HIGHWAY NOISE REDUCTION BY BARRIER WALLS

by

Murray F. Young
and
Donald L. Woods

Research Report Number 166-3
Urban Traffic Noise Reduction
Research Study Number 2-8-71-166

Sponsored by

The Texas Highway Department
In Cooperation with the
U.S. Department of Transportation
Federal Highway Administration

July, 1971

TEXAS TRANSPORTATION INSTITUTE
Texas A&M University
College Station, Texas

DISCLAIMER

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

RECOMMENDATIONS FOR FUTURE RESEARCH

The report indicates that further research is necessary in the following areas:

1. Barrier wall materials to give acceptable noise attenuation at reasonable costs.
2. The use of lightweight concrete walls on bridges.
3. The aesthetics of barrier wall design.
4. Costs and cost-effectiveness of noise reduction.
5. Safetv aspects of sound absorbing barriers.

RECOMMENDATIONS FOR IMPLEMENTATION

Based on research conducted in this study, it is recommended that either Fehr's equations or Galloway's design guide method be used to estimate noise reduction due to barrier walls.

A simple computer program has been written to calculate the noise reduction due to walls of various heights, with noise sources and receivers at various distances from the wall. It is recommended that these methods be used to estimate the attenuation of traffic noise due to barrier walls.

ABSTRACT

Traffic noise has recently been described as a form of environmental pollution. Society now demands that the highway engineer consider traffic noise effects for both future and existing highways.

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

Two sites were evaluated, one having data already available, while the other required the measurement of traffic noise in the field. These results were compared with those calculated using formulae developed by other researchers.

This report reviews the factors that affect noise attenuation by barrier walls and presents graphs that can be used by the highway engineer to calculate the reduction of traffic noise due to barrier walls.

TABLE OF CONTENTS

LIST OF FIGURES (Continued)

INTRODUCTION

In recent years highway noise pollution has been added to our environmental considerations. While the physical and psychological effects of highway noise are not in the same magnitude as found in many industries, highway noise does constitute an environmental issue for people living near a highway.

Highway noise pollution can be best defined as "unwanted traffic noise". This is a problem that has been magnified by the phenomenal traffic increase on the highway systems of this country during the last two decades.

Specifically, the increase in highway noise is mainly due to the growth of high-speed, high-density traffic on urban freeways which has cut through all land use areas, including residential sections. Attention is now being given to how this noise can be reduced, especially in urban residential areas. One method of decreasing this noise is through the use of barrier walls.

The primary causes of traffic noise are the exhaust systems of trucks and the tire-roadway interaction of autumobiles (1). Other factors such as wind drag (or shear), engine-transmission noise, and vehicle body noise also contribute, but to a lesser degree. Motorbikes also increase the peak noise levels due to their poor muffling characteristics, but since motorbikes only represent a very small percentage of the total traffic volume, this study is limited to a consideration of only automobile and truck noises. While it is unusual for automobile traffic to produce objectionable noise effects, it does contribute significantly to the ambient noise level (2).

There has been considerable variation of opinion as to how traffic noise should be measured. Colony (3) suggests use of the 600-hertz to 1200-hertz octave band to compute the Perceived-Noise Level (PNdb); there exists close correlation between the PNdb and the sound pressure level in this band. Although Perceived-Noise Level measurement is very precise, it has the disadvantage of being more complex than the sound level meter measurements. The precision sound level meter, using an "A" weighted network (dBA), has the advantages of simplicity in use, direct noise reading, and, most importantly, it has the best correlation to the noise as heard by the human ear (4). Measurement of highway noise in dBA units has now been approved by the International Standards Organization and the Acoustical Society of America for use in the measurement of traffic noise (5).

The "A" Scale recordings of a sound level meter are given in terms of dBA, the decibel value being logarithmically related to loudness. This is to say that dBA values and the loudness as perceived by the ear are not linearly related. Figure 1 (4) shows this relationship, and it can be seen that an increase of 10 dBA will be perceived by the ear as an approximate doubling of the loudness.

Before noise control by barriers can be considered, an understanding of acceptable noise levels is necessary. Unfortunately for the highway engineer, "acceptable" noise levels are subjective measures. Those levels which may be acceptable to one person or group of people may not be acceptable to others. However, general criteria have been established by

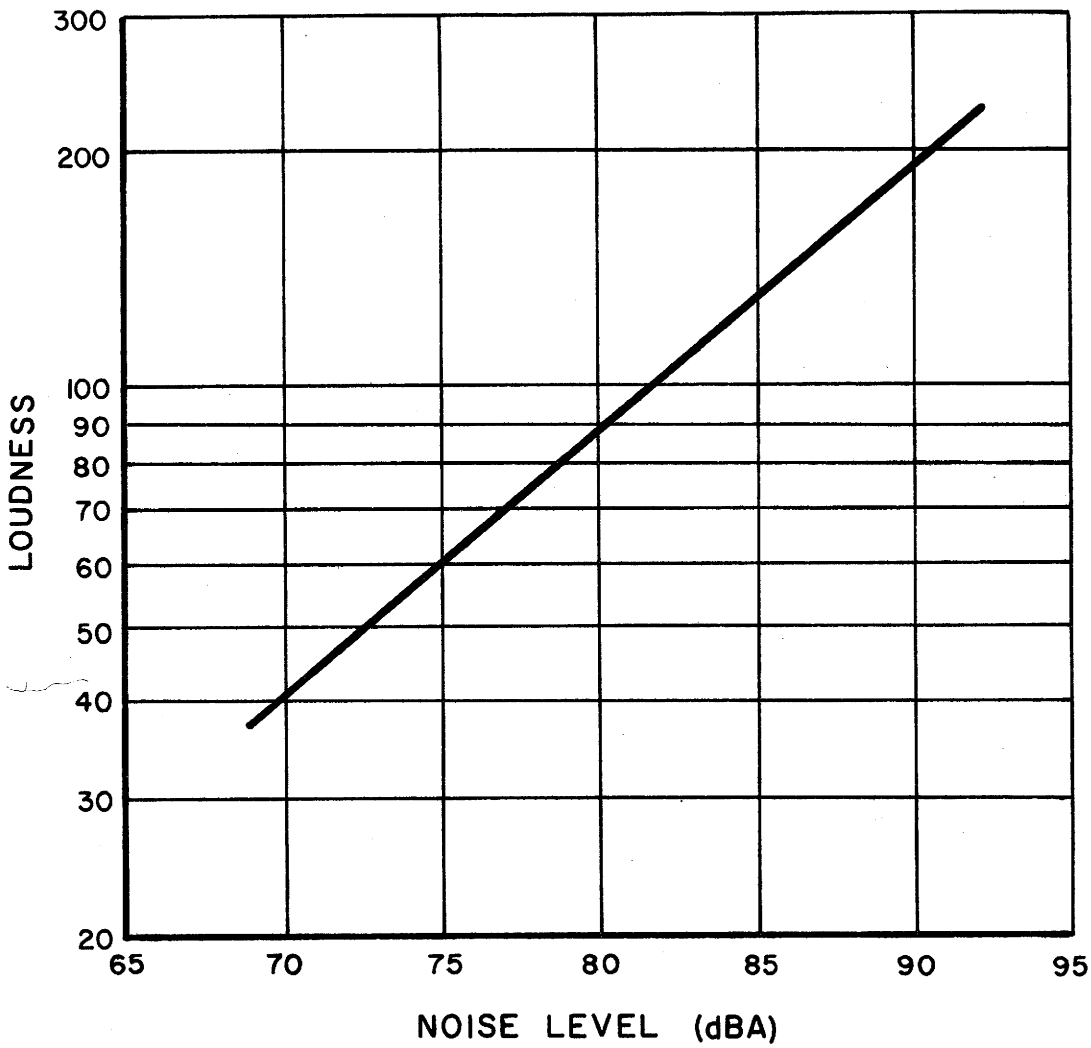


Figure 1. Relationship of loudness and noise level. (4)

Galloway (6) as guidelines for highway design engineers. Table 1 (6) shows these values, given in terms of land use adjacent to the highway and time. The night values are lower since during these hours the ambient noise level decreases, and the peak noises become relatively much louder; thus, sleep is disturbed.

Traffic noise can be emitted from either a point source or a finite straight line source (assuming the ideal conditions of freely moving, uniformly spaced vehicles). Point source criteria are considered to be valid when distances from source to receiver are small and/or the traffic density is low, giving a spacial separation relationship kd < 600 ft. - vehicles per mile (i.e. kd = traffic density, (k) in vehicles per mile x distance (d) from the road in feet). For this condition, noise levels are assumed to decrease at a rate of 6 decibels per doubling of distance between the source and observer. When kd > 600 ft.-vehicles per mile, the noise from individual vehicles can not be distinguished, and it appears as a line source. The mean and peak levels for this case decrease by 3 decibels for each doubling of the distance from the source (6). For the majority of highways the latter case governs.

Highway noise control can be considered basically a systems problem, in which many subsystems can be manipulated to effect the final result. The three basic subsystems are the noise source, the noise path, and the observer, each of these affecting the final noise that is heard by the ear. Constraints have been placed on these subsystems so as to give better

TABLE 1

MEAN NOISE LEVELS RELATIVE TO LAND USE (6)

STRUCTURE		MEAN NOISE LEVEL (dBA)	
		DAY	NIGHT
Residences	Inside*	45	40
	Outside*	50	45
Schools	Inside*	40	40
	Outside*	55	--
Churches	Inside	35	35
Hospitals	Inside	40	35
	Outside	50	45
Hotels	Inside	50	45

*Either inside or outside design criteria can be used depending upon the utility being evaluated.

definition to the problem. In practice, these subsystems are independent variables. The environmental conditions, such as humidity, wind direction and velocity, temperature, pavement texture, traffic speed, percentage of trucks in the system, density of the traffic, and highway grades all play important roles in the overall problem. Although these factors are not considered part of the system by definition, they do have an appreciable effect on highway noise control. These factors will be further discussed when the theoretical values are compared with the field measurements.

BACKGROUND INFORMATION ON NOISE BARRIERS

When a barrier wall is erected between the noise source and the observer, the noise level heard by the observer depends upon the amount of diffraction at the top of the wall, the degree of acoustical opaqueness of the wall, the distance between both the sound source and the wall and the wall and the observer, as well as the wavelength of the sound waves. Due to the large wavelengths (1000 Hz ≈ 1 foot), the sound is diffracted at the wall edge, and the noise waves are bent back toward the observer.

The attenuation increases with increased distance from the source, increased wall height, and an increase in the angle of diffraction of the wave. Attenuation decreases with distance between the source and barrier (7).

While there are several empirical equations to calculate the attenuation of highway traffic noise due to a barrier wall, perhaps the simplest has been described by Purcell (8) when he used Fehr's (9) equations in the (modified) form below:

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

$$\approx \frac{H^2}{\lambda a} \text{ if } b \gg a \geq H$$

where

Y = the noise reduction factor

H = the perpendicular height of the barrier in feet above the line of sight between source and observer (i.e., effective height)

λ = wavelength of sound in air (ft.)

a = horizontal distance in feet from source to barrier

b = horizontal distance in feet from barrier to the observer

Figure 2 (8) shows these variables.

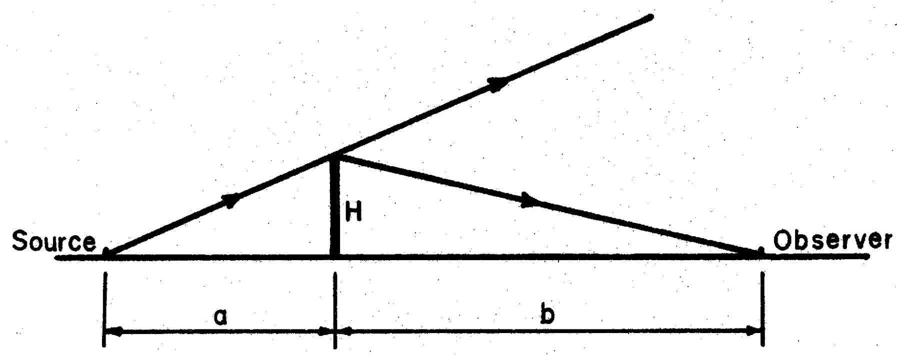


Figure 2. Purcell's variables. (8)

A conversion chart to convert the calculated value of Y to noise reduction in decibels is presented in Figure 3 (6).

Other work in this area has been undertaken by Maekawa (10) and Rettinger (11). Using Fresnel Integral numbers, they developed noise attenuation equations which did not readily lend themselves to the practical problems of noise attenuation. Galloway (12) further developed Maekawa's assumptions so that they can be applied to both single and line sources of sound. This study will compare field data with both Fehr's (9) equations and Galloway's (12) procedure to calculate noise attenuation.

The above equations assume that the barrier wall is acoustically opaque (i.e., impermeable to sound waves). Purcell (8) found that the noise transmission loss of a wall could be measured by the ratio of the acoustical energy transmitted through the wall to the acoustical

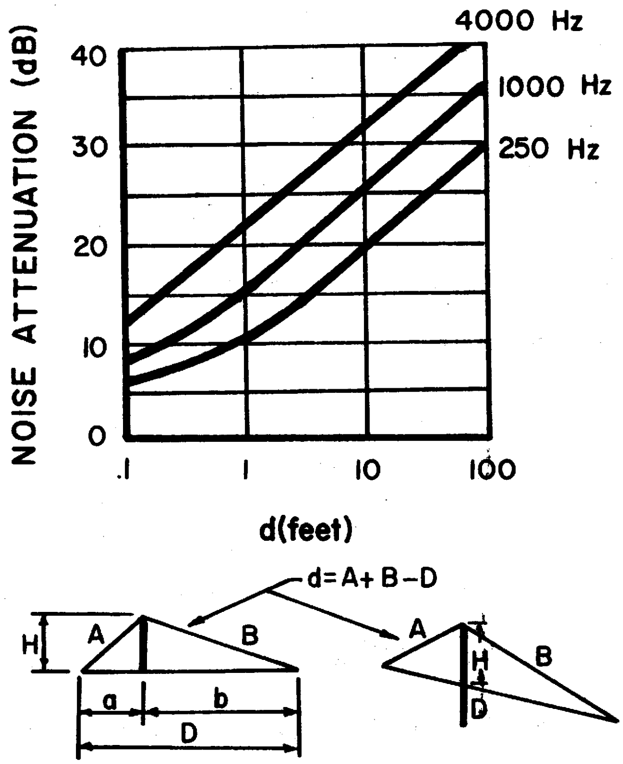


Figure 4. Relationship between noise attenuation and d. (14)

A noise level reduction of about 15 to 20 dB is common for a wall about 20 feet high. Doubling the wall height will only result in a 6-dB increase in sound attenuation for all frequencies (assuming that the source height is held constant). The X axis of Figure 4 shows d values of 0.1 through 100 since with a 20-foot maximum effective height of wall (for aesthetics), the d value is unlikely to exceed 10 to 20 feet (attenuations of more than 25 decibels).

Rettinger also used Fresnel Integrals to find the noise reductions of barriers. He used the following equation to find the sound-level reduction (11) $SLR = -3 + 10 \log \left[(\tfrac{1}{2}-x)^2 + (\tfrac{1}{2}-y)^2\right]$ decibels: where x and y values are found by first determining the value

$$v = p\sqrt{\frac{2a}{\lambda b(a+b)}} \quad (3)$$

where

λ = wavelength of the sound

a, b, and p are shown in Figure 5.

This equation can be written in terms of the effective wall height H (in feet),

$$v = \frac{H(a+b)}{a} \sqrt{\frac{2a}{\lambda b(a+b)}} = \frac{1.414\ H}{\sqrt{\lambda}} \sqrt{\frac{a+b}{ab}} \qquad (4)$$

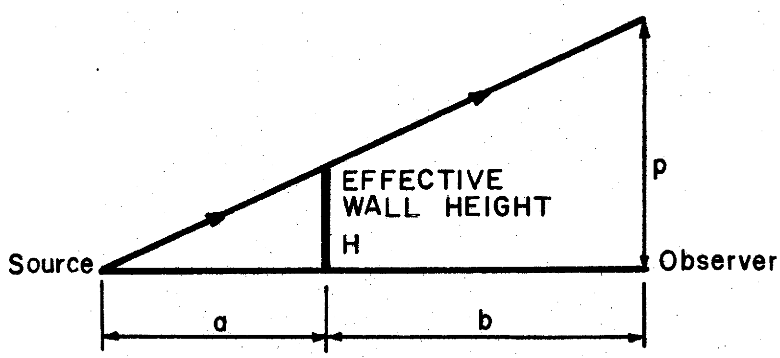


Figure 5. Rettinger's variables. (<u>11</u>)

Thus, with knowldege of a, b, H and λ (the wavelength of sound with a frequency of 1000 hertz), for this example, v can be calculated and, using the Fresnel Integrals tabulated in Table 2, the values of x and y can also be found. Substituting x and y into the sound level reduction equation, the decibel reduction is calculated. The last step can be simplified by using the graph of Sound Level Reduction versus the value of v, shown in Figure 6.

TABLE 2

TABLE OF FRESNEL INTEGRALS (11)

v	x	y	v	x	y
0.00	0.0000	0.0000	4.50	0.5261	0.4342
0.10	0.1000	0.0005	4.60	0.5673	0.5162
0.20	0.1999	0.0042	4.70	0.4914	0.5672
0.30	0.2994	0.0141	4.80	0.4338	0.4968
0.40	0.3975	0.0334	4.90	0.5002	0.4350
0.50	0.4923	0.0647	5.00	0.5637	0.4992
0.60	0.5811	0.1105	5.05	0.5450	0.5442
0.70	0.6597	0.1721	5.10	0.4998	0.5624
0.80	0.7230	0.2493	5.15	0.4553	0.5427
0.90	0.7648	0.3398	5.20	0.4389	0.4969
1.00	0.7799	0.4383	5.25	0.4610	0.4536
1.10	0.7638	0.5365	5.30	0.5078	0.4405
1.20	0.7154	0.6234	5.35	0.5490	0.4662
1.30	0.6386	0.6863	5.40	0.5573	0.5140
1.40	0.5431	0.7135	5.45	0.5269	0.5519
1.50	0.4453	0.6975	5.50	0.4784	0.5537
1.60	0.3655	0.6389	5.55	0.4456	0.5181
1.70	0.3238	0.5492	5.60	0.4517	0.4700
1.80	0.3336	0.4508	5.65	0.4926	0.4441
1.90	0.3944	0.3734	5.70	0.5385	0.4595
2.00	0.4882	0.3434	5.75	0.5551	0.5049
2.10	0.5815	0.3743	5.80	0.5298	0.5461
2.20	0.6363	0.4557	5.85	0.4819	0.5513
2.30	0.6266	0.5531	5.90	0.4486	0.5163
2.40	0.5550	0.6197	5.95	0.4566	0.4688
2.50	0.4574	0.6192	6.00	0.4995	0.4470
2.60	0.3890	0.5500	6.05	0.5424	0.4689
2.70	0.3925	0.4529	6.10	0.5495	0.5165
2.80	0.4675	0.3915	6.15	0.5146	0.5496
2.90	0.5626	0.4101	6.20	0.4676	0.5398
3.00	0.6058	0.4963	6.25	0.4493	0.4954
3.10	0.5616	0.5818	6.30	0.4760	0.4555
3.20	0.4664	0.5933	6.35	0.5240	0.4560
3.30	0.4058	0.5192	6.40	0.5496	0.4965
3.40	0.4385	0.4296	6.45	0.5292	0.5398
3.50	0.5326	0.4152	6.50	0.4816	0.5454
3.60	0.5880	0.4923	6.55	0.4520	0.5078
3.70	0.5420	0.5750	6.60	0.4690	0.4631
3.80	0.4481	0.5656	6.65	0.5161	0.4549
3.90	0.4223	0.4752	6.70	0.5467	0.4915
4.00	0.4984	0.4204	6.75	0.5302	0.5362
4.10	0.5738	0.4758	6.80	0.4831	0.5436
4.20	0.5418	0.5633	6.85	0.4539	0.5060
4.30	0.4494	0.5540	6.90	0.4732	0.4624
4.40	0.4383	0.4622	6.95	0.5207	0.4591

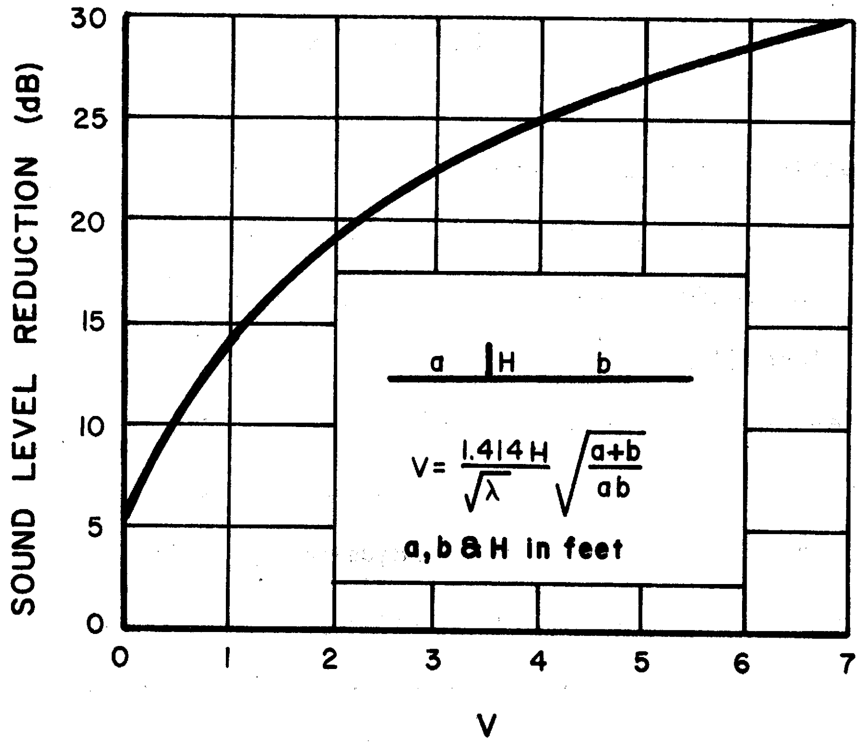


Figure 6. Relationship of sound-level reduction and v. (11)

PROBLEM STATEMENT

The objectives of this study are summarized below:

1. To predict the effects of various wall heights and distances from the roadway for noise attenuation using Fehr's equations (9).
2. To review the effects of environmental condition on the theoretical values and to outline the criteria that have been recommended for suitable adjustments in field application.
3. To review the acoustical treatments for barrier walls.
4. To gather field data to determine the relative accuracy of the theoretical equations.
5. To utilize published field data from a California site where an earth berm has been constructed between a highway and a drive-in church to determine the relative accuracy of the theoretical equations.

ACOUSTICAL MATERIALS FOR BARRIER WALLS

The acoustical materials reviewed in this section are considered to be relatively inexpensive and can be used under all weather conditions.

Before discussing the various types of acoustical materials 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. These components are 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 (15, 16).

Porous materials having a thickness greater than one-half inch dissipate sound energy by friction. Their voids progressively dampen the amplitudes of sound waves by increased friction; thus, there is a higher energy loss with increased material density. The flow resistance must be held between the limits of too low (high porosity) and too high (low porosity). If the material porosity is too low, the wave can not enter the voids of the material and are reflected, while a high porosity material has too many voids and insufficient friction, causing low energy dissipation.

The flow resistance of various materials is related to the thickness, density, orientation of the fibers or passageways with respect to the direction of the sound waves, fiber diameter, and percentage of the binder of the particular material (16).

The difference between sound transmission loss and sound absorption loss needs to 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 small attenuation. However, a barrier wall constructed of dense concrete or brick absorbs little sound and prevents its passage to the other side, thus giving a larger degree of attenuation (17). Reflected sound does contribute to the ambient noise level in the latter case.

Not only does the density of the wall affect the transmission of sound, but the frequency of the sound is important in sound-transmission loss. It should be noted that at low frequencies most materials have a lower transmission loss than at the middle and high frequencies. The above principles are illustrated in Figure 7 (17).

High transmission losses at low frequencies are hard to obtain. Fortunately, hearing and speech criteria allow higher sound levels at lower frequencies than in the higher frequency ranges. That is, the human ear is more sensitive to higher frequencies.

Both cost and noise energy attenuation must be considered when selecting acoustical materials. No one material can be generally recommended, since some materials which reduce the sound to a predetermined level might be too expensive and/or not applicable to every situation.

Waller (18) compares the performance and economics of noise-reducing materials in the construction industry and notes that not only the cost of the wall itself must be considered, but also the foundations, erection costs, and cost of attaching the acoustical material to the wall. He notes that the designer should seek a balance, an optimization, between sound absorbing and sound insulating materials. In large jobs this optimization can be programmed for

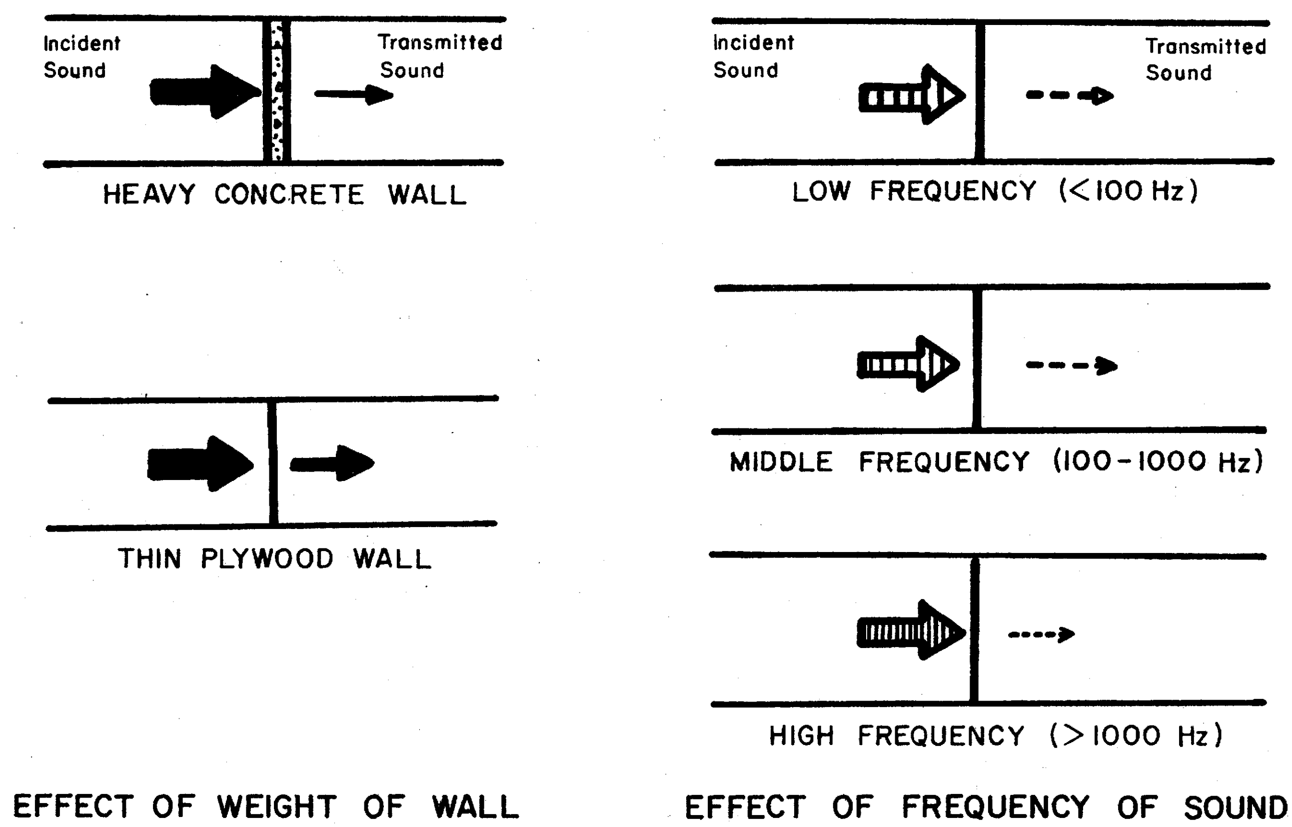


Figure 7. Basic principles in sound-transmission loss. (17)

computer analysis, and various trade-offs between total cost and amount of absorption can be made. Figure 8 (19), shows the relationship between the weight of a material and the transmission loss in decibels. This relationship can be expressed by the equation (20),

$$R \simeq 20 \log \frac{MW}{2\rho S} \qquad (5)$$

where R = sound reduction in dB;

M = mass of the wall per unit area in lbs/sq ft;

W = (2π)x(frequency of sound wave)in radians/sec;

ρ = mass density in lbs/cu ft; and

S = speed of sound in air in feet/sec.

The sound reduction increases logarithmically with the weight of the wall and frequency of the sound wave. If the weight of the wall or the frequency of the sound wave is doubled, the sound reduction is increased by 20 log 2 or 6 dB (for a free field case).

An example of the Mass Law relationship between sound transmission loss and mass per unit area of wall or partition can be see in Figure 8, when comparing the transmission loss of 30 dB for one-quarter inch glass (3-1/4 lbs/sq ft of exposed surface) and 45 dB for 4-inch brick (45 lbs/sq ft of exposed surface).

Sabine, et al (21), in their study of transmission losses in light-weight concrete, found that there was an increased transmission loss (17 dB) between an unplastered and plastered 4 inch cinder block.

It should be noted that paint makes no significant difference in the transmission of sound through a dense concrete block wall and only slightly improves the transmission loss with walls of moderately high flow resistance (Figure 9); even then, this only occurs at the lower frequencies. Figure 9 and 10 (21) show the noise transmission loss (in decibels) through two different walls versus the frequency of the noise.

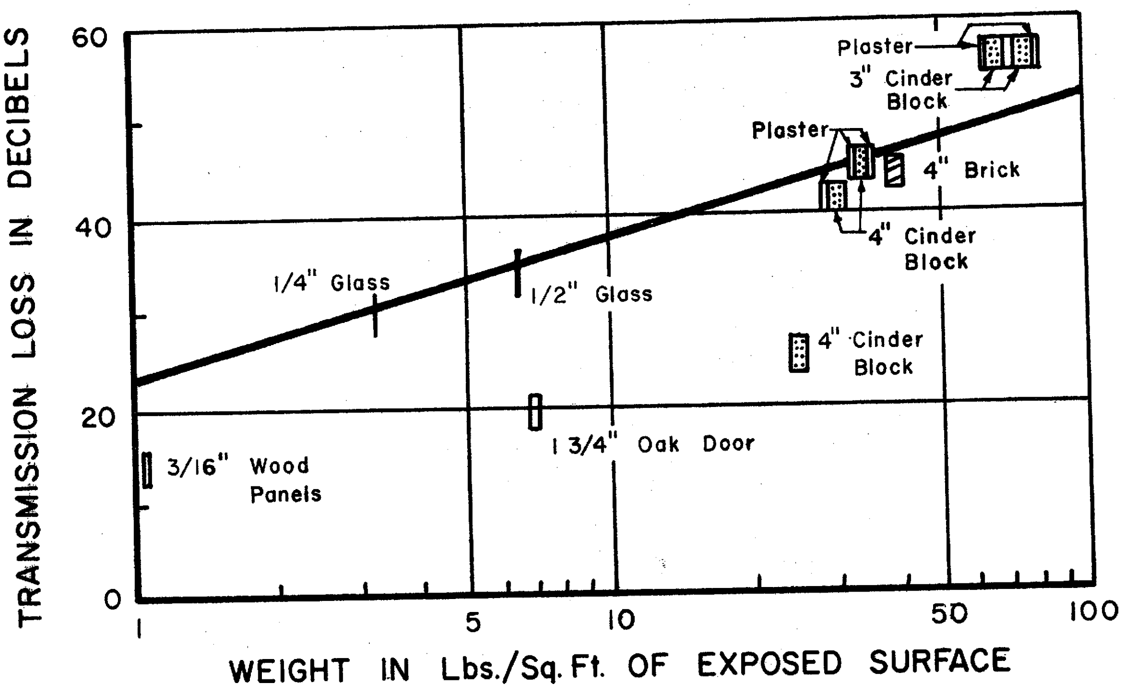


Figure 8. The Mass Law relationship. (19)

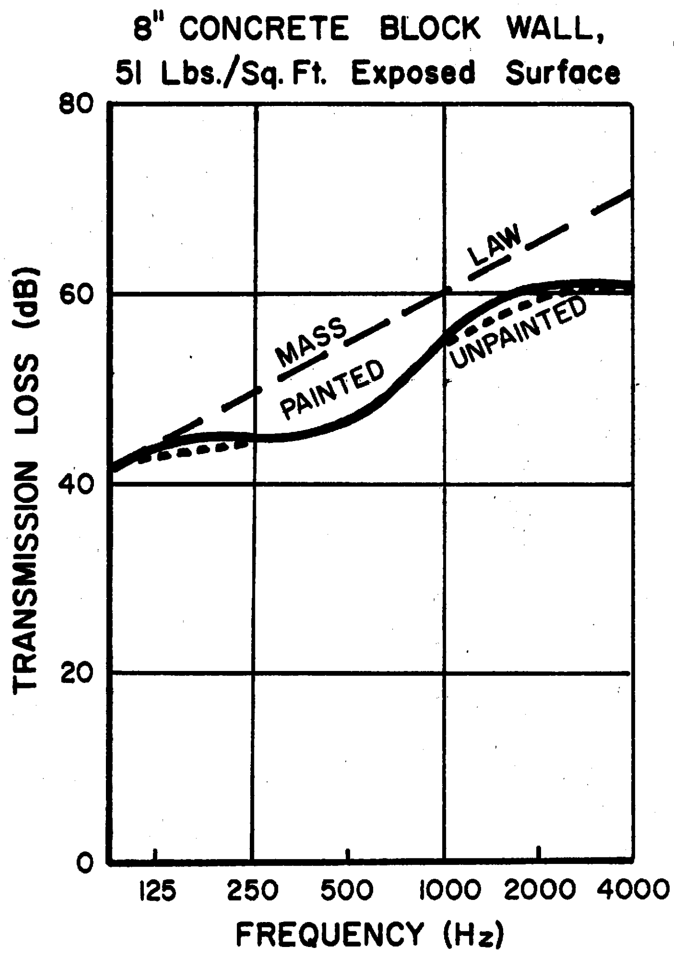


Figure 9. Transmission loss through a concrete wall. (21)

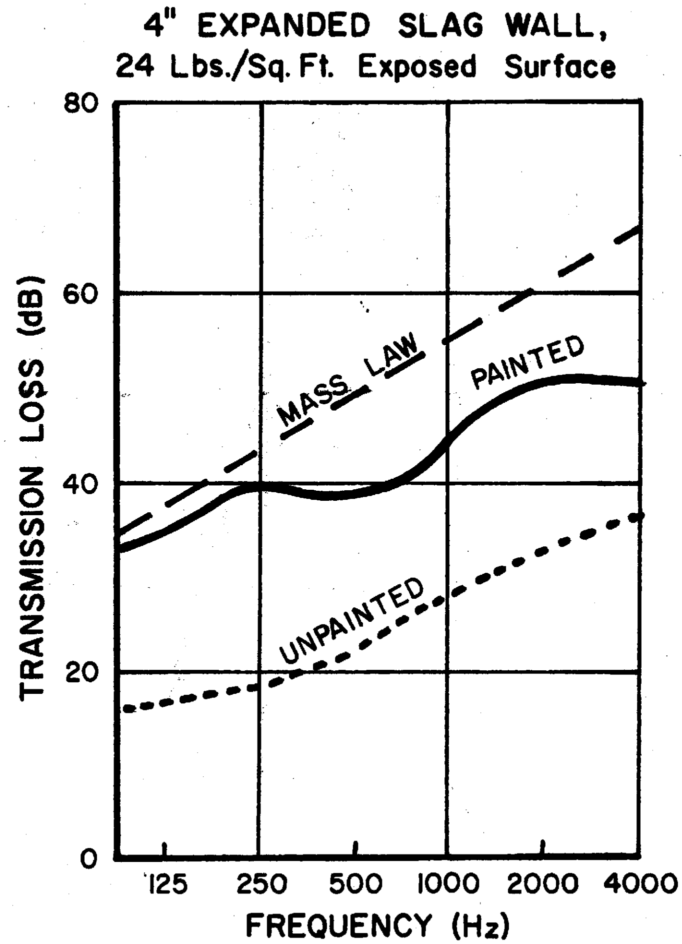


Figure 10. Transmission loss through an expanded slag wall. (21)

The straight Mass Law line shown in the graphs (of Figures 9 and 10) is defined by the relationship,

$$TL = 20 \log M + 20 \log f - 33 \text{ dB}$$

where

TL = transmission loss in dB;

M = weight of the wall or partition in lbs per square foot of exposed surface; and

f = frequency of the sound in hertz.

This relationship represents the theoretical transmission loss for sound incident on an impervious wall having only mass, with negligible stiffness and dampening. In both cases the transmission loss falls below the Mass Law line in the middle and high frequencies, due to the bending stiffness of the wall. Sabine, et al., concluded that a porous masonry wall which is painted heavily enough to seal the surface porosity has a transmission loss equal to that of a solid masonry wall of the same weight and stiffness. The average transmission loss versus wall weight for a heavily painted or non-porous concrete block wall is shown in Figure 11. They found that the transmission loss increased when the surfaces were painted. When the paint partially fills the voids, the frictional resistance to the wave energy increases. The transmission loss of a painted or plastered lightweight porous concrete wall depends only on the weight and stiffness of the wall and not on the void structure. Thus, the transmission loss of a painted porous wall is equal to that of a nonporous wall of similar weight and stiffness (19). Future research is needed to determine the feasibility of using a lightweight material, such as a vermiculite (kiln-expanded mica) concrete, on existing structures in residential areas of severe highway

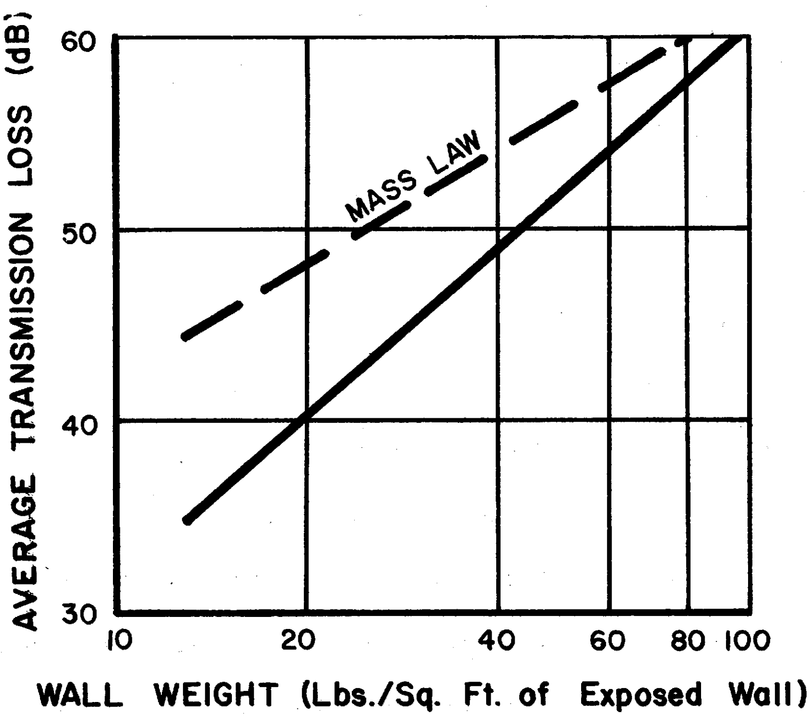


Figure 11. Transmission loss for non-porous walls. (21)

noise. Preliminary inspection tends to suggest that a vermiculite concrete wall might be used on bridges without major modifications of the structures.

Another lightweight barrier wall material is polystyrene foam. Because of its closed cell structure it offers a high resistance to moisture absorption and water-vapor diffusion. If polystyrene foam has an open cell wall, there exists an increased resistance to the transmission of sound and absorption of sound due to the many branch channels (21).

Sheets of polystyrene foam also have relatively good mechanical properties (shear and bending strength) and have the advantage of easy application, as well as being good sound-deadening materials. Softer and more flexible polystyrene foams have been developed for use as sound absorbing barriers. The difference in the sound absorption properties between the harder polystyrene and the softer open cell type is seen in Figure 12 (23). The sound absorption characteristics of the hard foam are greatly improved by needle puncturing and supporting the sheet away from the wall. The use of hard polystyrene foam sheeting directly on a wall does not reduce the absorption significantly.

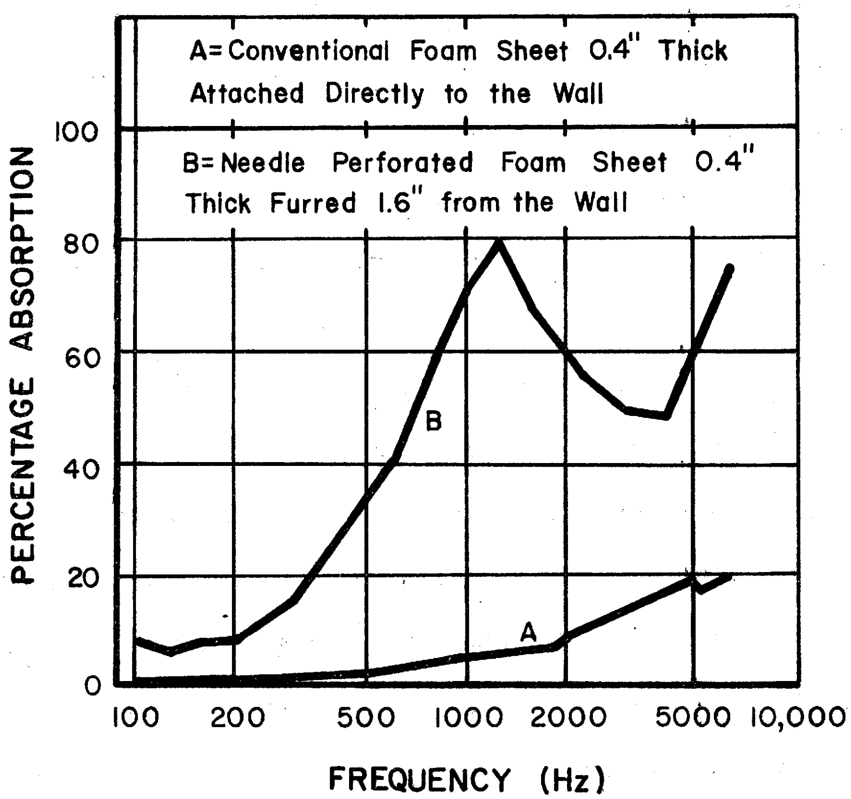


Figure 12. Sound absorption characteristics of polystyrene foam. (23)

On the other end of the barrier wall weight spectrum is lead sheeting. The St. Joseph Lead Company claims that the "dead" weight of lead makes it, pound for pound, a more effective means of preventing sound transmission (24). Table 3 shows the amount of lead required to provide the same degree of sound transmission loss as that provided by other types of materials used in barrier walls or partitions.

Lead has the advantage of limpness and high density which allows it to block sound transmission better than most construction materials. Thus, when weight and space are important, lead should be considered. Before recommending use of this or any other material, the engineer must consider the total cost, i.e., the cost of the material, as well as installation and maintenance costs.

While it is not the authors' intention to present a detailed discussion of the propogation of a sound wave through more than one material, it should be noted that the basic method of sound absorption includes the processes of facing and spacing. Facing materials include perforated or woven membranes, whereas spacing refers to the air space between the porous material and the wall (25). Figure 13 (20) shows diagrammatically the facing material, the wall, and the air space between: where,

1) d is the cavity width in feet;
2) P_i, P_t, P_r, are acoustic pressures in the incident, transmitted, and reflected waves in pounds/ft^2, respectively;
3) M_1 and M_2 are the masses of the acoustical material and wall, respectively, in lbs per sq ft;

TABLE 3

COMPARISON BETWEEN LEAD AND OTHER MATERIALS FOR AN EQUAL DEGREE OF SOUND TRANSMISSION LOSS (24)

Material	Weight of Material lbs/sq ft of exposed surface	Weight of Equivalent Lead lbs/sq ft of exposed surface	Weight Ratio	Thickness: Material Inches	Thickness: Equivalent Lead Inches
Plywood	2.3	0.5	4.9	0.8	.008
Solid Plaster	18	3.8	4.8	2.0	.062
Cinderblock	22	5.5	4.0	6.0	.094
Plaster on Studs	12	7.5	1.6	4.6	.125
Plaster on Double Studs	16	11.0	1.4	5.8	.188
Brick	104	15.0	8.0	6.0	.250

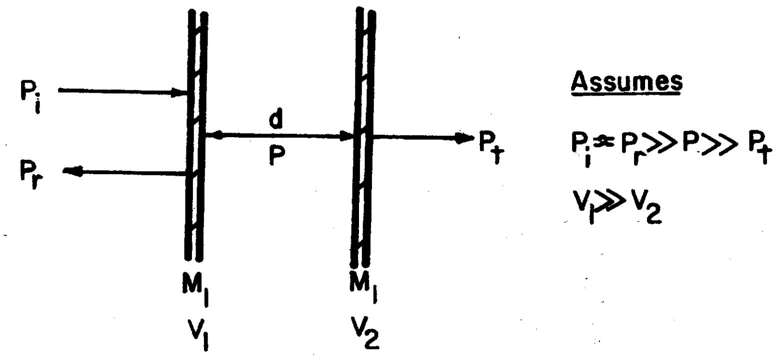


Figure 13. Sound reduction variables of separated materials. (20)

4) V_1 and V_2 are the velocity amplitudes of the vibrating material and wall in ft-ft/sec, respectively;

5) w = 2π x frequency in radians/sec;

6) ρ = mass density in lbs/cu ft; and

7) S = speed of sound in air

For sound reduction at intermediate frequencies

$$R = R_1 + R_2 - 20 \log \frac{S}{2wd}$$

where R_1 and R_2 are reductions for each material ($= 20 \log \frac{Mw}{2\rho S}$). The third term of the above equation reflects the increased reduction with increased distance between the material and the wall. The critical cavity width is proportional to one-half the wave length of the sound being transmitted through the wall. For frequencies of 1000 hertz (wavelength 12 inches) the optimum distance that the acoustical material should be positioned is six inches from the wall.

Care must be taken in selecting barrier wall materials from the vast array of products available on the market today, since the majority of the products have 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 deteriorate when exposed to the weather (wood and cellulose fibers, wool-felt, etc.), while others recommended for outside use (fiber glass blankets, rockwool or steel wool) perform well (15). Acoustical plaster applied by trowel or machine, can also be used but measurements have shown that variations exist between the field and laboratory sound absorption coefficients. Another material that can be used on walls is sprayed asbestos. Care must be taken with asbestos because it is fragile when set and the color is hard to match if a damaged section is replaced.

When discussing barrier walls and materials, mention needs to be made of the earth berm. If sufficient right-of-way is available, this type of barrier wall is likely to be the most economical and aesthetically pleasing available today.

On at-grade sections of a freeway, consideration should be given to construction of a 6-foot earth berm with a 6-foot barrier wall. By selective planting, the earth berm can be made aesthetically pleasing, and the driver only sees a 6-foot wall, rather than one that is 12 feet. This also helps to reduce the tunneling effect of the barrier walls. The side slopes of a depressed freeway section also act as noise barriers, although side slopes are relatively inefficient due to the distance between the source and their effective height as shown in Figure 19 on page 35.

In the summary, the highway engineer should recognize the trade-offs 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. These costs must include the foundation barrier wall material, construction and maintenance of the barrier walls and any sound-absorbing surface material that might be used (36). The highway engineer should recommend materials with good absorption properties, and if porous materials are used, at least one side must be painted or plastered.

SITE SELECTION AND DESCRIPTION

Sacramento Community Drive-In Church, California

The Sacramento Community Drive-In Church is located adjacent to Route 99, a heavily traveled route with a high percentage of trucks. Due to the 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. Figure 14 (22) shows the general layout of the site, with dBA values shown on both sides of the barrier.

The average reduction of truck noises on the eastern side of the barrier as compared with the western side was 12 to 14 dBA, except at the southern end where the mound terminates. At this end the noise flanks the barrier, and an extension of the barrier would be necessary to prevent this. Figure 14 shows this flanking effect by increased noise levels at points E and F and considerably higher levels at points G, H, and I. An extra length added to the southern end of the barrier would be sufficient to shift the 90-degree incident path to less than 30 degrees for locations G, H, and I.

Although there are some narrow paths through the wall, the values recorded on the northern end are uniform. As would be expected, the recorded values decrease since the effect of the barrier decreases as the observer moves farther away from it.

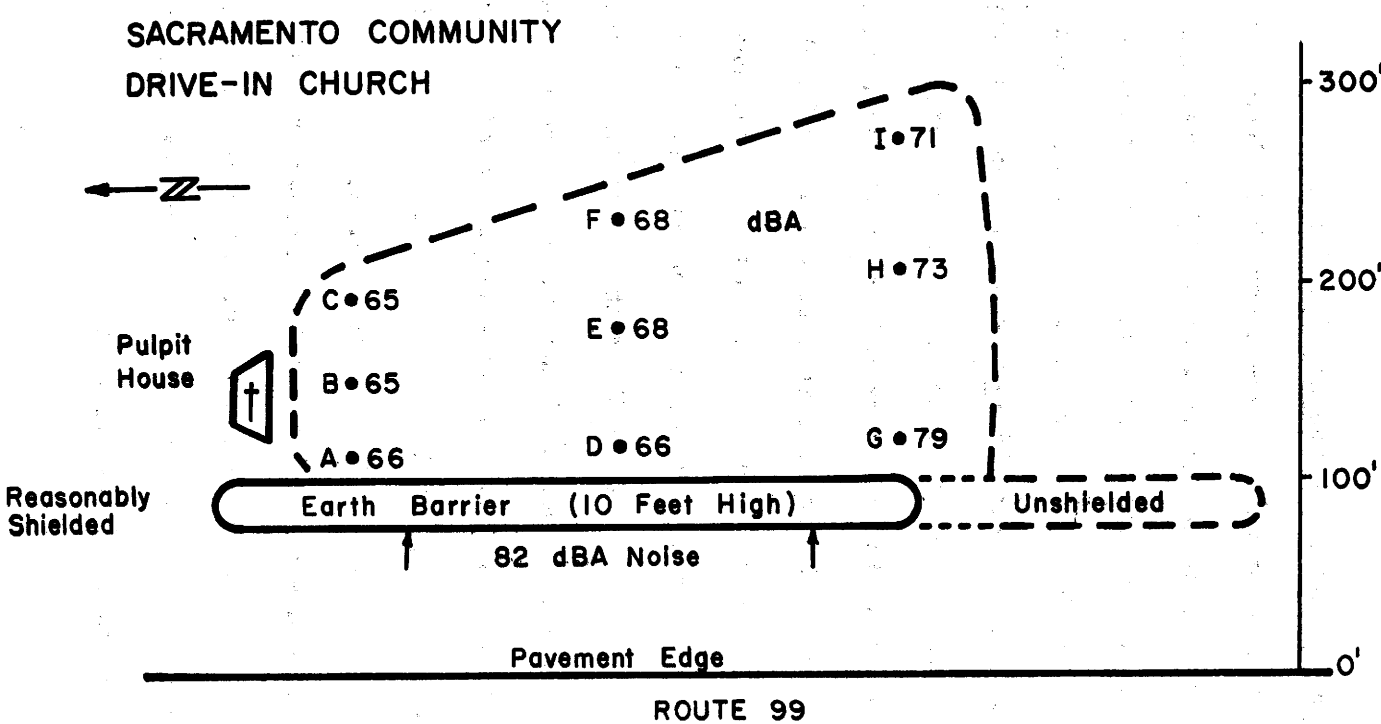


Figure 14. Sacramento drive-in church site layout. (22)

Katy Freeway (IH-10), Houston, Texas

When a freeway is located in a cut, the side slopes act as a barrier which causes a shadow area of diffracted sound waves, and in this area the sound decreases from a maximum at the edge of the shadow line to a minimum at ground level.

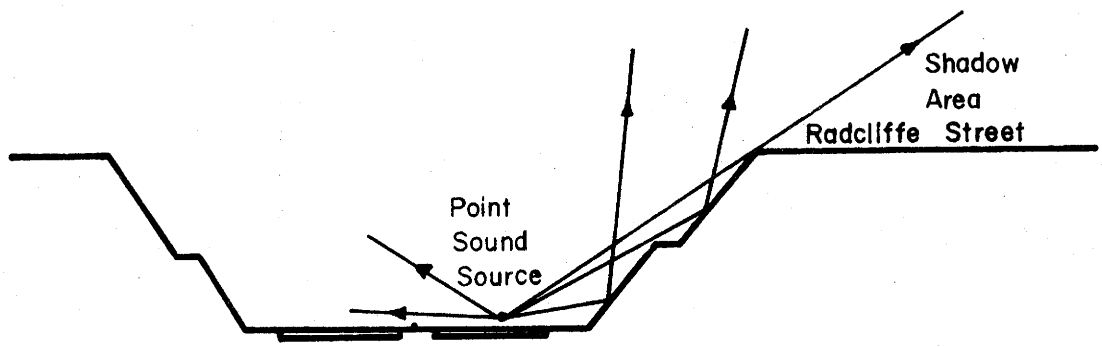


Figure 15. Shadow area of Radcliffe Street (Adjacent IH-10).

This form of barrier is not very effective, since the efficiency of a barrier decreases as the distance between the source and the barrier increases. The attenuation due to a side slope is also reduced by the lack of a "sharp edge" at the top of the cut. A blunt edge facilitates the diffraction of sound waves around the edge; consequently, the attenuation is decreased. This phenomenon of diffraction is counter to the concept of rectilinear propogation of oscillating energy. Diffraction is the fundamental property, and rectilinear transmission is the special case in which the wave front is unrestricted (14).

While the depressing of freeways creates a noise barrier, it is far more costly and less effective than the construction of a barrier close to an at-grade facility. It does, however, have the advantage of being less unsightly than the tunneling effect of a concrete wall close to the highway. Also, the absorption characteristics of the grassed side slopes aid in the reduction of the highway noise level.

The section of highway selected for this investigation was at the intersection of the Katy Freeway at Radcliffe Street, Houston, Texas. Measurements were taken 200 feet and 400 feet from the closest edge of the freeway, along Radcliffe Street. The number of automobiles and trucks were counted for each direction of travel.

The general dimensions of the test site are shown in Figure 16. Measurements taken at 200 feet and 400 feet from the traveled way, resulted in a variation in the effective height of the barrier. The top of the side slope represented the top of the theoretical wall, with the sound source located 20 feet below. If the source of the total sound from the 8 lanes is considered as an equivalent single

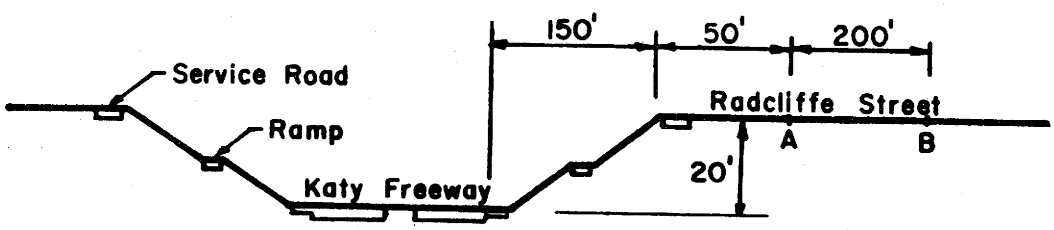


Figure 16. Cross section of Katy Freeway and Radcliffe Street.

lane (12), the distance from this lane to the wall is about 150 feet. Thus, the points selected for recording were 200 feet and 400 feet from the equivalent single lane. By geometry, this gives an effective barrier height of H_A = 5 feet and H_B = 13 feet, respectively (Figure 17).

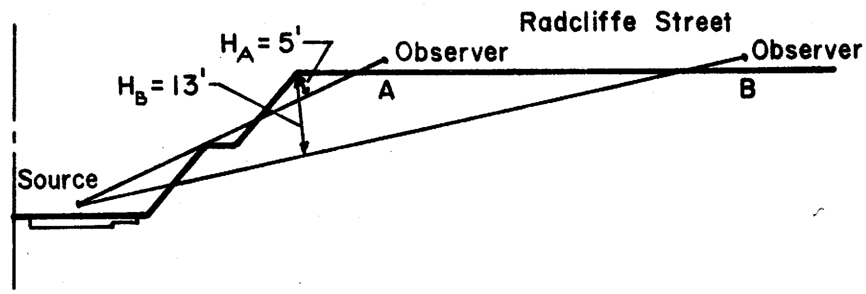


Figure 17. Effective barrier heights for Radcliffe Street sites.

Figure 18 (4) is included in this section, not for comparison of values obtained in the field, but for the comparison of vertical and sloping cut sections. The graphs shown are for 20-foot depths of cut, measured adjacent to various 6- and 8-lane freeways. The vertical 20-foot cut section gives greater attenuation than the sloping 20-foot section, especially within 200 feet of the traveled way. This is due to the effective height of the vertical side (H_V) being greater and closer to the noise source than the effective height of the sloping side section (H_S). As the receiver moves farther away from the noise source, the difference in the effective heights rapidly decreases. This can be seen in Figure 19, 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.

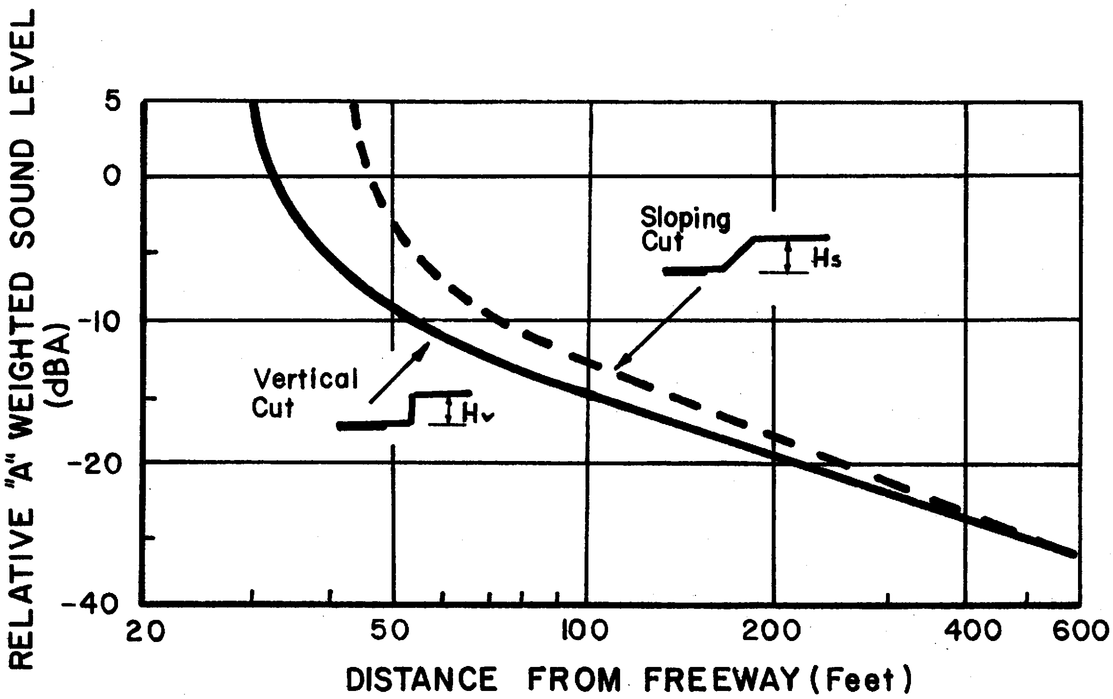


Figure 18. Noise reduction due to vertical and sloped sides. (4)

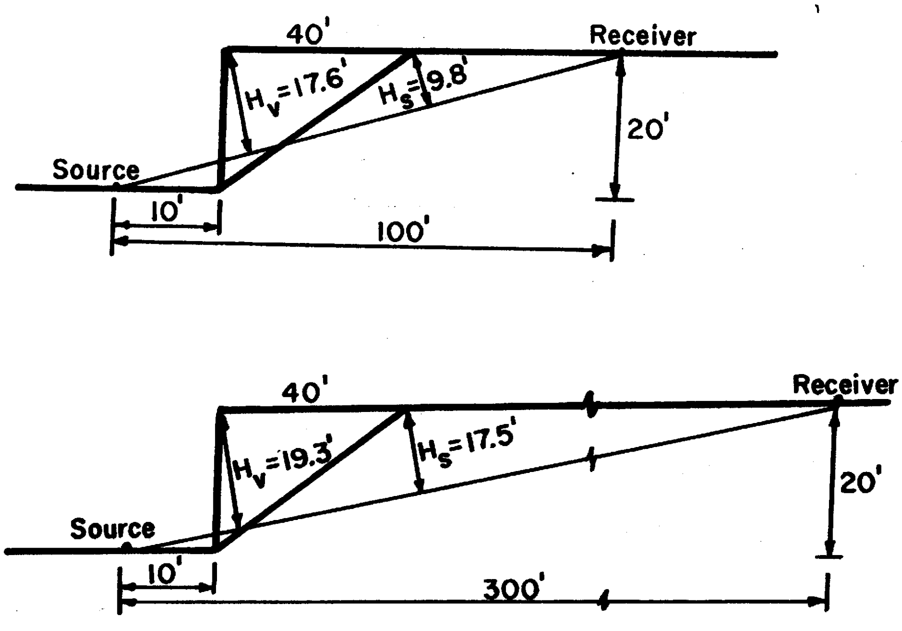


Figure 19. Effective heights of vertical and sloped sides.

ENVIRONMENTAL CONSIDERATIONS IN DESIGN

Gradient Adjustments

Galloway, et al. (6), note that while adjustments are necessary for trucks on grades, no adjustment is necessary for automobile traffic. The table 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 negligible.

TABLE 4

ADJUSTMENTS FOR TRUCKS ON GRADES

(Added to Estimated Noise Level for Level Roadway)

% 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. (6) , 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.

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

EXPERIMENTAL DATA & PROCEDURE

The aim of this study was to correlate noise values recorded in the field with those calculated using Fehr's equations (9). Two study sites were selected, one in Houston, Texas, where data were actually recorded, and the other in Sacramento, California, where the results had previously been published.

The equipment and method of measurement used to record data in Houston have already been described in a report by the author (29), and only a brief description will be included here.

(a) A General Radio Sound-Level Meter, Type 1565-A, using the "A" weighted network on both the fast and slow setting, recorded some of the data. A larger, more accurate Type 1551-C was occasionally used as a cross check for the accuracy of the 1565-A meter.

(b) A General Radio Data Recorder, Type 1525-A, was used to record the sound pressure level. This instrument is both a sound pressure level and audio tape recorder, and permits on-site measurements, as well as traffic noise recordings for later laboratory analysis.

(c) A General Radio microphone, Type 1560-P5, with tripod and cable was used for all recordings.

(d) A General Radio Sound-Level Calibrator, Type 1562- A, was used to check the acoustical calibration of the recording.

system and the hand-held sound pressure level meter.

(e) A Cornell-Dublier Inverter, Model 12ESW25, was used to provide power for the data recorder. The inverter was connected to a vehicle's 12-volt (DC) electrical system and supplied 110 volt (AC) to the recorder.

(f) A Honeywell Strip Chart, Model Number Electronik 193, was used to plot the recorded sound pressure level from the tapes.

The logarithmic nature of the decibel means that a unit output from the data recorder represents different changes in the sound pressure level, depending upon the magnitude of the sound pressure level. Thus, a conversion curve was developed to convert the strip chart vertical units to dBA values. These values must be added to the recording base value to give the total noise level in dBA units. The strip chart was adjusted to plot at a rate of one division per second to facilitate data analysis. Figure 20 shows the conversion curve described above. Figure 21 shows typical plots from the strip chart plotter as recorded in the field (note the interference from local traffic). The 1525-A Data Recorder has two channels, which permit the simultaneous recording of sound pressure level on the main channel and a description of the noise source and other pertinent data given by an observer on the secondary channel.

Recordings were made at the Houston site on Radcliffe Street, 200 feet and 400 feet from the near edge of the travelled way of Katy Freeway (IH-10), at 2:56-3:06 p.m. and 3:21-3:31 p.m., respectively, on January 12, 1971. Radcliffe Street terminates at the freeway service roadway. Care was exercised to identify other sources such as aircraft, wind, voices, and local traffic.

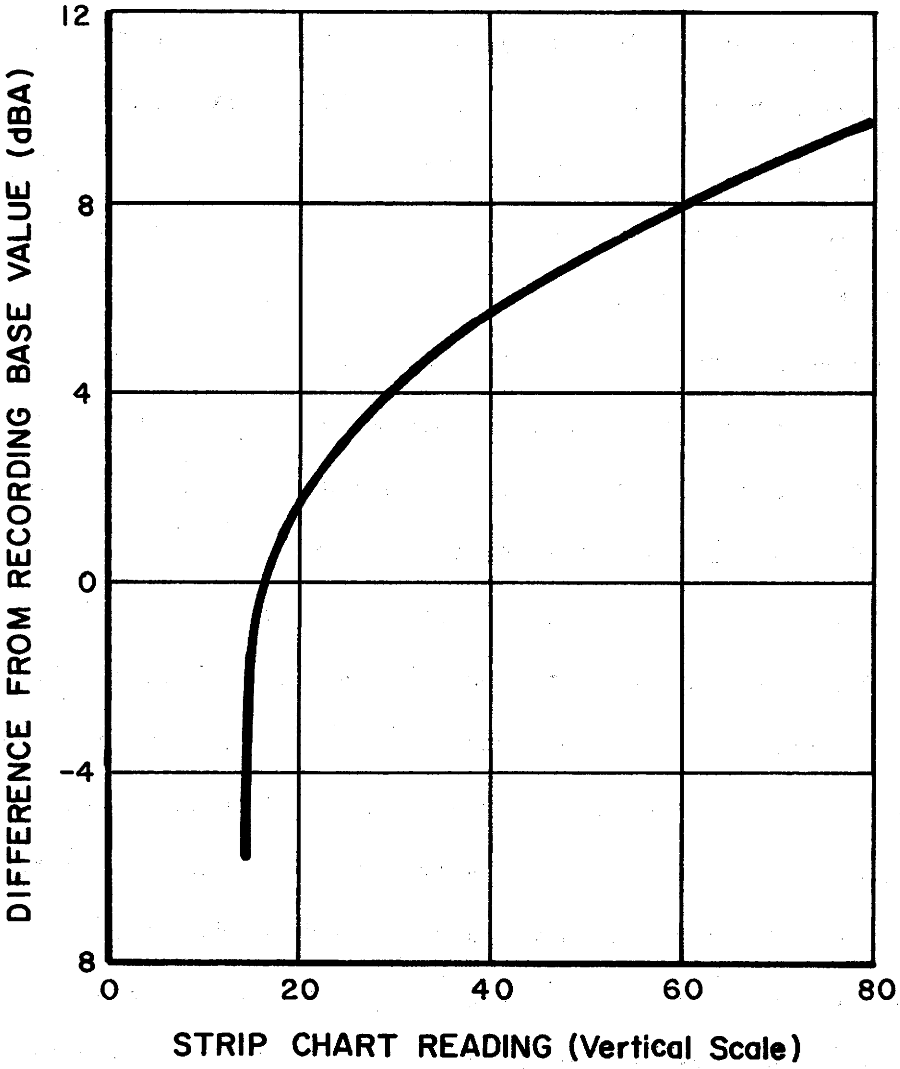


Figure 20. Conversion graph for strip chart readings.

At both positions, the microphone was positioned on a tripod, parallel to and about five feet above the ground, with the recording head pointed in a direction perpendicular to the traffic flow. The microphone was then attached to a Type 1525-A General Radio Data Recorder which was set on the "A" weighting scale.

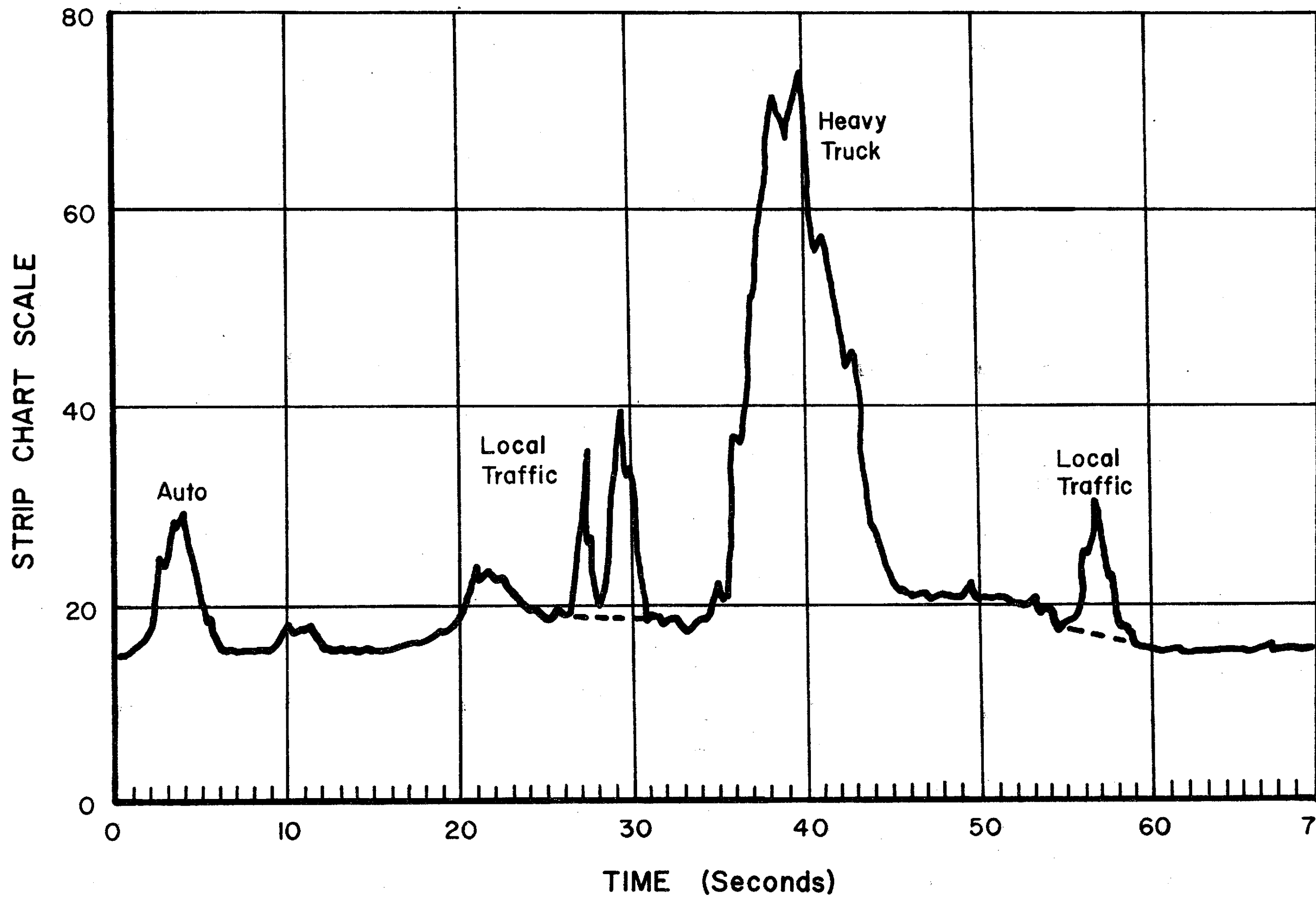


Figure 21. Typical strip chart plot.

Before each recording was taken, an acoustical calibration was performed. A sound pressure level calibrator with a sound pressure level of 114 dB was used to insure an accuracy of better than $\pm$ 0.5 dB. The proper base scale was selected by trial and error or prior experience, and the base scale selected for each recording was noted. This scale should be sensitive to the traffic noise, but not to such a degree that the noise level frequently goes outside the recording range. Both recordings were of 10 minutes duration, and background noises were noted on the secondary channel. These recordings were spot checked using the Type 1565-A and 1551-C sound-level meters.

NOISE LEVEL REDUCTION BY BARRIERS

Computer Solution Using Fehr's Equations

Using the graph presented by Fehr (9) to convert the noise reduction factor (Y) to a decibel value (dBA), a computer format can be developed to use the distances and wall heights from the input to output the actual dBA reduction. To do this, the logarithmic function of the graph must first be calculated, and using this equation the dBA values can be found. For simplicity, an "IF" statement was included in the program to prevent the very low values of "Y" becoming negative values (since values less than $\log_{10}$ are negative).

Using the index of dispersion method (30), the following equations can be found:

Let y = Mx+b be the equation of the regression line given by Purcell (8) using Fehr's (9) equations.

The slope $M = \frac{\Sigma xy - \bar{x}\bar{y}}{\Sigma x^2 - ix^2}$

where

i is the total number of observations

Thus, the equation of the regression line is:

$$y - \bar{y} = M(x - \bar{x}) \tag{8}$$

and from Purcell's graph (8), page 9

x	y	u=log y	x^2	ux
5	0.31	-0.5086	25	-2.543
10	1.00	0	100	0
15	3.10	0.4914	225	7.371
20	10.00	1.0000	400	20.000
25	31.00	1.4914	625	37.285
$\Sigma x=75$		$\Sigma u=2.4742$	$\Sigma x^2=1375$	$\Sigma ux=62.113$
i=5				

$$\bar{x} = \frac{75}{5} = 15 \text{ and } \bar{x}^2 = 225 \text{ and } i\bar{x}^2 = (5)(225) = 1125$$

$$\bar{u} = \frac{2.4742}{5} = 0.4950 \qquad i\bar{x}\bar{u} = (5)(0.495)(15) = 37.025$$

Now $M = \dfrac{\Sigma ux - i\bar{x}\bar{u}}{\Sigma x^2 - i\bar{x}^2} = \dfrac{62.113 - 37.025}{1375 - 1125} = \underline{0.100}$

Equation of the regression line = $u - \bar{u} = M(x-\bar{x})$

$\therefore U - 0.495 = 0.100(x-15)$

$\therefore U + 1.005 = 0.100x$

Now

$U = \log_{10} y$ and $\log_{10} 10.10 = 1.005$

$\therefore x = 10 \log_{10} 10.1\, y$

or dBA Reduction = $10 \log_{10} 10.1\, Y$

Using distance combinations of 25 feet, 50 feet, 100 feet, 200 feet, 400 feet and 800 feet for both sides of the barrier wall and wall heights of 2 feet to 20 feet, in increments of 2 feet, the "Y" value can be calculated;

$$Y = 2\left[a\left(\sqrt{(1+H^2/a^2)}-1\right) + b\left(\sqrt{1+H^2/b^2}-1\right)\right] \qquad (9)$$

Using the equation of the line (dBA Reduction = $10 \log_{10} 10.1Y$), noise reductions for the above combinations can be found in Figures 22-28 (p. 46-52).

Modification of the program will allow any value of a, b, or H to be used. The program format and calculations are included in Appendix B.

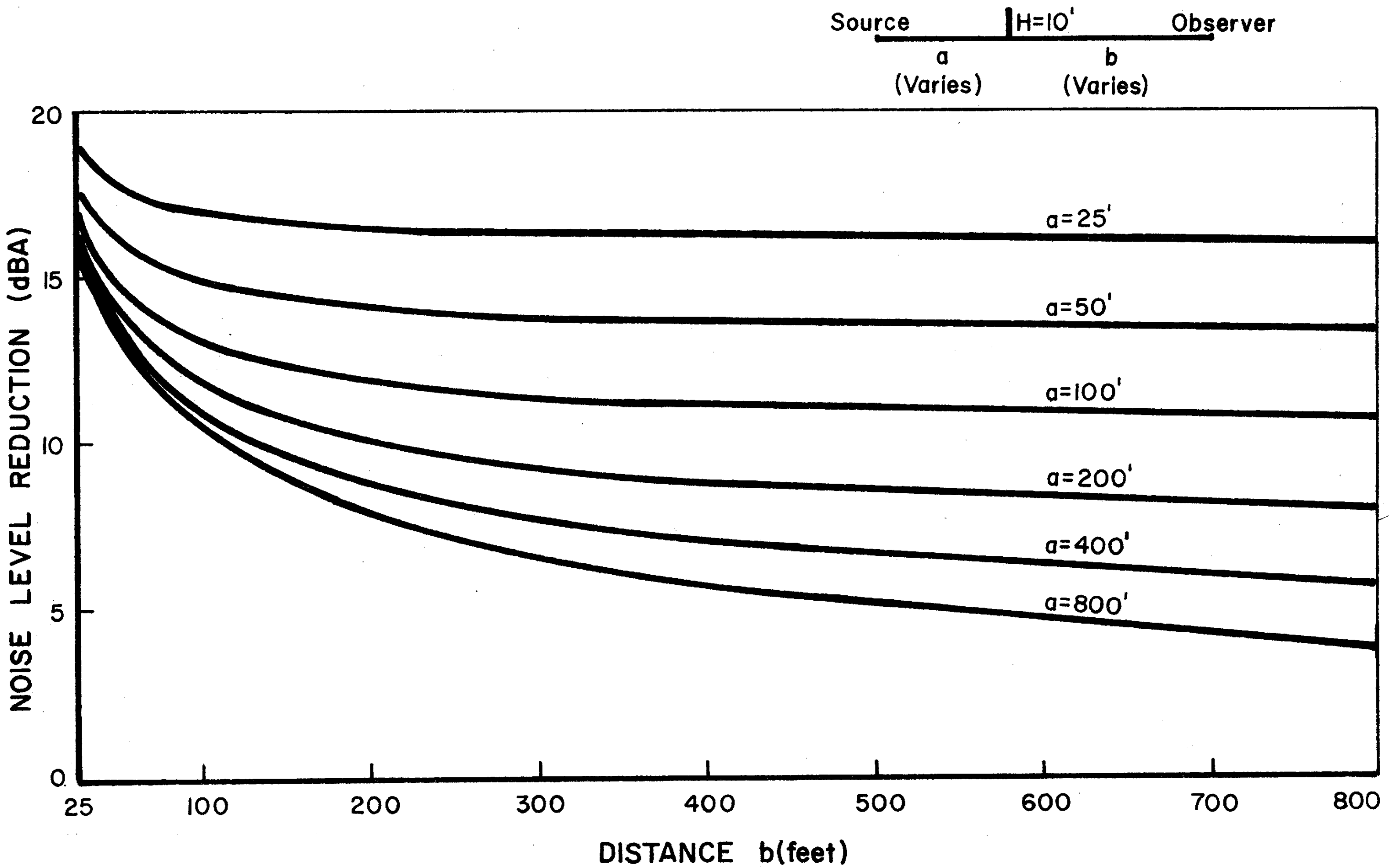


Figure 22. Noise reduction - 10 feet effective wall height.

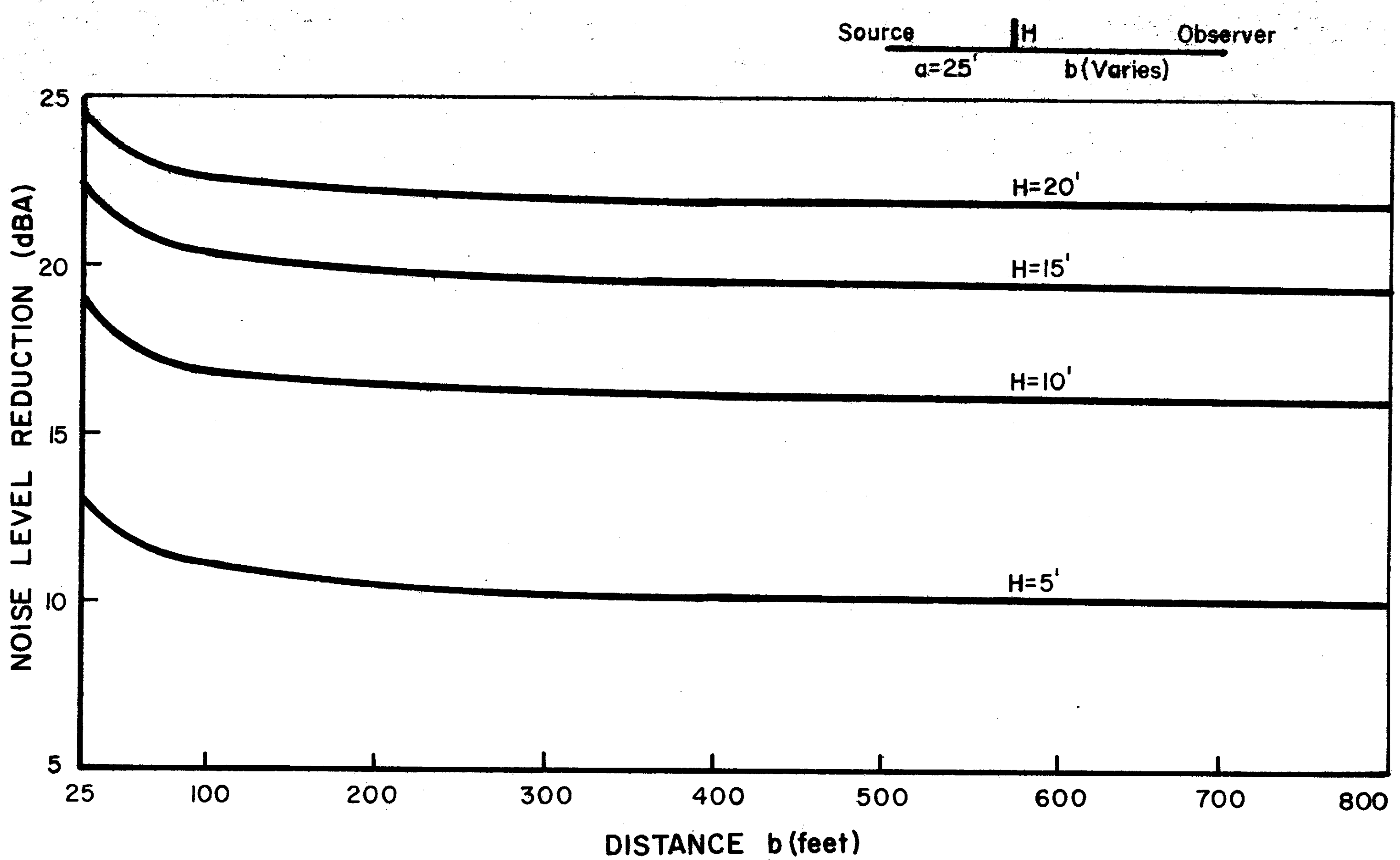


Figure 23. Noise reduction - source to wall distance 25 feet.

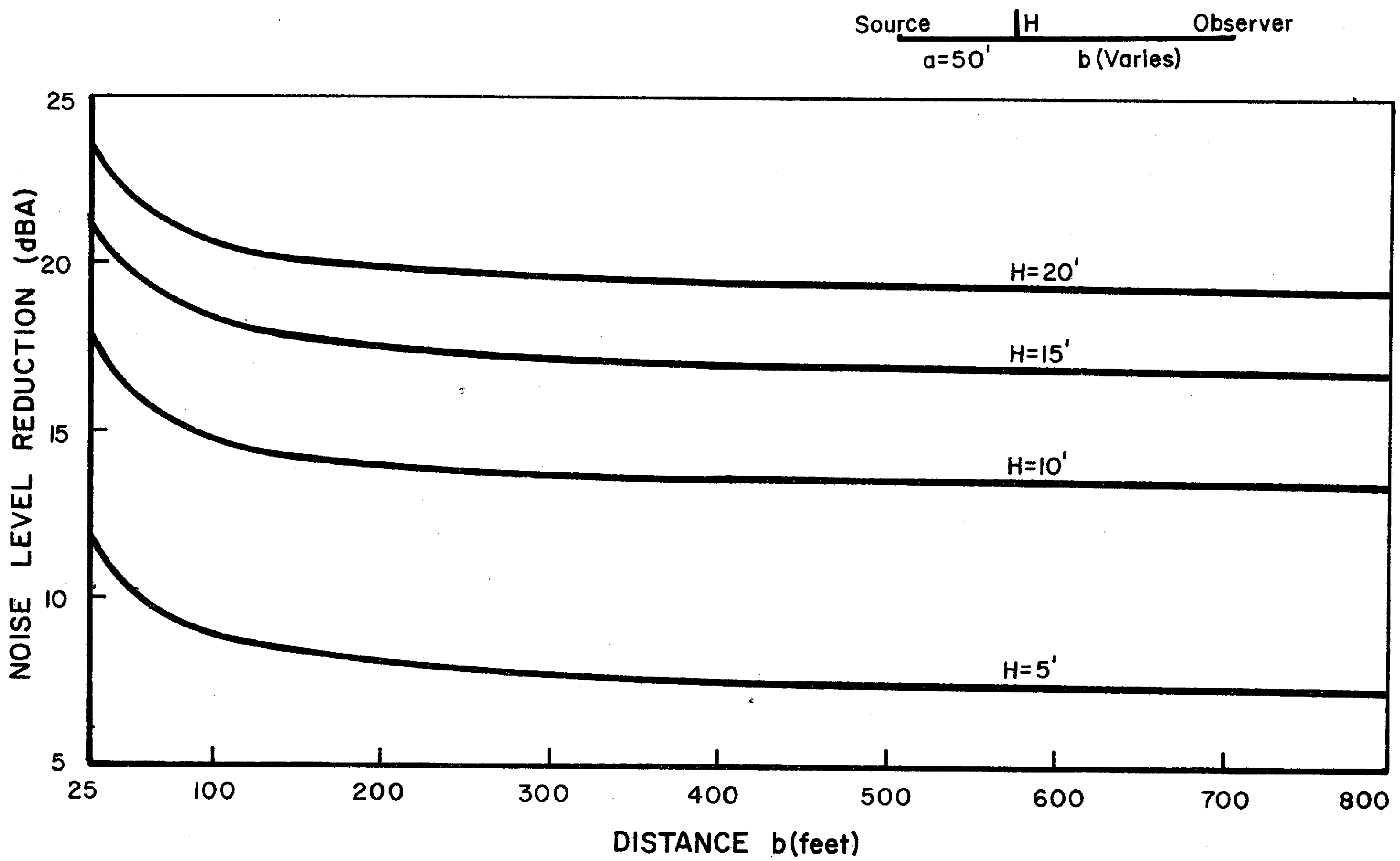


Figure 24. Noise reduction - source to wall distance 50 feet.

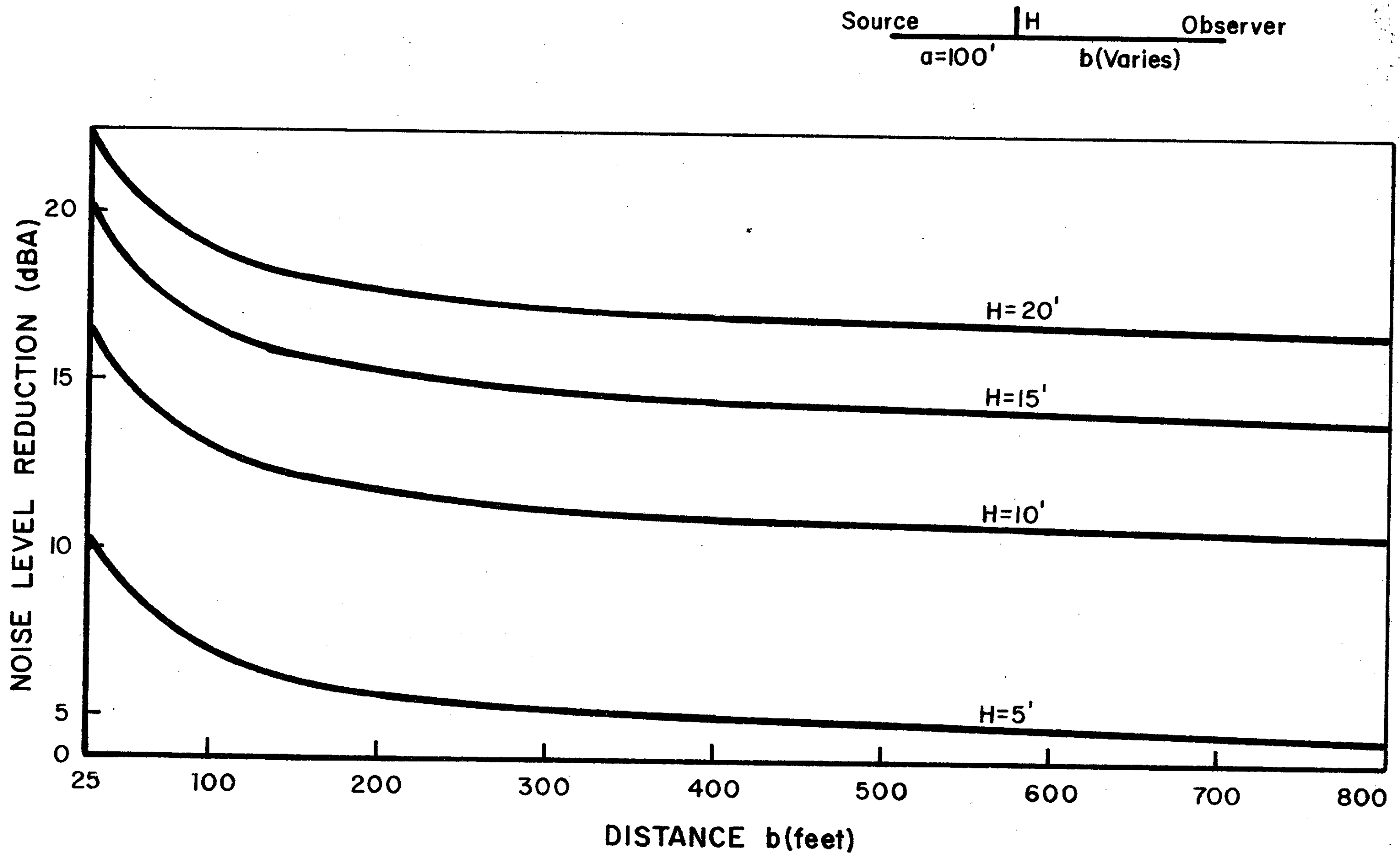


Figure 25. Noise reduction - source to wall distance 100 feet.

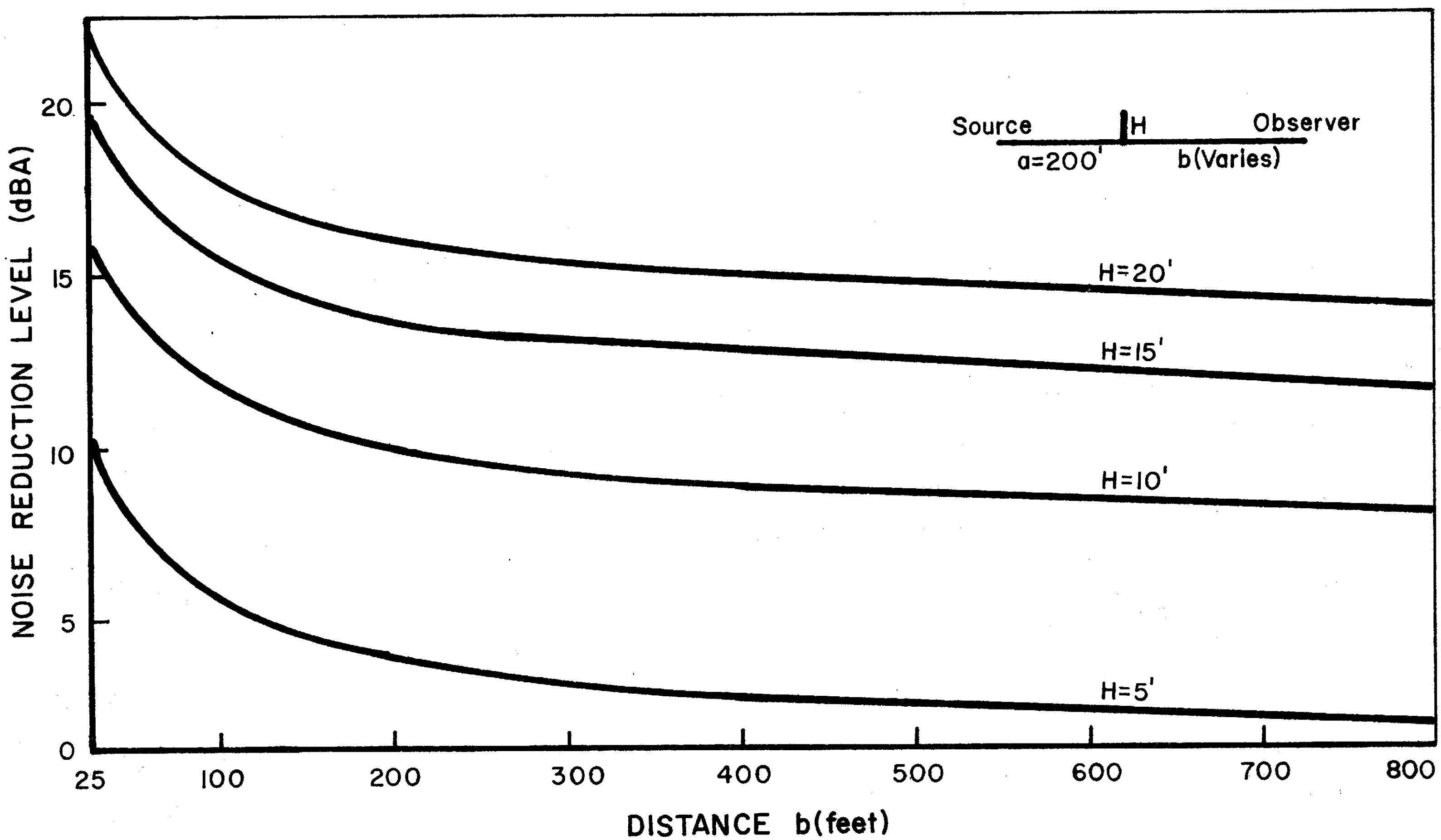


Figure 26. Noise reduction - source to wall distance 200 feet.

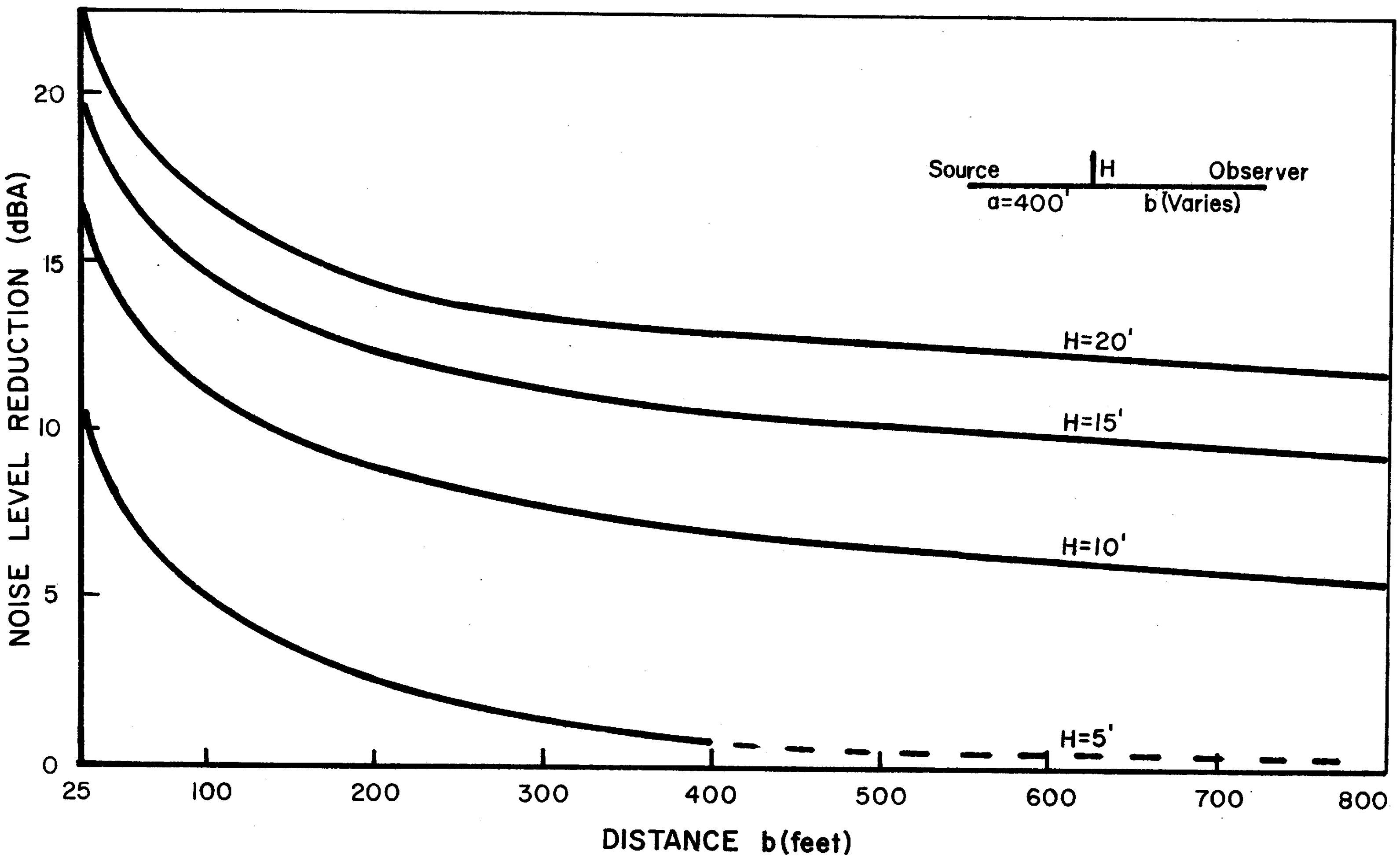


Figure 27. Noise reduction - source to wall distance 400 feet.

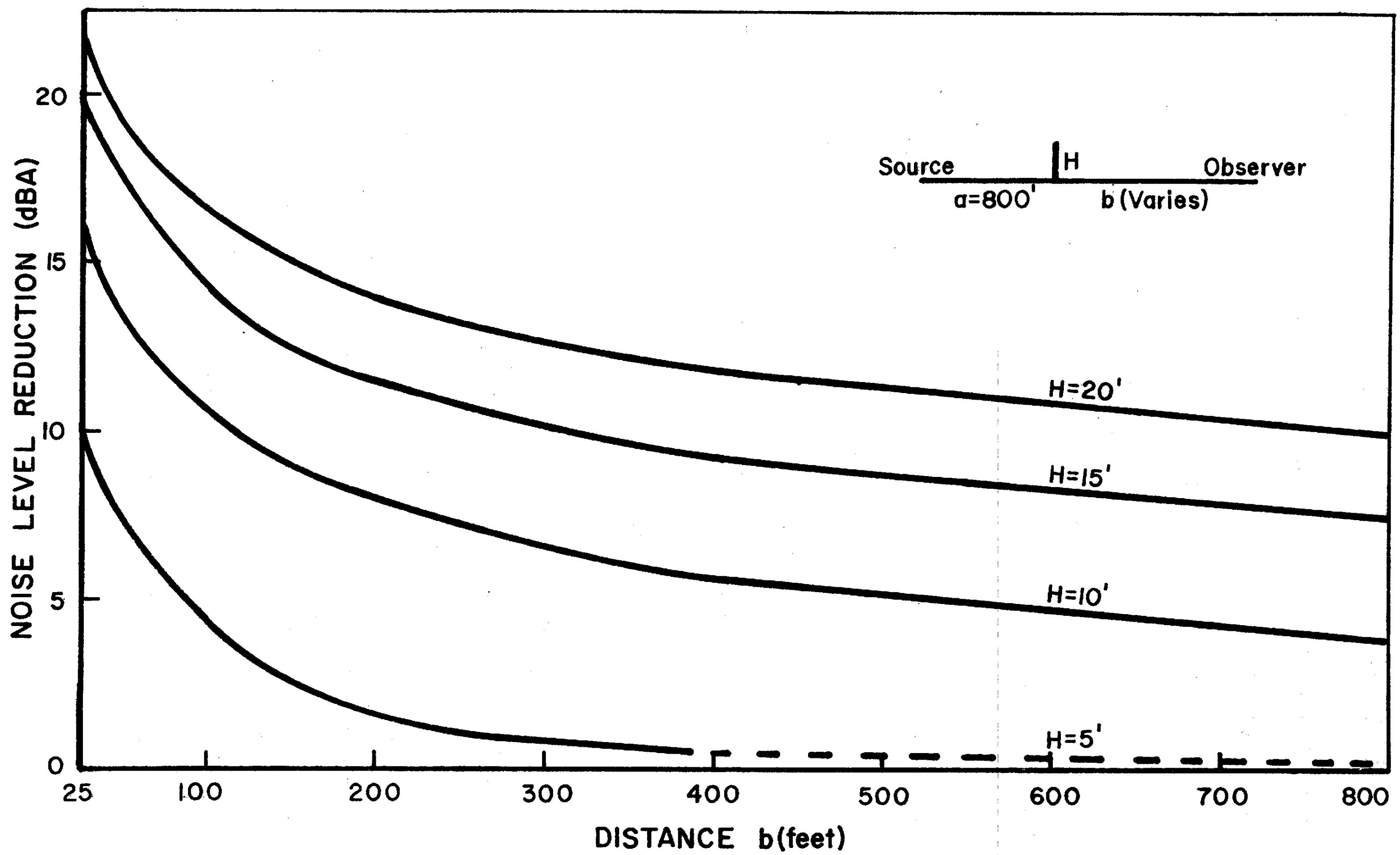


Figure 28. Noise reduction - source to wall distance 800 feet.

Sacramento Community Drive-In Church, California

The analysis of data recorded at this site necessitates the assumptions that: (1) the effective height of the earth barrier is 10 feet; (2) the attenuation is due to the barrier plus distance behind the barrier; (3) the attenuation in areas not fully protected by the barrier (where noise can flank the barrier) is due to the logarithmic sum of the noise after reduction by both the barrier and the distance measured perpendicularly from the roadway, added to the reduction due to the noise of the flanking sound; (4) the 82-dBA value on the highway side of the barrier represents the noise source (in practice this is likely to be slightly higher); and (5) the highway is four lanes wide (width of 50 feet). Figure 29 shows the cross section dimensions for the church site (see Figure 14 for layout).

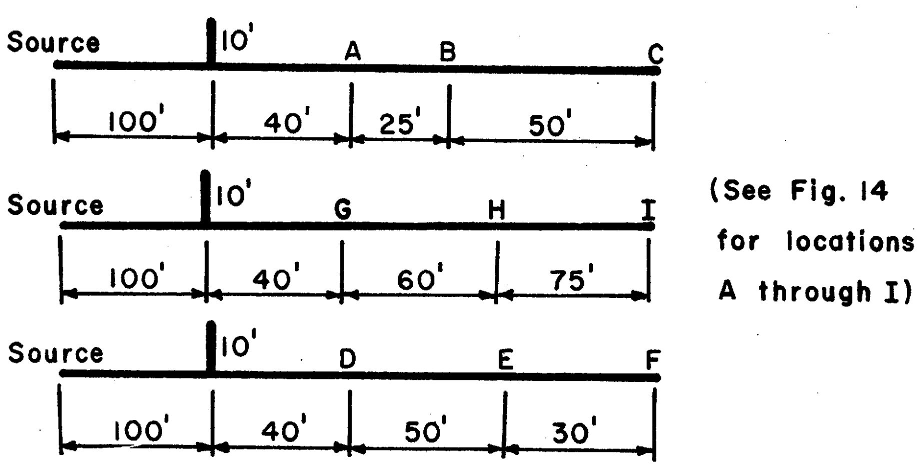


Figure 29. Cross sections of the Sacramento Drive-In Church site.

Table 6 shows the noise level reduction for locations A through I, due to the barrier and distance from the source.

TABLE 6

NOISE REDUCTIONS DUE TO BARRIER EFFECTS AND DISTANCE

Location	Noise Reduction Due to Barrier dBA	Noise Reduction Due to Distance dBA (Fig. 29)	Total Noise Reduction dBA	Calculated Noise Level dBA
A	-15	-2	-17	65
B	-14	-3	-17	65
C	-12	-5	-17	65
D	-15	-2	-17	65
E	-13	-4	-17	65
F	-12	-7	-19	63
G	-15	-2	-17	65
H	-13	-5	-18	64
I	-12	-7	-19	63

However, locations E through F are affected by the flanking of noise at the southern end of the berm. This noise must be added logarithmically to that found above and is reduced from the initial 82 dBA by distance only (Table 7).

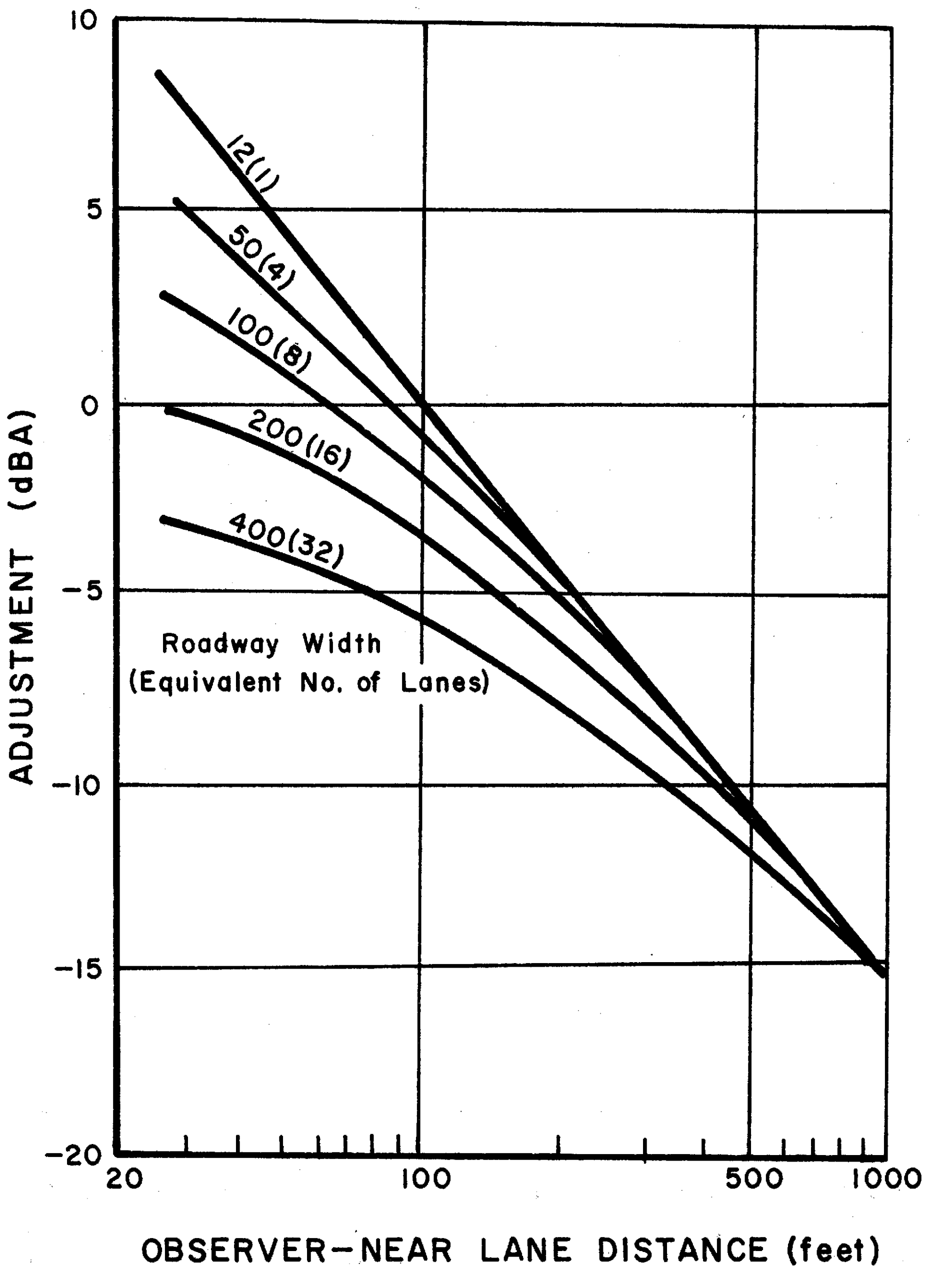
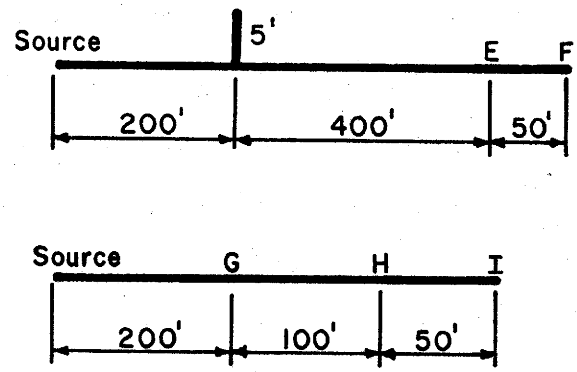


Figure 30. Sound pressure level adjustment due to distance. (12)



(See Fig. 14 for locations E through I)

Figure 31. Barrier flanking sections at the Sacramento Church.

TABLE 7

NOISE REDUCTIONS DUE TO BARRIER EFFECTS (INCLUDING FLANKING) AND DISTANCE

Location	Noise Reduction Due to Barrier dBA	Noise Reduction Due to Distance dBA (Figure 29)	Calculated Noise Level dBA	Total* Calculated Noise Level dBA
E	-3	-12	82-15=67	69
F	-3	-13	82-16=66	68
G	NA	-4	82-4=78	78
H	NA	-7	82-7=75	75
I	NA	-9	82-9=73	73

*Total calculated values are the calculated noise values in Table 7, added logarithmically to the calculated noise level values in Table 6.

Katy Freeway and Radcliffe Street, Houston

The diagrammatic sketch below (Figure 32) shows the depressed cross section in the form considered previously, i.e., on a horizontal plane with a vertical wall between the source and the receiving points A and B; H_A and H_B are the effective wall heights of the sloping sides of the depressed freeway (see Figure 17).

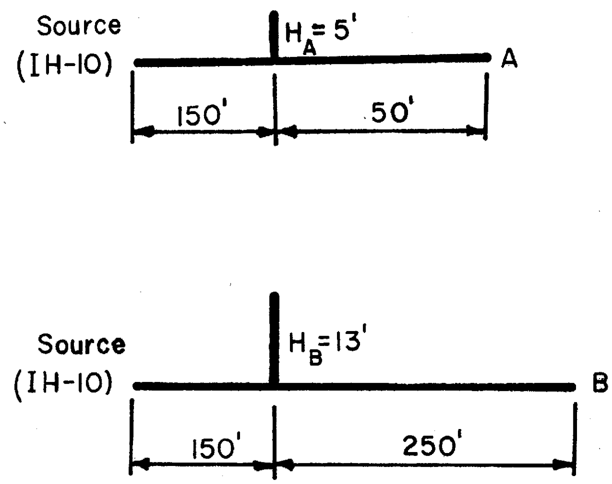


Figure 32. Effective barrier heights and distances on Radcliffe Street.

Using Fehr's equations the reduction due to any wall height up to 25 feet and due to distances from 25 feet to 800 feet between wall and source or wall and receiver can be calculated. The graphs in Figures 22-28 have been plotted for specific wall heights and/or distances. Similar graphs can be drawn for other combinations of wall heights and distances by using the computer program in Appendix B. The Fresnel noise reduction factor and a conversion to noise reduction in dBA values is necessary and are presented in Table 8.

TABLE 8

TOTAL NOISE REDUCTIONS AT RADCLIFFE STREET SITES

Locations	Reduction in Noise Due to Barrier (dBA)	Reduction in Noise Due to Distance (dBA) (Figure 29)	Total Noise Reduction (dBA)
A (200')	-6	-6	-12
B (400')	-12	-9	-21

Since Katy Freeway has a gradient of less than 2 percent at Radcliffe Street, no corrections are necessary for this factor. Knowing that there was a flow rate of 3810 autos per hour and 400 trucks per hour when observing from A, and 4250 autos per hour and 400 trucks per hour when at B, the noise due to these sources can be calculated using the Galloway, et al., method (12). From Figures A-3 and A-4 in Appendix A, the mean sound level due to flow and speed can be calculated (A and B equal 75 dBA, see Table 9). Average speeds of 65 mph for automobiles and 55 mph for trucks were calculated by measuring the time taken by the traffic over a known distance.

Since the Katy Freeway has a rough concrete surface and raised expansion and contraction joints, a 5-dBA increase must be added to the two values found in Table 9, i.e., A = 75 + 5 = 80 dBA and B = 75 + 5 = 80 dBA.

TABLE 9

TOTAL MEAN SOUND PRESSURE LEVEL DUE TO FREEWAY TRAFFIC AT RADCLIFFE STREET SITES

Location	Mean Sound Level Due to Autos (dBA)	Mean Sound Level Due to Trucks (dBA)	Total Mean Sound Level Due to Traffic (dBA)-Table 10
A (200')	70	73	75
B (400')	71	73	75

The final noise levels, after consideration of the effects from the distance and the wall, are A = 80 - 12 (Table 8) = 68 dBA and B = 80 - 21 (Table 8) = 59 dBA.

TABLE 10

DECIBEL ADDITION (12)

Source	Sound Level dB	Antilog Columns - Left Digit of Sound Level								Antilog Table	
		9	8	7	6	5	4	3	2	Right Digit of Sound Level	Antilog
A (200')										0	1000
Autos	70			1	0	0	0			1	1259
Trucks	73			1	9	9	5			2	1585
Total	75			2	9	9	5			3	1995
B (400')										4	2512
Autos	71			1	2	5	9			5	3162
Trucks	73			1	9	9	5			6	3981
Total	75			3	2	5	4			7	5013
										8	6311
										9	7944

COMPARISON OF FIELD AND CALCULATED DATA

Sacramento Community Drive-In Church, California

Figure 33 shows the previously measured sound pressure level readings at the church, compared with the calculated values given in parentheses. The difference between these values is very small, with only the values at points H and I having differences of more than 1 dBA.

The differences between the values at locations A and D are relatively insignificant (1 dBA). The higher recorded values could be due to one of the narrow pathways in the barrier being located near A and D. The difference between the field and calculated values of locations H and I (2 dBA) could easily result from vegetation in the unshielded section between the southern end of the drive-in area and the highway.

Several assumptions were made in calculating these sound pressure levels; however, it appears that a combination of Fehr's equations (9) for sound pressure level reduction due to barrier walls and Galloway's figures (12) for sound pressure level reduction due to distance give valid results.

Katy Freeway and Radcliffe Street, Houston

The following table compares the values found using the sound level estimation method (29), the design guide method (12), the complete analysis using the data recorder (29), and the method of

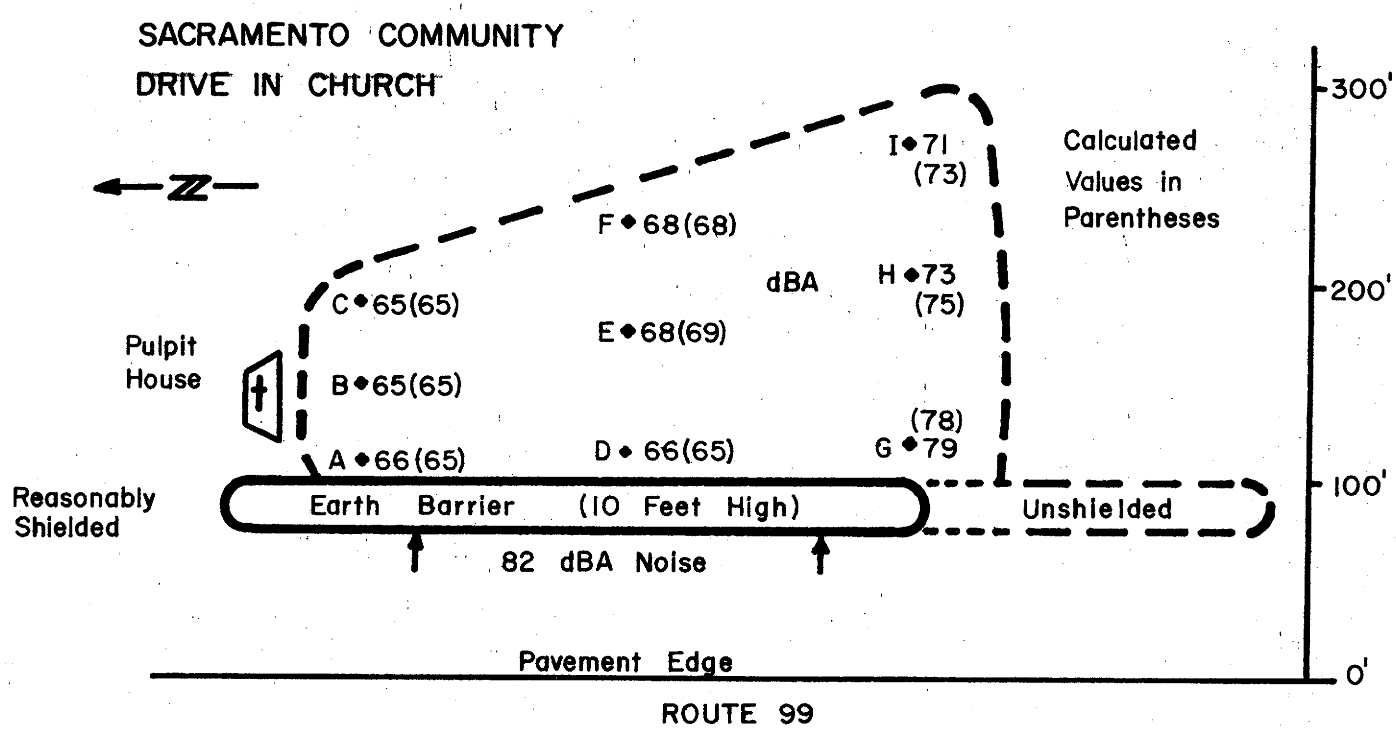


Figure 33. Calculated and measured values at the Sacramento site.

considering the side slopes of a depressed freeway as a barrier.

TABLE 11

COMPARISON OF 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) p.64
A (200')	67,68	67	68	68
B (400')	61	60	63	59

Slightly lower values were calculated using the design guide method (see Appendix A for complete calculations) and the side slope method. Since these two methods are somewhat similar, it is not surprising that they both show such discrepancies. The mean value recorded at Site B (400 feet) appears high; this is probably due to the ambient sound pressure level which is nearly equal to, or perhaps above, the noise level heard from the freeway traffic.

These results show such close correlation that the effective height of the side slope of a depressed section can be considered a vertical wall for purposes of engineering evaluation. Using Fehr's equations (9), the resulting attenuation due to the "effective height" of the side slope can be thus found.

Summary

The sound pressure level at selected points on Radcliffe Street have been determined using the four methods outlined previously. It was found that these methods gave similar results, with only a one- or two-decibel difference among all four methods.

The calculated sound pressure levels at the Sacramento Drive-In Church, from Fehr's barrier equations (9) combined with Galloway's noise reduction due to distance figures (12), gave results similar to those previously recorded in the field.

SUMMARY OF FINDINGS

1. 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.
2. 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 from source to observer to the top of the side slope.
3. 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.
4. 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.
5. All four methods 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.

REFERENCES

1. Beaton, J. L. and Bourget, L. Can Noise Radiation from Highways Be Reduced by Design? Highway Research Record 232, 1968, pp. 1-8.

2. Young, M. F. and Woods, D. L. Urban Highway Noise Considerations in Design. Presented at the Texas Section, ASCE Spring Meeting, College Station, Texas, April 17, 1971.

3. Colony, D. C. Expressway Traffic Noise and Residential Properties. Research Foundation, University of Toledo, Toledo, Ohio, July 1, 1967.

4. Galloway, W. J. et al. Highway Noise: Measurement, Simulation and Mixed Reaction. NCHRP Report 78, 1969.

5. Andrews, B. and Finch, D. M. Truck-Noise Measurement. HRB Proceedings, Vol. 31, pp. 456-465.

6. Galloway, W. J. et al. Evaluation of Highway Noise. NCHRP 3-7/1, Final Report, January 1970.

7. Harmelink, M. D. Noise and Vibration Control for Transportation Systems. D.H.O. Report No. RR168, Department of Highways, Ontario, October 1970.

8. Purcell, J. B. C. Control of Airborne Sound by Barriers. Noise Control, Vol. 3, No. 4, July 1957, pp. 20-26; 56,58.

9. Fehr, R. O. The Reduction of Industrial Machine Noise. Proceedings 2nd Annual National Noise Abatement Symposium, Armour Research Foundation, Vol. 2, 1951, pp. 93-103.

10. Maekawa, Z. Noise Reduction by Screens. Applied Acoustics, Vol. 1, 1968, pp. 157-173.

11. Rettinger, M. Noise Level Reductions of Barriers. Noise Control, Vol. 3, No. 5, September 1957, pp. 50-52.

12. Galloway, W. J. et al. Highway Noise, A Design Guide for Highway Engineers. NCHRP 3-7/1, Final Report, January 1970.

13. Wiener, F. M. Sound Propogation Outdoors. Chapter 9, Noise Reduction, McGraw-Hill, 1960.

14. Rettinger, M. Noise Reduction. Chapter 4, Acoustics-Room Design and Noise Control, Chemical Publishing, 1968.

15. Beranek, L. L. and Labate, S. Properties of Porous Acoustical Materials. Chapter 12, Noise Reduction, McGraw-Hill, 1960.

16. Sabine, H. J. Acoustic Materials. Chapter 18, Handbook of Noise Control, McGraw-Hill, 1957.

17. Galloway, D. B. Design of Noise Control Structures. Noise Control, Vol. 1, No. 5, September, 1955, pp. 50-51.

18. Waller, R. A. The Performance and Economics of Noise and Vibration Reducing Materials in the Construction Industry. J. Sound Vib., Vol. 8, No. 2, 1968, pp. 177-185.

19. Cook, R. K, and Chrzanowski, P. Transmission of Noise Through Walls and Floors. Chapter 20, Handbook of Noise Control, McGraw-Hill, 1957.

20. Schiller, K. K. Physical Aspects of Sound Insulation through Walls. J. Sound Vib., Vol. 6, No. 3, 1967, pp. 283-295.

21. Sabine, H. J. et al. Effect of Painting on Sound Transmission Loss of Light Weight Concrete Block Partitions. Noise Control, Vol. 6, No. 2, March-April, 1960, pp. 6-10.

22. Traffic Noise Near Highways. Materials and Research Department, California Division of Highways, Project Report, January, 1970.

23. Osken, H. Mechanical-Acoustical Behavior of Polystyrene Foam. Sound, Vol. 1, No. 2, March-April, 1962, pp. 37-41.

24. Land, "Light Weight Champion" of Noise Barriers Sound. Vol. 2, No. 1, January-February, 1963.

25. Beranek, L. L. Sound Transmission Through Structures Containing Porous Materials, Chapter 14, Noise Reduction, McGraw-Hill, 1960.

26. Bolt, R. H. and Ingard, K. U. System Considerations in Noise-Control Problems. Chapter 22, Handbook of Noise Control, McGraw-Hill, 1957.

27. Scholes, W. E. and Parkin, P. H. The Effect of Small Changes in Source Height on the Propogation of Sound over Grassland. J. Sound Vib., Vol. 3, No. 6, 1976, pp 424-442.

28. A Review of Road Traffic Noise. Road Research Laboratory, Ministry of Transport, RRL Report LR 357, Berkshire, England, 1970.

29. Woods, D. L. and Young, M. F. Highway Noise Measurement for Engineering Decisions. Research Report No. 166-2, Texas Transportation Institute, Texas A&M University, June, 1971.

30. Schwar, J. F. and Puy-Huarte, J. Statistical Methods in Traffic Engineering. The Ohio State University, Columbus, Ohio, August, 1967.

APPENDIX A

DESIGN GUIDE METHOD

DESIGN GUIDE METHOD

The design guide method (12) for the analysis of the sound pressure level on Radcliffe Street, Houston, Texas, has been included in this Appendix to show how the values in Table 11 were derived. The tables and charts recommended for use by Galloway, et al. (12), have been modified for simplicity. Figures 16 and 17 show the cross-section dimensions for the Katy Freeway-Radcliffe Street site and the location of Sites A and B.

TABLE A-1

ROAD ELEMENT IDENTIFICATION

Description	Change in			
	Alignment	Section	Gradient	Flow
20' Depressed Section, measured 200' from Katy Freeway (on Radcliffe St.), Houston, Tx. SITE A	NONE	NONE	NONE	NONE
20' Depressed Section, measured 400' from Katy Freeway (on Radcliffe St.), Houston, Tx. SITE B	NONE	NONE	NONE	NONE

TABLE A-2

POSITION PARAMETERS

	Position Parameters			Pavement	
Description	D	L	Φ	P	N
Site A Depressed Section (D=200') Type 1 (Infinite Element)	200'	1600'	154	116'	8
Site B Depressed Section (D=400') Type 3 (Finite Element)	400'	400'	158	116'	8

TABLE A-3

TRAFFIC FLOW PARAMETERS

Road Element	Run Number	6	7
	Type	1	3
Time Interval		2:56- 3:06pm	3:21- 3:31pm
Truck Volume, vph		402	396
Auto Volume, vph		3810	4248
Average Truck Speed, mph		55	55
Average Auto Speed, mph		65	65

TABLE A-4

PARAMETER WORK SHEET

	Road Element		Run Number	6	7
			Type	1	3
Traffic Parameters	Time Interval			2:56-3:06	3:21-3:31
	Vehicle Volume (vph)	(a)	Autos	3810	4248
		(b)	Trucks	402	396
	Average Speed (mph)	(a)	Autos	65	65
		(b)	Trucks	55	55
Roadway Characteristics	Flow Characteristics	(a)	Uninterrupted	X	X
		(b)	Interrupted		
	Pavement	(a)	Width (P)	116	116
		(b)	No. Lanes (N)	8	8
	Percentage Gradient (If>2%)			NA	NA
	Vertical Configuration	(a)	Elevated		
		(b)	Depressed	X	X
		(c)	At Grade		
	Road Surface	(a)	Smooth		
		(b)	Normal		
		(c)	Rough	X	X
Observer Characteristics	Position Parameters	(a)	D ft.	200	400
		(b)	De ft.	240	430
		(c)	L ft.	1600	400
		(d)	ϕ deg.	154	158
	Shielding Effects	(a)	Barrier		
		(b)	Buildings		
		(c)	Others	X	X
		(d)	None		
	Terrain Effects			X	X

TABLE A-5

DEPRESSED HIGHWAY ADJUSTMENT

Road Element		Run Number	6	7
		Type	1	3
Time Interval (pm)			2:56-3:06	3:21-3:31
Depressed Freeway	Depth of Depressed F/way		20'	20'
	Observer-Equivalent Lane (Figure A-1) Distance = D_e		240'	430'
	Observer-Cut Distance = D_c		100'	300'
	$A = H^2/(D_e - D_c)$		3.1	2.9
	$B = H^2/D_c$		4.0	1.3
DEPRESSED FREEWAY ADJUSTMENT (Figure A-2)		Auto	-12	-15
		Trucks*	-7	-10

*For trucks add +5 dB to auto value

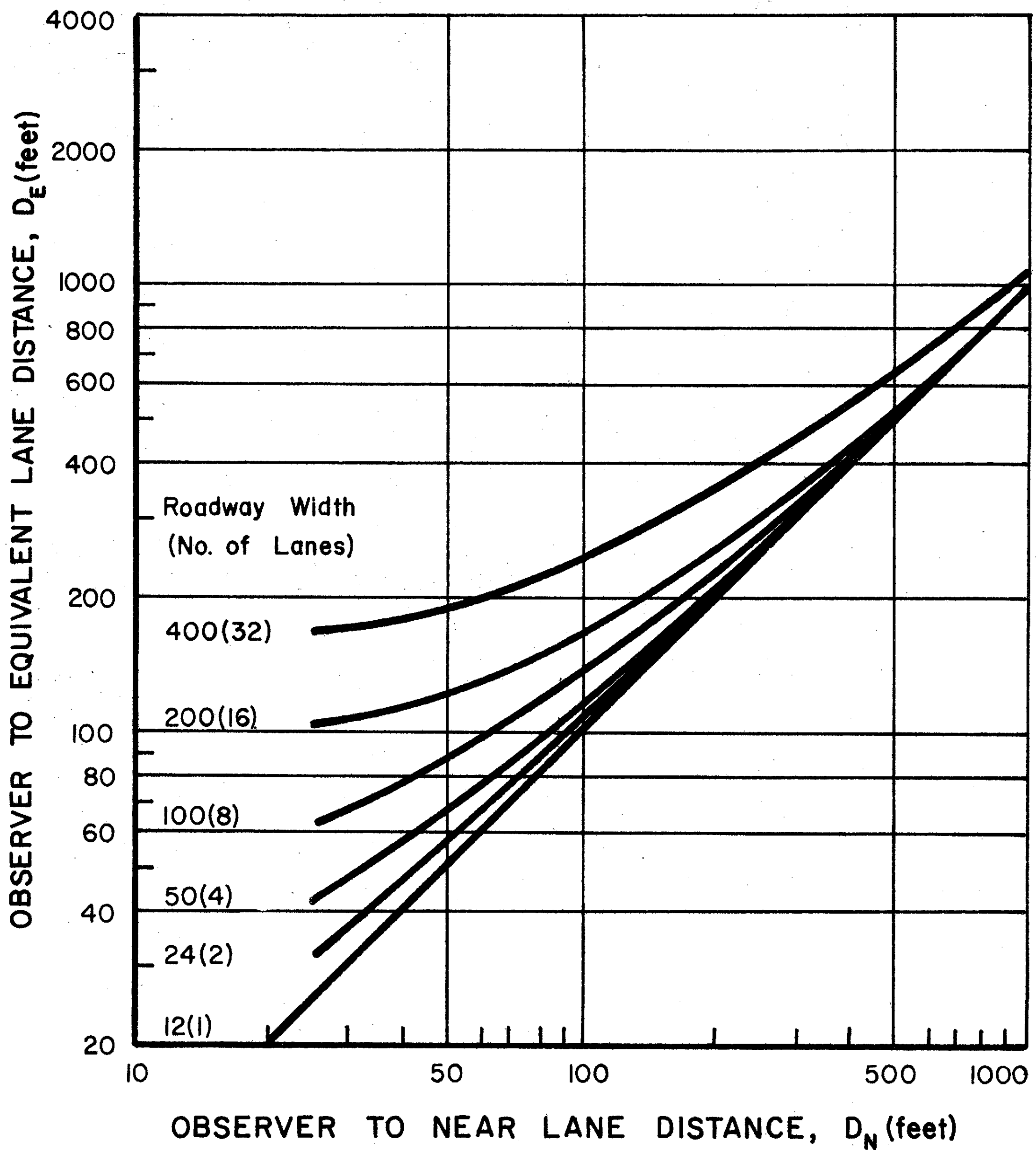


Figure A-1. Equivalent lane distance. (12)

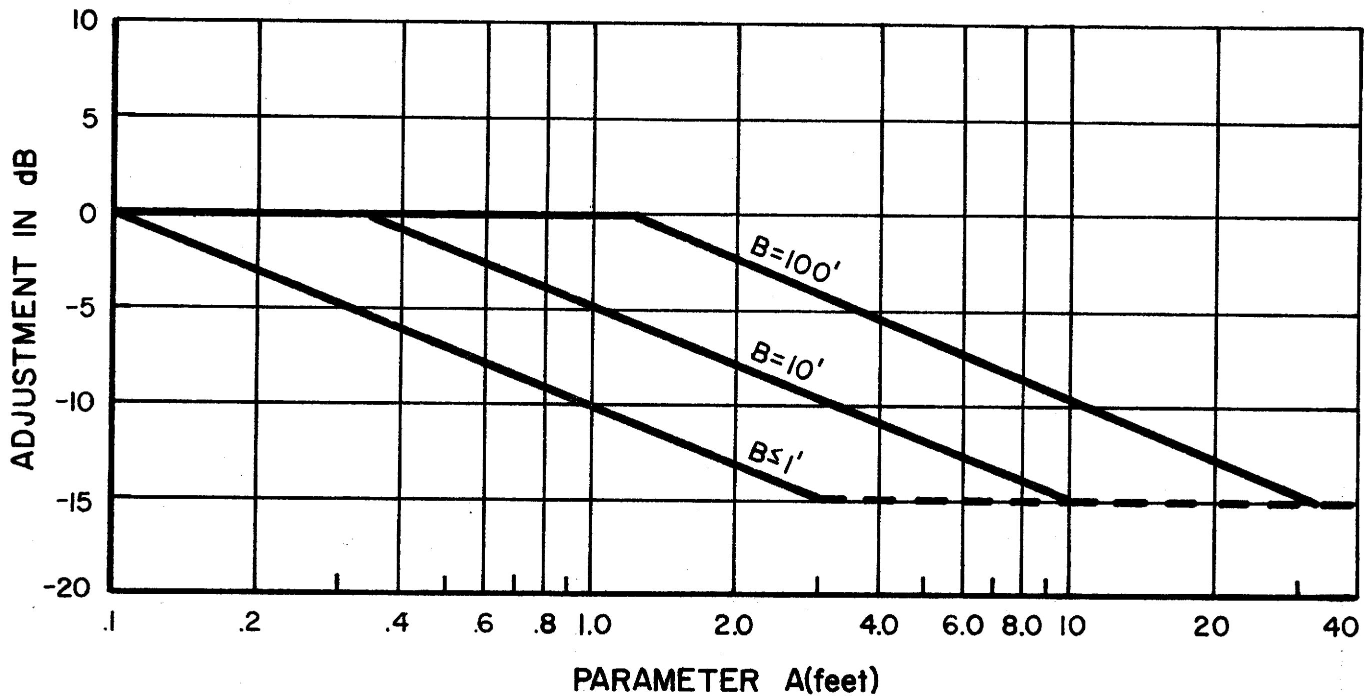


Figure A-2. Adjustment for elevation and depressed roadway. (12)

TABLE A-6

NOISE PREDICTION WORK SHEET

Roadway Element		Run Number	6		7	
		Type	1		3	
Time Interval			2:56-3:06pm		3:21-3:31pm	
Vehicle Type			Auto	Truck	Auto	Truck
Reference L50 at 100' (Figures A-3 and A-4)			70	73	71	73
ADJUSTMENTS	Distance (Figure A-5)		-5	-5	-9	-9
	Gradient (Table 4, p.36)		0	0	0	0
	Element (Figure A-6)		NA	NA	0	0
	Vertical (Table A-5)		-12	-7	-15	-10
	Surface (Table 5, p.40)		+5	+5	+5	+5
	Shielding (Barriers, etc)		NA	NA	NA	NA
Total Adjustment (add rows 2 through 6)			-12	-7	-19	-14
L50 (Mean Value) at Observer (add rows 1 through 7)			58	66	52	59
ELEMENT TOTAL (Table A-7)			67		60	

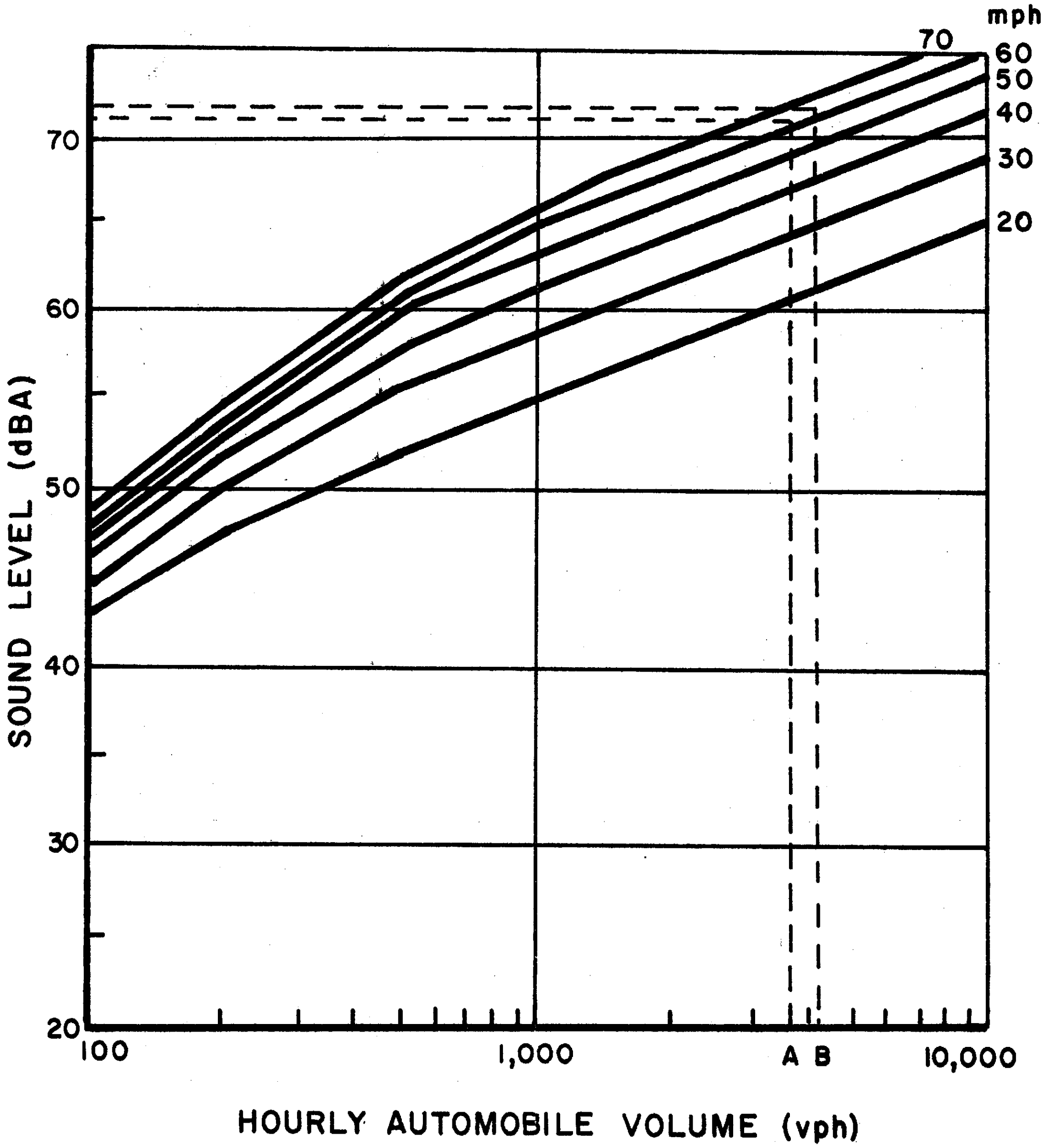


Figure A-3. Sound pressure level for autos - Radcliffe Street. (12)

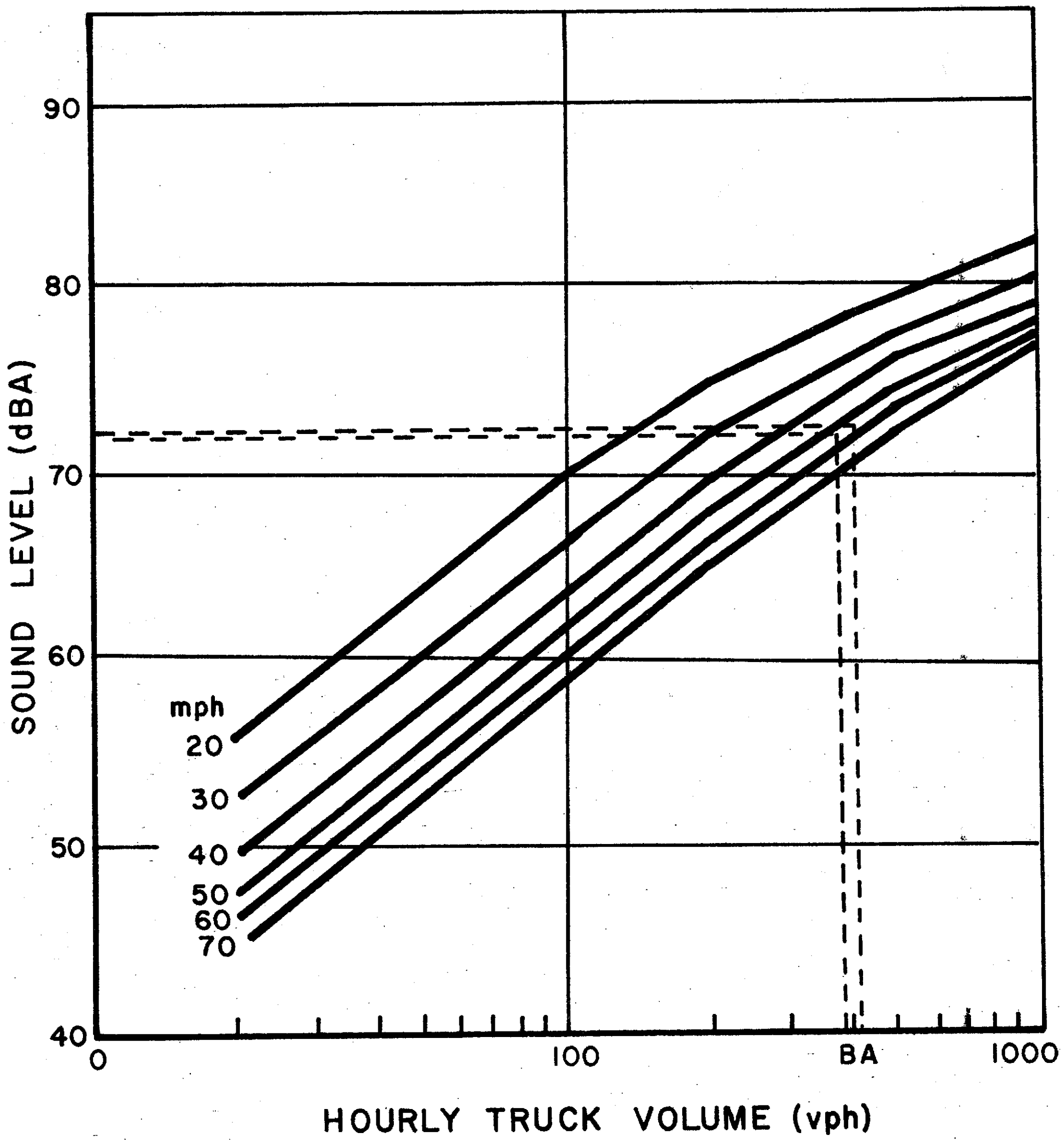


Figure A-4. Sound pressure level for trucks - Radcliffe Street. (12)

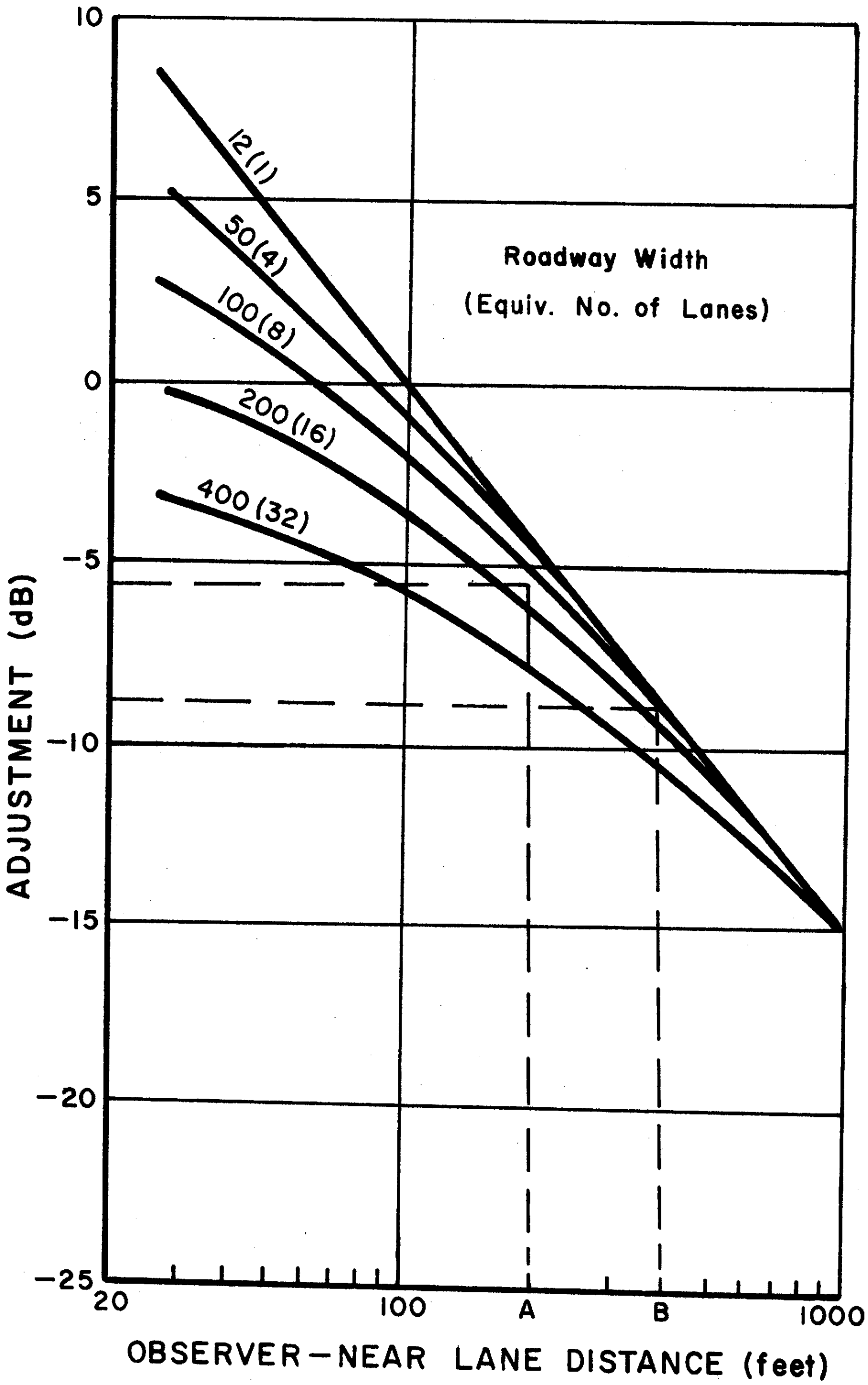


Figure A-5. Sound pressure level adjustment due to distance. (12)

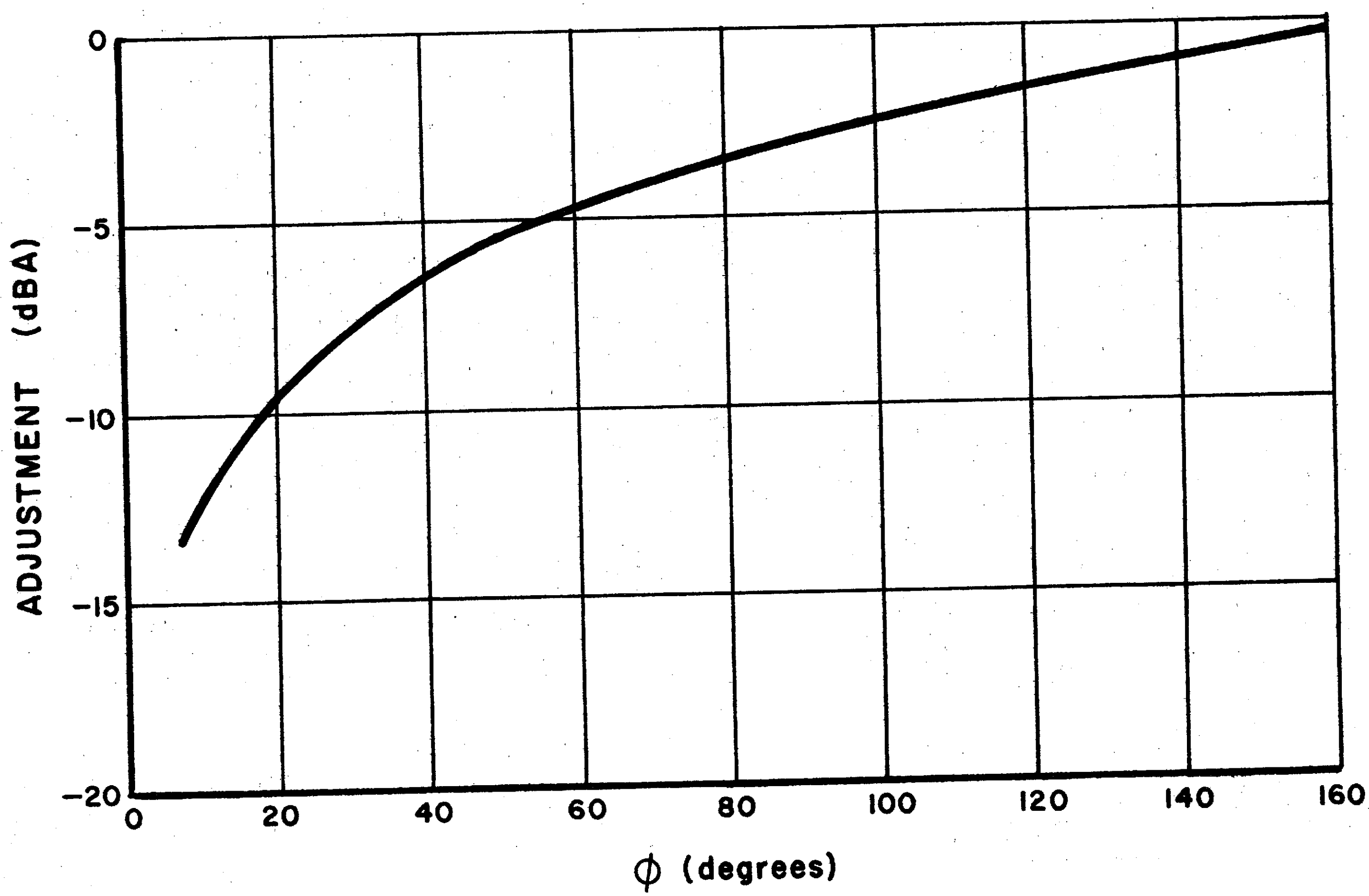


Figure A-6. Adjustment for finite element lengths. (12)

TABLE A-7

DECIBEL ADDITION (12)

Source	Sound Level dB	Antilog Columns-Left Digit of Sound Level								Antilog Table	
		9	8	7	6	5	4	3	2	Right Digit of Sound Level	Antilog
A(200')										0	1000
	58					6	3	1	1	1	1259
	66				3	9	8	1		2	1585
Total	67				4	6	1	2	1	3	1995
										4	2512
B(400')										5	3162
	52					1	5	8	5	6	3981
	59					7	9	4	4	7	5013
Total	60					9	5	2	9	8	6311
										9	7944

APPENDIX B

COMPUTER SOLUTION TO NOISE REDUCTION BY BARRIERS

```
//$WATFIVR JOB (129W5,8-G  ,*30,006,  ),' YOUNG   T.T.1.
      A=12.5
      WRITE(6,200)
      DO 10 I=1,6
      A=A*2
      B=12.5
      DO 10 J=1,6
      B=B*2
      H=0.0
      DO 10 K=1,10
      H=H+2
      Y=2*(A*(SQRT(1+H**2/A**2)-1)+B*(SQRT(1+H**2/B**2)-1))
      DBA=10*(ALOG10(10.1*Y))
      IF(Y.LE.0.10) DBA=0.0
   10 WRITE(6,100) A,B,H,Y,DBA
  100 FORMAT(1H ,2X,F4.0,5X,F4.0,6X,F4.0,F10.5,F10.1)
  200 FORMAT(1H1,4X,'A',8X,'B',9X,'H',7X,'Y',8X,'RED.(DBA)'//)
      STOP
      END

//$DATA
```

A	B	H	Y	RED.(DBA)
25.	25.	2.	0.31939	5.1
25.	25.	4.	1.27182	11.1
25.	25.	6.	2.83957	14.6
25.	25.	8.	4.99516	17.0
25.	25.	10.	7.70321	18.9
25.	25.	12.	10.92329	20.4
25.	25.	14.	14.61229	21.7
25.	25.	16.	18.72653	22.8
25.	25.	18.	23.22330	23.7
25.	25.	20.	28.06244	24.5
25.	50.	2.	0.23961	3.8
25.	50.	4.	0.95530	9.8
25.	50.	6.	2.13714	13.3
25.	50.	8.	3.76940	15.8
25.	50.	10.	5.83191	17.7
25.	50.	12.	8.30121	19.2
25.	50.	14.	11.15212	20.5
25.	50.	16.	14.35843	21.6
25.	50.	18.	17.89426	22.6
25.	50.	20.	21.73442	23.4
25.	100.	2.	0.19956	3.0
25.	100.	4.	0.79575	9.1
25.	100.	6.	1.77932	12.5
25.	100.	8.	3.13635	15.0
25.	100.	10.	4.84896	16.9
25.	100.	12.	6.89635	18.4
25.	100.	14.	9.25660	19.7
25.	100.	16.	11.90691	20.8
25.	100.	18.	14.82573	21.8
25.	100.	20.	17.99182	22.6
25.	200.	2.	0.17915	2.6
25.	200.	4.	0.71564	8.6
25.	200.	6.	1.59945	12.1
25.	200.	8.	2.81725	14.5
25.	200.	10.	4.35095	16.4
25.	200.	12.	6.18072	18.0
25.	200.	14.	8.28462	19.2
25.	200.	16.	10.64081	20.3
25.	200.	18.	13.22794	21.3
25.	200.	20.	16.02592	22.1
25.	400.	2.	0.16885	2.3

A	B	H	Y	RED.(DBA)
25.	400.	4.	0.67482	8.3
25.	400.	6.	1.50905	11.8
25.	400.	8.	2.65703	14.3
25.	400.	10.	4.10109	16.2
25.	400.	12.	5.82099	17.7
25.	400.	14.	7.79519	19.0
25.	400.	16.	10.00261	20.0
25.	400.	18.	12.42037	21.0
25.	400.	20.	15.02991	21.8
25.	800.	2.	0.16274	2.2
25.	800.	4.	0.65422	8.2
25.	800.	6.	1.46251	11.7
25.	800.	8.	2.57540	14.2
25.	800.	10.	3.97520	16.0
25.	800.	12.	5.64017	17.6
25.	800.	14.	7.55029	18.8
25.	800.	16.	9.68218	19.9
25.	800.	18.	12.01448	20.8
25.	800.	20.	14.53018	21.7
50.	25.	2.	0.23961	3.8
50.	25.	4.	0.95530	9.8
50.	25.	6.	2.13714	13.3
50.	25.	8.	3.76940	15.8
50.	25.	10.	5.83191	17.7
50.	25.	12.	8.30121	19.2
50.	25.	14.	11.15212	20.5
50.	25.	16.	14.35843	21.6
50.	25.	18.	17.89426	22.6
50.	25.	20.	21.73442	23.4
50.	50.	2.	0.15984	2.1
50.	50.	4.	0.63877	8.1
50.	50.	6.	1.43471	11.6
50.	50.	8.	2.54364	14.1
50.	50.	10.	3.96061	16.0
50.	50.	12.	5.67913	17.6
50.	50.	14.	7.69196	18.9
50.	50.	16.	9.99031	20.0
50.	50.	18.	12.56523	21.0
50.	50.	20.	15.40642	21.9
50.	100.	2.	0.11978	0.8
50.	100.	4.	0.47922	6.8
50.	100.	6.	1.07689	10.4
50.	100.	8.	1.91059	12.9

A	B	H	Y	RED.(DBA)
50.	100.	10.	2.97766	14.8
50.	100.	12.	4.27427	16.4
50.	100.	14.	5.79643	17.7
50.	100.	16.	7.53880	18.8
50.	100.	18.	9.49669	19.8
50.	100.	20.	11.66382	20.7
50.	200.	2.	0.09937	0.0
50.	200.	4.	0.39911	6.1
50.	200.	6.	0.89703	9.6
50.	200.	8.	1.59149	12.1
50.	200.	10.	2.47965	14.0
50.	200.	12.	3.55864	15.6
50.	200.	14.	4.82445	16.9
50.	200.	16.	6.27270	18.0
50.	200.	18.	7.89890	19.0
50.	200.	20.	9.69791	19.9
50.	400.	2.	0.08907	0.0
50.	400.	4.	0.35830	5.6
50.	400.	6.	0.80662	9.1
50.	400.	8.	1.43127	11.6
50.	400.	10.	2.22979	13.5
50.	400.	12.	3.19891	15.1
50.	400.	14.	4.33502	16.4
50.	400.	16.	5.63450	17.6
50.	400.	18.	7.09133	18.6
50.	400.	20.	8.70190	19.4
50.	800.	2.	0.08297	0.0
50.	800.	4.	0.33770	5.3
50.	800.	6.	0.76008	8.9
50.	800.	8.	1.34964	11.3
50.	800.	10.	2.10390	13.3
50.	800.	12.	3.01809	14.8
50.	800.	14.	4.09012	16.2
50.	800.	16.	5.31406	17.3
50.	800.	18.	6.68545	18.3
50.	800.	20.	8.20217	19.2
100.	25.	2.	0.19956	3.0
100.	25.	4.	0.79575	9.1
100.	25.	6.	1.77932	12.5
100.	25.	8.	3.13635	15.0
100.	25.	10.	4.84896	16.9
100.	25.	12.	6.89635	18.4
100.	25.	14.	9.25660	19.7

A	B	H	Y	RED.(DBA)
100.	25.	16.	11.90691	20.8
100.	25.	18.	14.82573	21.8
100.	25.	20.	17.99182	22.6
100.	50.	2.	0.11978	0.8
100.	50.	4.	0.47922	6.8
100.	50.	6.	1.07689	10.4
100.	50.	8.	1.91059	12.9
100.	50.	10.	2.97766	14.8
100.	50.	12.	4.27427	16.4
100.	50.	14.	5.79643	17.7
100.	50.	16.	7.53880	18.8
100.	50.	18.	9.49669	19.8
100.	50.	20.	11.66382	20.7
100.	100.	2.	0.07973	0.0
100.	100.	4.	0.31967	5.1
100.	100.	6.	0.71907	8.6
100.	100.	8.	1.27754	11.1
100.	100.	10.	1.99471	13.0
100.	100.	12.	2.86942	14.6
100.	100.	14.	3.90091	16.0
100.	100.	16.	5.08728	17.1
100.	100.	18.	6.42815	18.1
100.	100.	20.	7.92122	19.0
100.	200.	2.	0.05932	0.0
100.	200.	4.	0.23956	3.8
100.	200.	6.	0.53921	7.4
100.	200.	8.	0.95844	9.9
100.	200.	10.	1.49670	11.8
100.	200.	12.	2.15378	13.4
100.	200.	14.	2.92892	14.7
100.	200.	16.	3.82118	15.9
100.	200.	18.	4.83036	16.9
100.	200.	20.	5.95531	17.8
100.	400.	2.	0.04902	0.0
100.	400.	4.	0.19875	3.0
100.	400.	6.	0.44880	6.6
100.	400.	8.	0.79823	9.1
100.	400.	10.	1.24683	11.0
100.	400.	12.	1.79405	12.6
100.	400.	14.	2.43950	13.9
100.	400.	16.	3.18298	15.1
100.	400.	18.	4.02279	16.1

A	B	H	Y	RED.(DBA)
100.	400.	20.	4.95930	17.0
100.	800.	2.	0.04292	0.0
100.	800.	4.	0.17815	2.6
100.	800.	6.	0.40226	6.1
100.	800.	8.	0.71659	8.6
100.	800.	10.	1.12095	10.5
100.	800.	12.	1.61324	12.1
100.	800.	14.	2.19460	13.5
100.	800.	16.	2.86255	14.6
100.	800.	18.	3.61691	15.6
100.	800.	20.	4.45957	16.5
200.	25.	2.	0.17915	2.6
200.	25.	4.	0.71564	8.6
200.	25.	6.	1.59945	12.1
200.	25.	8.	2.81725	14.5
200.	25.	10.	4.35095	16.4
200.	25.	12.	6.18072	18.0
200.	25.	14.	8.28462	19.2
200.	25.	16.	10.64081	20.3
200.	25.	18.	13.22794	21.3
200.	25.	20.	16.02592	22.1
200.	50.	2.	0.09937	0.0
200.	50.	4.	0.39911	6.1
200.	50.	6.	0.89703	9.6
200.	50.	8.	1.59149	12.1
200.	50.	10.	2.47965	14.0
200.	50.	12.	3.55364	15.6
200.	50.	14.	4.82445	16.9
200.	50.	16.	6.27270	18.0
200.	50.	18.	7.89890	19.0
200.	50.	20.	9.69791	19.9
200.	100.	2.	0.05932	0.0
200.	100.	4.	0.23956	3.8
200.	100.	6.	0.53921	7.4
200.	100.	8.	0.95844	9.9
200.	100.	10.	1.49670	11.8
200.	100.	12.	2.15378	13.4
200.	100.	14.	2.92892	14.7
200.	100.	16.	3.82118	15.9
200.	100.	18.	4.83036	16.9
200.	100.	20.	5.95531	17.8
200.	200.	2.	0.03891	0.0
200.	200.	4.	0.15945	2.1

A	B	H	Y	RED.(DBA)
200.	200.	6.	0.35934	5.6
200.	200.	8.	0.63934	8.1
200.	200.	10.	0.99869	10.0
200.	200.	12.	1.43814	11.6
200.	200.	14.	1.95694	13.0
200.	200.	16.	2.55508	14.1
200.	200.	18.	3.23257	15.1
200.	200.	20.	3.98941	16.1
200.	400.	2.	0.02861	0.0
200.	400.	4.	0.11864	0.8
200.	400.	6.	0.26894	4.3
200.	400.	8.	0.47913	6.8
200.	400.	10.	0.74883	8.8
200.	400.	12.	1.07841	10.4
200.	400.	14.	1.46751	11.7
200.	400.	16.	1.91689	12.9
200.	400.	18.	2.42500	13.9
200.	400.	20.	2.99339	14.8
200.	800.	2.	0.02251	0.0
200.	800.	4.	0.09804	0.0
200.	800.	6.	0.22240	3.5
200.	800.	8.	0.39749	6.0
200.	800.	10.	0.62294	8.0
200.	800.	12.	0.89760	9.6
200.	800.	14.	1.22261	10.9
200.	800.	16.	1.59645	12.1
200.	800.	18.	2.01912	13.1
200.	800.	20.	2.49367	14.0
400.	25.	2.	0.16885	2.3
400.	25.	4.	0.67482	8.3
400.	25.	6.	1.50905	11.8
400.	25.	8.	2.65703	14.3
400.	25.	10.	4.10109	16.2
400.	25.	12.	5.82099	17.7
400.	25.	14.	7.79519	19.0
400.	25.	16.	10.00261	20.0
400.	25.	18.	12.42037	21.0
400.	25.	20.	15.02991	21.8
400.	50.	2.	0.08907	0.0
400.	50.	4.	0.35830	5.6
400.	50.	6.	0.80662	9.1
400.	50.	8.	1.43127	11.6
400.	50.	10.	2.22979	13.5

A	B	H	Y	RED.(DBA)
400.	50.	12.	3.19891	15.1
400.	50.	14.	4.33502	16.4
400.	50.	16.	5.63450	17.6
400.	50.	18.	7.09133	18.6
400.	50.	20.	8.70190	19.4
400.	100.	2.	0.04902	0.0
400.	100.	4.	0.19875	3.0
400.	100.	6.	0.44880	6.6
400.	100.	8.	0.79823	9.1
400.	100.	10.	1.24683	11.0
400.	100.	12.	1.79405	12.6
400.	100.	14.	2.43950	13.9
400.	100.	16.	3.18298	15.1
400.	100.	18.	4.02279	16.1
400.	100.	20.	4.95930	17.0
400.	200.	2.	0.02861	0.0
400.	200.	4.	0.11864	0.8
400.	200.	6.	0.26894	4.3
400.	200.	8.	0.47913	6.8
400.	200.	10.	0.74883	8.8
400.	200.	12.	1.07841	10.4
400.	200.	14.	1.46751	11.7
400.	200.	16.	1.91689	12.9
400.	200.	18.	2.42500	13.9
400.	200.	20.	2.99339	14.8
400.	400.	2.	0.01831	0.0
400.	400.	4.	0.07782	0.0
400.	400.	6.	0.17853	2.6
400.	400.	8.	0.31891	5.1
400.	400.	10.	0.49896	7.0
400.	400.	12.	0.71869	8.6
400.	400.	14.	0.97809	9.9
400.	400.	16.	1.27869	11.1
400.	400.	18.	1.61743	12.1
400.	400.	20.	1.99738	13.0
400.	800.	2.	0.01221	0.0
400.	800.	4.	0.05722	0.0
400.	800.	6.	0.13199	1.2
400.	800.	8.	0.23727	3.8
400.	800.	10.	0.37308	5.8
400.	800.	12.	0.53787	7.4
400.	800.	14.	0.73318	8.7

A	B	H	Y	RED.(DBA)
400.	50.	12.	3.19891	15.1
400.	50.	14.	4.33502	16.4
400.	50.	16.	5.63450	17.6
400.	50.	18.	7.09133	18.6
400.	50.	20.	8.70190	19.4
400.	100.	2.	0.04902	0.0
400.	100.	4.	0.19875	3.0
400.	100.	6.	0.44880	6.6
400.	100.	8.	0.79823	9.1
400.	100.	10.	1.24683	11.0
400.	100.	12.	1.79405	12.6
400.	100.	14.	2.43950	13.9
400.	100.	16.	3.18298	15.1
400.	100.	18.	4.02279	16.1
400.	100.	20.	4.95930	17.0
400.	200.	2.	0.02861	0.0
400.	200.	4.	0.11864	0.8
400.	200.	6.	0.26894	4.3
400.	200.	8.	0.47913	6.8
400.	200.	10.	0.74883	8.8
400.	200.	12.	1.07841	10.4
400.	200.	14.	1.46751	11.7
400.	200.	16.	1.91689	12.9
400.	200.	18.	2.42590	13.9
400.	200.	20.	2.99339	14.8
400.	400.	2.	0.01831	0.0
400.	400.	4.	0.07782	0.0
400.	400.	6.	0.17853	2.6
400.	400.	8.	0.31891	5.1
400.	400.	10.	0.49896	7.0
400.	400.	12.	0.71869	8.6
400.	400.	14.	0.97809	9.9
400.	400.	16.	1.27869	11.1
400.	400.	18.	1.61743	12.1
400.	400.	20.	1.99738	13.0
400.	800.	2.	0.01221	0.0
400.	800.	4.	0.05722	0.0
400.	800.	6.	0.13199	1.2
400.	800.	8.	0.23727	3.8
400.	800.	10.	0.37308	5.8
400.	800.	12.	0.53787	7.4
400.	800.	14.	0.73318	8.7

A	B	H	Y	RED.(DBA)
400.	800.	16.	0.95825	9.9
400.	800.	18.	1.21155	10.9
400.	800.	20.	1.49765	11.8
800.	25.	2.	0.16274	2.2
800.	25.	4.	0.65422	8.2
800.	25.	6.	1.46251	11.7
800.	25.	8.	2.57540	14.2
800.	25.	10.	3.97520	16.0
800.	25.	12.	5.64017	17.6
800.	25.	14.	7.55029	18.8
800.	25.	16.	9.68218	19.9
800.	25.	18.	12.01448	20.8
800.	25.	20.	14.53018	21.7
800.	50.	2.	0.08297	0.0
800.	50.	4.	0.33770	5.3
800.	50.	6.	0.76008	8.9
800.	50.	8.	1.34964	11.3
800.	50.	10.	2.10390	13.3
800.	50.	12.	3.01809	14.8
800.	50.	14.	4.09012	16.2
800.	50.	16.	5.31406	17.3
800.	50.	18.	6.68545	18.3
800.	50.	20.	8.20217	19.2
800.	100.	2.	0.04292	0.0
800.	100.	4.	0.17815	2.6
800.	100.	6.	0.40226	6.1
800.	100.	8.	0.71659	8.6
800.	100.	10.	1.12095	10.5
800.	100.	12.	1.61324	12.1
800.	100.	14.	2.19460	13.5
800.	100.	16.	2.86255	14.6
800.	100.	18.	3.61691	15.6
800.	100.	20.	4.45957	16.5
800.	200.	2.	0.02251	0.0
800.	200.	4.	0.09804	0.0
800.	200.	6.	0.22240	3.5
800.	200.	8.	0.39749	6.0
800.	200.	10.	0.62294	8.0
800.	200.	12.	0.89760	9.6
800.	200.	14.	1.22261	10.9
800.	200.	16.	1.59645	12.1
800.	200.	18.	2.01912	13.1
800.	200.	20.	2.49367	14.0

A	B	H	Y	RED.(DBA)
800.	400.	2.	0.01221	0.0
800.	400.	4.	0.05722	0.0
800.	400.	6.	0.13199	1.2
800.	400.	8.	0.23727	3.8
800.	400.	10.	0.37308	5.8
800.	400.	12.	0.53787	7.4
800.	400.	14.	0.73318	8.7
800.	400.	16.	0.95825	9.9
800.	400.	18.	1.21155	10.9
800.	400.	20.	1.49765	11.8
800.	800.	2.	0.00610	0.0
800.	800.	4.	0.03662	0.0
800.	800.	6.	0.08545	0.0
800.	800.	8.	0.15564	2.0
800.	800.	10.	0.24719	4.0
800.	800.	12.	0.35706	5.6
800.	800.	14.	0.48828	6.9
800.	800.	16.	0.63782	8.1
800.	800.	18.	0.80566	9.1
800.	800.	20.	0.99792	10.0

APPENDIX C

Glossary of Terminology

Acoustical Terms (23, 12)

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 of 10 decibels.

Free Field - If a point sound source is in the air far from other objects, including the ground, the sound pressure produced by the source is the same in every direction at equal distances from the point source.

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

Hertz (Hz) - 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

Perceived Noise Level - The level in dB assigned to a noise by means of a calculation procedure that is based on an approximation to subjective evaluations of "noisiness" (in PNdB units)

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

Roadway Terms (12)

Depressed Roadway	- A roadway element that 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	- A roadway segment no longer than 8Dn centered about the observer, where Dn is the distance from the observer to the nearest lane
Infinite Roadway Element	- A (centered about the observer) roadway segment longer than 8Dn, where Dn is the distance from the observer to the nearest lane
Semi-Infinite Roadway Element	- A roadway element that extends across 4Dn in one direction but which terminates within 8Dn, where Dn is the distance from the observer to the nearest lane
Single Lane Equivalent	- A hypothetical single lane which represents the roadway and which is to the observer acoustically similar to the real roadway