HIGHWAY RESEARCH RECORD

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Subject Areas

22 Highway Design
52 Road User Characteristics
82 Urban Community Values

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CONTENTS

FOREWORD

The papers in this RECORD address the problem of traffic noise control, a subject of increasing interest to transportation agencies and environmentalists.

Galloway provides a broad overview of traffic noise and its effect on people by indicating the basic variables of sound that must be considered. He emphasizes the distinction between traffic noise effects that are comparatively easy to quantify, such as speech interference, and traffic noise effects that are comparatively difficult to quantify, such as sleep interference and general annoyance.

A basic starting point for all discussions of noise phenomena is the characterization of the noise source. In the paper by Close, four categories of noise (intake, exhaust, engine, and chain noise) are described for four types of vehicles (automobiles, trucks, motorcycles, and buses).

Rupert outlines the noise standards for federal-aid highways that have been developed by the Federal Highway Administration under the authority of the Federal-Aid Highway Act of 1970. The impact of the standards on various highway configurations is illustrated.

Since 1964, the National Cooperative Highway Research Program has supported research on the analysis and control of highway noise. A major product of this effort was the development of a highway noise model and design guide published by the Highway Research Board as NCHRP Report 117. Kugler and Piersol discuss the results of a field testing program that was conducted to validate the model and design guide procedures.

One method of controlling traffic noise on major highways that has been the subject of considerable discussion is the construction of noise barriers at critical points along rights-of-way to shield adjacent properties from vehicle noise. The paper by Beaton and Bourget and the paper by Harmelink and Hajek present data on the noise reduction effectiveness of specific highway noise barriers. The papers reach different conclusions regarding the potential usefulness of such barriers. Beaton and Bourget also describe a nomograph procedure for estimating peak highway noise levels.

Finally, Hauskins describes a new concept in highway noise barrier design, the Kinematic Sound Screen. The special feature of this barrier is that the spacing between the columns that make up the sound screen permits the motorist to "see through" the barrier at highway speeds.

TRAFFIC NOISE AND ITS EFFECT ON PEOPLE

William J. Galloway, Bolt Beranek and Newman Inc.

A descriptive apparatus is formulated to provide a means of relating traffic noise to human response. The basic variables of a sound that are intrinsic to any element of human response (magnitude, frequency distribution, and temporal characteristics) are specified. Maximum noise levels that permit satisfactory speech and listening environments for various types of spaces are given; it was found to be impossible to provide similar levels to prevent sleep interference. It was concluded that specifying criteria for different levels of annoyance is highly dependent on the nature of the intruding noise, the individual, local or regional attitudes, and even the socioeconomic status of the listeners.

•THE basic elements in describing any sound consist of measures of the magnitude of the sound, how its energy is distributed over the audible frequency range, and how its characteristics change with time. The magnitude of a sound is formally described in terms of its intensity, or the amount of energy radiated through a unit area in unit time. This method of description is, unfortunately, of little practical use. The range of intensity involved is easily 20 orders of magnitude in extent, and intensity itself is a vector quantity, difficult to measure.

Fortunately, both of these limitations are eliminated in practice by the use of a logarithmic scale for intensity, and, for most cases of practical concern, the square of sound pressure is proportional to sound intensity. The logarithmic scale is defined in terms of decibels, with intensity or sound pressure being the logarithmic ratio of that value for the particular sound of concern to that of an appropriate reference quantity. Thus, sound pressure level L (the word level being used to denote a measure in decibels) is defined as $L = 20 \log_{10} (p/p_o)$, where p is the root-mean-square value of the sound pressure, and p_o is the reference base of 2 nPa (0.0002 $dyne/cm^2$), roughly the threshold of hearing for humans. It should be remembered that the value of L will change with distance from a sound source. If this measure of magnitude is used to describe a specific sound source, it must always be accompanied by a measure of distance from the source.

Knowledge of the distribution of sound energy over the frequency range of audibility is of major importance because of the way in which the human hearing mechanism discriminates sound. We are most sensitive to sound in the midfrequency range, where the intelligence in speech is conveyed, and considerably less sensitive at lower and very high frequencies. For many engineering purposes it is often desirable to use sets of electrical filters to segment the sound level into various frequency ranges. The most common filter sets break the audible spectrum into slices an octave or less in frequency in width. An octave-band filter set typically uses eight values to separate the frequency components of a sound over the frequency range of audible interest for many applications.

Rather than have a whole series of sound levels for various frequency bands as the descriptor for a sound, it is often desirable to have a single number measure that conveys a frequency-weighted connotation. A number of frequency-weighting or "equalization" networks have evolved and have been standardized over time. It has been found

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through psychoacoustical evaluations that many sounds, when measured with the network designated "A," are subjectively judged to be approximately equal in noisiness when their "A-weighted" sound pressure levels are of equal magnitude. This finding has had wide application in motor vehicle noise where noise levels are most often measured or specified in sound level A, or less accurately, dBA.

The variation with time of a noise signal is the third important item in noise description. Just as people respond differently to noises having different frequency content, they also respond differently to temporal characteristics. Noises of the same A-level, but of different duration, are judged to have different noisiness values. The rate of change of noise level has been shown in some experiments to be of importance. The transient sound of a door slam or backfire has a startle effect due to the temporal characteristics of the sound.

Fortunately, in most traffic-noise situations we are concerned with two types of temporal characteristics for the sound signals. The first case is the passage of a single vehicle. This usually produces a smoothly varying sound signal, rising from some residual background noise level value to a maximum, then smoothly decaying to the background level as the vehicle has passed. This type of time pattern can easily be described by the maximum level produced and the duration between two points in the time pattern on either side of the maximum, say, 10 dB below it. An alternate description is the integral of level over the time history of the event, producing a numerical value equivalent to that which a steady signal of equal duration would have produced.

The second type of traffic noise signal of major concern is that produced by the noise from many vehicles combined, i.e., traffic noise. In this type of noise, the sound of any one individual vehicle is often indistinguishable from the merged contributions of the others. Of course, noises significantly higher than the average, e.g., individual diesel truck sounds superposed over automobile traffic, will stand out as discrete noise signals. This general type of noise is most easily considered as a random noise signal made up of a large number of individual contributions and is best described by statistical parameters.

If the traffic consists largely of automobiles, with only a few percent diesel trucks, at flow rates of more than a few hundred vehicles per hour, the noise levels have the characteristics of a normal statistical distribution. Thus the distribution can be described by a mean (average) noise level and the variance in the distribution. This noise level distribution comes about due to a normal distribution of individual vehicle source noise levels, a normal distribution in individual vehicle speeds, and the nature of the probability of the number of vehicles passing an observation point in a series of discrete slices of time (a Poisson distribution).

An example of a distribution of individual passenger vehicle noise levels is shown in Figure 1 (1). A predictive model for traffic noise, which is based on average traffic flow densities and speeds, is compared to an observed traffic noise distribution (Fig. 2) (2).

The problem is not so clearly described when the proportion of diesel trucks to passenger vehicles is higher than a few percent. In this case there is a superposition of basically two different normal distributions, one for each vehicle class, with substantially different means and variances for the two distributions. The result, of course, can often be a bimodal distribution of noise levels. An example is shown in Figure 3.

A convenient way to describe the generalized case of traffic-noise level distributions is in terms of the percentile points of a cumulative distribution. The points of interest in the distribution are designated by the levels that are exceeded a given percentage of the time and are written as subscripts to the sound level designator L. Thus the median level, that occurring just one-half of the time, is designated as L_{50}.

Two other values used frequently in describing traffic noise are that point exceeded 90 percent of the time, L_{90}, and that exceeded only 10 percent of the time, L_{10}. The lower value, L_{90}, is often used as a measure of background level and the upper value, L_{10}, as a measure for various "not-to-exceed" noise criteria. Obviously other values can be specified, but the extreme points involve confidence interval problems, sampling

Figure 1. Noise level distribution (normal highway cruise speed).

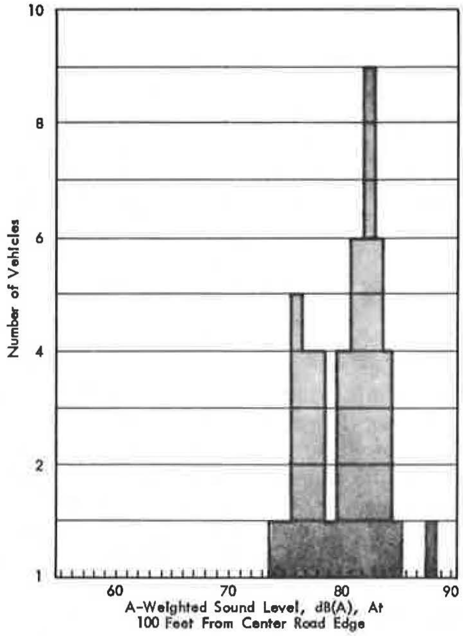


Figure 2. Comparison of prediction model and measured noise levels for passenger automobiles.

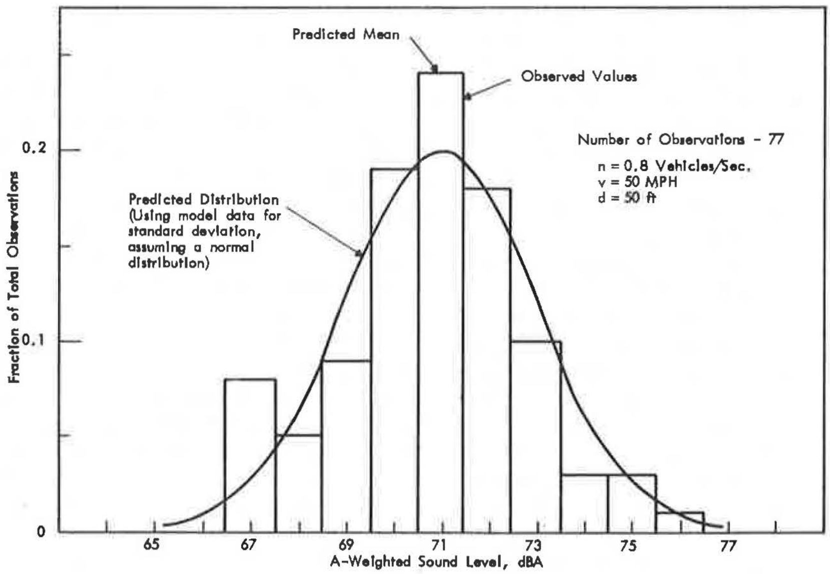


Figure 3. Typical noise distribution level for mixed traffic.

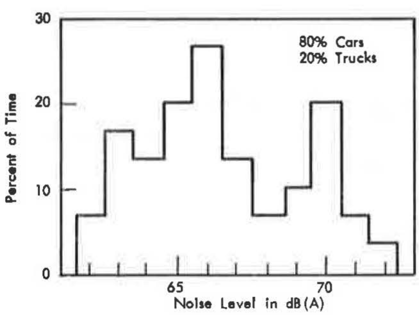
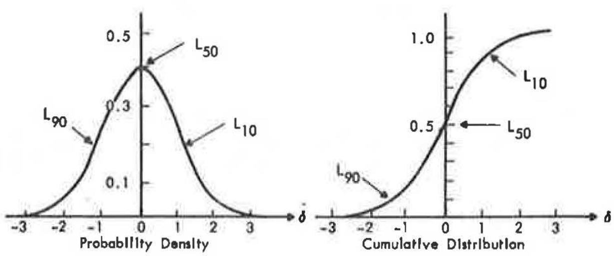


Figure 4. Relation among L_{10}, L_{50}, and L_{90} for normal distribution of sound level.



rates and total duration of sample periods used in measurements, and other statistical problems. It can be noted that, for a normal distribution, the L_{50} value is also the mean, and the L_{90} and L_{10} values are symmetrically disposed about the L_{50} value and are related to the standard deviation, σ, by $L_{10} - L_{90} = 2.56\sigma$. Schematic examples of these points are shown for both cumulative and density distributions in Figure 4.

The purpose of all this descriptive apparatus is to provide means for relating traffic noise to human response. We have already specified the basic variables of a sound that are intrinsic to any element of human response: magnitude, frequency distribution, and temporal characteristics. Let us now briefly consider the kinds of human response that noise engenders.

First, excessively high noise levels can cause temporary or permanent loss of hearing. Fortunately, traffic noise does not generate levels so high that they will cause hearing damage. It is thus more significant here to consider those human responses having to do with discription of specific activities and general annoyance.

The two most commonly discussed activity interference situations are those of speech communication and sleep disturbance. Of these two, disruption of speech communication is by far the better understood. By "speech interference" we also imply interference with listening to television and radio, or the ability to use a telephone satisfactorily. Relatively simple experiments allow criteria to be developed that specify how loud a noise will be before speech intelligibility is degraded. These criteria take into account the distance between people wishing to communicate, the voice power used, e.g., normal voice and raised voice, and the nature of the space in which the communication takes place, e.g., living room, office, schoolroom, factory, or out-of-doors.

Sleep disturbance by noise is much more difficult to quantify. Serious research on this subject has been pursued mostly in the past few years. Major problems are present in even defining what is meant by sleep and what is meant by disturbance of sleep. Even when operational definitions are specified, relatively little is known as to whether, and to what extent, human physiological or psychological functions are affected.

Annoyance from noise, on the other hand, is an aggregate of all the responses, feelings, and interpretations that people put to their relative acceptance of noises. These responses are not only to the physical characteristics of the noise but also to the information conveyed by the noise, that is, its semantic or contextual content. For example, a dripping faucet, a crying baby, the sound of surf or a waterfall, and squealing brakes all have different semantic content. The acceptability or annoyance engendered by a noise is also dependent on whether people expect that noise to be as it is, or what I term its "appropriateness." People expect it to be noisy adjacent to a busy urban street; they do not expect it to be noisy at a mountain retreat.

In summary, it is relatively easy to specify maximum noise levels to permit satisfactory speech and listening environments for various types of spaces where human activity takes place. It is impossible at this time to provide similar criteria for sleep interference. Specifying criteria for different levels of annoyance is highly dependent on the nature of the intruding noise, individual, local or regional attitudes, and even the socioeconomic status of the listeners.

In concluding this brief presentation, one can observe that most studies of annoyance show that, in addition to the other factors, speech and sleep interference become strong components of annoyance when these interferences are triggered by noise. The administrator faced with specification of acceptable noise levels, as he weighs all these factors, will most likely consider speech interference and rather coarse concepts of the related annoyance elements in arriving at this final position.

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2. Galloway, W. J., Clark, W. E., and Kerrick, J. S. Highway Noise Measurement, Simulation, and Mixed Reactions. NCHRP Rept. 78, 1969, 78 pp.

HIGHWAY NOISE SOURCES

William H. Close, U.S. Department of Transportation

Noise sources vary with speed and operating conditions. Four categories of noise (intake, exhaust, engine, and chain noise) are investigated for cars, trucks, motorcycles, and buses. Means of controlling the various noise sources are discussed.

•IN the United States there are more than 120 million vehicles. The vehicles provide our country with unparalleled mobility; however, they also generate noise and penetrate communities as a potential for interrupting human privacy.

Perhaps the best way to introduce the range of problems that we encounter when attempting to categorize the noise sources on highways and streets is to present some data acquired in 1971 by the California Highway Patrol (1). Figure 1 shows a compilation of much of the survey data presented as the percentage of vehicles exceeding a given sound level versus the sound level measured 50 ft to the side of the centerline of the vehicle path. The curves shown represent automobiles moving at 35 mph or less (the lower noise category), trucks at freeway speeds in excess of 35 mph (the highest noise level category), and, grouped together in the middle category, motorcycles at low and high speeds, automibiles at freeway speeds, and trucks at speeds of 35 mph or less. From Figure 1 two things are immediately evident: As speeds increase the noise levels generated by automobiles and trucks drastically increase, and, under comparable operating conditions, trucks produce higher sound levels than do automobiles—on the order of 8 dB higher. It is also evident that the ranges of sound levels generated by these vehicles overlap when one compares the noisiest in each particular category to the quietest of another category. That is to say, the noisiest 10 percent of automobiles, for example, generated as much noise on streets as did the quietest 30 percent of motorcycles or trucks at speeds of 35 mph or less.

Let us center our attention now on the classes of vehicles and examine the component sources of noise generated by individual vehicles in normal operation. Beginning with the trucks, Figure 2 shows the noise sources of a typical over-the-road diesel truck. The mechanical and combustion noises produced by the rapid pressure rise of diesel engine combustion chambers is radiated by the vibrations of the engine block and attached fixtures. In this case a sound level of 81 dBA (sound level in decibels as measured on the A-scale) has been attributed to the engine source. Engine exhaust noise is the noise radiated from the exhaust pipe outlet and that radiated by the vibration of the pipes and mufflers. A level of 84 dBA is generated by exhaust noise in this example. Engine air intake or induction noise is created by the pulsating column of air moving into the engine. A relatively low 75 dBA is generated by the induction process in this particular case. The engine cooling fan, which moves large quantities of air through the radiator in a very restricted flow condition, generates quite high noise levels. Fan noise is second only to typical engine exhaust noise levels. Tire, aerodynamic, and miscellaneous chassis noise sources make up the final category of noise, which is assigned a level of 80 dBA in this example.

Adding the component noise sources provides a truck that generates 88 dBA. This combination of noise sources represents a relatively modern truck design that is in compliance with noise regulations that exist in various states and localities.

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For various reasons, perhaps half of the large trucks today have either inadequate exhaust muffling or no muffling at all, which would make exhaust noise considerably higher than that shown in Figure 2. The problem is to reduce the noise level of these loudest vehicles on the highways. To place the approach in somewhat clearer perspective, however, let us presume that the hypothetical truck has a completely silent exhaust, that is, that the noise level shown in this figure of 84 dBA will be reduced to zero. If we could accomplish this exhaust silencing without changing any of the remaining components of the vehicle, the sound level of the overall vehicle would be reduced only to 86 dBA. It is evident, therefore, that a concerted attack on all sources of noise emanating from this heavy truck must be made simultaneously to reduce the noise level to values that are sought by legislators and expected by residents of communities adjacent to the highways.

We must be cognizant of the variations of these noise levels as a function of engine design and operating parameters. The most important parameter is engine speed. Figure 3 (2) shows typical exhaust noise levels at 50 ft for diesel engines as a function of engine speed. Unfortunately, for the residents adjacent to a highway, heavy-duty trucks normally operate quite near rated horsepower, which means quite near their rated engine speed. Thus, although there appears to be a wide variation of noise levels possible through control of engine speed, for the most part truck engine noise levels will be relatively constant because of the vehicle speed selectivity offered by the transmission.

Figure 3, however, indicates in a gross sense what can be achieved by the application of properly designed exhaust mufflers. Figure 4 shows more clearly the attenuation capability of large-volume exhaust mufflers applied to diesel trucks (3). The lower curve shown in Figure 4 represents the basic volume attenuation afforded by using the volume that is available in the muffler. The second curve, labeled maximum attenuation, shows the state of the art of muffler manufacturers using acoustic elements within the muffler package. The design of such acoustic elements is the "bag of tricks" or "black art" applied by muffler designers. Indicated on the right-hand ordinate is the percentage of initial sound power transmitted through the muffler. The sound level reduction is indicated on the left-hand ordinate. If we took the unmuffled engine example shown in Figure 3 at 100 dBA and attempted to reduce it to 70 dBA, the muffler would have to attenuate 99.9 percent of the engine sound power. This figure, however, indicates that such sound power reductions can be achieved for induction and exhaust with modern design practices.

For heavy-duty truck applications, the attenuation of exhaust noise is particularly important in reducing the community noise level because of the low-frequency content of exhaust noise that propagates farther than high-frequency noise. More importantly, however, a typical diesel exhaust stack outlet is located 12 to 15 ft above the road. This is a very important factor when considering the application of highway noise barriers. In arriving at our "balanced noise reduction design," this source-height consideration must be taken into account and given some special attention.

In the fan noise area, problems are more severe than in the case of the intake and exhaust muffler. American trucks have been very productive largely because of the very efficient cooling systems provided. The fan must move large volumes of air through the radiator to achieve the required cooling. This may be called the essence of simplicity, and accordingly the typical cooling fan is a stamped sheet-metal, riveted subassembly driven by a belt directly coupled to the engine.

The sound pressure level generated by fans varies principally with fan tip speeds as shown in Figure 5 (4). Decreasing fan tip speeds by increasing the number of blades and reducing rotational velocity or diameter are the directions to proceed in reducing fan noise. Aerodynamic shaping of fan blades and closer shrouding of tips may provide other avenues to reduce fan noise level. Much more research is required in the fan area. A new trend in diesel truck design is increased radiator size and thermostatically controlled fans that rotate only a small portion of the time. This will greatly reduce this contributor to overall vehicle noise level. The advanced design practices previously noted must be applied nevertheless to abate this source of noise during the periods of fan operation.

Engine combustion, accessories, and other miscellaneous noise within the engine area can be attenuated by the application of engine enclosures and/or application of vibration damping material to inspection panels, valve covers, and oil pans.

All of these avenues will be thoroughly explored in the upcoming U.S. Department of Transportation (DOT) Diesel Truck Noise Reduction Project, which will include the identification of all noise sources and balanced attenuation of the noise. This will be followed by 1 year of in-service evaluation hauling freight. We anticipate that maximum diesel truck noise levels of the order of 75 dBA measured at 50 ft may be demonstrated in this project.

If we can demonstrate such a low mechanical noise level, half of our problem, the low speed problem, will be solved. At high speeds, however, the tire noise of large trucks becomes the dominant source of community noise. Figure 6 (5) shows the variations of A-weighted sound levels measured at 50 ft as a function of speed for a loaded single drive axle truck with quiet rib tires on the steering axle and various test tires (four) on the rear drive axle. As we can see in this figure, the rib tires that have tread designs similar to summer passenger automobile tires are the quietest of the commercially available truck tires. Crossbar tires with tread elements arranged somewhat similar to passenger automobile snow tires generate approximately 10 dB higher noise levels throughout the speed range. These crossbar tires are frequently found on the drive axles of heavy trucks affording off-the-road traction and, most importantly to the trucker, up to twice the mileage of the shallow tread depth rib tires. Certain low-cost retread tire designs indicated by retread I in this figure generate such high sound levels and persist for such extended time periods after a truck has passed that these tires are known in the trade as "Singing Sams." It is evident from this figure that if crossbar or pocket retread tires are used on 75-dBA trucks, little benefit would be provided residents adjacent to highways where trucks pass at speeds in excess of 40 mph. Even with the application of current rib-type tires, at 60 mph tire noise would be dominant.

I must caution that this figure represents the sound levels generated by new tires. Figure 7 shows further results of the DOT tire research program indicating the increase in sound level as the tire is worn. These higher sound levels are more representative of typical highway sounds than the sound levels shown in Figure 6 for new tires.

The results of our tire noise research have shown that in all cases tire sound levels increase with speed, with loading, with wear (except for retread I) and with increased number of tires, e.g., 18-wheeled tractor-semitrailer combinations. There are some variations of sound level as a result of road surface. The smoothest and roughest road surfaces produce the highest sound levels. Moderate aggregate road surfaces generally produce the lowest community sound levels. Time does not permit a detailed discussion of the reasons for these variations; however, this information is given elsewhere (5, 6).

Tire manufacturers are currently attempting to develop a tire noise testing standard and the California Highway Patrol has been directed by the California legislature to establish tire noise certification regulations in the very near future. DOT, through its research programs, is working very closely with both of these groups and the users, the American trucking associations, to try to evolve standardized test procedures, best design and use practices, and ultimately new long-wearing, low-noise truck tires.

Exhaust noist source heights vary from 1 to 15 ft above the road. The engine noise sources as previously discussed emanate from the engine compartment and, therefore, generally are considered to be radiated at a source height of about 3 ft off the road. The tire sounds are generated in the immediate vicinity of the tire-roadway interface and could be given an effective source height of approximately 2 to 3 in. off the road. Directivity of the noises is not so well defined but should also be considered by vehicle and highway designers.

The sources of automobile noise, as was the case for trucks, vary with speed and operating conditions. Under maximum acceleration conditions, automobiles designed to meet the new noise level standards generate approximately equivalent fan and exhaust noise levels. Because of the high degree of muffling of intake and exhaust and the use of quieter fans, passenger automobile tire sounds enter the picture at quite low

Figure 1. 1971 noise survey results (1).

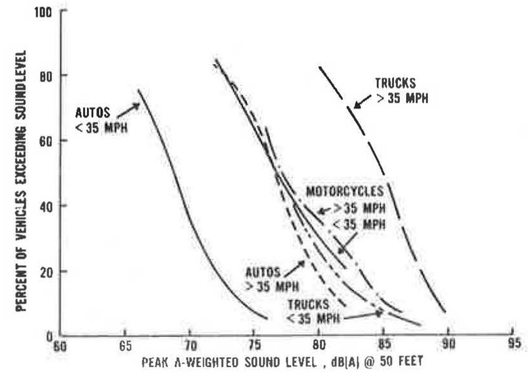


Figure 2. Diesel truck noise sources.

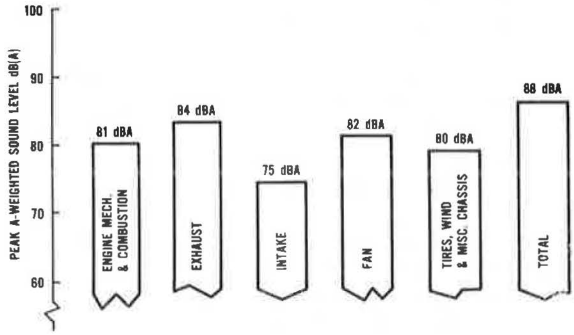


Figure 3. Diesel engine exhaust noise.

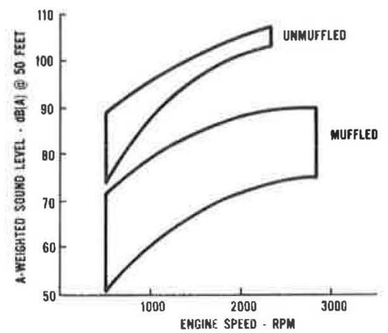
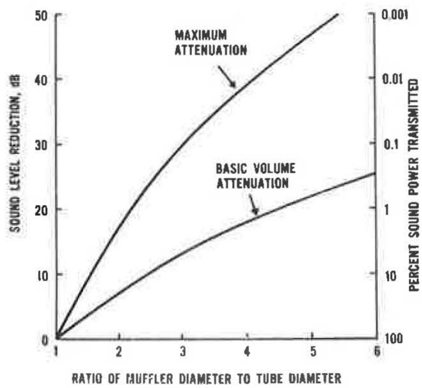


Figure 4. Intake and exhaust muffler effectiveness.



ADD 2dB PER FOOTLENGTH WHEN $D_M / D_T = 2$

ADD 5dB PER FOOT LENGTH WHEN $D_M / D_T = 3$

Figure 5. Effect of speed on fan noise.

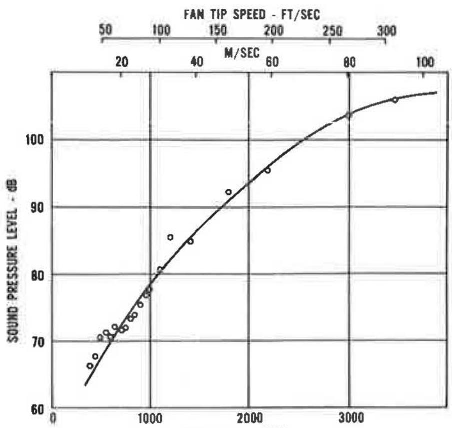
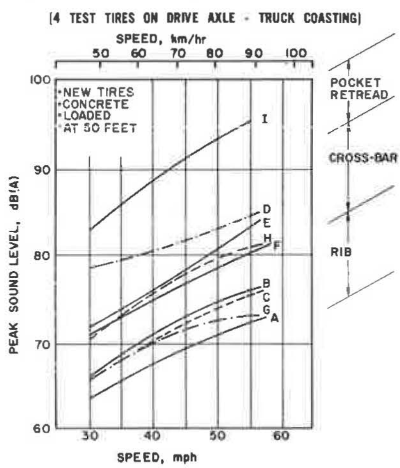


Figure 6. Truck tire noise levels.



vehicle speeds. As vehicle speed is increased, engine speed, and therefore engine noise, increases. The limited number of gear ratios available in the typical passenger automobile differs from the typical truck design that offers gear ratios to match almost any speed.

Figure 8 shows the effect of operating mode and speed. On the left-hand portion of the figure, the percentage of automobiles exceeding the sound level on the abscissa is indicated for vehicles at speeds of less than 35 mph on level road, when accelerating, and on climbing grades. On the right-hand side of the figure, we indicate the sound levels exceeded by vehicles for freeway operations: maintaining constant speed on the level road, climbing grades, and accelerating at on-ramps.

For the less than 35-mph data set, it can be seen that maintaining constant speed is the quietest operation. Pulling a grade while maintaining a constant speed required additional power and results in an approximate 1½-dB increase in sound level. Accelerating requires additional power and higher rpm at lower gear settings, which results in another 1½-dB average increase in sound level.

Under freeway conditions, however, it can be seen that level road conditions produce the highest sound levels on the average. Operations on grades where the traffic typically slows slightly result in lower sound levels, and the lowest sound levels are recorded for the freeway on-ramp acceleration case. In the California Highway Patrol survey report (1), it was noted that the acceleration sound level data are perhaps not representative because of the visibility of the police cruiser at one on-ramp location. The trend, however, indicates that the highest speed operations produce the highest sound levels, whereas lower speed freeway operations represented by the grade or on-ramp acceleration cases produce lower sound levels. Although this is not conclusive proof of tire noise dominance of freeway noise, it does very much indicate the presence of a dominant noise source not directly connected with engine power at freeway speeds.

In 1970 a DOT-sponsored pilot measurement program of passenger automobile noise levels was conducted on a newly laid section of Interstate 95 north of Washington, D.C. Utilizing a four-door sedan and a variety of test tires, coast-noise measurements were made with the engine shut off and transmission in neutral. The results of this experiment are shown in Figure 9. The presumably quietest commercial tire with no sipes and only four circumferential grooves is the ASTM skid-test tire. The sound level produced by the skid-test tire was slightly lower at 30 mph but merged in with the general pattern of deluxe rib, economy rib, and radial tire sound levels at higher speeds. With typical snow tires mounted on the rear axle of the same sedan, however, it can be seen that an increase in sound level of 5 dBA was measured. It should be noted that these tires were new, and, if the trends established by our truck tire tests carry over to the softer passenger automobile tires, these sound levels would tend to increase as the tires are worn. It should also be noted, however, that the noisy snow tires are still below the sound level generated by more than 80 percent of the trucks at freeway speeds in the California survey (1).

The level of motorcycle noise (Fig. 1) falls generally between automobile and truck noise levels. The literature does not reveal a significant amount of information on motorcycle noise levels; however, it is clear that exhaust noise is a dominant feature of motorcycles, followed closely by intake, engine, and chain noises. Figure 10 shows the noise level measured under maximum acceleration conditions for a variety of motorcycles as a function of engine displacement in cubic inches. The lower curve indicates the general trend with standard production mufflers, whereas the upper curve indicates the impact of application of modified mufflers that many motorcyclists prefer. These tests were performed by the Ontario Department of Highways in 1967 (7). The specific test procedures were made in accordance with the International Standards Organization Recommendation 362, which prescribes a sideline measurement distance of 25 ft. In this figure we have extrapolated the measured sound levels to an equivalent 50-ft sideline level for consistency with the other vehicle sound levels presented. For motorcycles the approximate difference in 25- and 50-ft levels is 6 dB as indicated on the shifted ordinate on the left-hand side of Figure 10.

It can be seen from Figure 10 that the smaller motorcycles are considerably quieter than the largest 1,200-cc U.S. manufactured motorcycle. With modified exhaust

Figure 7. Effect of tire wear on sound levels.

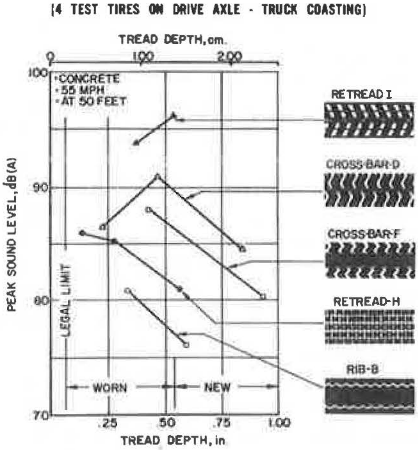


Figure 8. Effects of speed and operating mode on automobile noise levels.

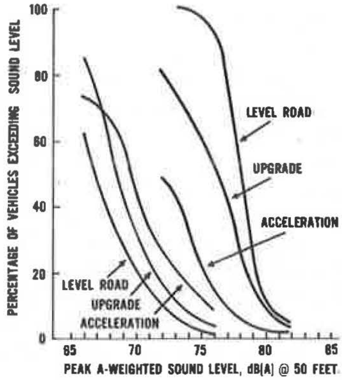


Figure 9. Passenger automobile tire noise.

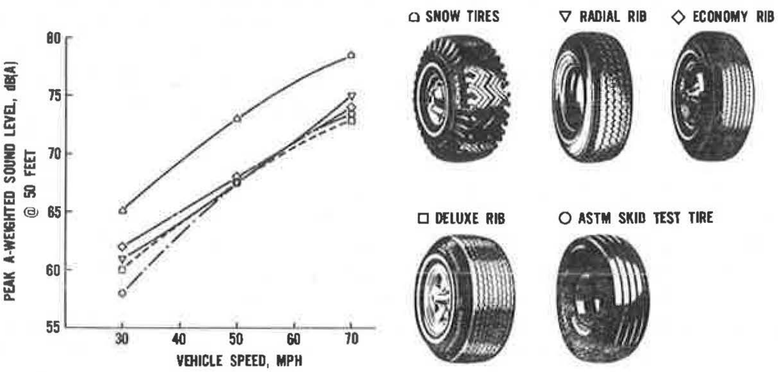
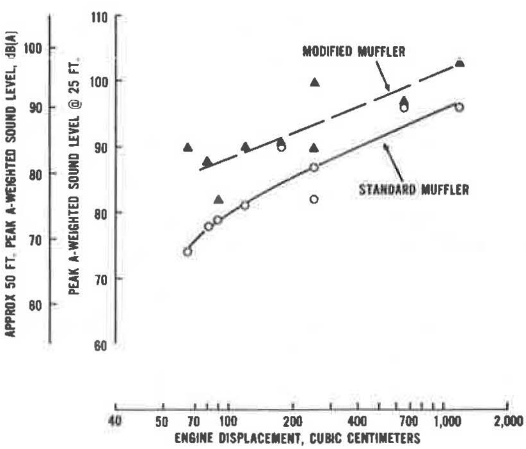


Figure 10. Maximum noise levels of motorcycles.



systems, however, it can also be seen that even the smaller bikes can produce untenably high sound levels. Further reduction of exhaust noise from motorcycles is possible; however, intake and engine noise is very close behind the noise levels generated with standard exhaust mufflers. The application of engine enclosures for these small air-cooled engines presents a number of problems not encountered with the water-cooled automobile and truck engines. Notwithstanding these problems, industry members of the President's National Industrial Pollution Control Council suggested that current levels of industry voluntary maximum noise standards for motorcycles with engines of greater than 240-cc displacement could be reduced from the current 92 dBA at 50 ft to 90 dBA by 1973, to 86 dBA by 1978, and to 77 dBA by 1983 (8). Comparable recommended maximum sound levels for motorcycles under 240-cc displacement are 2 to 3 dB lower.

The growing body of research and regulatory pressures lead us to believe that the mechanical noise levels generated by highway vehicles can indeed be significantly reduced without undue penalty to the purchaser or operator of these vehicles. The mechanically generated noise of automobiles is already quite low although most automobiles can generate noise levels approximating those of large over-the-road diesel trucks. Continued pressure by the average purchaser will retain the normal automobile noise level at the tolerable levels experienced today. The roadside enforcement of motor vehicle noise regulations will play the critical role in the control of excessive noise produced by poorly maintained or modified exhaust systems and wild operations.

Reduction of diesel truck noise levels from mechanical sources is moving forward with the assistance of federal research and the pressure of state and local regulations. Prospects for significant improvement in this regard are just around the corner.

Tire noise generation is another matter, however. Prospects for reducing truck tire noise levels in the near future are not so clear. The facts are now on the table as a result of DOT and General Motors research efforts; however, the stimulation or driving force has not been brought to bear to require operators to use quieter commercially available tires. California once again will likely be the spearhead of this effort by establishing tire noise regulations. Industry research, however, must be increased to clarify the mechanisms of tire noise generation and to find competitive solutions to the reduction of noise levels emanating from truck and passenger automobile tires.

Near-term control of highway noise levels will require continued enforcement of vehicle noise levels with emphasis on exhaust, induction, and tire noise sources. Longer term improvements in vehicle levels can be achieved through redesign of vehicle components such as fans, radiators, engine enclosures, and tires coupled with highway design features such as noise barriers.

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NOISE STANDARDS FOR FEDERAL HIGHWAYS

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The Federal-Aid Highway Act of 1970 requires that noise standards be developed, promulgated, and applied to the planning and design of highway projects. Many considerations must be weighed during the development of such standards: the comprehensive overall strategy for traffic noise control, standards, or policies already adopted by other agencies; desirable noise levels; noise prediction capability; currently available abatement techniques (and their effectiveness); and the effect of standards on the highway program. Each of these factors has been given thorough examination. The standards will accomplish all that the law requires and more.

•THE nation is witnessing the beginning of an all-out effort to control noise. This effort is part of the overall response of government, industry, and institutions of higher learning to the public's expression of deep concern for the environment. The Congress shared this concern and expressed its desire to correct environmental intrusions such as noise by mandating the promulgation of highway noise standards. State and local governments have also taken action in this area. Some of the sources of noise that are currently being controlled or being considered for control are aircraft, motor vehicles, industries, appliances, electric power substations, and construction operations (1).

The highway-related noise problem is very complex, and there are no quick or simple solutions. Complete elimination of this nuisance may continue to elude us for a long time to come. Even so, substantial noise reductions are possible, though they will require coordinated efforts from a variety of directions. A three-part approach is needed to attack the traffic noise problem: reduction of sound at the source (the motor vehicle), control of the use of land in the vicinity of highways, and noise abatement measures in the planning and design of highway projects.

Trucks, particularly diesel trucks, are a chief source of motor vehicle noise. Many trucks are not equipped with mufflers by the manufacturer, and those mufflers provided by the manufacturers are sometimes removed or altered. Other noise comes from excessively noisy retread tire designs. Modification of exhaust systems on motorcycles, sports cars, and hot rods for the specific purpose of creating a higher noise level is commonplace (2).

Reduction of noise at the source, that is, on the vehicle itself, is potentially the most fruitful way to reduce the problems of motor vehicle noise (3). Quieter vehicles would bring about a substantial reduction of noise along millions of miles of existing roads and streets where no other corrective measures are possible. Legislation is being considered by Congress for control of noise from manufactured products. Several state and local governments have enacted numerical noise level limits that (from a noise standpoint) require proper maintenance and operation of motor vehicles (1). These actions are important beginning steps to achieve the first part of the three-part approach.

The second part of a balanced attack on the highway noise problem is the control of land use. Many years ago we learned that most kinds of development should be prohibited in flood plains subject to frequent and severe flooding. It is of comparable importance to consider land use control in areas where noise is a problem. The lands

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need not necessarily remain vacant. Most commercial and industrial activities can coexist with a noisy environment. Many other types of activities can be accommodated through proper site location, building design, and acoustical treatment (soundproofing) (4).

Not infrequently, complaints about highway traffic noise come from residents occupying homes built adjacent to a highway after the highway was already in place. Many of these highways were originally constructed through undeveloped lands. Even though highway agencies may be knowledgeable about existing zoning and planning, they are not able to foretell when and where future development will occur, what such development will be, and the degree of soundproofing that will be built into future buildings. To require noise abatement measures on highway projects based on such unreliable estimates would be unreasonable and uneconomical and would result in the construction of many white-elephant noise barriers along many new highways where expected development patterns changed. Moreover, there are several hundred thousand miles of existing highways that are bordered by vacant land. Much of this land will someday be developed. Sensible land use control could help prevent future traffic noise conflicts in these areas. Such controls need not prohibit development but rather should use reasonable setback distances, soundproofing, or abatement measures to avoid future noise disturbances.

The noise standards issued in 1971 by the Department of Housing and Urban Development (HUD), to avoid noise problems connected with future federally insured housing, are a step in the right direction. However, more measures, which are beyond the scope of the highway noise standards and are not covered by the HUD standards, are needed in this area.

The third part of the three-part approach, the consideration and abatement of traffic noise in the planning and design of highway projects, is required by the proposed standards. It has been pointed out previously that this part can only be regarded as a limited approach. It does have a major role in reducing the magnitude of the nation's traffic noise problem, but it cannot solve the entire problem alone.

The fundamental goal during the development of the standards has been to reduce the effects of traffic noise by the greatest possible extent without neglecting other important considerations. It is important to recognize that there will continue to be situations where, no matter what ameliorative measures are taken, some objectionable noise will remain. In some instances, measures taken to achieve compliance with the standards may conflict with other social and environmental objectives. For example, a wall constructed as a noise barrier could have an adverse aesthetic effect, or depressing a highway may reduce noise impacts on adjacent properties but increase the concentration of air pollution on the highway. The possibility of such detrimental effects should be carefully studied in each instance and a decision to proceed with a proposed noise abatement measure be made only if it is clear that the importance of noise abatement outweighs possible adverse effects. Noise is only one of many social, economic, and environmental factors considered, none of which is controlling. Section 136(b) of the Federal-Aid Highway Act of 1970 requires not only that social, economic, and environmental factors be fully considered but that "final decisions on highway projects (are made) in the best overall public interest taking into consideration the need for fast, safe, and efficient transportation, public services, and the costs of eliminating or minimizing such adverse effects." Therefore, it was considered neither feasible nor prudent to make noise the preeminent consideration in highway decisions. These conflicts have been foreseen during the development of standards, and provisions have been made for their resolution.

CONTENTS OF THE STANDARDS

The standards require that noise-sensitive land uses and activities in the vicinity of highway projects be identified and that anticipated noise levels be computed for the noise-sensitive areas on the basis of the worst noise situation expected to occur from the highway in question. The standards also contain design noise levels for different exterior land uses and activities and also for certain interior uses.

The design noise levels in the standards should not be exceeded more than 10 percent of the time during the worst hour of the day during the design year. This statistical description is needed because of the fluctuation of noise levels with time. For exteriors of schools and residences, the design noise level is 70 dBA (noise measured in decibels on A-scale). This means that, where the design noise level is met, the 70-dBA level would be exceeded not more than 6 min during the hour when the worst noise conditions exist. For 54 min of this hour, the noise would be less than 70 dBA. The abbreviation for the noise level exceeded no more than 10 percent of the time is L_{10}.

The noise predictions are to be compared with the appropriate design noise levels to determine the need for noise abatement measures. Such measures are to be taken on all projects to meet the design noise levels, to the extent that opportunities to control noise reasonably exist. However, there will be projects for which abatement measures cannot feasibly achieve the design noise levels. Consequently, the standards include provisions for handling exceptions.

The design noise levels apply only to developed lands. Even so, the standards indicate that highway agencies may consider the desirability of applying them to undeveloped lands subject to development. In addition, highway agencies are to furnish to local officials approximate generalized noise levels for various distances from the highway improvement and other information that would be useful to local governments in developing or implementing programs (such as zoning or subdivision control) to protect against future development along the highway that would be incompatible with the expected noise levels.

CONSULTATION AND COORDINATION

Extensive consultation and coordination have played a very important role in the development of the standards. These efforts have provided broad-based inputs from a variety of experts experienced in the study of highway noise problems. Individuals and organizational representatives with different perspectives have participated at various stages in the development of the standards.

Much of the technical foundation for the preparation of the standards was provided by the DOT Office of Noise Abatement and the DOT Transportation Systems Center (a center having good acoustical study facilities).

The first draft of the standards was prepared in November 1971. This was furnished to an advisory committee of highway noise experts that met in December 1971. The membership of this group included representatives from state highway departments, a city department of public works, city environmental agencies, acoustical consultants, the Society of Automotive Engineers, and the Highway Research Board.

Following review by the advisory committee, a second draft was circulated to state highway agencies and FHWA field offices for review and comments. While the states were individually reviewing the standards, a special task force from the American Association of State Highway Officials Operating Subcommittee on Roadway Design met to review the draft standards.

Meetings were also held with the noise staffs of the U.S. Environmental Protection Agency and HUD to explain the standards and to coordinate the standards with related activities of those two agencies.

BASIS OF THE DESIGN NOISE LEVELS

Establishing the proper figures for the design noise levels is essentially a problem of balancing the desirability of eliminating (or minimizing) future increases in highway noise levels against the economic, physical, and aesthetic considerations related to noise abatement measures.

Current ambient noise levels in many developed areas are, at best, annoying and, at worst, a hindrance to many human activities. Any measure that serves to limit future increases would be welcome. On the other hand, effective noise abatement measures are often extremely expensive or disruptive or both and, in some cases, are simply not feasible. The terrain can render abatement measures ineffective or cause the costs of corrective measures to be high in relation to the benefits achieved. The measures required to abate noise conditions can conflict seriously with other important values such as desirable aesthetic standards, important ecological conditions, highway safety, air quality, or other similar considerations. It would be nearly impossible to incorporate noise abatement measures for highway projects involving an increase in traffic volume or speed (and therefore an increase in traffic noise) on existing city streets or arterials without completely disrupting existing development. The difficulties arise from numerous points of access, the close proximity of storefronts and dwellings, grade intersections, limited ability to acquire additional right-of-way as buffer zones, and the impossibility of altering roadway grades, constructing noise barriers, and taking advantage of the terrain and other natural features. Reduction of the noise source appears to offer the only possibility for reduction of noise levels in these situations. The problems are also complicated by the fact that, below the level of physical harm, reactions to noise are largely subjective, and people will have differing sensitivity to a given noise level.

Several approaches to the establishment of design noise levels on a relatively systematic basis have been considered. These include possible hearing impairment, annoyance or disturbance, and interference with speech communication (5).

The first approach deals in terms of very loud noises seldom encountered for a highway project beyond the roadway proper. The second approach is desirable in principle but insufficiently researched to be used as the sole basis. However, the third, speech interference, can be usefully applied to the problem of highway noise. A combination of the latter two approaches has been used to establish the design noise levels.

As previously mentioned, noise predictions are made for the worst hour (out of 24) and compared with the design noise levels. The worst hour was chosen because of the extreme difficulty in predicting hourly traffic variations for some future year. Highway engineers are usually happy when they can forecast future daily volumes of cars and trucks, let alone the manner in which these volumes will be distributed over a 24-hour period. Consequently, there are no design noise levels for night.

Figure 1 shows measured traffic and computed noise from a heavily traveled urban freeway with high truck volumes throughout the night. It can be seen that the computed noise levels during the night average about 6 dB less than the peak that occurs during the worst hour. For those roadways where night traffic is light, the reduction should be even greater.

If traffic forecasting techniques were sophisticated and precise enough to predict hourly traffic fluctuations, some basis other than the worst hour would have been used in the noise standards.

COMPARISON WITH HUD STANDARDS

A comparison of the standards with those already promulgated by HUD may be useful. For exterior residential use, the upper limit of the HUD normally acceptable range is 65 dBA, not to be exceeded more than 8 hours out of 24. The FHWA exterior design noise level for residential activities is 70 dBA, not to be exceeded more than 6 min out of the 60 min representing one of the noisiest hours of the day. When the HUD and FHWA values are put on a comparable basis, the exterior design noise level proposed by FHWA falls within the HUD normally acceptable range.

EFFECTS OF THE STANDARDS ON HIGHWAY PROJECTS

There is no question that it would be desirable to aim for even lower noise levels than those in the standards. For example, a residential backyard L_{10} level of 60 dBA would be preferable to the proposed 70-dBA value. Even so, although such lower levels were extensively explored in the development of the standards, they were finally judged beyond the reasonable capability of highway agencies to meet with highway measures alone. Figures 2 through 5 (prepared from procedures given elsewhere, 5) demonstrate some of the difficulties anticipated in the application of the proposed design levels.

Figures 2, 3, and 4 relate noise levels to distance from the nearest lane for four-, six-, and eight-lane freeways respectively and for differing traffic conditions. For example, in Figure 3, with the conditions indicated and 800 trucks per hour, the noise

Figure 1. Heavily traveled freeway noise levels.

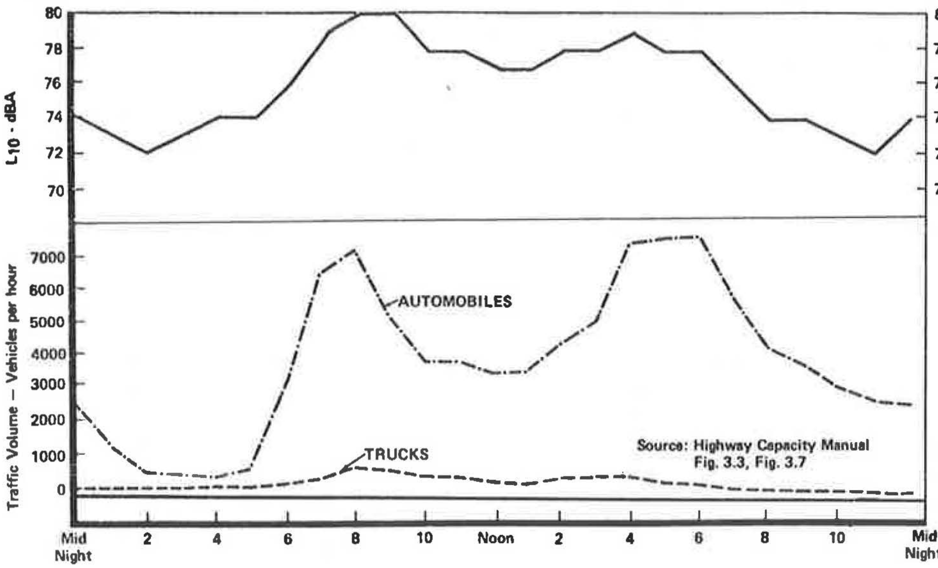


Figure 2. Noise levels for four-lane highway.

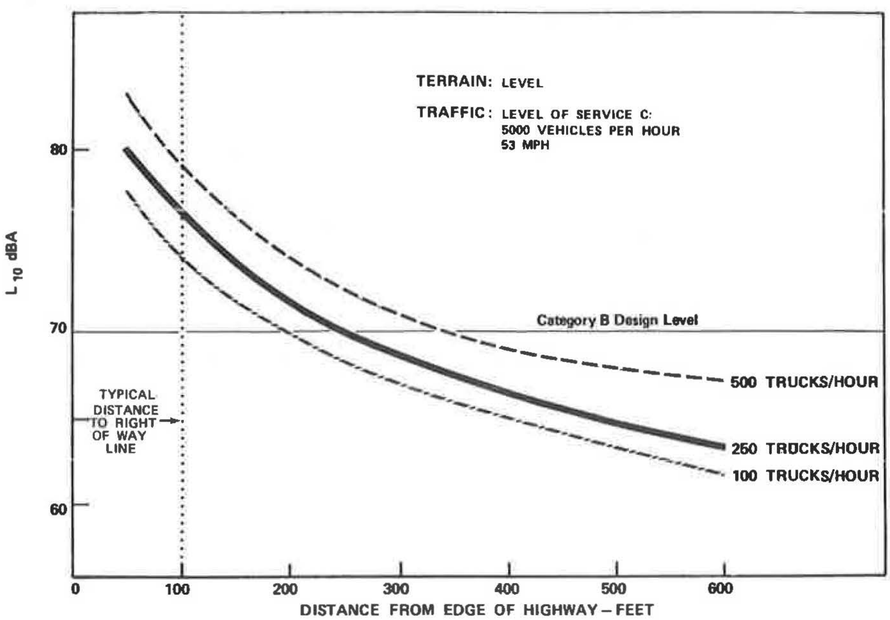


Figure 3. Noise levels for six-lane highway.

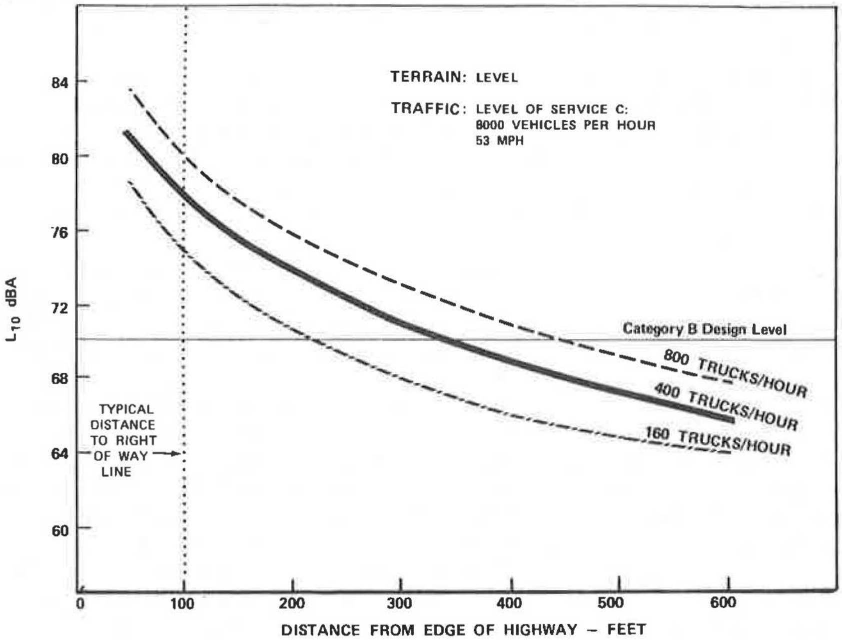
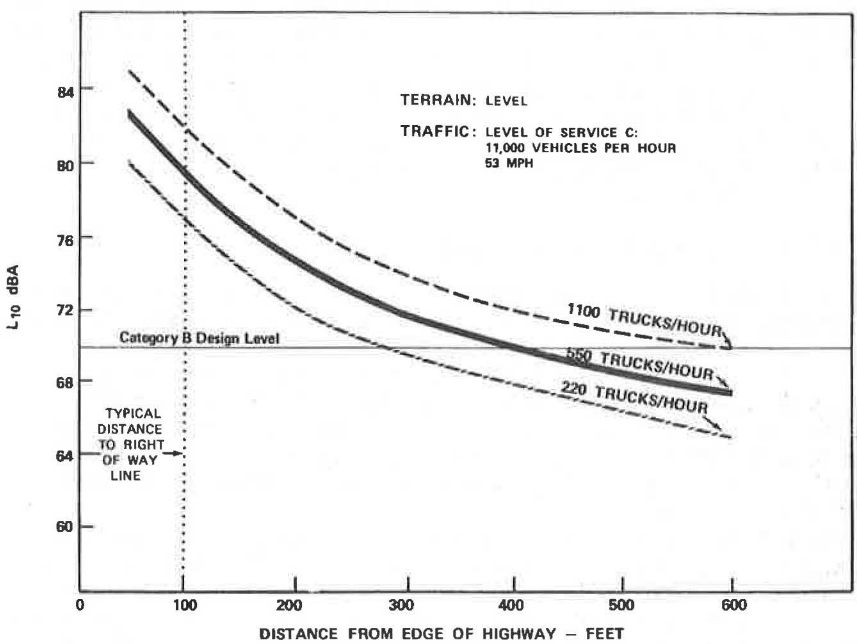


Figure 4. Noise levels for eight-lane highway.



level 200 ft from the nearest lane would be 76 dBA, that is, 6 dBA higher than the exterior design noise level for residential use. In fact, all of the examples shown in these three figures indicate noise levels higher than 70 dBA for distances ranging from 200 to nearly 600 ft from the nearest lane.

Figure 5 shows the same information for a two-lane highway (not a freeway). Even for this type of highway, all of the conditions shown produce noise levels exceeding 70 dBA for some distance from the near lane, although the distances are less than for the freeways shown in Figures 2, 3, and 4. For example, the most severe condition would result in a noise level exceeding 70 dBA for a distance extending up to 190 ft from the near lane. For highways of this type, developed land uses, such as residences, are typically found within 50 ft of the pavement edge.

Figures 6, 7, and 8 carry this analysis one step further. They show a comparison of the effect of noise abatement measures at varying distances from the roadway. For four-, six-, and eight-lane freeways (Figs. 6, 7, and 8) at a distance of 125 ft from the pavement (assumed as the typical distance to a residential backyard) and with no noise abatement measures, the exterior noise levels would be 75, 77, and 79 dBA respectively. All exceed the exterior design noise level for residential land use of 70 dBA by a considerable margin. For a four-lane freeway (Fig. 6) compliance with the design noise level of 70 dBA would require either (a) a buffer zone extending from the edge of pavement nearly 300 ft, (b) 100 ft of dense landscaping, (c) some type of barrier, or (d) depressing the highway 10 ft. It should be noted that, for vegetation to be effective, it must be very dense and high enough to intercept the line of sight between the noise source and a receiver. From Figures 7 and 8 for six- and eight-lane freeways, it can be observed that meeting the 70-dBA design noise level would be even more difficult, requiring either a 400-ft buffer zone, 200 ft of dense landscaping, or a solid barrier at least 6 ft high.

From this analysis it is evident that the design noise levels will call for substantial noise abatement measures for a large number of highway projects. However, there are serious questions as to the extent of relief that is possible from highway measures alone. Given the levels of noise currently generated by vehicles, it is doubtful that any more stringent design noise levels than those proposed by the standards are within the practical limits of the highway program. Additional reduction in traffic noise must come in the form of control of the source of noise itself, namely, through control of the noise generated by noisy vehicles, particularly trucks. If legislation for controlling vehicular noise is to be developed and applied, a reduction in design noise levels may well prove both desirable and feasible.

WHAT THE STANDARDS SHOULD ACCOMPLISH

The standards will not guarantee the elimination of annoyance or disturbance from traffic noise even in those situations where the design noise levels are met. The standards are designed to reduce overall background noises that interfere with human activity and the frequently repeated peak noises. Occasional peak noises, such as those that occur from the passage of a few trucks per hour, will not be controlled. The reduction of these occasional noise peaks (and concurrent reduction of annoyance) will come when the appropriate governmental agencies provide for reduction of the noise at its source—the motor vehicle. The same is true of the unmuffled or otherwise unnecessarily noisy vehicles.

The standards will ensure that noise is given proper consideration in the development of highway projects. Highway agencies will have to develop or obtain expertise in acoustics and noise control to apply the standards. This will ensure that detailed examination will be made of the noise aspects of future highway projects. Noise effects will be given greater weight during highway location studies now that a yardstick is available for quantifying noise effects. Noise abatement measures will be incorporated into many new highway projects.

The standards should also have an effect on local land use control because they require state highway agencies to cooperate with local officials by providing information on expected future highway noise levels for undeveloped lands near new highway projects

Figure 5. Noise levels for two-lane highway.

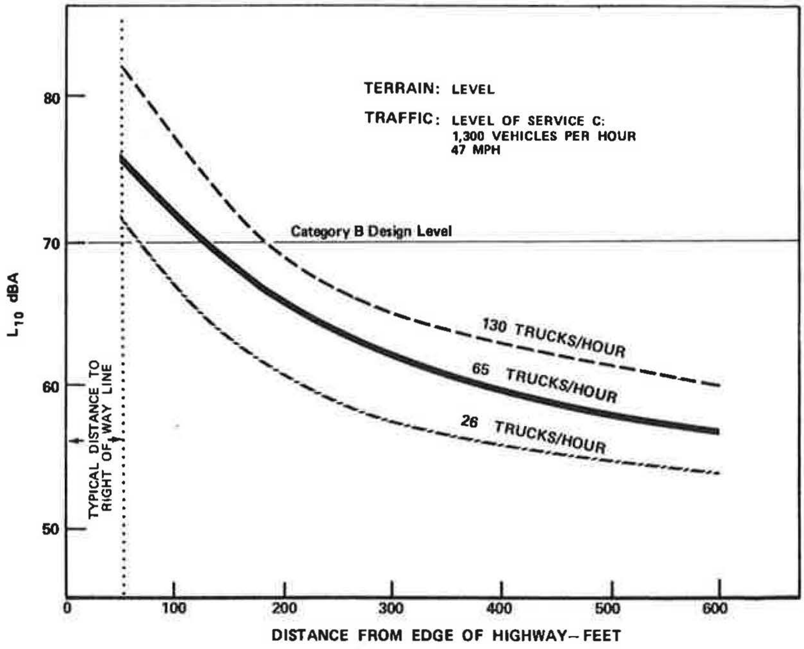


Figure 6. Highway noise from edge of four-lane highway.

TRAFFIC: 5,000 VEHICLES PER HOURS, 5% TRUCKS, 53 MPH

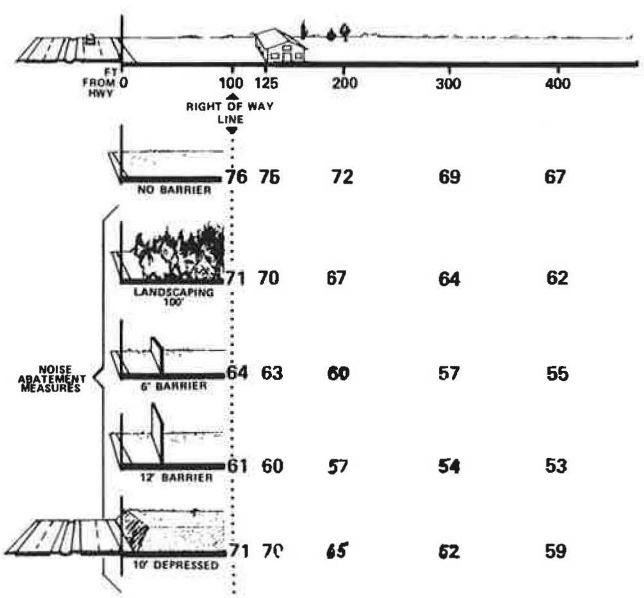


Figure 7. Highway noise from edge of six-lane highway.

TRAFFIC: 8,000 VEHICLES PER HOUR, 5% TRUCKS, 53 MPH

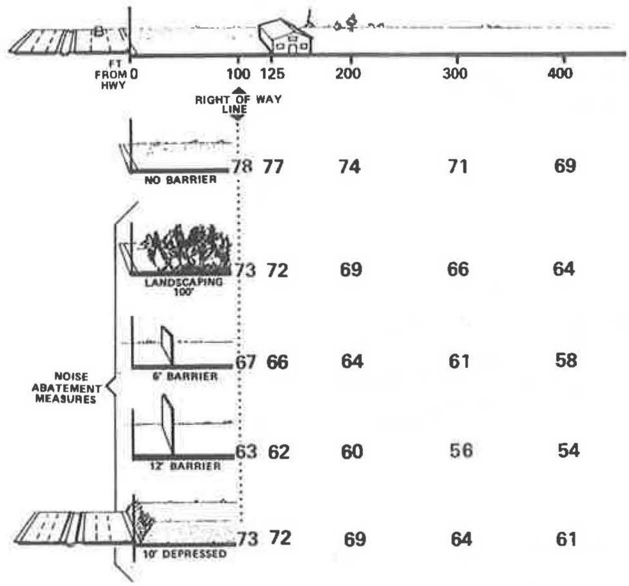
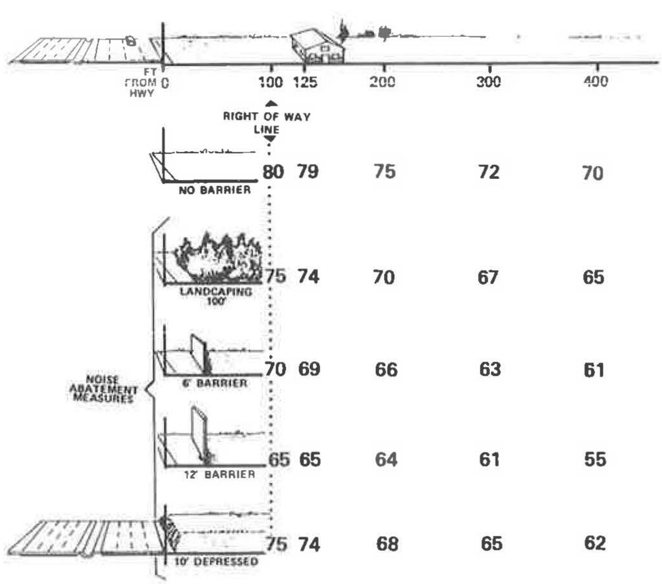


Figure 8. Highway noise from edge of eight-lane highway.

TRAFFIC: 11,000 VEHICLES PER HOUR, 5% TRUCKS, 53 MPH



together with information on the types of new land uses that would be compatible with the highway. It is anticpated that this information will stimulate local officials to adopt zoning regulations and subdivision controls to prevent conflicts of traffic noise with future land uses that may occupy portions of transportation corridors. As previously mentioned, this would not necessarily prohibit future development but rather utilize reasonable setback distances, soundproofing, or other abatement measures to avoid future noise problems.

The standards will clearly accomplish all that Congress mandated, and more. However, it will take time for most of the results to become apparent. Our institutions are large and somewhat unwieldy. Many of the highway projects to which the noise standards will be applied in 1972 will not be constructed for at least 5 years. Much time will be required to develop regulations, technology, and manufacturing changes to reduce noise at the source. Local governments will have difficulty in overcoming resistance to land use controls to reduce noise effects. All of these things will happen, but it will take time. The FHWA will shorten this time by promulgation of the noise standards that have been developed.

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FIELD EVALUATION OF TRAFFIC NOISE REDUCTION MEASURES

B. A. Kugler and A. G. Piersol, Bolt Beranek and Newman Inc.

As part of a continuing research program, approximately 400 acoustic noise records plus supporting traffic and environmental data were acquired in the vicinity of six highway sites representing four types of traffic noise reduction measures: roadside barriers, elevated highways, depressed highways, and roadside structures. The ultimate goal of the noise surveys was to validate or modify as required the noise reduction prediction procedures outlined in NCHRP Report 117 (1). To this end, the traffic noise data were converted to noise reductions at specific locations in terms of A-weighted L_{50} (median) sound pressure levels and then compared to the predicted noise reductions. Agreement was assessed in terms of the least squares line for the measured versus predicted noise reductions and the average discrepancy between the measured and predicted results as a function of the receiver distance from the roadside and height above the ground. The results indicate that the best agreement between the predicted and measured data is provided by the elevated highway and roadside structures configurations. For the roadside barrier and depressed highway configurations, the procedures of NCHRP Report 117 appear to underpredict the noise reductions at those locations where there is nearly a direct line of sight to the traffic flow. Based on these results, modifications to the noise reduction curves in NCHRP Report 117 are derived and presented.

•TRAFFIC noise generated on modern highways is a major source of environmental noise pollution. Urgent needs exist not only for realistic highway noise standards but also for engineering tools that can be implemented by highway designers to control this form of noise pollution. In a previous study published by the Highway Research Board, systematic procedures for the calculation of highway noise levels were presented in the form of a design guide for highway noise prediction (1), hereafter referred to as the "design guide." The methods suggested in the design guide represent an important step toward the solution of traffic noise problems in that they allow a highway engineer to predict the expected noise levels for particular highway configurations and to assess the changes in noise levels due to modifications of highway geometry. However, the design guide methods were based in part on theoretical model studies involving many simplifying assumptions, particularly in the calculation procedures for the amount of noise reduction provided by various highway noise control measures.

Several theoretical and empirical methods have previously been proposed for estimating how barriers reduce the sound level from a point source (2-7). Of course, the applicability of these methods to field situations is somewhat questionable because an actual highway entails a source that is distributed over the roadway geometry. In developing the design guide, a limited field measurement program was conducted to evaluate previous theoretical prediction procedures and to modify them as required to account for an extended noise source. More recently, a further refined model for predicting barrier noise reductions has been suggested (8) where the noise source is

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modified to represent an incoherent line source. Nevertheless, the potential of various highway noise reduction measures under actual traffic and environmental conditions remains only partially understood.

In recognition of this fact, a study was initiated by the Highway Research Board with the following objectives:

1. Review and analyze the present state of the art in the prediction of acoustic performance for various highway noise reduction measures including roadside barriers, elevated highway sections, depressed highway sections, and roadside structures;
2. Locate operational examples of typical constructions and conduct a data acquisition program to collect field noise reduction measurements;
3. Interpret the field data in terms of the parameters that modify the noise reduction effectiveness of each construction;
4. Relate the preceding information to current prediction techniques and validate or modify the current procedures presented in the design guide; and
5. Prepare, when appropriate, corrected noise prediction procedures for the various constructions in a form that can be incorporated into the design guide.

The approach pursued in this recently completed study, along with the general results, is summarized in this paper.

APPROACH

The initial task was to define, locate, and select the basic geometries to be evaluated. After an intensive search of existing configurations throughout the country, six test sites were selected for acoustical evaluation as follows:

1. Site 1—a roadside barrier configuration along a section of I-680 in Milpitas, California;
2. Site 2—an elevated highway configuration along a section of US-101 (Ventura Freeway) in Encino, California;
3. Site 3—an elevated highway configuration along a section of I-405 (San Diego Freeway) in Van Nuys, California;
4. Site 5—a roadside structures configuration along a section of I-35W in Richfield, Minnesota;
5. Site 6—a roadside structures configuration along a section of I-94 in Ypsilanti, Michigan; and
6. Site 9—a depressed highway configuration along a section of I-35W in Minneapolis, Minnesota.

The next task was to design a measurement program for each test site capable of collecting data to provide an adequate site description in acoustic terms. This was followed by the data acquisition program in which the sites were acoustically surveyed. The basic information collected during the data acquisition program was as follows:

1. Noise levels—Ten-min tape recordings were made of the noise levels at each of numerous different positions located various distances from the highway and above the ground. Figure 1 shows an outline of the measurement locations at site 2. Note that, during the recording of noise levels at all shielded locations (stations B, C, and D, Fig. 1), a noise measurement was simultaneously recorded at a free field location (station a, Fig. 1) for reference purposes.
2. Traffic conditions—Average traffic volume (vehicles per hour), speed, and truck-automobile mix were determined during the 10-min noise measurement runs. Photographic techniques were used to record these parameters.
3. Environmental conditions—Wind velocity and direction, temperature, and relative humidity were measured at the start of most measurement runs.

Note that the goal was to obtain noise measurements under a wide range of traffic and environmental conditions. However, the data collected were necessarily confined to the actual conditions found at each site.

The third task was the reduction of the field recordings into meaningful measures of acoustic noise. This was done by first reducing each 10-min data record in terms of the A-weighted sound pressure level as a function of time. The A-weighted levels were then passed through a statistical distribution analyzer to obtain the sample distribution function of the levels over the 10-min measurement run. Figure 2 shows the statistical distributions for selected measurement runs at site 2. These statistical distributions were then fitted by a normal distribution, and the L_{50} and L_{10} levels were computed from the normal approximation.

The final task was the evaluation of the data. The L_{50} (median) levels computed from the measurements at each test site were used for the evaluation in most cases. Specifically, the basic L_{50} noise data were converted to excess noise reductions at various locations (distances from the roadside and heights above the ground) by subtracting the shielded L_{50} levels from the free field L_{50} levels. The free field L_{50} levels at the shielded locations were estimated by extrapolating the L_{50} levels measured at the unshielded reference location (station A) based on the modified line source distance attenuation rule used in the design guide (4.5-dB decrease per doubling of distance).

EVALUATION PROCEDURES

The noise reductions predicted by the design guide, as well as other prediction procedures of interest, were computed at each location where measurements were obtained. This provided a direct comparison of the measured and predicted noise reductions at each measurement location for each site. The agreement between the measurements and predictions was evaluated by computing various statistical parameters as follows:

1. Average discrepancy between the measured and predicted noise reductions (discrepancy Δ = predicted value minus measured value);
2. Standard deviation of the discrepancy between the measured and predicted noise reductions;
3. Least squares line for measured versus predicted noise reductions;
4. Average discrepancy between the measured and predicted noise reductions versus distance from the roadside, computed by averaging the discrepancies over all heights at each distance; and
5. Average discrepancy between the measured and predicted noise reductions versus height above the ground, computed by averaging the discrepancies over all distances at each height.

The first two parameters constitute estimates of the overall bias error and random error respectively in the predictions relative to the measurements. The third parameter, the least squares line, provides an indication of the agreement between the measurements and predictions as a function of the magnitude of the predicted noise reduction. The last two parameters indicate the accuracy of the predictions as a function of the observer location in terms of distance from the roadside and height above the ground respectively. In all cases, the computed values of the parameters in question were tested for a statistically significant difference from zero at the 1 percent level of significance by conventional statistical testing procedures (9).

As an illustration of the evaluation procedure, the detailed results for the comparison of the measured noise reduction data at site 2 (as shown in Fig. 1) versus the noise reductions predicted by the design guide procedures are given in Table 1 and Figures 3 and 4. During the measurement runs at this site, the average traffic volume was 10,000 to 14,000 vehicles per hour (heavy), the average traffic speed was 50 to 60 mph, and the truck-automobile mix was 2 to 6 percent. The environmental conditions included a southeasterly wind of less than 8 mph, temperatures ranging from 62 to 85 F, and a relative humidity of 40 to 90 percent.

The predicted noise reductions were computed to be an average of 1.33 dBA higher than the measured noise reductions (Table 1). In other words, the design guide procedure appears to be slightly biased toward overprediction for this case. There is also a random error (scatter) between the measured and predicted results as indicated by the standard deviation of 2.33 dBA in the discrepancies. The least squares line for the measured versus predicted noise reductions suggests that the tendency toward overprediction occurs primarily at the 5-to-10-dBA noise reduction level, as shown

Figure 1. Cross section and acoustic measurement stations for site 2.

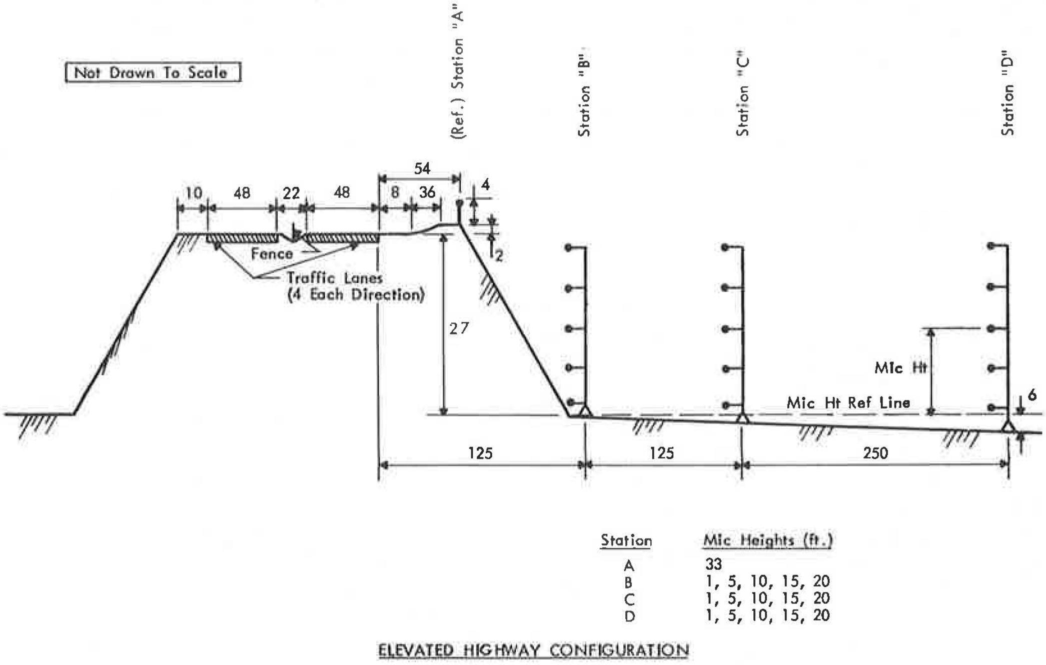
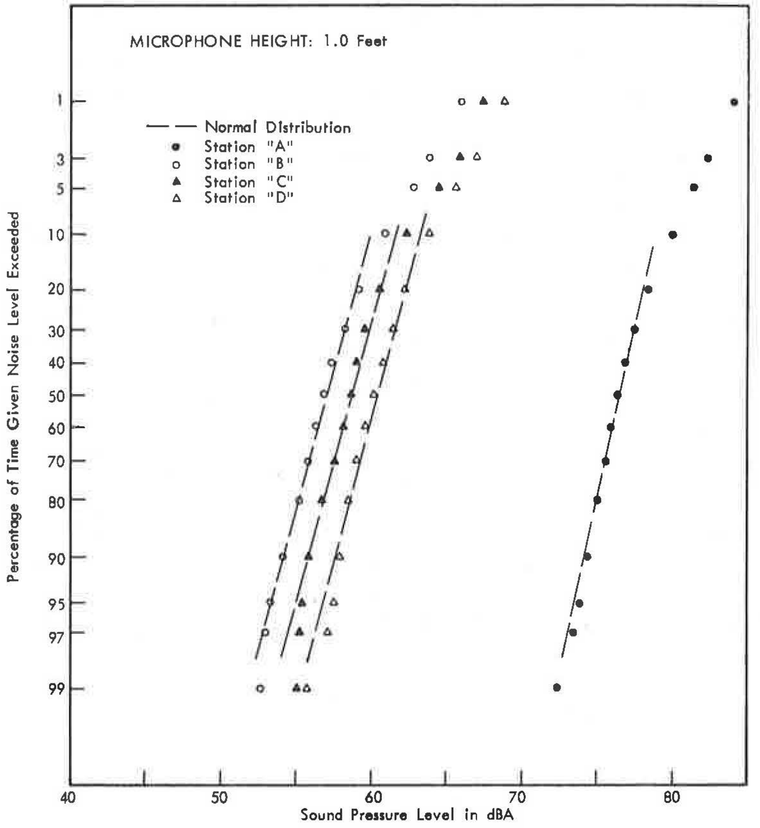


Figure 2. Cumulative distribution curves for site 2.



in Figure 3. There is no significant variation in the discrepancy at various distances from the roadside. There is, however, a small but statistically significant variation in the discrepancy at various heights above the ground, as shown in Figure 4b.

The foregoing type of evaluation was applied to the measured noise reductions at all six sites in comparison to the predictions afforded by several procedures, including the design guide (1), a modified line source model, and, in some cases, the point and line source models of Maekawa (2, 3) and Kurtz and Anderson (8) respectively. A summary of the basic noise reduction curves for these various models is shown in Figure 5. Other evaluations included studies of possible variations in the discrepancy between measured and predicted noise reductions as a function of traffic volume, traffic speed, truck-automobile mix, wind, and air temperature.

SUMMARY OF RESULTS

A summary of results of the comparisons of the measured noise reductions and the design guide predictions for all six sites are given in Table 2. Note that, for convenience and direct comparability of results, the design guide model curve of Figure 5 was used to predict the noise reductions for the elevated and depressed highway sites as well as for the roadside barrier site. The actual curves in the design guide, when converted to the format of Figure 5, differ slightly from this model for the case of elevated and depressed highway configurations.

Reasonably good agreement is achieved between the measured and predicted noise reductions for the elevated highway configuration (Table 2). For the two sites (sites 2 and 3) with this configuration, the average difference between the measurements and predictions is less than 1.4 dBA. Furthermore, the variation in the prediction accuracy is negligible with distance from the roadside. On the other hand, the data suggest a significant variation with distance above the ground, and the least squares lines, when investigated together in detail, indicate a tendency to overpredict at points of intermediate noise reduction (5 to 10 dBA) and underpredict at points of very low noise reduction (less than 3 dBA).

The results for the roadside structures cases (sites 5 and 6) reveal surprisingly good agreement considering the simplicity of the design guide procedure for this configuration (5 dBA of noise reduction per row of structures to a maximum of 15 dBA). There is, however, a tendency toward underprediction for a single row of structures and overprediction for three rows of structures.

The poorest agreement between the measured and predicted noise reductions occurs for the roadside barrier and depressed highway configurations. In both cases, the results indicate a strong tendency for the design guide precedures to underpredict, by an average of 5 or 6 dBA, the noise reductions at locations associated with small values of the path-length difference parameter δ (Fig. 5 gives a definition of δ). This leads to the clear suggestion that a noise reduction model more like that proposed by Maekawa or Kurtz and Anderson (Fig. 5) would provide better agreement. Indeed, when the data in terms of L_{10} levels for the roadside barrier site were evaluated in comparison to the predictions provided by the Maekawa curve, no significant differences were found between the measured and predicted results in any of the categories given in Table 2.

Further studies of the agreement between the measured and predicted noise reductions as a function of various traffic and environmental factors indicated no significant variations in the agreement for variations in traffic volume, traffic speed, truck-automobile traffic mix, wind, and air temperature. However, the range of values for the dependent variable in many of these cases was not sufficient to make the results conclusive. For example, measurements were rarely made when wind velocities were greater than 8 mph because of the potential problem of wind noise at the measurement microphones. When this is coupled with the fact that most measurements were made within 250 ft of the source, it is not surprising that no significant influence of wind could be identified in the data. There is little question in practice that wind can, under certain conditions, have a strong influence on apparent noise reductions, particularly at locations upwind from the source (10).

Table 1. Results of design guide predictions for site 2.

Statistical Parameter	Computed Results	Ideal Results	Statistical Significance[a]
Average discrepancy, $\bar{\Delta}$ ($\Delta = x - y$)[b]	1.33 dBA	0	Yes
Standard deviation, s_Δ	2.33 dBA	0	Yes
Least squares line[b] (Fig. 3)	y = -2.76, +1.18x	y = x	Yes
Range of $\bar{\Delta}$ with distance from roadside (Fig. 4a)	1.7 dBA	0	No
Range of $\bar{\Delta}$ with distance above ground (Fig. 4b)	2.5 dBA	0	Yes

Note: Sample size was 47.

[a]All difference tests performed at 1 percent level of significance.
[b]x = predicted noise reduction; y = measured noise reduction.

Figure 3. Measured versus predicted noise reductions for site 2 using design guide predictions.

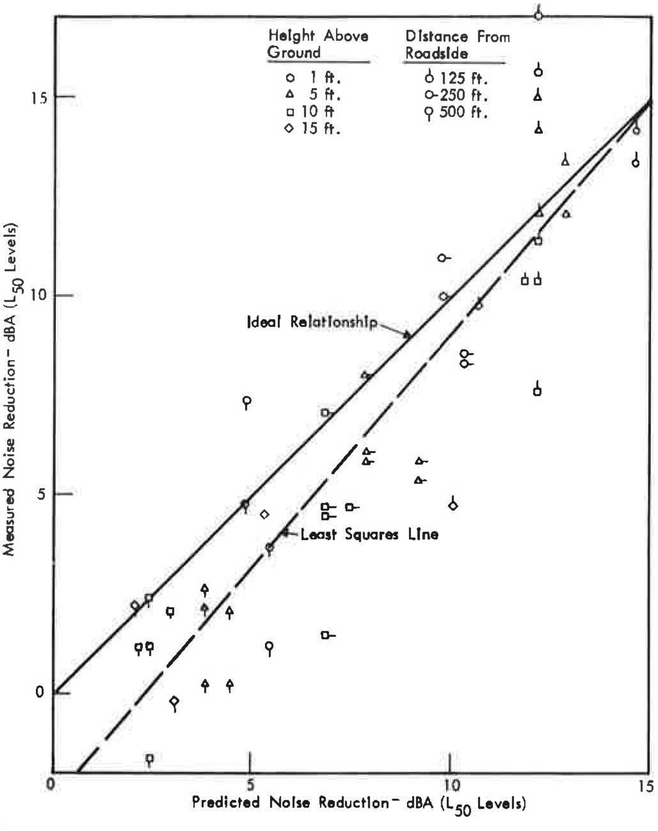


Figure 4. Discrepancy between measured and predicted noise reduction versus location for site 2 using design guide predictions.

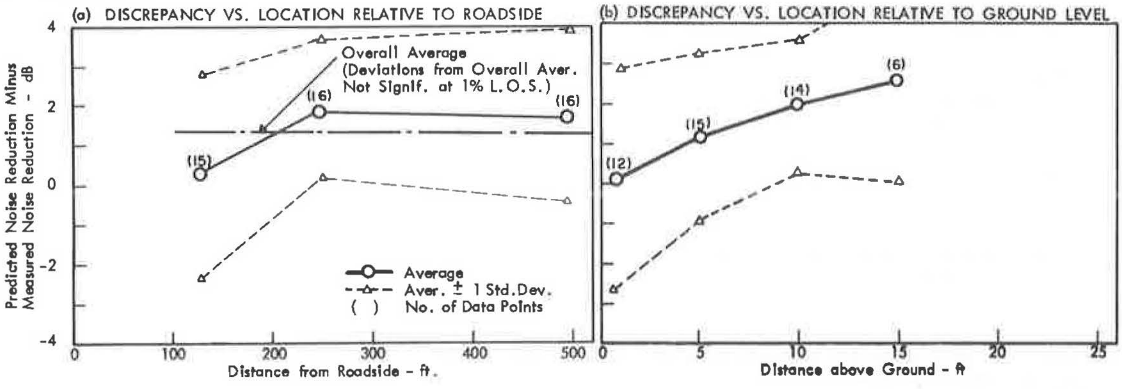


Figure 5. Attenuation of infinite acoustic barrier for point source and infinite line source.

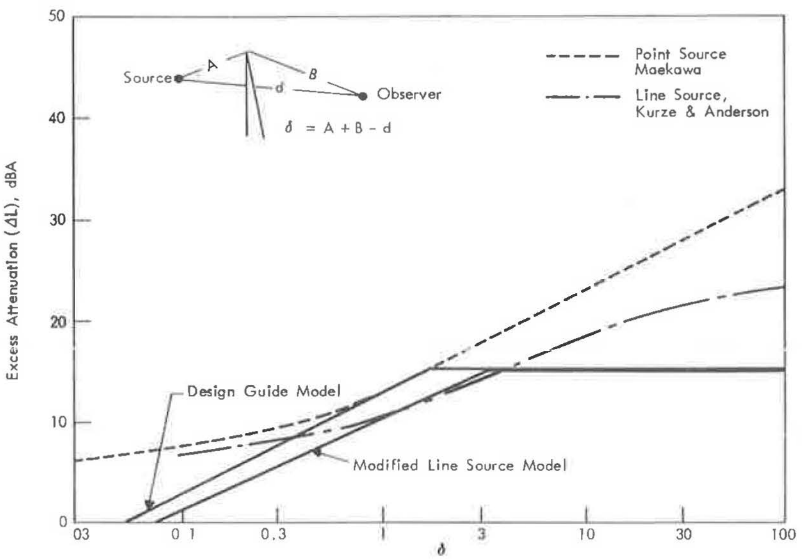


Table 2. Results of design guide predictions for all sites.

Statistical Parameter	Measurement Site: 1 (roadside barrier)	2 (elevated highway)	3 (elevated highway)	5 (roadside structures)	6 (roadside structures)	9 (depressed highway)
Sample size, n	59	47	54	12	18	59
Average discrepancy, $\overline{\Delta}$	-1.67 dBA	1.33 dBA	0[a]	0[a]	0[a]	-3.04 dBA
Standard deviation, s_{Δ}	2.87 dBA	2.33 dBA	2.78	1.95 dBA	3.18 dBA	2.96 dBA
Least squares line	y = 6.76, +0.50x	y = -2.76, +1.18x	y = 1.60, +0.44x	—[b]	—[b]	y = 3.04, +1.00x
Range of $\overline{\Delta}$ with distance from roadside	3.4 dBA	0[a]	0[a]	0[a]	6.0 dBA	2.9 dBA
Range of $\overline{\Delta}$ with distance above ground	6.6 dBA	2.5 dBA	5.5 dBA	—[b]	—[b]	4.7 dBA

[a]Computed values not significantly different from zero (or y = x) at 1 percent level of significance. [b]Insufficient data for meaningful calculations.

Figure 6. Adjustment for roadside barriers.

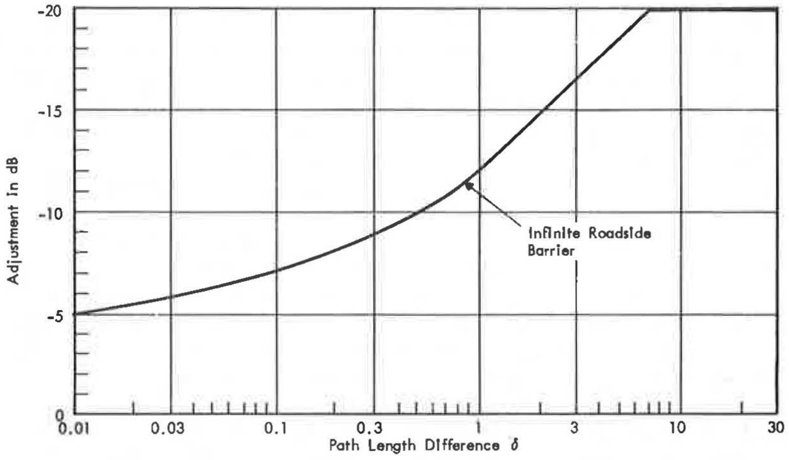
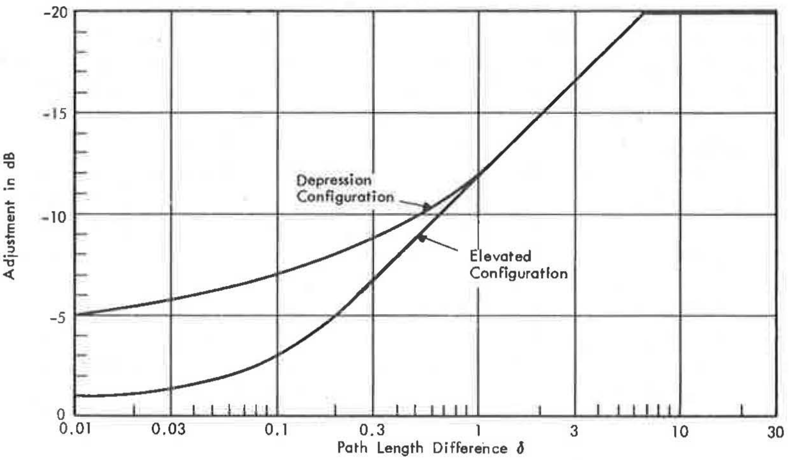


Figure 7. Adjustment for elevated and depressed roadway configurations.



CONCLUSIONS

The results of the study indicate that some modifications of the prediction procedures presented in the design guide (1) are in order. Specifically, it is recommended that the basic noise reduction curves for roadside barriers be changed to that shown in Figure 6 and, for elevated and depressed highway configurations, to those shown in Figure 7. It is further recommended that the procedure for estimating the noise reduction due to roadside structures be altered to specify 4.5 dBA of noise reduction for the first row of structures plus 1.5 dBA for each additional row of structures to a maximum of 10 dBA of reduction.

These recommended changes can be incorporated into the design guide without major alterations or complications of the current overall procedure. It should be mentioned that more precise noise reduction predictions might be achieved by major modifications of the design guide procedure, particularly as it deals with the truck-automobile noise reduction problem. However, it is not believed that the increased complexity of such procedures would be justified by the limited potential improvement in the final results provided by applications of the design guide to highway design problems.

Beyond the direct conclusions relating to the design guide procedures, two peripheral conclusions that suggest areas for future research resulted from this study. The recommended noise reduction curve for roadside barriers (Fig. 6) is very similar to the analytical line source model suggested by Kurtz and Anderson, as shown in Figure 5. It is believed that the exact Kurtz and Anderson model might provide an excellent fit to the data if it were not for the difference in source heights between trucks and automobiles. Specifically, from the viewpoint of a distant observer, automobile noise appears to radiate from a point near ground level (primarily tire noise), whereas truck noise often includes major contributions from the exhaust stack that extends well above ground level. A difference of several feet in source height can make a significant difference in the path-length difference parameter δ and hence in the effective noise reduction provided by a barrier. The design guide deals with this problem by simply estimating the noise reduction for trucks as 5 dBA less than the noise reduction computed assuming a source at ground level. More research on the basic characteristics and mechanisms of truck noise generation is needed before improved procedures for predicting the reduction of truck noise by barriers can be formulated.

The second peripheral conclusion evolves from the difference between the measured noise reductions for roadside barrier and depressed highway configurations and the elevated highway configuration, as indicated by the recommended noise reduction curves shown in Figures 6 and 7. Specifically, the data acquired during this study support the conclusion that roadside barriers and depressed highway configurations provide noise reductions at small values of path-length difference similar to the predictions of Maekawa or Kurtz and Anderson (Fig. 5). However, the data for the elevated highway sites do not correspond in that significantly lower noise reductions at small values of path-length difference were measured. The reason for this difference between the roadside barrier and depressed highway configurations and the elevated highway configuration is not clear, but it might be due to the directivity pattern of the tire noise radiated from the automobile traffic.

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TRAFFIC NOISE NEAR HIGHWAYS: TESTING AND EVALUATION

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A test method for measuring and evaluating noise at properties adjacent to highways is described. Also presented is a quick and simple method for determining the noise reduction offered by noise barriers of varying height, from a cross section and by use of a noise nomograph, as an aid in barrier design. Empirical verification is cited under precise field conditions.

•THE public is aroused and is demanding better laws to protect mankind from pollution of the environment. There is a growing awareness in the world that most of the environmental contamination can be prevented through better engineering practices and that these better engineering practices can be employed without undue loss of progress and without returning to a primitive way of life.

Some industrialists have long insisted that noise and pollution of the water and air were the price that must be paid for industrial progress. This traditional view is crumbling, as evidenced by the new image being presented in advertisements and news releases.

Noise is a problem of growing concern, and many rules and regulations for control are being formulated and adopted at local, state, and national levels. A most important problem is the noise that emanates from vehicles traveling on highways.

The disturbing effects of vehicle noise on people, during the daylight hours, are mainly from the highest peak levels reaching and penetrating the nearest dwellings. The disturbance increases with the occurrence rate. The highest transient peaks result from diesel-powered trucks, but there are also other important factors to be recognized. The peak levels reached by trucks are the same at any hour, day or night, and, even though the nighttime occurrence rate may be only 5 percent or less of that in the daytime, the lower night rate does not automatically reduce the disturbance. The sleeping hours are a vastly more sensitive period and are characterized by a tremendous drop in level from all other noise sources that help to mask highway noise sources. The combined effects of the greater need for quiet and the lack of daytime masking noise sources tend to magnify the disturbance to people. This more than offsets the disparity in occurrence rate.

The California Division of Highways has been engaged in studies on transportation noise for a number of years. These studies led to the development of a simple test method and procedure for preparing a quantitative noise report together with necessary information on possible mitigation measures. The noise report provides the following information:

1. The present noise levels in the immediate area of the proposed project and their typical occurrence rate,
2. The projected noise levels in the immediate area after the project is built and their occurrence rate, and
3. Identification of the adjacent areas that will require noise reduction in highway design considerations.

The purpose of this report is to present a discussion of the development and use of a test procedure by the California Division of Highways and the results of our continuing studies on design and field testing of attenuation devices.

Publication of this paper sponsored by Committee on Geometric Highway Design.

DEVELOPMENT OF TEST PROCEDURE

The state of California has been and continues to be a leader in the adoption of laws for regulating transportation noise.

All of the laws are based on standards that use the A-weighted sound level and on methods that require the actual measurement of sound levels in the field with approved instruments. Therefore, in conformance with our legislative policy expressed in the laws, we adopted the A-weighted sound level that, in our opinion, provides the most sensible measure of noise intensity in terms of human response.

It was many years ago that we first encountered discussions on noise at our public hearings on proposed projects. Over the years, two questions have been asked most often:

1. What is the present noise level in my neighborhood?
2. What will the noise level be when the project is constructed?

Therefore, the first objective in the development of our method to answer these questions was to adopt an instrument that would provide a direct reading of the noise level in A-weighted decibels (dBA). This provides interested people with a test reading that is understandable in terms of existing noise laws. We were also interested in an instrument that can be checked with calibration standards, is relatively inexpensive, and is simple enough to be operated by field personnel after a short training period.

The second question was more difficult to answer. At the time of the development of our method, and even today, models for predicting noise levels from transportation vehicles were still being developed, and very little validation of such models is in evidence. We, therefore, began a measurement program of determining sound levels from many different highways in California. These measurements were made near all types of highways and both outside and inside of the nearest sensitive buildings. We observed that diesel-powered transports produced the highest readings of all vehicles. Measurements were made at various distances to determine the rate of decay. This provided information on noise levels from the loudest noise source to individuals who had full visual exposure to the roadway (1). Noise charts were developed that employed truck noises as the basic "worst case" reference. In our opinion, the peak noise range from diesel trucks provides the best key for answering the second question. We again wish to stress that the charts are based entirely on field measurements near existing highways and are periodically verified by checking "chart-predicted" noise levels for future highways against the actual levels attained after the highways are completed and reach normal traffic conditions.

Figure 1 in the Appendix can be used to plot the noise contours, for worst case conditions, directly on a map of the proposed highway.

Highways and Freeways

The unshielded and fully exposed highway truck noise contours can be accurately predicted from Figure 1 in the Appendix. All such noise contour lines should be identified with the normal range of ±6 dBA from the mean truck level; i.e., include the ±6 dBA after the base figure (70 ± 6 dBA or 80 ± 6 dBA). Do not use a mean figure without stating ±6. There is no such thing as a single noise level for all trucks. The ±6 dB represents the normal range of noise peaks for all legally muffled trucks in California at the present time.

Wherever existing highways carry no diesel trucks but do carry gasoline-powered trucks, one may subtract 6 dB from the chart figures in plotting the contour lines (±6, as before stated). Legally muffled motorcycles are generally in a noise class similar to the gasoline-powered trucks.

Wherever existing highways carry virtually no trucks at all and no cross country buses, one may safely subtract 10 dB from the chart figures to arrive at the automobile levels (±6, as before stated).

City Streets and Highways, 35-mph Maximum Speed

Noise contour lines may be predicted at lower speeds within cities from Figure 1 in the Appendix by subtracting an additional 7 dBA from the chart values; i.e., the 80 ± 6 dBA for highway diesel trucks at 100 ft from the edge of the pavement will become 73 ± 6 dBA at the lower city speed limits (25 to 35 mph). Statements by others to the effect that diesel trucks make the same noise output regardless of speed have not been borne out by our tests. The 7-dBA correction has been verified by tests made within cities by the Materials and Research Department.

The same 7-dBA correction also applies to the noise from gasoline-powered trucks or family automobiles. Automobiles may be nearer to -10 dB (below city diesel trucks) when they are traveling at one-half of freeway speeds, but the 7-dB figure allows for the frequent sports car or speeder. This is a conservative engineering practice.

Effects of Solid Screening (Simple Approximation)

Wherever the residences will be completely shielded from a view of the trucks by intervening earth contours or commercial frontage buildings, one may subtract an additional 15 dB from the highway chart levels or the lower derived city levels (where 25- to 35-mph speeds prevail).

Where the residences will be only partly shielded from a view of the trucks, the noise reduction will vary from 3 to 7 dB from the values shown in Figure 1 in the Appendix, depending on the amount of visual shielding (up the side of a truck) from the observer's position. About 1 dB of noise reduction is obtained for each foot of optical screening up the side of a diesel truck for the first 6 ft of screening. Each additional foot of screening yields about 1.4 dB of noise reduction. A more sophisticated method employing a noise nomograph is presented later in this paper.

The key points in the test method (Appendix) are as follows:

1. The equipment in the field is carefully calibrated before every test.
2. The location including the distance from the nearest highway edge of pavement (if built) and the distance or distances to other local noise sources of interest are clearly described. The reference point is the nearest residence, school, or other inhabited properties adjacent to the highway.
3. A "before-construction" graphic level recording of the noise at the same distance and height as the nearest residential windows, for a future construction project is made. A "before-modification" graphic level recording of the noise near existing highways that will be widened or otherwise changed so as to bring the noise sources closer to the local inhabitants of adjacent properties is also made.
4. A descriptive evaluation of the highest range of noise levels encountered (from the loudest vehicles) and a comparison with the future highest levels anticipated after the construction or changes are completed. As previously noted the projected noise levels are derived from charts prepared from thousands of noise recordings made near existing highways in California. These charts are periodically checked for any required changes, by making new noise tests in the field. The changes have not been significant for the various classes of vehicles, in the past 10 years, because most of the improvements in muffling have been largely offset by larger engines and the trend toward higher vehicle speeds on freeways.
5. The approximate number of peak noise events per hour is reported. The term employed is occurrence rate rather than frequency because frequency has another meaning in acoustics.
6. An evaluation is made of the noise impact. This is based on the highest decibel range anticipated from legally muffled diesel trucks, at the nearest properties, and the occurrence rate of these noise peaks.

Diesel trucks are the preferred noise reference because they produce the highest noise peaks of all highway vehicles. Our long-term experience with public complaints verifies that diesel trucks are the prime source of public disturbance and annoyance according to public protests both verbal and written. There is no evidence from our past experience that justifies some other form of evaluation that either "averages" the loud peaks with weaker background noises or allows for a certain percentage of "free time" where noise may exceed any limit and be ignored (L_{10}, for example). The public record does not indicate that the human ear performs an integration such that loud noises are mitigated by periods of quiet, no matter how long the quiet periods between loud noise peaks. It has also been observed that an increase in the number of noise peaks per hour is not interpreted by the public as a louder noise. The public correctly assesses a higher occurrence rate of peak noise as a more frequent disturbance, not as a louder disturbance. The two are not the same thing. A similar response has been noted in the case of sonic boom versus normal jet aircraft noise. One sonic boom will cause more complaint than a host of lesser aircraft noises spaced randomly over a period of time.

About 18 months ago, all 11 of California's highway districts were furnished with noise-measuring equipment, as described in the test method. Personnel were trained in the use of the equipment and the preparation of quantitative noise reports. The method has proved to be simple and workable by actual field experience and, in our judgment, has furnished the necessary information for making decisions on the need for noise attenuation devices. As an example of the simple and direct approach of the test procedure, we note the following:

1. Recently the California legislature passed a noise control bill for schools near highways. This bill states that highway traffic noise penetrations into the classroom shall not be permitted to rise above 50 dBA because of the construction of a highway in the vicinity of the school.

The employment of the method in all of the districts has permitted a rapid evaluation of before-and-after conditions and, through the use of our charts, identification of the need for attenuation devices. In response to requests for noise surveys, the district environmental units produce comprehensive studies in a short period of time. Because all existing and projected values in our method are in dBA levels, a direct comparison with the requirements of the law are immediately available for management decisions. Because all measurements are either directly determined in the field by approved and fully calibrated instruments or taken from charts based on actual field studies, the results have been fully accepted by school authorities and other interested parties. The noise prognosis is always checked by measurement after the highway is fully activated.

2. Recent legislation requires California counties to place noise contours on their land use plans. The simple method described herein permits contours to be drawn from the charts, and, with correction already noted, application may be made to city streets and other situations encountered by local engineering staffs.

3. A recent request was made for a noise attentuation survey of the state highway system with an estimate of costs of barrier construction for various possible management or legislative decisions. This information was rapidly assembled by district environmental units using the California method.

4. Numerous individual complaints may be handled with the test method. The procedure is easily explained and understood when measurements are made in the presence of the complaining party. The party may directly read the instrument and from a noise chart can quickly understand the magnitude of the noise.

IMPLEMENTATION

The information from the field noise report and evaluation is given to the highway design engineers. The highway designer has the task of determining the method of attenuation to achieve the desired limit for maximum peak noise exposure from legally muffled trucks. The goal for the maximum permissible residential exposure has been rather loosely defined in the past, although a 70-dBA maximum is our goal.

WHAT SHOULD THE NOISE GOALS BE?

There continues to be a critical need for more information on people's reactions to transportation noise, as indicated by the different approaches to the problem of measurement and setting of standards (2, 3, 4).

From our studies the first objective or short-term goal should be to limit the noise peaks that reach the nearest residences to 70 dBA or less from all legally muffled diesel trucks. [Note: This requires that the windows be closed in the nearest residence to achieve a peak limitation at the interior of 45 dBA (1). This is no panacea, but it will be a tremendous improvement over the existing situation.]

Many experts in the field are now advocating a residential exterior limit of 60 dBA for peaks from legally muffled trucks. This is especially desirable where the bedrooms of residences face the noise source. It would also lessen the disturbances within family patio areas, which are an intimate part of home living in California.

The long-term goals expressed by some are to reduce noise penetrations to acceptable speech interference levels in family patios. This is on the order of 50 dBA for maximum peak levels where the people are 6 ft apart (4).

The attainment of these goals is of course not the sole responsibility of a state highway department. We are convinced from our noise research to date that to materially reduce freeway traffic noise to the proposed values requires a concerted three-pronged attack involving reduction of noise from motor vehicles, adequate land use zoning adjacent to highways by local government, and proper highway design and location.

The most direct and effective approach to minimize traffic noise is to reduce the legally allowable noise emissions from motor vehicles and enforce these lower limits. The state of California has adopted a scale of required noise reductions for all new vehicles over a period of years, and since 1968 the California Highway Patrol has had measurement and enforcement teams checking on noise levels on our highways.

Another approach is through better control of the use of property adjacent to highways. The Division is strongly encouraging local jurisdictions having control of land use and structures that are to be built adjacent to freeways to adopt land use plans and zoning, building, and housing regulations that will be more compatible with the anticipated traffic noise. Good examples are air-conditioned stores or office buildings, service stations, drive-ins, and all businesses that depend on visibility to the passing motorist.

WHAT ARE THE MOST EFFECTIVE CONTROLS AVAILABLE TO THE HIGHWAY DESIGNER?

The most effective highway noise controls are various forms of barriers. These may be any stout solid form that hides the vehicles from view when looking out of the nearest residential windows. The mass and stiffness should be sufficient to prevent bending or buckling in the strongest windstorms. There is no point in testing various materials for transmission loss because the leakage over the top of the barrier determines the net result. Any solid panel or form that can withstand the greatest anticipated wind load, without buckling, will make an effective sound barrier, if tall enough to intercept the noise path.

The most economical and visually acceptable barrier is a greenery-covered earth berm. These are especially desirable along the crest of the cut slopes of depressed highways. The usual height required in this situation is only about 6 ft. Taller berms are needed for highways built on flat terrain.

Another relatively inexpensive form of barrier is possible by converting the standard chain link fence into a stucco wall (or by building a wall in lieu of the chain link fence during original construction). This has been done experimentally by attaching metal lath to the wire mesh and applying a scratch coat. This is followed by the spraying of two coats of concrete plaster (Gunite Mixture) on each side of the structure. There are many other ways to construct such barriers.

Barrier Effectiveness

The most frequent question asked is how to estimate the noise reduction of a barrier. A noise nomograph (Figs. 1 and 2) has been developed considering the theoretical approach of Rettinger (5) and the later version of Foss (6). A cross section must be drawn to scale. A straight line is then drawn from the noise source epicenter to the nearest window at ear height indoors.

Figure 1. Noise barrier attenuation nomograph.

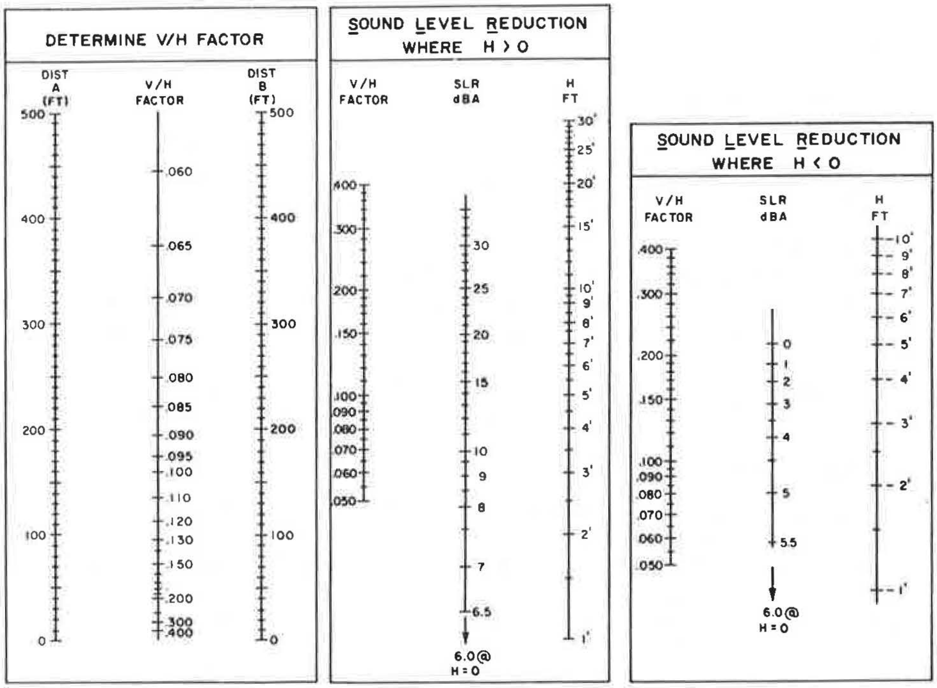


Figure 2. Noise nomograph for vehicles weighing more than 6,000 lb.

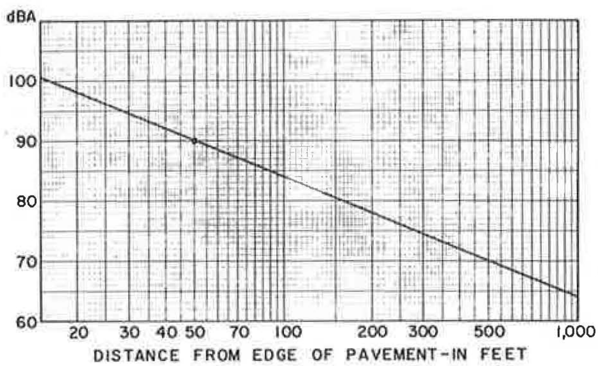
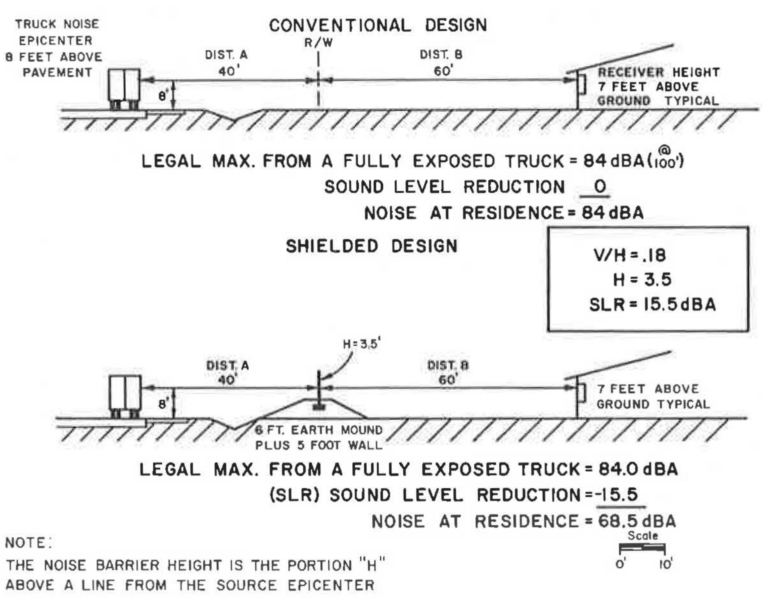


Figure 3. Use of noise nomograph for highways on flat terrain.



The fundamental equation (5) is $SLR = -3 + 10 \log [(\frac{1}{2} - x)^2 + (\frac{1}{2} - y)^2]$. x and y are derived from a table of Fresnel integrals offered by Rettinger (5).

For the convenience of the reader, we have reduced the complicated routine to a convenient noise nomograph. The required information on the cross section is as follows:

1. Distance A from source to barrier,
2. Distance B from barrier to receiver,
3. Height of noise source epicenter (given as 8 ft above pavement for a diesel truck),
4. Ear height of the receiver (typically 7 ft aboveground at the nearest residential window), and
5. Optical height (which is acoustical height) of the barrier relative to a straight line between the noise epicenter and the receiver ear height aboveground.

Using the Noise Nomograph

The relation V/H is determined from distance A and distance B (Fig. 1). The "acoustical height" of the barrier will either be above (+) or below (-) the line between the source height and the receiver height. If the barrier is higher than the "acoustical path line," then H is greater than zero, and the center chart (Fig. 1) should be used. If the barrier is below the level of the acoustical path line, then H is less than zero, and the far right chart should be used.

Sample diagrams (Figs. 3, 4, and 5) are shown for three types of highways: at grade in flat terrain, elevated, and depressed. Both unshielded and shielded examples are offered. The use of the noise nomograph should be obvious from the coding on the sample diagrams.

The noise nomograph provides an accurate figure for the sound level reduction (SLR) of truck peak noise because it has been adjusted to agree with empirical noise measurements made in the field. The basic requirement for field proof testing demands strict site conditions near the barrier; i.e., the local noise background from all other sources must be more than 10 dB under the truck noise being measured at the shielded microphone position behind the barrier. If this condition is not met, the noise reduction of the barrier cannot be measured. Failure to observe this site requirement will result in false conclusions that barriers do not perform up to expectations. This may be the reason for some of the apparent disparities found in recently presented papers by other investigators.

The now well-known experimental Milpitas noise barrier (route I-680) offered nearly ideal conditions for testing before the 1-mile shielded section was opened to traffic. Figure 6 shows the test site. The results of 20 runs (10 in each direction) with simultaneous measurements on the unshielded and the shielded sides, and with both microphones at 80 ft from a fully loaded diesel truck, are given in Table 1. A chart of the 20 test runs is shown in Figure 7. The average noise reduction was 15.65 dB on the shielded side of the highway.

The microphones were then moved twice as far away, and 10 more runs were made (5 in each direction). The noise attenuation offered by the barrier (in addition to distance losses) was 15.4 dB. The decibel readings and charts of these runs are given in Table 2 and Figure 8 respectively.

The results of these and other experimental barriers tested by our organization indicate the definite reduction in noise levels attained by a barrier.

CONCLUSIONS

In conclusion, we believe that the California test method, developed after some 15 years of study, provides a simple, straightforward procedure for measuring in numerical terms existing and future noise levels. It does not require any complicated procedures, computations, or a computer program. The only requirement is a simple sound level meter and an easy-to-use chart derived from hundreds of actual on-site noise level readings.

Figure 4. Use of noise nomograph for elevated highways.

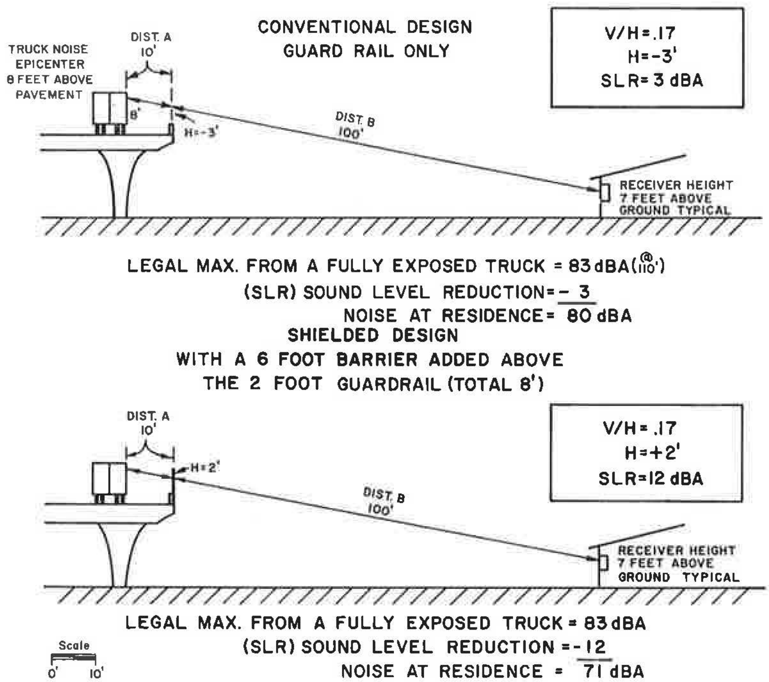


Figure 5. Use of noise nomograph for depressed highways.

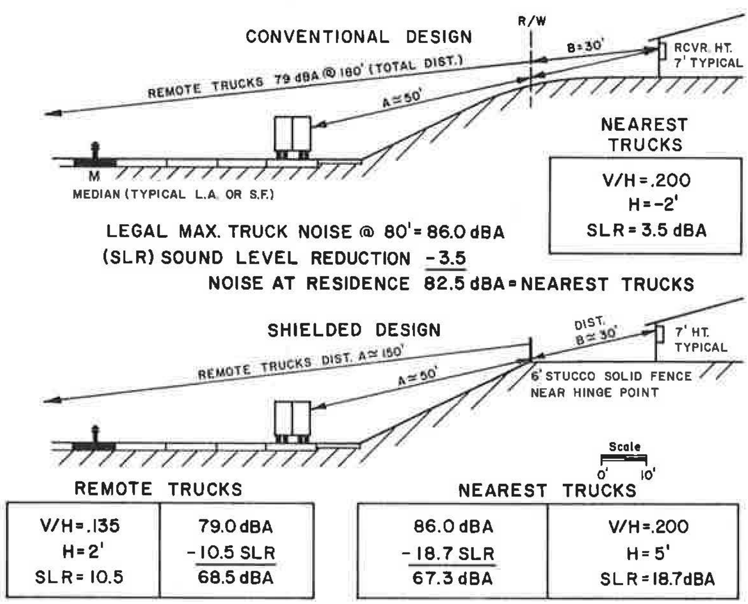


Figure 6. Noise barrier test site.

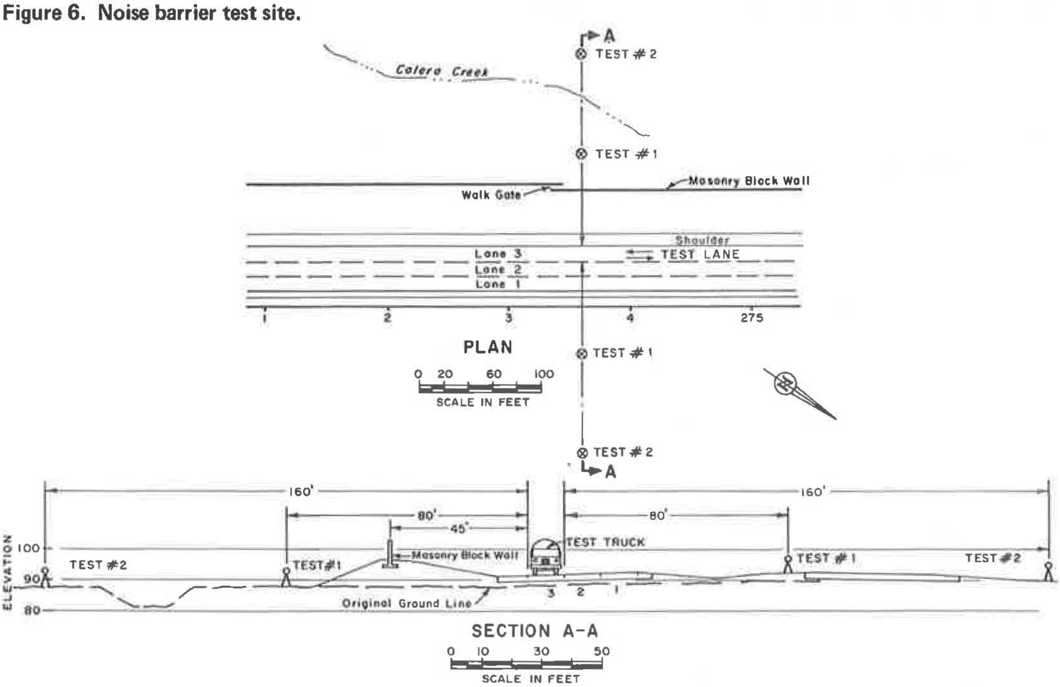


Table 1. Noise barrier tests at 80 ft from path of unmuffled diesel truck.

Run	Exposed Side (dBA)	Shielded Side (dBA)	Noise Reduction (dBA)
N-1	92.0	74.5	17.5
S-1	90.0	75.0	15.0
N-2	93.0	76.0	15.5
S-2	92.0	76.5	15.5
N-3	91.0	74.0	17.0
S-3	90.5	75.5	15.0
N-4	92.0	75.0	17.0
S-4	91.5	78.0	13.5
N-5	93.5	75.0	18.5
S-5	89.0	75.0	14.0
N-6	92.0	76.0	16.0
S-6	90.5	77.5	13.0
N-7	92.0	76.5	15.5
S-7	91.0	77.0	14.0
N-8	93.0	74.0	19.0
S-8	91.5	77.0	14.5
N-9	93.5	77.0	16.5
S-9	86.5	72.5	14.0
N-10	92.5	77.0	15.5
S-10	90.0	75.0	15.0
Average	91.35	75.70	15.65

Note: The average noise reduction was 15.65 dBA for the test truck, which was a large diesel tanker with no muffler and a high vertical exhaust pipe on right side. This is equal to moving the truck about 5 times farther away and reducing loudness by about 3 to 1.

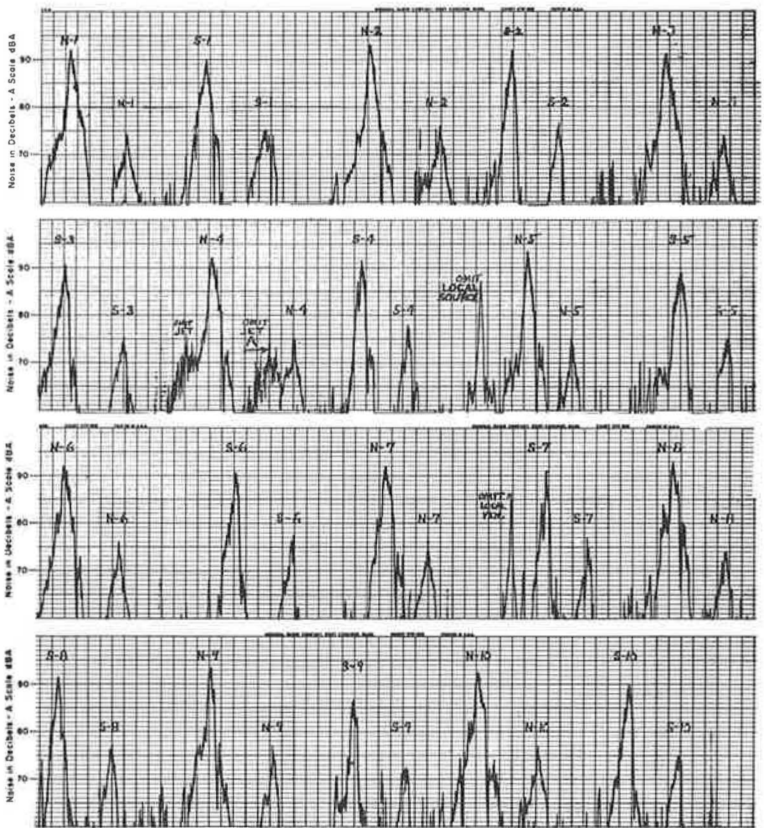
Table 2. Noise barrier tests at 160 ft from path of unmuffled diesel truck.

Run	Exposed Side (dBA)	Shielded Side (dBA)	Noise Reduction (dBA)
S-11	87.0	72.0	15.0
N-11	89.5	71.0	18.5
S-12	86.0	72.0	14.0
N-12	86.5	70.5	16.0
S-13	83.0	67.5	15.5
N-13	86.5	69.5	17.0
S-14	82.0	69.5	12.5[a]
N-14	85.5	70.5	15.0
S-15	84.5	70.0	14.5
N-15	86.0	70.0	16.0
Average	85.65	70.25	15.4

Note: The truck noise is nearly 6 dBA less at this greater distance, but the additional noise reduction offered by the barrier is 15.4 dBA. This is virtually the same as that measured at the 80-ft distance.

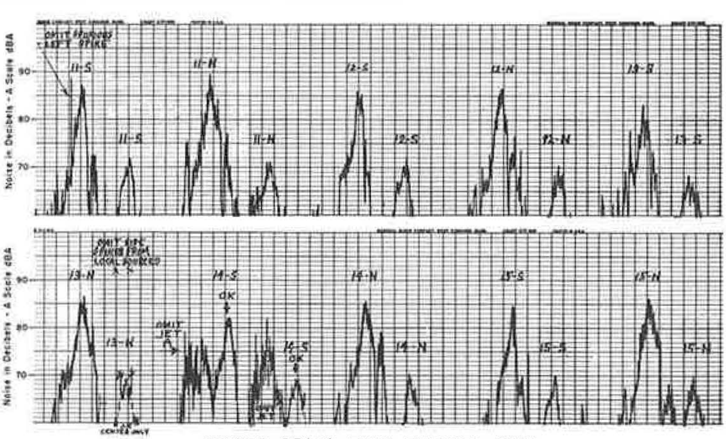
[a]Jet air interference.

Figure 7. Test charts (barrier 80 ft from path of unmuffled diesel truck).



HIGHER PEAKS FROM EXPOSED SIDE.
LOWER PEAKS FROM SHIELDED SIDE.

Figure 8. Test charts (barrier 160 ft from path of unmuffled diesel truck).



HIGHER PEAKS FROM EXPOSED SIDE.
LOWER PEAKS FROM SHIELDED SIDE.

The approach of deciding on remedial measures based on measuring the range of truck peaks has proved to be the most nearly responsive to our most frequent complaint. The most frequent complaint emanates from the inability to sleep because of residential noise intrusions from bursts of high-level noise from passing diesel-powered trucks.

Our studies to date on actual field tests of experimental barriers clearly indicate the marked reduction in noise levels that may be attained by proper design and construction of this type of noise attenuation device.

ACKNOWLEDGMENTS

This work was accomplished in cooperation with the U.S. Department of Transportation, Federal Highway Administration. The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the state of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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APPENDIX

TEST METHOD NO. CALIF. 701-A

METHOD FOR MEASURING NOISE LEVELS

Scope

The procedures for measuring noise levels in areas adjacent to proposed or existing highways are described in this test method. A procedure is also described for estimating future noise levels from either new construction or changes in existing roadways.

This test method is divided into three parts. Two methods of noise measurement are described in the first two parts.

Part I. Visually Observed dBA Levels on a Sound Level Meter (SLM)

Part II. Chart Recorded dBA Levels Obtained from a Sound Level Meter and Graphic Level Recorder

Part III. Noise Study Reports

General

Sound level meters measure the intensity level of sound in decibels (abbreviated "dB").

Sound intensities in highway work are normally measured on the A scale. This is chosen because it more nearly parallels human response for the noise studied than do the two other scales (B and C) in common use.

Both methods of noise measurement described in this test method use the same SLM and have the same inherent accuracy. The visual method permits the operator greater freedom in reaching difficult locations. It also permits conversing with an assistant when necessary without including this noise as part of the record. The chart method provides a permanent record but may restrict mobility in the field because an AC power source is required. The operator must also identify the source of noise peaks on the chart so that unrelated local sources are not counted as roadway noise. The chart method offers a wider dynamic range and eliminates the need for frequent changing of the decibel range switch on the Sound Level Meter.

The greatest noise exposure and changes in levels will occur at the nearest remaining frontage buildings after the construction of a roadway. Therefore, the most important measurements and noise projections will be at this distance from the roadway edge of pavement (EP), particularly near schools, residences, apartments, convalescent homes and hospitals.

The more remote dwellings, if protected by intervening buildings that obscure direct line of sight noise paths, may have from 5 to 15 dBA of extra noise shielding over that offered by distance alone. However, exposed buildings or parts of buildings will not have this extra noise protection.

Before and after noise measurements at public schools are particularly important in compliance with the requirements of Section 216 of the Streets and Highways Code.

Apparatus—for Visual Measurements

1. Sound Level Meter (abbrev. SLM) ANSI Specification S1.4-1961
2. Sound Level Calibrator designed for the SLM.
3. Supporting stand or tripod (a tripod adapter may be obtained for the SLM at any camera supply store).
4. Wind Screen, General Radio type 1560-9521; or a frame conforming to following requirements: A windscreen frame large enough to hold the entire SLM with the Sound Level Calibrator on the microphone. The open frame may be of wood or metal with the front, top and sides covered with metal window screen and open mesh plastic grille cloth. The base should have rubber feet and a tripod socket for ¼" bolt, 20 thread/inch. The wind screen must be a locally fabricated item. Noise measurements should not be made when winds exceed 15 mph. The wind screen is useful in winds from 10 to 15 mph. Wind flutter should be at least 10 dBA below the noises you are trying to measure.
5. Note pad and pencils.

Apparatus—for Graphic Level Recording

1. In addition to the five items listed under Apparatus for Visual Measurements the following additional equipment will be needed:

   a. Graphic Level Recorder, designed for use with the Sound Level Meter.

   b. A power inverter for operating the recorder from an automobile: Power inverter, 12 volts DC to 110/120 volts, 60 Hz AC rated at 75 to 100 watts, with adapter cord and plug for cigarette lighter socket. Examples:

   ATR—Model 12 T-RME,
   Terado—Model 50-127,
   CDE—Model 12B-8 or equal

2. A 12-foot AC extension cord.
3. Cable: 30 feet of RG/62U (or RG 59/U) coaxial cable with a standard phone plug at one end and banana plugs at the opposite end; to connect the SLM to the Graphic Level Recorder. This must be locally fabricated.
4. Optional: A 100-foot cable and reel similar to Item 3, locally fabricated.

Preliminary Preparation

Before leaving for the field:

1. Test the SLM batteries.

   Raise the microphone. Switch to each of the three battery test positions, FIL 1, 2 and PL. Good batteries will read above the center of the white band marked BAT on the meter.

2. Calibrate acoustically.

   Set the SLM to 110 on the *C* scale. Check the acoustical calibrator battery (once briefly) and switch to 500 Hz. The calibrator supplies a 114 *dBC* level to the SLM microphone. Rotate the CAL control on the SLM to read 114 *dBC*. Switch the SLM to the A scale. The meter should read 111 dBA within 0.5 dBA. This completes the calibration. The 500 Hz setting is the most accurate factory setting on the calibrator.

PART I. VISUAL SLM MEASUREMENTS

A. Procedure

1. Identify the location; the distance to predominant noise sources, highway or local street EP; and the environment; residential, school or other. Record the date and time of day.

2. Most measurements should be made at about 5 feet above ground or at window height.

3. Set the meter switches to the FAST position and the A scale.

4. Start with the meter range at 100 dBA and switch down to a lower scale until the meter yields visible readings.

5. Record all noise peak readings and typical background levels. A ten minute period will usually suffice where noise peaks are fairly persistent. Wide variations may require longer sampling. Highway noise peaks, if present, should be separately identified from local traffic or other noise sources.

B. Noise Evaluation

1. If the location is reasonably quiet, say 50 to 60 dBA or less, the automobiles are rare and no higher than 65 dBA, the background noise will determine the description of the noise environment.

2. If the location is exposed to frequent noise peaks from local or highway traffic the noise character will be determined by the range of the noise peaks. If the highest noise peaks exceed the background by 12 dBA or more, identify the range of these peaks and the mean of the highest 12 dBA region. For example: Peak range 70 to 82 dBA; mean peak value 76 ± 6 dBA.

3. If the peak noises are frequent but exceed the background by less than 12 dBA, identify the peak range and the mean peak level. For example: Peak range 76 to 84 dBA; mean peak value 80 ± 4 dBA.

PART II. CHART RECORDED dBA LEVELS OBTAINED FROM A SOUND LEVELMETER AND GRAPHIC LEVEL RECORDER

A. Procedure

General procedure is the same as for visual measurement.

With the sound meter and the recorder both turned off:

1. Plug the recorder into a 110 volt AC power source but leave it turned off at this time.

2. Connect the coaxial cable from the OUTPUT of the SLM, to the input of the recorder. Observe polarity. The shield (or ground) goes to the Black terminal, and the center lead goes to the Red terminal.

3. Set the INPUT ATTENUATOR to 30, the WRITING SPEED to 10, and the right hand chart drive to neutral "N". Roll out a few inches of chart paper. Note your location, date, distance from EP or local street, time of day and any other pertinent information: traffic exposed or shielded from view; outside or inside of building, windows partly open or closed.

4. Insert a pen in the recorder and turn on the power switch. The pen carriage will oscillate once or twice and come to rest. Turn on the SLM; switch to 110 dBC and acoustically calibrate at 500 Hz 114 dBC. The recorder pen should land four lines left of center. Adjust pen position with CAL button (at lower left of recorder panel). Switch to A scale on the SLM. The recorder pen should now be one line left of center (111 dBA). The recorder is now calibrated. From here on the dBA range selected on the SLM will become the chart centerline. If the SLM range is set to 70 dBA the center of the chart will be 70 dBA and the recorder will have a range of 50 to 90 dBA (20 divisions either side of center). *Always mark the chart center according to the dBA range selected on the SLM. If you change this setting, stop the chart, and change your marking.*

5. A 70 dBA center is usually adequate for exterior recordings at 100 feet or more from diesel trucks. An 80 dBA center may be needed at distances between 50 and 100 feet. Indoor noise measurements usually take a 60 dBA center. A 50 dBA center may be needed in very quiet locations.

6. The recorders are equipped with a medium speed motor, $\frac{1}{5}$ of the chart speed marked on the panel. Gear settings of 1 x 7.5 should give a chart speed of 1.5 inches per minute. This is the preferred chart speed. Set the gears and turn on the chart motor when you are ready to record. Avoid talking near the sound level meter. Peak noises should be coded on the chart: T for trucks, M—motorcycles, A—aircraft, C—cars. Local sources of noise peaks should be separately identified.

B. Noise Evaluation

Follow same procedure as for Noise Evaluation in Part I.

PART III. NOISE STUDY REPORTS

A. Procedure

1. The purpose of the noise report is to identify the existing preconstruction noise levels and the estimated future levels during roadway operation. A comparison of the following *before and after information* is most important:

a. Approximate distance to edge of pavement and other significant noise sources.

b. Typical background levels.

c. Range of peak noise levels and the approximate occurrence rate per hour.

2. The future typical noise range from trucks (± 6 dBA) can be estimated at any exposed distance from the EP of conventional roadways with the graph shown in Figure 1.

3. In using this chart, note that the full amount of noise reduction offered by a depressed freeway applies only where visible sight of the vehicles will be cut off at the residential windows according to the cross section employed. If the nearest residences are ex-

posed, the noise will be equal to a flat section at a similar line of sight distance.

4. The noise advantage of an elevated highway applies only to adjacent single story structures 20 feet or more below the grade of the highway. It does not apply to the exposed upper levels of multi-story apartments nor to higher exposed slopes that equal or exceed the height of the highway. These exposures will also be equal to a flat section at a similar line of sight distance.

5. If the design of the future highway has not been determined, it is conservative engineering practice to estimate future noise on the basis of the most fully exposed and least favorable condition.

6. Realignment or widening that brings an exposed freeway EP closer to prior exposed frontage buildings will increase the noise as follows:

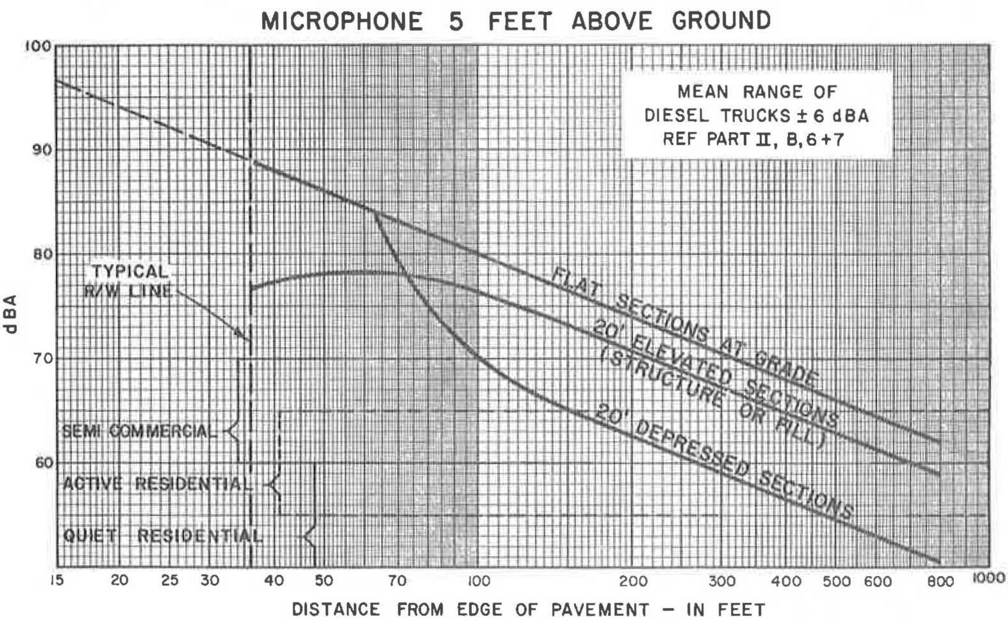
Percent Loss of Setback Distance	*Noise Increase*
20%	2.0 dBA
29	3.0
37	4.0
44	5.0
50	6.0
55	7.0
60	8.0
64	9.0
68	10.0
75	12.0

REFERENCE

ANSI Specification S 1.4-1961

End of Text on Calif. 701-A

Figure 1. Typical truck noise measurements.



EVALUATION OF FREEWAY NOISE BARRIERS

M. D. Harmelink and J. J. Hajek, Ontario Ministry of Transportation
and Communications

Of the various noise control methods, the construction of freeway noise barriers is often the only noise protective measure that can be directly implemented along existing freeways by a transportation department. This paper describes five different noise barriers, including their materials, type of support, and costs, constructed in metropolitan Toronto and provides data on their effectiveness. The results indicated that barriers 10 to 12 ft high, located midway between the houses and the pavement or at the highway shoulder, 60 to 140 ft from the nearest houses, provided only a 2- to 6-dBA reduction at the first row of houses, 4 ft above ground. Immediately behind the barriers, where the reductions are of little real benefit, reductions of 8 to 14 dBA were achieved. In addition to the overall decrease of sound levels, the sound level fluctuation, defined as the standard deviation of the recorded signal, was decreased at the first row of houses by 0.4 to 1.0 dBA. Measured sound levels and measured reductions due to the barriers were compared with calculated sound levels. In general, calculated reductions due to a barrier were overestimated rather than underestimated. A variety of other results and conclusions related to the influence of barrier height, the vertical distribution of sound levels, and the effects of cut and fill sections were quantified and are described.

•IN recent years, complaints about freeway noise have increased significantly. A solution commonly preferred by residents living adjacent to freeways is construction of a noise barrier (1). Although there are several approaches that must be combined to achieve effective freeway noise control (2), construction of noise barriers is often the only noise protective measure that can be directly implemented along existing freeways by a highway agency.

Data on the field performance of noise barriers are scarce. Field testing of noise barriers in Germany (3) showed that barriers, in addition to reducing overall sound levels, reduce the fluctuation of sound levels. Rapin (4) carried out extensive laboratory measurements of sound level reductions resulting from the use of barriers and other highway design features. His results, obtained on small models, were in good agreement with theory (5). Full-scale noise barrier testing conducted in the United Kingdom using a point source (6) showed that, due to ground attenuation effects, measured sound level reductions (based on measured levels without barriers) were considerably smaller (2 to 10 dBA) than the reductions calculated by a theoretical method developed by Maekawa (7).

In response to complaints of local residents and in view of an apparent lack of data on full-scale field performance of noise barriers adjacent to freeways, the Ontario Ministry of Transportation and Communications constructed an experimental noise barrier in a location where it would also provide useful noise protection. The resulting 1.2-mile long barrier constructed by the Ministry in metropolitan Toronto in the summer of 1971 will be referred to as the Highway 401 barrier. At about the same time, in response to similar complaints, the Metropolitan Toronto Roads and Traffic Depart-

Publication of this paper sponsored by Task Force on Highways and the Environment.

ment constructed four relatively short barriers of different types along the Don Valley Parkway. The acoustical evaluation of all barriers was conducted by the Ministry.

The principal objectives of the paper are (a) to review briefly the types of noise abatement walls constructed in the metropolitan Toronto area, (b) to report results on the effectiveness of barriers in attenuating highway traffic noise, (c) to compare sound levels calculated by means of an existing highway noise estimation procedure (8, 9) with the sound levels measured in the field, and (d) to provide data on measured sound level reductions resulting from cut and fill sections and intervening houses.

METHOD OF ANALYSIS

Effect of Barrier

A nonporous wall of sufficient mass (minimum of about 4 lb/ft^2) interposed between source and receiver can produce a significant noise reduction because sound waves can reach the receiver only by diffraction around the barrier edges. The expected sound level reduction due to the wall is governed by the following formula (10):

$$\text{Sound level reduction} = f\ (\text{SWR},\ D,\ \lambda) \qquad (1)$$

where (according to Fig. 1)

SWR = distance traveled by the diffracted sound waves (source, top of wall, receiver),
D = distance between the source and the receiver, and
λ = wave length of the sound.

The attenuation of sound due to barriers is highly dependent on the frequency spectrum of the sound. Low-frequency sound, having sound waves several feet long, diffracts over the top of a barrier considerably more than high-frequency sound, which is effectively reflected and absorbed by the barrier. Figure 2 shows sound spectra measured behind a 12-ft wall, constructed along a 6-lane freeway, at various distances from the wall and heights above the ground. Figure 2 shows that the reductions due to the barrier tend to decrease with increasing distance from the barrier because sound waves, diffracted over the top of the barrier, can reach the points farther from the barrier more easily.

Barrier Design Criteria

Equation 1 suggests that, given adequate barrier density and fixed barrier location relative to source and receiver location, the design problem becomes one of defining the height of barrier required to reduce sound levels to a desired value. Preliminary studies obtained L_{10} sound levels (levels exceeded 10 percent of the time) of 70 to 80 dBA at the first row of houses at the proposed Highway 401 barrier location. Slightly lower values were obtained at the locations of the Don Valley Parkway barriers. The Bolt, Baranek and Newman (BBN) noise estimation procedure (9) was used to estimate the height of the barrier required to reduce the sound levels to "acceptable" values. Although it was thought desirable to achieve L_{10} levels of about 60 dBA at the first row of houses [comparable to a design criterion of a 70-dBA peak applied in California with apparent success (11)], barrier heights greater than about 10 to 12 ft were considered unacceptable because of cost, aesthetics, and possible snow-drifting. For the most part, the 10- to 12-ft height criterion governed the design.

The barriers were designed to resist severe weather and salt spray and to withstand wind forces up to 80 mph. Damaged portions of the barriers may be easily replaced if necessary. Also, in some cases, wall heights and lengths could be increased if required.

Barrier Description

A detailed description of the noise barriers was given in an earlier report (12). Briefly, the Highway 401 barrier, constructed along the 10-lane expressway, is

6,170 ft long and incorporates 5 different barrier types. The setting of the barrier, highway, and adjacent houses is shown in Figure 3. Data on barrier materials, type of support, prices, and so forth are given in Table 1.

Four relatively short barriers were constructed along the 6-lane Don Valley Parkway: a plywood barrier, an aluminum panel wall, a gabion wall, and a precast lightweight cellular concrete panel wall. Figures 4 through 7 show the general settings of the highway, the barriers, adjacent houses, and sound measurement observation points and data. Additional data are given in Table 1. The appearance of two of the barriers is shown in Figures 8 and 9.

Sound Measurement Program

Short sound recording tests, generally 10 to 15 min in duration, were carried out before and after the construction of the barriers to investigate barrier effectiveness. Measurements were taken about 4 ft above ground level on the locations shown in Figures 3 through 7. Uncontrollable variations were minimized by duplicating the weekday and starting time of the measurements for both before and after measurements. Continuous 16-hour tests investigating the variation of sound levels from about 6:00 p.m. to midnight were also carried out simultaneously with traffic classification surveys and speed measurements. These tests indicated little variation in sound levels throughout the day, about 5 to 9 dBA during this period.

Sound was monitored by a 1-in. wind-shielded microphone connected to a B&K 2204 precision sound level meter and was recorded by a tape recorder. During the measurements, wind speed and direction, temperature, and atmospheric pressure were also recorded. No measurements were made at wind speeds exceeding 10 mph. Details on the equipment used to record sound in the field and to analyze recorded sound in the laboratory are given elsewhere (13) Factors influencing sound propagation outdoors have been discussed elsewhere (10).

EVALUATION OF HIGHWAY 401 NOISE BARRIERS

Sound Levels Before Construction of Barrier

Sound recording tests were conducted on 66 observation points (Fig. 3) during several discrete 2- to 3-hour daily time periods. The sequence of measurements on the observation points and the time interval in which the sound was recorded during a certain period were randomized. Statistical analyses were conducted on the "before" sound measurement results to determine whether sound levels differed significantly during various time periods. Because no statistically significant difference was found between sound levels measured during two time periods (1:00 to 4:15 p.m. and 4:15 to 6:30 p.m.) (13), sound levels for these periods were averaged for each observation point. The average values were then used for construction of measured isodecibel lines shown in Figure 10 to illustrate measured sound levels simply and graphically. As such they are not "true" isodecibel lines, which would exhibit large variations due to individual houses. In Figure 10, the dashed lines indicate calculated isodecibel lines.

Sound Level Reductions Due to Barrier

After construction of the barrier, a series of "after" measurements was conducted on all observation points used for the before survey, during the two time periods. Averaged after values for each observation point were subtracted from the values obtained before the construction of the barrier. The sound level reductions are shown in the form of isodecibel lines (Fig. 11). The reductions are relatively small, the maximum reductions at the first row of houses being on the order of 6 dBA. Immediately behind the barrier, where the benefit of reductions is limited, reductions of 8 to 14 dBA were achieved. The small reductions measured near the constructed earth barrier (HEPC open field) probably result from the existence of an earth mound, deposited along the highway right-of-way prior to the performance of the before study for use in the future earth barrier. Unfortunately, the smallest first-row reductions (3 dBA) were obtained in an area with several two-story houses. Consequently, upper bedroom stories received no protection.

Figure 1. Effective height of barrier.

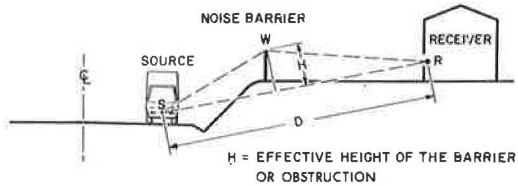


Figure 2. Sound spectrums measured behind 12-ft high wall.

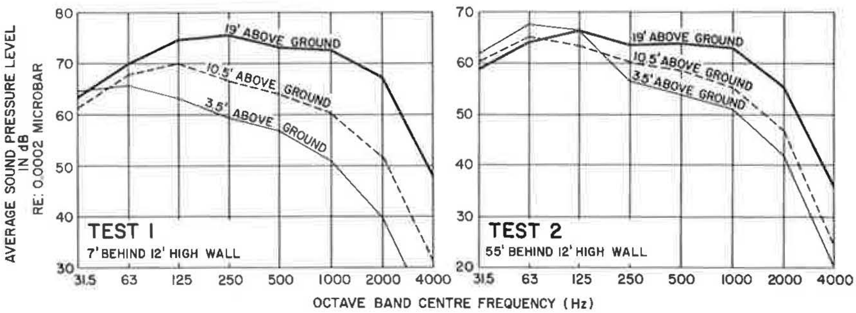


Figure 3. Highway 401 noise barrier, general setting.

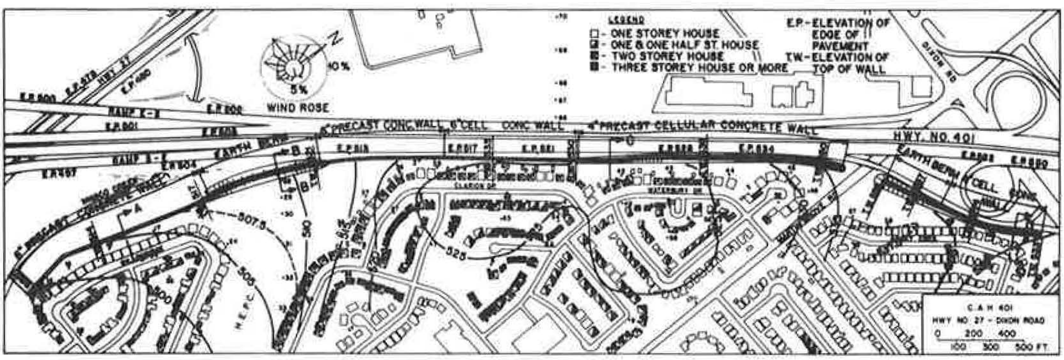


Figure 4. Sound levels before and after construction of aluminum wall (1:00 p.m. to 4:15 p.m.).

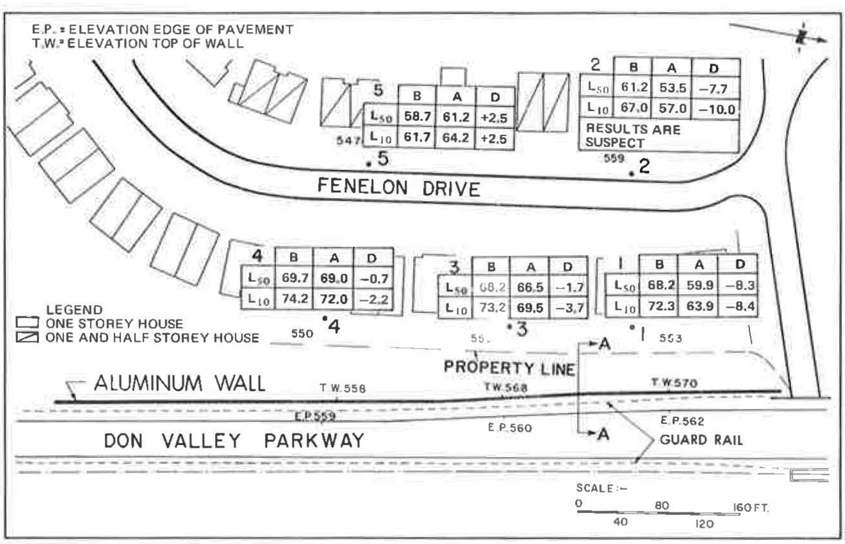


Table 1. Description of noise barriers.

Type Number	Barrier Description	Location	Thickness (in.)	Height (ft)	Total Length (ft)	Type of Support	Barrier Material	Actual Costs per Linear Foot[a] (in dollars)	Approximate Costs per Linear Foot of 10-Ft High Barrier[a] (in dollars)
1	Precast concrete wall	Highway 401, Willowridge Road, Clarion Road	6	8½ to 11	2,021	Concrete "H" columns 25 ft apart	Reinforced concrete, 4,000 psi at 28 days	48	42
2	Earth berm	Highway 401, HEPC Field, Arkley Crescent	60 (on top)	9 to 10	1,010	–	Earth fill, topsoil, sodding	25	25
3	Precast cellular concrete wall	Highway 401, Clarion Road	6	8½	800	Steel columns 8I23 20 ft apart	Reinforced concrete, 600 psi at 28 days, density 35 lb/ft^3	44	55
4	Precast cellular concrete wall on top of earth berm 5 to 8 ft high	Highway 401, Waterbury Drive	4	3½ to 7½	1,650	Steel columns 6I12.5 10 ft apart	Reinforced concrete, 600 psi at 28 days, density 35 lb/ft^3	36[b]	36
5	Precast cellular concrete wall	Highway 401, Arkley Crescent	4	9	690	Steel columns 6I12.5 10 ft apart	Reinforced concrete, 600 psi at 28 days, density 35 lb/ft^3	41	45
6	Aluminum wall	DVP, Fenelon Drive	3	8[c]	720	Aluminum "H" columns 18 ft apart	⅛-in. aluminum plate	40	40
7	Wooden wall	DVP, Larabee Crescent	¾	9	400	Structure attached to fence	Treated fir plywood panels	12	15
8	Gabion wall	DVP, Groveland Crescent	36	8[c]	810	—	Coarse gravel	80 to 90	60
9	Porex concrete wall	DVP, Cassandra Boulevard	4	12	1,400	Steel columns 10 ft apart	Reinforced low density concrete, 40 lb/ft^3	35	30

[a]Excludes costs of engineering and relocation of sewers. [b]5-ft high wall and 5-ft high earth berm. [c]Above edge of pavement.

Figure 5. Sound levels before and after construction of wooden wall (10:00 p.m. to 11:00 p.m.).

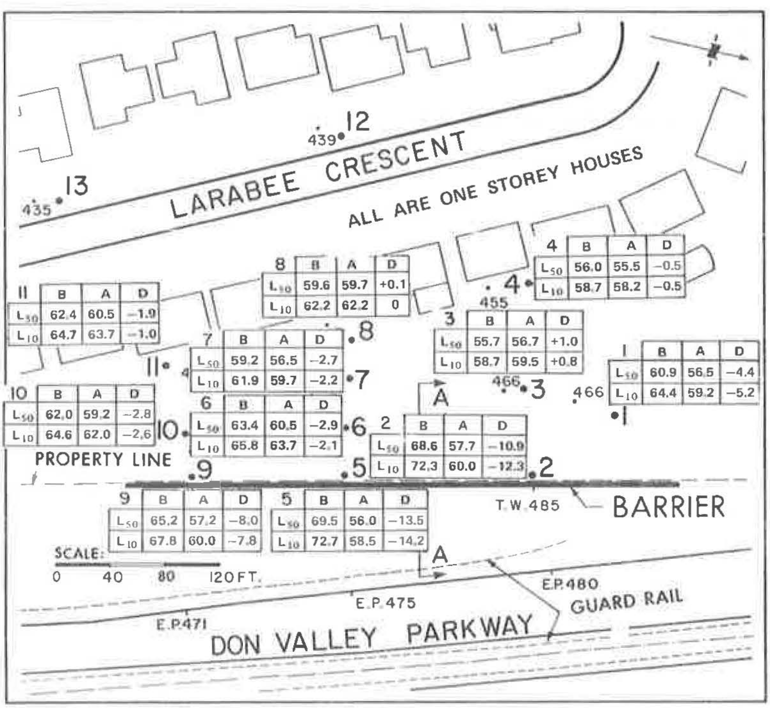


Figure 6. Sound levels before and after construction of gabion wall (9:00 a.m. to noon).

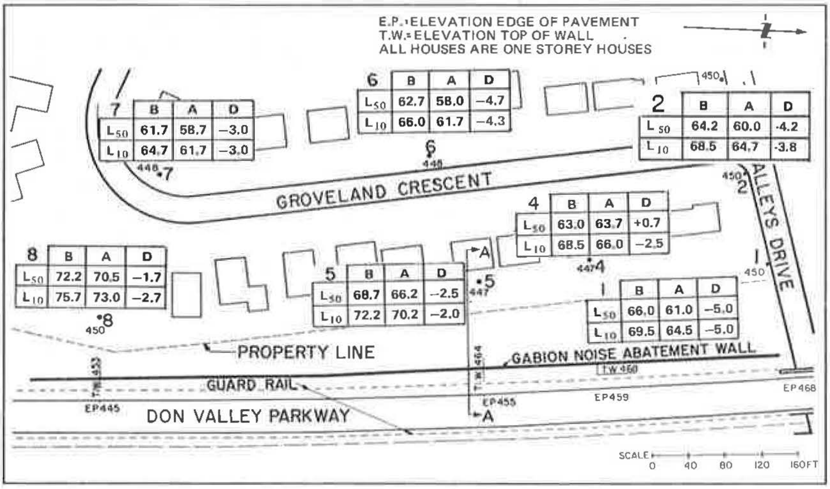


Figure 7. Sound levels before and after construction of cellular concrete wall (4:15 p.m. to 6:30 p.m.).

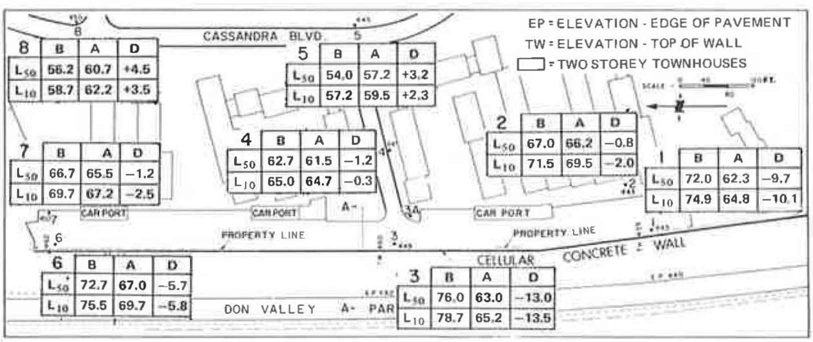


Figure 8. Highway 401 noise barrier.

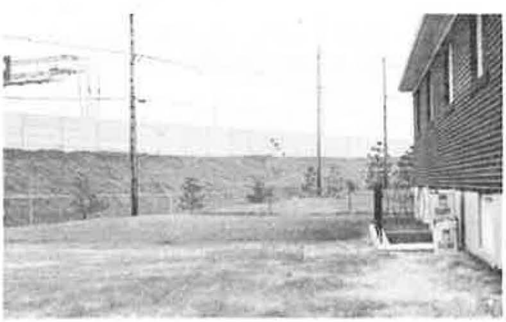


Figure 9. Gabion wall, Don Valley Parkway.

Reduction of Sound Level Fluctuation

Sound level fluctuation, that is, the variation in sound level within a measurement interval, e.g., 15 min in duration, was characterized by the standard deviation of the recorded sound divided into 0.3-sec intervals. The standard deviations were calculated for sound samples recorded at observation points located behind the central part of the Highway 401 barrier during the two time intervals (1:00 to 4:15 p.m. and 4:15 to 6:30 p.m.) for both before and after conditions. These standard deviations were statistically analyzed to determine if there were significant differences in standard deviations due to various factors (barrier, distance, and time of day) and their interactions. The selected factorial design, given in Table 2 together with average values of the standard deviations, was repeated 7 times. The details on the statistical analyses are given elsewhere (13). In general, the results show that the barrier significantly reduces sound level fluctuation during both time periods but only for locations close to the expressway.

The reductions are of interest for those noise rating methods that take into account noise fluctuation, for example, Robinson's noise pollution level, L_{NP}, defined as (14)

$$L_{NP} = L_{50} + 2.56\sigma \text{ (dBA)} \quad (2)$$

According to Eq. 2, a 1-dBA reduction of the standard deviation, σ, can have the same influence on human response as a 2.56-dBA reduction of L_{50} level (level exceeded 50 percent of the time). In this instance, however, the reductions in standard deviation due to the barrier are almost negligible because the decreases are all smaller than 1 dBA.

Effect of Increasing Height

Because the barriers were found to provide little protection, the effect of increasing the Highway 401 barrier to 20 ft was analyzed. The analysis indicated that, at best, only slight improvement would be achieved. At 4 ft above ground, where the 3-dBA reductions were measured, a further 4- to 6-dBA reduction might be achieved for a total 7- to 9-dBA reduction. At the second-story level, an additional (and total) reduction of about 3 dBA would be achieved.

EVALUATION OF DON VALLEY PARKWAY BARRIERS

The before (B) and after (A) sound level measurements and their differences (D) for the 4 Parkway barriers are shown in Figures 4 through 7. The results are very similar to those obtained for the Highway 401 barrier and show no detectable variation among the barriers. Again, sound levels immediately behind the barriers were reduced by 8 to 14 dBA, but near the houses the sound level reductions were much smaller, typically 1 to 4 dBA. It is believed that the increase in sound levels, obtained for some observation points located relatively far from the barriers, indicated by the plus sign in Figures 4 through 7, should be attributed to experimental error and should not be considered a genuine barrier effect.

RELATED STUDIES

Correlation With BBN Noise Estimation Method

During the past few years, various highway noise estimation procedures have been developed for determining sound levels without requiring direct measurement. The BBN method (8, 9) is one of the most fully developed and best known procedures. Data collected in this study were used to validate the BBN procedure. However, the full validation of all aspects of the BBN method would require much more data than it was possible to collect within the scope of this study. The calculation of sound levels has been done by a computer program based on the BBN method and its inherent approximations (9).

"Before" Isodecibel Lines at Highway 401 Test Site—Measured and calculated isodecibel lines, shown in Figure 10, show very good agreement in the central part of the test site close to the freeway. The calculated and measured isodecibel lines are close together and, for a given dBA level, generally fall between the same rows of houses. With increasing distance from the freeway, calculated values tend to be somewhat overestimated. The discrepancy between measured and calculated levels in the western part of the area is again due to earth material deposited prior to the performance of the before measurements.

Calculated Reductions—Measured sound level reduction isodecibel lines (4 ft above ground), shown in Figure 11, agree within 1 to 4 dBA with the calculated sound level reduction isodecibel lines shown in Figure 12 in the central and eastern parts of the area. Calculated reductions are usually somewhat larger than measured reductions. Comparisons in the western part of the area are again complicated because of the earth mound deposited prior to performance of the before survey.

Attenuation Due to Distance and Houses—Measured and calculated sound attenuations due to distance are shown in Figure 13. The measured values shown in Figure 13 are averages of 4 measurements taken 4 ft above ground in observation points 66 through 70 (Fig. 3) under various weather and traffic conditions. The calculated values of sound levels, estimated for the same conditions, exhibit an attenuation of 2.9 dBA per doubling of distance from edge of pavement, compared to the measured rate of 4.0 dBA.

Because the BBN method incorporates a distance attenuation of 4 dBA per doubling of distance, Figure 13, which shows a calculated attenuation of 2.9 dBA, requires some explanation. The discrepancy is caused by division of the 10-lane freeway into separate eastbound and westbound elements, as recommended by the method. This results in two parallel line sources with the shown combined sound attenuation of 2.9 dBA. This probably explains the tendency for sound levels to be overestimated with increasing distance from the freeway, as shown in Figure 10. It should be noted that the rate of attenuation due to distance was related to the edge of pavement. Slightly higher rates of attenuation with distance would result if the source of sound was assumed somewhere between the edge of pavement and the median of the 10-lane freeway.

Figure 13 also shows some experimental data pertaining to the combined effects of distance and houses. There is considerable scatter in the measured values, but, on the average, a single row, double row, and three or more rows of houses produced further attenuations of about 4 dBA, 8 dBA, and 9 dBA respectively. This agrees quite well with the BBN recommendations of 5 dBA, 10 dBA, and 10 dBA for the same conditions, considering that different results might be expected for different sized houses and distances among them.

Vertical Distribution of Sound Levels—Figure 14 shows the vertical distribution of sound levels in open field and behind the Highway 401 barrier projected on vertical planes perpendicular to the highway. On one plane are also projected the outlines of the nearest houses. Measured sound levels plotted on the figure were obtained by using simultaneously 3 or 4 microphones mounted on a 20-ft long pole. For comparison, the results of calculated noise levels using the BBN method are also plotted.

Measured sound levels vary by as much as 10 dBA with a change of elevation of 10 to 12 ft even if there are no obstructions. This variation is not accounted for by the BBN method, which reports only one noise level for a certain distance from the highway. This effect of ground attenuation has also been noted by Scholes and Sargent (15), who cite Ingard (16) and Delany and Bazley (17) in attributing it to destructive interference between direct sound and sound that has undergone a complex reflection from the ground surface.

With a noise barrier, variation of noise levels with elevation is expected, but some differences appear when measured values are compared with calculated values. Perhaps one of the most important comparisons is at the second-story windows of houses adjacent to the highway, where measured noise levels are approximately 5 dBA higher than the values calculated. Measured and calculated reductions at the same location differ by about 5 dBA.

Attenuation Due to Cut and Fill Sections

Sound attenuation due to highway features, such as cut and fill sections, is governed by the same relation as is sound attenuation due to barriers. Figure 15 shows the

Figure 10. Measured and calculated sound levels (L_{10}) before barrier construction.

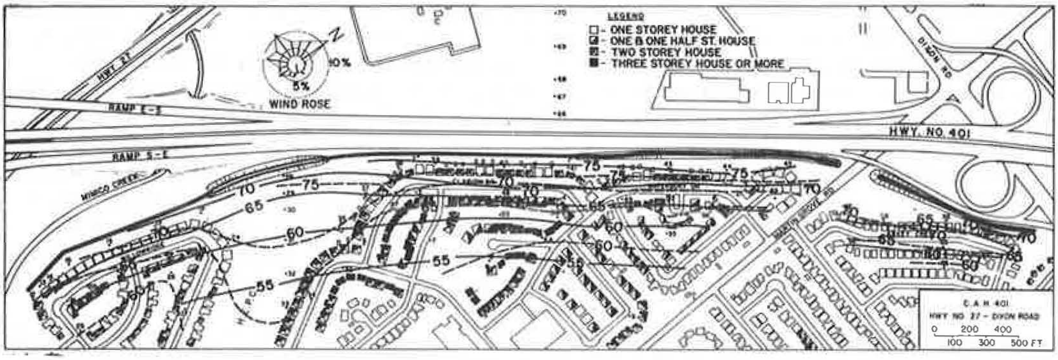


Figure 11. Measured reductions of sound levels (L_{10}) due to Highway 401 barrier.

Table 2. Sound level standard deviations.

Group Number	Sound Level Before Construction of Barrier		Sound Level After Construction of Barrier	
	1:00 to 4:15 p.m.	4:15 to 6:30 p.m.	1:00 to 4:15 p.m.	4:15 to 6:30 p.m.
1	3.351	2.576	2.399	2.185
2	2.118	2.271	1.991	1.913
3	2.325	2.471	2.533	2.102

Note: Observation points (Fig. 3) in group 1 were 38, 39, 40, 41, 43, 44, and 45; in group 2 they were 3, 4, 48, 49, 50, 51, and 52; and in group 3 they were 6, 7, 8A, 53, 54, 55, and 56.

Figure 12. Calculated reductions of sound levels (L_{10}) due to Highway 401 barrier.

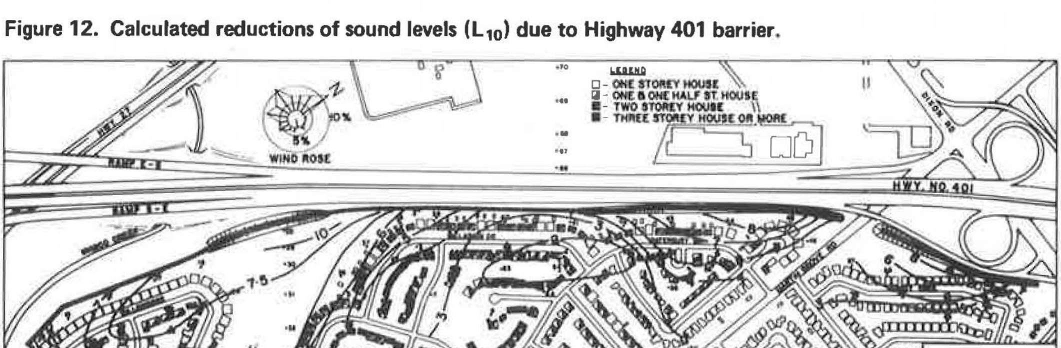


Figure 13. Attenuation of sound due to distance and houses.

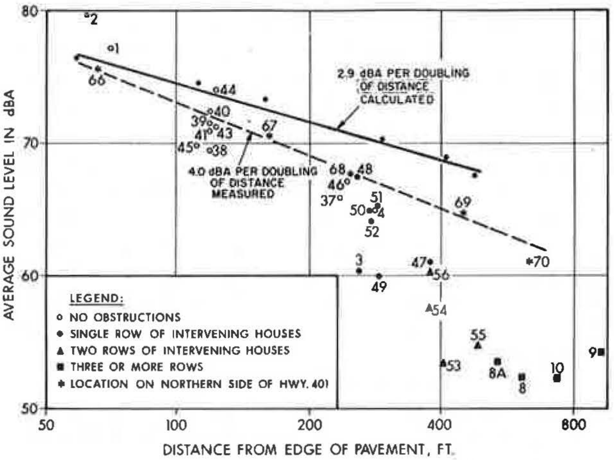
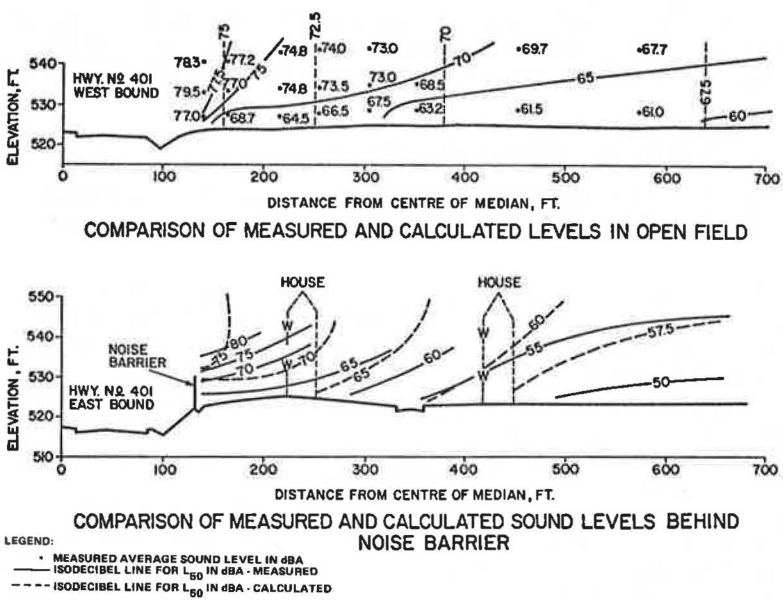


Figure 14. Vertical distribution of measured and calculated sound levels.



vertical distribution of measured sound levels emitted by traffic on major expressways in the vicinity of an open field, an earth embankment (Highway 401 barrier test site), and cut and fill retaining walls. The measurements were conducted using simultaneously four sound recording sets. Three microphones, mounted at different heights on a 20-ft long pole, were placed successively at increasing distances from the expressway. One microphone monitored sound levels close to the expressway to eliminate effects of sound level variation during the successive measurements.

Sound attenuation due to different highway features and distance (Fig. 15) was compared with the sound attenuation due to distance in the open field for two heights above ground: 5 ft and 20 ft. The results, shown in Figure 16, were related to an arbitrary value of 75 dBA, 50 ft from edge of pavement in open field and 20 ft above ground.

It may be noted that the height of the retaining walls and the height of the earth berm are approximately the same: 11 to 12 ft above or below a flat terrain. Traffic flow composition and speed were similar at all four test locations, and the measurements were conducted under similar weather conditions.

Figure 16 suggests that the most effective measure, of those evaluated, is a cut section. Reductions of sound levels were obtained at both low and high positions above ground (5 ft and 20 ft), and the rate of reduction increased with distance from the expressway. Reductions of sound levels due to the fill section were obtained only at low heights above ground, and the reduction generally decreased with distance from the expressway. The effect of the earth berm was similar to the effect of the fill sections at low heights above ground. However, for positions close to the barrier, sound levels 20 ft above ground were up to 3 dBA higher than the corresponding sound levels in the open field. This phenomenon is probably attributable to the relative position of the sound source for the "shadow zone" behind the barrier, which is effectively shifted to the top of the barrier.

SUMMARY AND CONCLUSIONS

Five experimental 8- to 12-ft high noise barriers were constructed in metropolitan Toronto during 1971. Results of the field evaluation studies on these barriers are summarized as follows:

1. "Before" and "after" surveys indicated that immediately behind the barriers, where the reductions are of little real benefit, sound level reductions of 8 to 14 dBA could be achieved. At the first row of houses, 4 ft above ground level, sound level reductions were considerably smaller, typically 1 to 6 dBA.
2. The sound level reductions due to the barrier decreased with distance from the barrier and were highly frequency dependent.
3. There was no indication in the study that barrier material significantly affected barrier effectiveness. All barriers performed in a similar manner.
4. There was a small reduction in the fluctuation (standard deviation) of sound levels about the mean level due to the barrier, not exceeding 1 dB. Some researchers (14) have suggested that a reduction in the standard deviation of the sound level may be several times as effective in reducing annoyance as an equal decibel reduction in the mean sound level.
5. A brief social survey indicated that people living behind Don Valley Parkway barriers considered them beneficial in that their retention was favored. Possible side benefits of even low barriers (7 to 10 ft) may be psychological (visual) shielding and shielding against headlight glare, dust, and salt spray.
6. To be effective (sound level reductions of 8 to 10 dBA) noise barriers would have to be constructed to heights of 20 to 25 ft (on level terrain, possibly less with favorable topography) at estimated costs of at least $100 per linear foot.
7. Even 20- to 25-ft high barriers appear to be effective only for single-story houses. Second and higher stories become virtually unprotectable by noise barriers.

Related studies and studies performed to validate the BBN noise estimation procedure (9) have led to the summarized conclusions that follow. The tentative nature

Figure 15. Vertical distribution of sound levels (L_{50}).

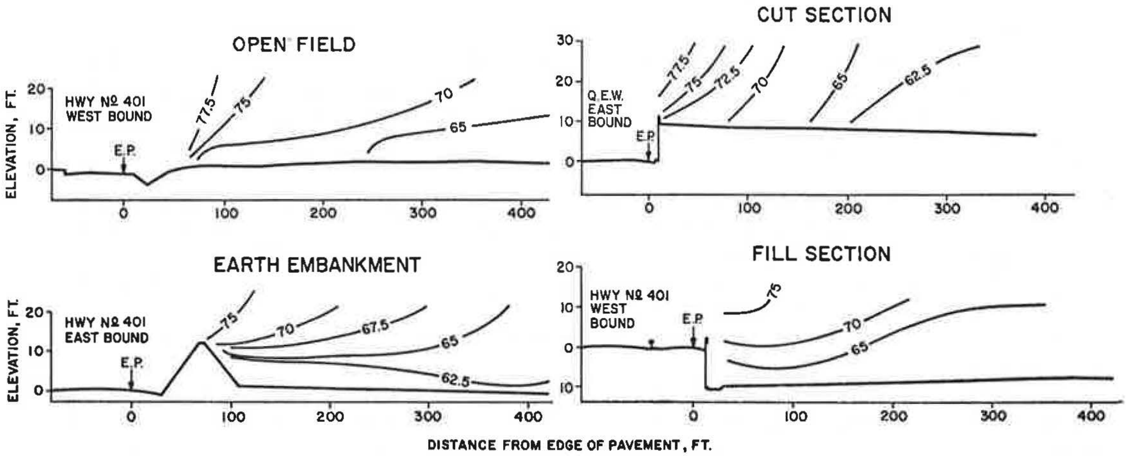
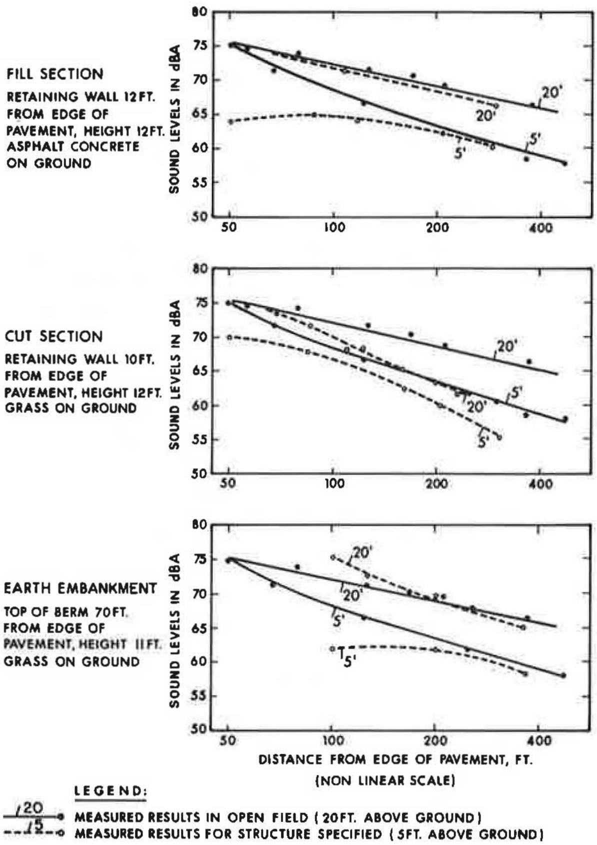


Figure 16. Effectiveness of highway structures in reducing sound levels.



of these findings should be stressed. A full validation of the BBN procedure would require considerably more data than were collected during this program. The conclusions are as follows:

1. Calculated sound levels, both without and with the barrier, for locations close to a wide expressway (60 to 120 ft from edge of pavement and about 4 ft above ground) are in good agreement with measured sound levels (generally within ±3 dBA).
2. Sound levels tend to be overestimated with increasing distance from the freeway (Fig. 13).
3. Sound level reductions due to a barrier located close to a freeway, calculated for observation points (4 ft above ground) at distances in the range of 120 to 200 ft from the barrier were overestimated by 2 to 5 dBA. In general, calculated sound reductions due to a barrier are overestimated rather than underestimated. At the second-story level, reductions were overestimated by about 5 dBA.
4. Sound level reductions provided by rows of intervening houses appear to be estimated properly.
5. Highway traffic noise levels in dBA depend on both distance from the highway and distance above ground. Figure 14 suggests that the assumption of variation of sound levels with distance from the highway only can yield errors of 5 to 10 dBA relatively close to the highway.
6. Reductions of sound levels due to fill sections are achieved only at low elevations close to the fill slope or face, as expected. Cut sections have limited effectiveness very close to the expressway, but their effectiveness increases with distance (Fig. 16). The most effective section appears to be a cut section with an earth embankment or other barrier on the crest.

In conclusion, barriers alone, because of their high cost, limited effectiveness, and other adverse effects (aesthetics, shadow, and effect on snow-drifting), do not appear to be the most cost-effective solution to highway noise. Greater attention and emphasis should be given to other noise control measures such as housing modifications, land use control, and control of vehicular noise emissions at the source.

ACKNOWLEDGMENTS

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THE KINEMATIC SOUND SCREEN: AN EFFECTIVE SOLUTION TO HIGHWAY NOISE ABATEMENT

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Simple barriers of earthwork or solid construction have been widely used to reduce traffic noise levels in neighborhoods adjacent to urban freeways. The Kinematic Sound Screen is a new concept in noise barrier design. It consists of a series of hollow, triangular-shaped columns acting as Helmholtz resonators. The spacing between columns permits the motorist to "see through" the barrier at highway speeds while at the same time screening the traffic from the view of observers in nearby residential areas. Laboratory testing of Kinematic Sound Screen panels demonstrated that an approximate 15-dB attenuation in transmitted noise levels can be achieved with this approach, which is comparable to that obtained with conventional, solid barriers. A full-scale sound screen has been constructed along a freeway in Phoenix, Arizona, and field evaluation of this prototype demonstrated that attenuation of greater than 10 dB is achievable using a 12-ft high screen with greater attenuation possible. The Kinematic Sound Screen offers a promising alternative to conventional barriers along future urban freeways.

• BEGINNING in July 1972 the Federal Highway Administration Policy and Procedures Memorandum (PPM) 90-2 made it necessary for the highway design engineer to consider noise abatement measures on all new highway construction projects. The stated purpose of PPM 90-2 is to reduce the effects of traffic noise by the greatest possible extent without neglecting other important considerations. Section 136(b) of the Federal-Aid Highway Act of 1970 requires not only that noise be fully considered but also that other economic, social, and environmental effects be considered and that "final decisions on highway projects (be made) in the best overall public interest taking into condideration the need for fast, safe and efficient transportation, public services and the cost of eliminating or minimizing such adverse effects."

At this point, the following questions are pertinent:

1. Just how stringent are these standards imposed on new highway construction by PPM 90-2?
2. What measures are available to enable the design engineer to comply with these standards?

The noise standards specified in PPM 90-2 require in part that the sound levels experienced at the exteriors of schools, parks, and residences near proposed highways not exceed 70 dBA (70 A-weighted decibels) more than 10 percent of the time during the worst hour of the day. The magnitude of the noise abatement problem is shown in Figure 1, which depicts the noise levels that are exceeded more than 10 percent of the time (designated as L_{10}) for a typical four-lane highway, assuming moderate traffic flow. Note that, for sections of such a highway, some type of noise abatement measure is required if residences, schools, or parks are within 250 ft of the nearest lane of traffic.

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Figure 1 also indicates some methods for attenuating (or reducing) the sound levels produced by nearby highway traffic for buildings at various distances from the highway. It is clear that the most effective attenuation is achieved through the use of barriers and that the higher the barrier is the more effective it is in reducing the sound level. This is due in part to the fact that a large portion of the noise produced by diesel trucks is emitted from the exhaust stack at heights of 10 to 15 ft above the roadway. Thus, low barriers do not attenuate exhaust stack noises to any appreciable extent.

Solid barriers can be thought of as a "plate" having elastic properties and known thickness. Such barriers affect a sound field in two ways: diffraction and transmission of sound waves over and through the barrier and reflection of sound waves off the face of the barrier. Figure 2 shows the action of these influences on a typical sound wave striking a barrier. As might be expected, the objective in barrier design is to keep the sum of the diffracted component (L_D) and the transmitted component (L_T) as small as possible with respect to the incident sound energy level (L_I). As will be shown, this objective can be achieved with only limited success using solid upright barriers.

Maekawa (1) developed a mathematical model for the performance of acoustic barriers. His research indicated that the noise attenuation of a solid barrier is directly proportional to a factor δ, where $\delta = A + B - C$ as shown in Figure 3.

It is clear from this model that, the greater is the angle AB (i.e., the higher the barrier relative to the observer and source), the greater will be the effective attenuation of a given solid barrier.

Maekawa also demonstrated, however, that barrier attenuation is inversely proportional to the wavelength (λ) of the incident sound waves. Thus, long wavelengths of 4 to 10 ft are relatively unaffected by solid barriers because they are easily diffracted over the top except for wall heights greater than 25 ft. Because the apparent sound level at any given time is slightly greater than the level of the loudest sound present, this means that the overall effectiveness of any simple barrier is limited by its ability to screen out low-frequency sounds. In practice, this limit is approximately 15 dB for simple barriers less than 25 ft high (2). When it is recognized that traffic noise levels peak in the frequency range of 125 to 250 Hz (3), the true limitation of simple barriers as traffic noise attenuators can be appreciated.

INITIAL CONCEPT DEVELOPMENT

It is precisely the state of affairs just described that led to consideration of alternatives to conventional solid noise barriers in 1970. At that time, the Engineering Corporation of America was commissioned to study the environmental effects of a section of proposed freeway running through an established residential neighborhood in Phoenix, Arizona. Cursory analysis of the expected noise levels in the adjacent community after freeway construction indicated that some type of noise abatement measure along the edge of the roadway would be desirable. Our research into the attenuation qualities of solid barriers indicated that, at best, the overall sound level could only be reduced about 15 dB using this approach. When the poor aesthetic and environmental impact of such a barrier was considered, we began to search for a viable alternative that would present a pleasing architectural appearance and at the same time equal or exceed the attenuation qualities of conventional barriers.

A major objection to the use of conventional solid barriers is their inherent opacity, which is highly confining and potentially hazardous for the motorist, especially in view of the extreme wall heights required to reach an appreciable attenuation level. Therefore, the possibility of using transparent plastic panels was explored. However, no measurements relating the effective attenuation of plexiglass barriers to conventional solid barriers have been reported. Also, maintenance would be a frequent and costly consideration.

The beginnings of a feasible solution to this barrier problem became evident when it was decided to investigate the possibilities of using the principles of Edison's Kinetoscope in this application. The Kinetoscope is a forerunner of the modern movie projector. It consists of a film strip transported in front of a light source. A rotating shutter containing a single aperture is rotated rapidly such that 46 times a second the aperture is precisely positioned over an individual frame. The effect of motion depended on spinning the shutter rapidly in synchronization with advance of sequential frames on the film strip. It was apparent that apertures in a barrier might permit the surrounding countryside to be viewed in similar fashion as a continuous panorama for observers passing by closely spaced apertures at highway speeds.

Thus, the obvious physical characteristic that distinguished the Kinematic Sound Screen from conventional barriers was established. From its original conception to the present time, the screen has consisted of a series of triangular-shaped columns separated by narrow apertures as shown in Figure 4.

At this point, it was necessary to consider methods for improving the sound attenuation qualities of the Kinematic Sound Screen. The objective at this point was to compensate for the sound transmission characteristics of the apertures through proper design of the triangular columns separating the apertures.

Rayleigh (4) established the side branch as having a damping effect on sounds transmitted through tubes. In the case of the sound screen, the analog to Rayleigh's side branch is the Helmholtz resonator. The Helmholtz resonator consists of a chamber with an orifice that couples the air inside the chamber to the air outside. The Helmholtz resonator was adapted for the sound screen by hollowing out the triangular columns between the apertures as shown in Figure 5.

Note that each triangular column incorporates two orifices. These orifices (or absorption slits) are located adjacent to the apertures on both sides of the column. As an incident sound wave strikes the front faces of the columns, it is compressed as it proceeds through what is, in effect, an acoustic horn toward the aperture. When a given wave reaches the absorption slit openings, a large portion of its energy is expended in moving the column of air in the orifice to the resonating chambers. The resulting sound waves in the chamber bounce off the walls, scattering and losing energy. Eventually, some portion of the original sound energy is passed back out of the chamber as a reflected wave. Thus, the sound screen permits only a small portion of the incident sound energy to be passed through the apertures between columns. The remainder is dissipated through heat in the Helmholtz chambers or is reflected back toward the source.

ACOUSTIC PROPERTIES OF THE SOUND SCREEN

If we consider each hollow column of the sound screen to be a Helmholtz resonator acting as a side branch, then the ratio of the power transmitted into the chamber to that of the incident wave is given by the standard formula:

$$\alpha_b = \frac{\frac{\rho_o C}{A} R_b}{\left(\frac{\rho_o C}{2A} + R_b\right)^2 + X_b^2} \tag{1}$$

where

ρ_o = density of air at STP,
C = speed of sound in air at STP,
A = cross-sectional area of cavity orifice,
R_b = acoustic resistance of the resonating chamber = $\rho_o CK^2/2\pi = \rho_o A/2\pi L'V$,
L' = effective length of orifice neck,
V = volume of chamber,
X_b = acoustic reactance of the resonating chamber = $\rho_o\left(\frac{\omega L'}{\pi A^2} - \frac{V}{\rho_o^2 C^4 \omega}\right)$, and
ω = frequency of incident sound wave.

Therefore, the preceding formula reduces to

$$\alpha_b = \frac{C}{2\pi L' V} \bigg/ \left(\frac{C}{2A} + \frac{A}{2\pi L' V}\right)^2 + \left(\frac{\omega L'}{\pi A^2} - \frac{V}{\rho_o \omega C^4}\right)^2 \tag{2}$$

For values of $V < 10^8\ cm^3$, as in the case of the sound screen, the term $V/\rho_0\omega C^4$ becomes insignificant. For hardware design purposes, then, the formula can be expressed as

$$\alpha_b \simeq \frac{C}{2\pi L'V} \Bigg/ \left(\frac{C}{2A} + \frac{A}{2\pi L'V}\right)^2 + \left(\frac{\omega L'}{\pi A^2}\right)^2 \quad (3)$$

Therefore, maximum dissipation of energy in each Helmholtz resonating chamber can be achieved by adjusting the values for orifice area (A), orifice neck length (L′), and chamber volume (V).

It is clear from Eq. 3 that chambers of a given volume and orifice configuration will be more efficient at some sound frequencies than at others because of the influence of the factor ω. Because the majority of traffic noises occur in the frequency band of 125 to 1,000 Hz, this feature offered the possibility for selectively tuning the resonating chambers for maximum absorption in the frequency band of interest. Maximum absorption occurs at the resonant frequency of a given chamber.

It should be noted that the density of the chamber walls is not an influencing factor in the calculation of absorption efficiency for the Helmholtz resonators. Early in the research effort it was thought that the chamber wall material might affect absorption. However, subsequent testing with a variety of construction materials confirms that the choice of material is of little significance, with one qualification. The validity of considering the Helmholtz resonating chambers as side branches is based on the assumption that the chamber walls behave acoustically in the same fashion as the walls of an acoustic pipe, that is, as high-density elastic plates. Therefore, it appears likely that the ultimate material selection will be from high-density nonfrangible material such as plywood, precast concrete, plastics, sheet metal (steel), or cast or extruded aluminum.

LABORATORY TESTING

Initial testing of the Kinematic Sound Screen concept was conducted using a small concrete box with a door on one side and a microphone placed inside. Three doors were used in the preliminary tests. The first consisted of a solid, 2-in. thick concrete panel, the second door was a similar panel having a ½-in. slot, and the third door contained a V-shaped depression in the face leading to a slot having the same dimensions as the slot in door number two. Testing with the unslotted door resulted in a transmission loss of sound into the chamber of approximately 30 dB. Testing of the other two doors indicated that transmission loss was approximately 15 dB for the slotted door and slightly greater for the door with the V-shaped slot. It was theorized that the difference in transmission between the slotted and V-shaped slotted configurations was due to the scattering effect of the acoustic horn produced by the V configuration. By coupling the horn to Helmholtz resonators, it was felt that a 25-dB attenuation in transmitted sound level could be achieved for the full-scale sound screen. This level is comparable to the noise attenuation of conventional solid barriers. The sound screen, however, would have the advantage of "see-through" characteristics.

On the basis of the preliminary test results, a laboratory research program was initiated with funding from the research division of the Arizona Highway Department. The objective of this program was to set up a sound laboratory and evaluate the sound transmission characteristics of prototype sound screen panels. The laboratory consisted of a dual anechoic chamber as shown in Figure 6 and included a precision sound measurement and recording system with calibrated accuracies complying with National Bureau of Standards requirements.

The sound input system consisted of a "pink" noise pseudorandom generator driving two preamplifiers. The signal was then passed through a spectrum shaper to eliminate equipment anomalies within the generating equipment and reproduced by means of a bank of matched loudspeakers. Sound level recordings were taken from calibrated microphones located in the source chamber and the receiver chamber, using a real-time audio spectrum analyzer to drive a precision x-y plotter.

Figure 1. Highway noise levels (dBA, L_{10}) at various distances from edge of four-lane highway.

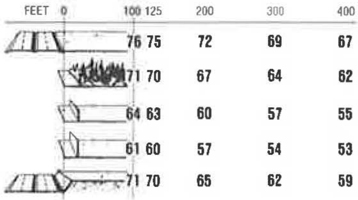


Figure 2. Acoustic effects of sound wave from line source impinging on barrier of finite thickness.

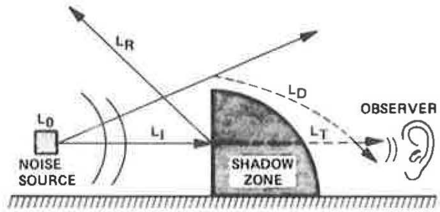


Figure 3. Significant distance relations for computing barrier attenuation.

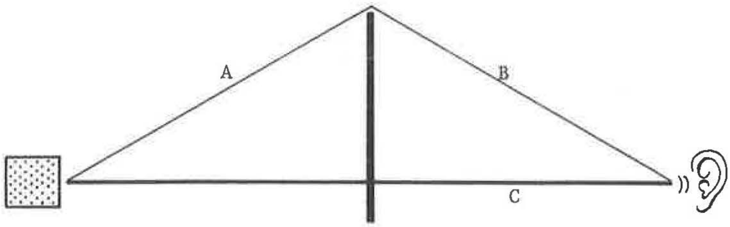


Figure 4. Optical design concept for Kinematic Sound Screen.

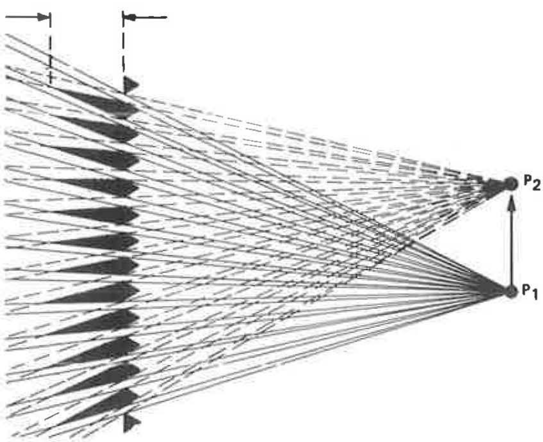


Figure 5. Acoustic design concept for Kinematic Sound Screen.

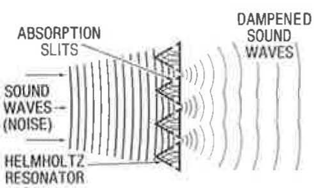
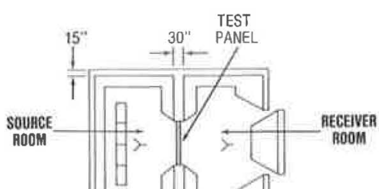


Figure 6. Layout of anechoic chamber.



Five test panels were fabricated and tested under this program. The physical characteristics of the panels are given in Table 1, and a typical test panel is shown in Figure 7.

The results of the initial testing for transmission losses through the sound screen panels were in the range of 17 to 20 dBA. Panels 2 and 3 were identical in construction except for material (concrete and wood respectively); however, the difference in measured attenuation was less than 1 dB. Hence, it was concluded that the construction material has no significant effect on the attenuation characteristics of the sound screen.

Of particular interest in this test series was the correlation between calculated resonant frequency and the frequency of maximum absorption. Without exception, maximum absorption occurred at or near the calculated resonant frequency. The absorption peaks were 10 to 15 dB greater than the average attenuation at other frequencies. Thus, the fundamental objective of selective tuning to reduce noise levels in specific frequency ranges appeared to be achievable.

Concurrent with the early laboratory tests, an evaluation of the optical properties of the sound screen was made using a pasteboard mock-up of the screen. It was discovered that the panel configuration used in the sound tests (that is, 6-in. wide columns with ⅛-in. apertures between them) did not provide good resolution of the background when viewed by a passing motorist at freeway speeds. Alternate column widths of 1, 2, 3, and 4 in. were evaluated, the 1-in. width providing the best clarity. As a compromise between the optical features and the necessary minimum volume and strength characteristics desired in full-scale sound screens, the 3-in. column width was selected for further evaluation.

FIELD EVALUATION

At this point in the program, the sponsor requested that a 350-ft segment of 12-ft high sound screen be built along a Phoenix freeway to permit field evaluation of the concept.

Various materials were considered and evaluated for use in this full-scale screen, including plexiglass, sheet metal, concrete, and aluminum. On the basis of cost, availability, and ease of installation, the selected material was aluminum. The prototype sound screen was constructed in 4-ft sections, each 3 ft high, with a solid support column at the ends of each section. The hollow resonating chambers were formed as extruded segments 3 ft long and snap-fitted and glued to form a closed cavity. Cross-sectional views of the extrusions making up each column are shown in Figure 8.

It should be noted that the exterior view of the support columns is identical to that of the hollow Helmholtz cavities. This approach was selected to enhance the pleasing appearance of the sound screen from the motorist's point of view.

After the 3- by 4-ft sections were assembled off-site, they were then stacked at the construction site four tiers high on a concrete pad to provide a 12-ft barrier. The completed sound screen is shown in Figure 9.

Laboratory testing of these panels indicated that the attenuation of transmitted noise levels approached 15 dBA. Subsequently, tests were performed in the field with one microphone placed 5 ft in front of the screen and another placed approximately 15 ft behind the screen near the center of the 350-ft long section. The difference in sound levels between the front and back sides of the screen was considered to be the attenuation due to the sound screen. Although this testing demonstrated an overall noise reduction of approximately 10 dB, the greatest attenuation occurred in the higher frequency ranges. This corresponds well with the calculated resonant frequency for these panels, which was 798 Hz. The resonant frequency appears to act as a low-frequency threshold noise attenuation. Although noise absorption peaks at that frequency, there is a significantly diminished effect on lower frequencies. For this reason, it is desirable to design the Helmholtz chambers to resonate at as low a frequency as practicable.

Future testing planned for the Kinematic Sound Screen includes measuring the actual sound energy absorbed by the Helmholtz chambers at various frequencies. In addition, we plan to test panels without apertures (that is, solid screens with Helmholtz

Table 1. Physical characteristics of test panels.

Physical Data	Panel 1, Stucco	Panel 2, Continuously Poured Concrete	Panel 3, Plywood	Panel 4, Plywood	Panel 5, Plywood
Thickness (in.)	7	7	7	4¼	4
Weight (lb)	200	450	95	100	100
Aperture thickness (in.)	⅛	⅛	⅛	⅛	⅛
Angle of acoustic horn (deg)	47	52	52	71	76
Interior volume (cm^3)	1,945	2,999	2,999	1,105	1,029.7
Size of cavity opening (in.)	⅛	⅛	⅛	⅛	¼
Calculated resonant frequency (H_3)	359	316	316	500	725
Neck length (cm)	2.6	2.2	2.2	2.3	2.35
Neck area (cm^2)	21.37	21.37	21.37	21.37	42.60

Note: All panels were 2 by 4 ft.

Figure 7. Plywood test panel with ¼-in. cavity openings.

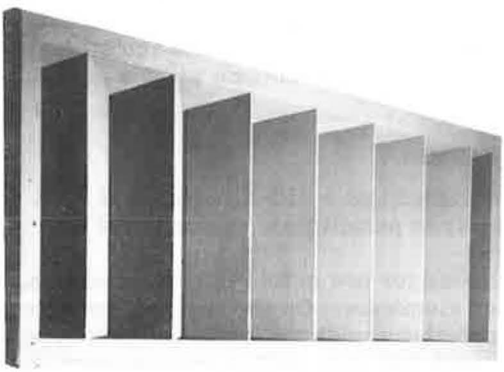


Figure 8. Cross-sectional views of aluminum extrusions used to construct full-scale Kinematic Sound Screen.

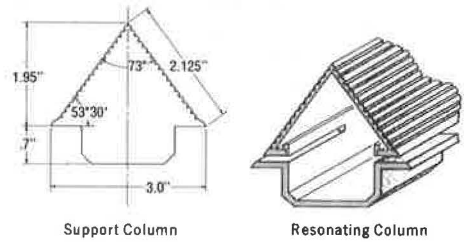


Figure 9. Full-scale Kinematic Sound Screen (aluminum construction).

resonators mounted on the front face) to determine the maximum attenuation that can be achieved with this concept.

CONCLUSIONS

In conclusion, the principle of the Kinematic Sound Screen is well supported by acoustic and optical theory. Testing, both in the laboratory and in the field, has demonstrated that the sound screen reduces transmitted noise levels by approximately 15 dB, with an overall reduction in traffic noise levels of more than 10 dB. With refinements in tuning the sound screen for the lower frequencies, it is anticipated that 15-dB attenuation can be achieved.

Thus, it appears that the Kinematic Sound Screen can provide the traffic noise attenuation required to ensure compliance with PPM 90-2 for adjacent schools, parks, and residences. Additionally, the unique "see-through" features of the Kinematic Sound Screen should make it popular with the motoring public and local residents alike.

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