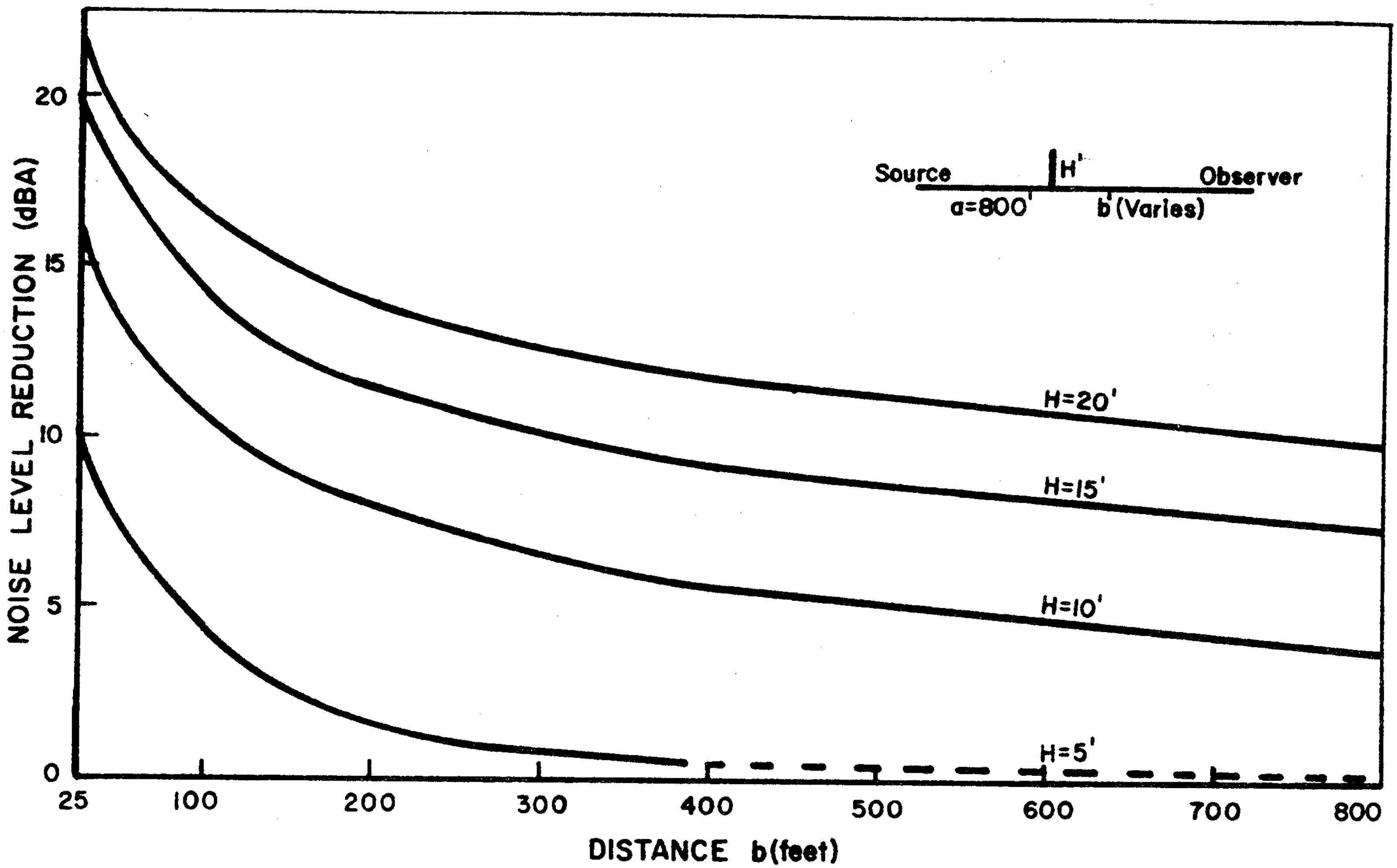


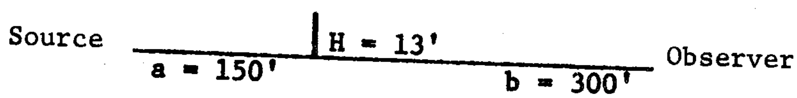
Figure A-6 Noise reduction - source to wall distance 800 feet.

APPENDIX B - Nomograph Solution Using Fehr's Equations

Nomograph Solution Using Fehr's Equations

A nomograph solution has been developed, to calculate noise reduction for any combination of distance and wall height.

An example of how the nomograph is used is shown below. The reduction in noise due to a barrier with a 13-foot effective height has been calculated:



Noise Reduction Factor $Y = \frac{2}{\lambda}\left[a\left(\sqrt{(1 + H^2/a^2)}-1\right) + b\left(\sqrt{(1 + H^2/b^2)}-1\right)\right]$

When λ = wavelength of sound in air

= 1.0 for a frequency of 1000 Hz.

$$\therefore\ Y = 2\left[\left(a\sqrt{(1 + H^2/a^2)}-1\right) + \left(b\sqrt{(1 + H^2/b^2)}-1\right)\right]$$

$$= ax + by$$

$$= N_1 + N_2$$

where

$$x = 2\left[\sqrt{(1 + H^2/a^2)}-1\right] \text{ and } y = 2\left[\sqrt{(1 + H^2/b^2)}-1\right]$$

Example:

when, H = 13', a = 150', b = 300'

$$x = 2\left[\sqrt{(1 + \frac{169}{22,500})}-1\right] \text{ and } y = 2\left[\sqrt{(1 + \frac{169}{90,000})}-1\right]$$

$= 2[\sqrt{1.0075} - 1]$	$= 2[\sqrt{1.0019} - 1]$
$= 2(1.0038 - 1)$	$= 2(1.00095 - 1)$
$= 2(.0038)$	$= 2(.00095)$
$= \underline{.0076}$	$= \underline{.0019}$

Refering to Figure B-1, connect the "x" value to the "a" value and the "y" value to the "b" value. This gives N_1 = 1.10 and N_2 = 0.52, and these summed give the noise reduction factor, Y = 1.62. From Figure B-2, the reduction in noise due to the wall is 12.0 dBA.

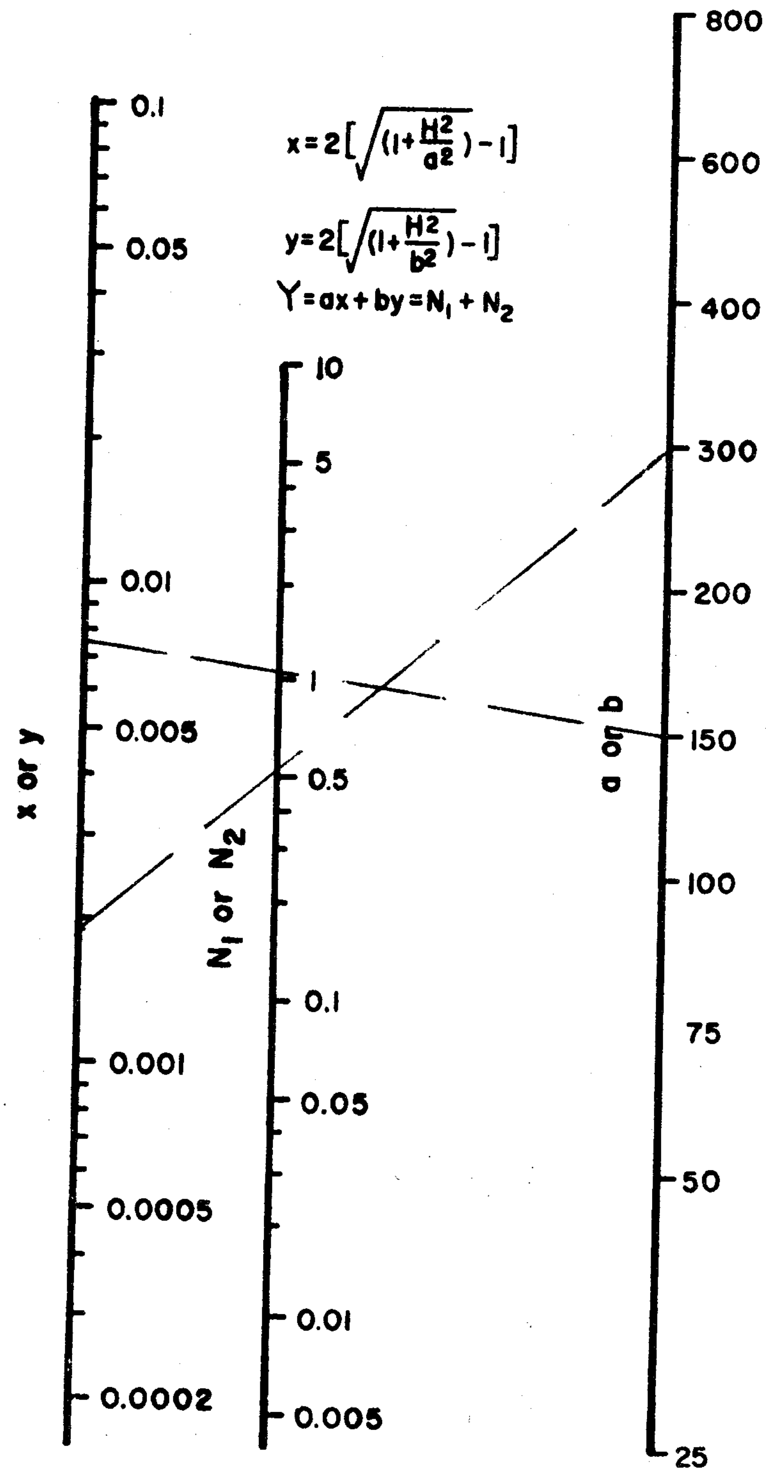


Figure B-1 Nomograph conversion of Fehr's equations.

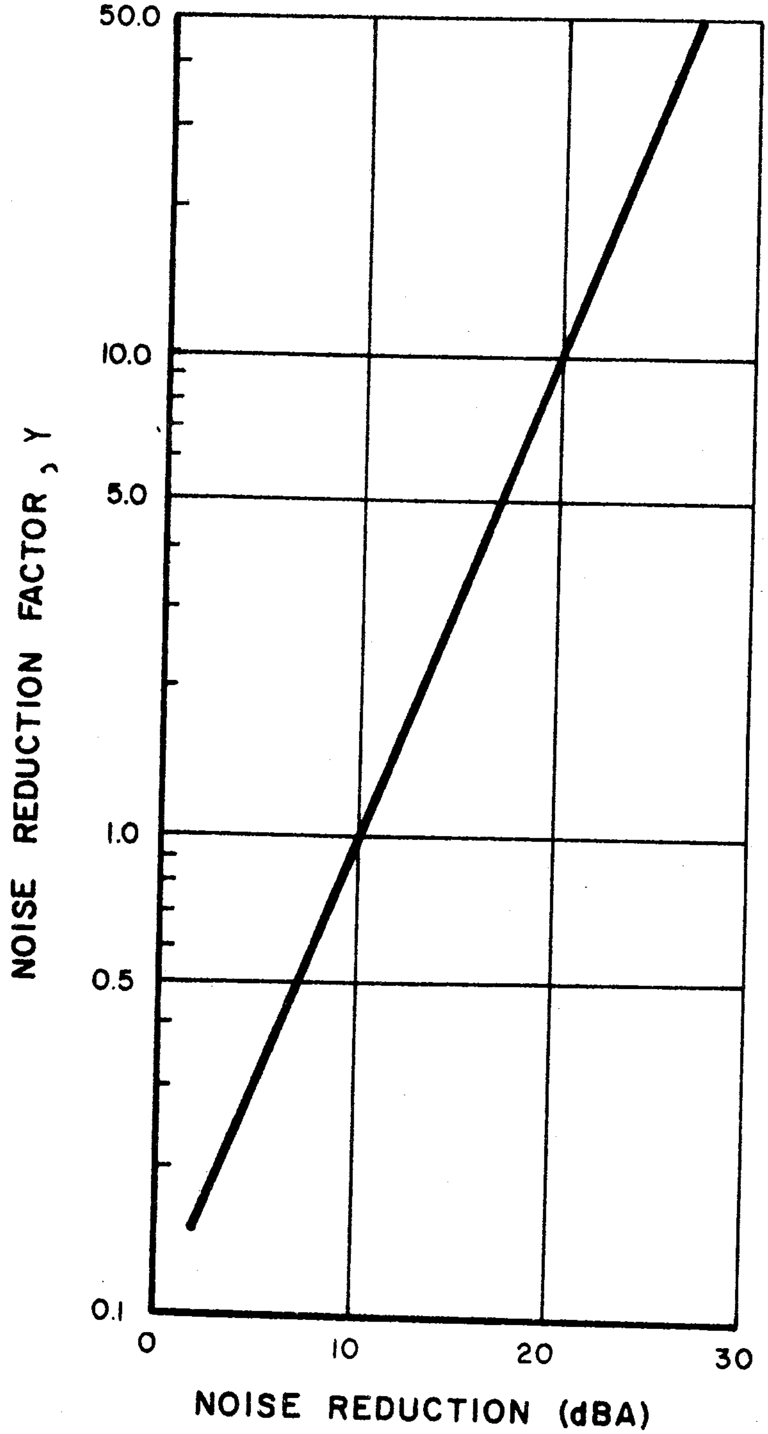


Figure B-2 Noise reduction and noise reduction factor. (8)

APPENDIX C - Typical Procedures Manual

A PROCEDURE FOR CONDUCTING PERIODIC SAMPLING MEASUREMENTS FOR THE EVALUATION OF HIGHWAY NOISE PROBLEMS

Pre-Field Phase (Supervising Engineer)

1. Select site or sites at which a measurement is to be made. For example, if a complaint has been received, measurements should be made at a point opposite the property line nearest the objectionable source (highway), opposite the property line farthest from the source and at selected points between the property and the source. Distances of 50, 100, 200, and 400 feet are recommended as common recording points.

2. Select the sampling interval and duration of recording to be used. A 15-second sampling interval for 5 minutes duration is recommended.

3. Determine whether peak noise levels are to be recorded in the field, since these may be of interest in the evaluation of the total problem. However, these data can be estimated with acceptable accuracy using the techniques outlined in the evaluation section of this procedure.

4. Select the level of peak noises to be estimated (90th percent, 95th percent, etc.).

5. Advise the technician to use the "FAST" response on the sound pressure level meter if the peak noises are to be recorded. In other cases use the "SLOW" response setting.

6. Remind field personnel to use the "A" weighting network.

7. Ensure that the sound pressure meter is checked for both electrical and acoustical calibration before leaving the office.

8. Remind field personnel to take the acoustical calibrator into the field with them.

9. Advise field personnel as to procedure to be used when dealing with the public. For example, in a routine investigation of a complaint, getting in touch with the individual involved and simply advising him that the Department is concerned and is attempting to evaluate his complaint, can have a very positive public relations result. Stress the importance of being a good listener and being courteous at all times.

10. Necessary supplementary information will include the volume and speed of automobiles and trucks. If these data are not available, measurement should be made in the field concurrent with the sound pressure level measurements.

FIELD PROCEDURE FOR CONDUCTING PERIODIC SAMPLING MEASUREMENTS OF HIGHWAY NOISE

Field Phase (Field Personnel)

a) Review site to insure that study locations planned in the office are feasible.
b) Mark distances of 50, 100, 200, and 400 feet from the near edge of the traveled way, as well as other points as identified by the supervising engineer.
c) Set the selector switch on the "A" weighting network.
d) Check electrical calibration of sound pressure level meter.
e) Check acoustical calibration of sound pressure level meter. A frequency of 1000 hertz (cps) is recommended for acoustical calibration.
f) Fill out site reference information on the data sheet including location sketch in the back of the data form.
g) Select and record the base level (use a base value which will keep the needle on the scale for a majority of the time).
h) Set response switch to either "FAST" (F) or 'SLOW" (S) as instructed by the supervising engineer.
i) Record time at the beginning of the data recording.
j) Begin sound pressure level recordings using the "A" weighting scale at the sampling interval and for the duration given by the supervising engineer.
k) Record time at the end of the data collection.
l) Recheck both electrical and accoustical calibration to insure that no appreciable change has occurred.
m) Check data sheet to be certain that all information has been recorded.

Post Field Phase (Field Personnel)

1. Review data sheet for completeness. Note any omissions or difficulty in reading recorded data.

2. Compute the number of observations (A) and the sum of the observations (B) and enter them at the appropriate points (A or B) on the form.

3. Compute the mean sound pressure level and enter it in the space (C) provided on the form.

4. Using the percentile level previously selected by the supervising engineer, estimate the sound pressure level for the appropriate percentile from Figure A-1 and record it in the space provided on the form (D).

5. Return completed data form to the supervisor.

SOUND PRESSURE LEVEL ESTIMATION

Location: ____
(Route Number or Street Address)

Site Description: Roadway Elevated _____ Feet; Roadway Depressed _____ Feet;
Roadway At-grade

Distance From Near Edge of Traveled Way: ______________________ Feet

Is Line of Sight to Traffic Stream Blocked: Yes ________ No ________

If "Yes" by what? ____

Date: __/__/__ Recorder: ______________ Meter: ______________

Scale: Fast ______; Slow ______ Weighting Network: "A"

Sampling Interval: ____ seconds, Sampling Duration: ________ minutes

(1) Observation Number	(2) Time of Day Hr	Min	Sec	(3) Base Level (dBA)	(4) Meter Reading (dBA)	(5) Instantaneous Sound Pressure Level (dBA) (Base Value + Meter Reading)	(6) Maximum Observed Noise in Interval (dBA)	(7) Comments
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
19								
20								
21								

No. of OBS = (A) = ____________ Sum of Col. 5 = (B) = ____________ dBA

Mean Sound Pressure Level = $\frac{\text{Sum of Col. 5}}{\text{No. of OBS}}$ = (B)/(A) = ____ = C = ____ dBA (No Fractions)

Estimated ____ percentile sound pressure level = (D) = ____________ dBA

Was Contact made with complaintant? Yes ____________ No ____________

If "Yes" give name or address of person contacted: ____________

Remarks: ____

Reference Sketches

1. Show North arrow
2. Show roadway from which noise occurs
3. Show measurement points
4. Locate buildings and trees
5. Draw cross section along line of measurement

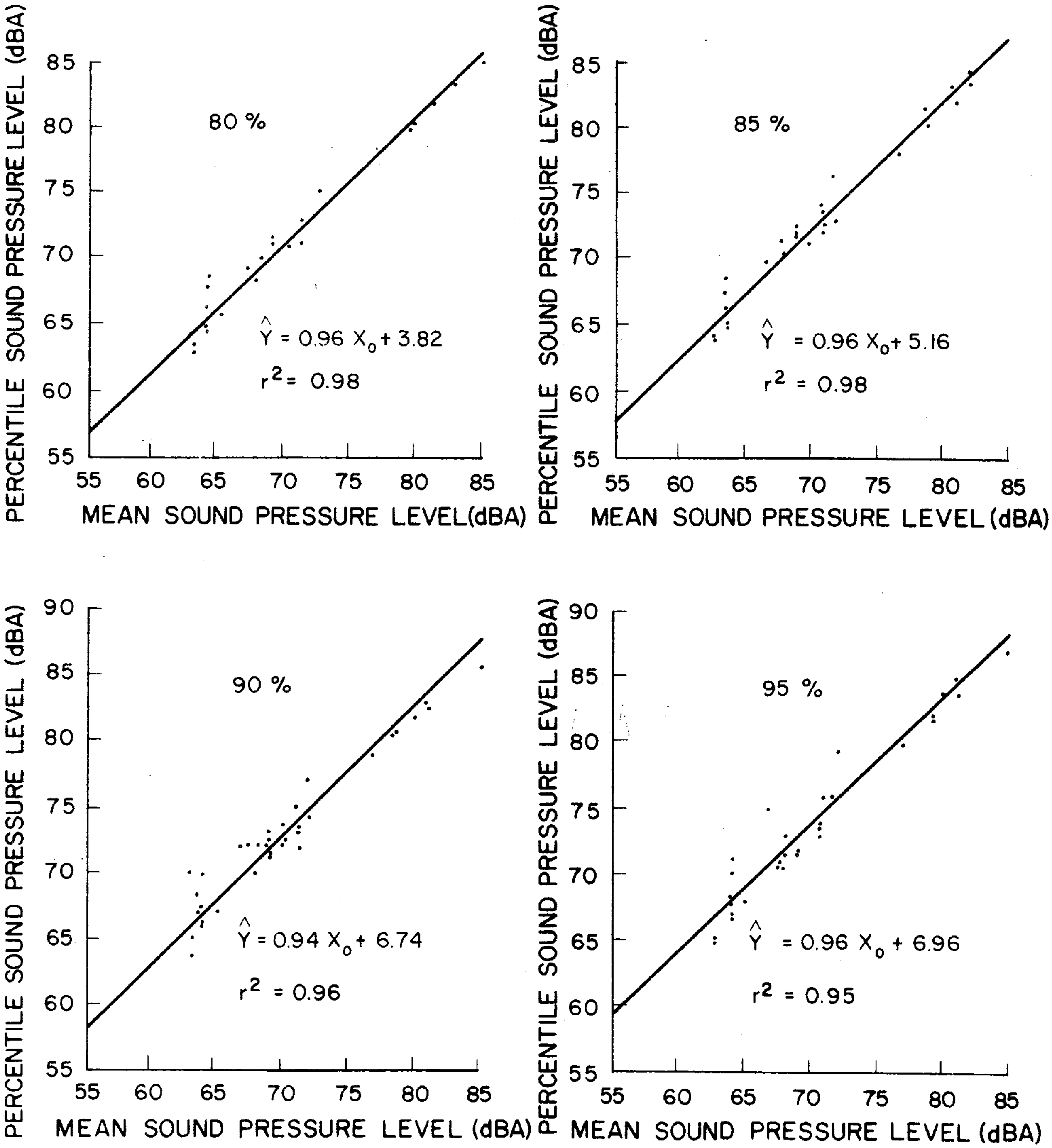


FIGURE C-1. LEAST SQUARES LINEAR REGRESSION LINES FOR VARIOUS PERCENTILE LEVELS AND THE MEAN SOUND PRESSURE LEVEL.

APPENDIX D: GLOSSARY OF TERMINOLOGY

TERMINOLOGY

Acoustical Terms (1, 16)

Ambient Noise Level - The background noise of an area, measured in dBA units.

dBA - The "A" weighted decibel. A unit of sound level which gives lesser weight to the lower frequencies of sound and is used in traffic noise measurement due to the good correlation with subjective reactions of humans to the noise.

Decibel (dB) - A logarithmic unit which indicates the ratio between two powers. A ratio of 10 corresponds to a difference in 10 decibels.

Frequency - Rate of repetition of a sine wave of sound. The unit of frequency is the hertz (Hz) or, until recently, cycles per second (cps).

Hertz (H_z) - The unit of frequency (cycles per second)

Loudness - A subjective impression of the strength of a sound. A sound level increase of 10 decibels approximates a doubling of loudness

Noise - Unwanted sound

Sound Pressure Level- The root-mean-square sound pressure, p, related in decibels to a reference pressure. The SPL value is read directly from a sound level meter (in dBA)

Roadway Terms (1)

Depressed Roadway	- When a roadway element is depressed below the immediate surrounding terrain
Percent Gradient	- Change in roadway elevation per 100 feet of roadway
Roadway Element	- A section of roadway with constant characteristics of geometry and vehicular operating conditions
Finite Roadway Element	- When a roadway element starts and finishes within the 8Dn limits of the roadway, where Dn is the distance from the observer to the nearest lane
Infinite Roadway Element	- When the roadway element length is larger than 8Dn, where Dn is the distance from the observer to the nearest lane
Semi-Infinite Roadway Element	- When the roadway element extends across 4Dn in one direction but which terminates within the 8Dn roadway length, where Dn is the distance from the observer to the nearest lane
Single Lane Equivalent	- Of a roadway is a hypothetical single lane which represents the roadway and which is to the observer acoustically similar to the real roadway