NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT **78**

HIGHWAY NOISE
MEASUREMENT, SIMULATION, AND MIXED REACTIONS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT 78

HIGHWAY NOISE
MEASUREMENT, SIMULATION, AND MIXED REACTIONS

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VAN NUYS, CALIFORNIA

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION
OF STATE HIGHWAY OFFICIALS IN COOPERATION
WITH THE BUREAU OF PUBLIC ROADS

SUBJECT CLASSIFICATION:
HIGHWAY DESIGN
ROAD USER CHARACTERISTICS
URBAN COMMUNITY VALUES

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Bureau of Public Roads, United States Department of Transportation.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

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

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

This report is one of a series of reports issued from a continuing research program conducted under a three-way agreement entered into in June 1962 by and among the National Academy of Sciences-National Research Council, the American Association of State Highway Officials, and the U. S. Bureau of Public Roads. Individual fiscal agreements are executed annually by the Academy-Research Council, the Bureau of Public Roads, and participating state highway departments, members of the American Association of State Highway Officials.

This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the contract. It has been accepted by the Highway Research Board and published in the interest of an effectual dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area.

NCHRP Project 3-7 FY '64 and '65

NAS-NRC Publication 309-01774-2

Library of Congress Catalog Card Number: 76-603751

FOREWORD

By Staff

Highway Research Board

This report will be of special interest to highway design engineers, highway planners, architects, tire manufacturers, automobile manufacturers, legislators, and other officials who have to deal with the problems created by noisy cars and trucks. The material presented includes guidelines that highway design engineers can use in the creation of new facilities, shows the contribution to noise abatement that might be achieved through the design of less noisy tires and less noisy automotive units, and provides information that will help architects to more accurately consider traffic noise in the design of buildings. The research includes a standard technique for the roadside measurement of the noise produced by motor vehicles.

Questions related to highway noise levels and their effects on users of adjacent property arise frequently in the planning and design of highway improvements, particularly in urban areas. It is important to have means of evaluating probable noise levels adjacent to highways so that noise may be considered in the design of highway features and reduced through legislative actions or by enforcement of vehicle regulations. It was with these thoughts in mind that this research was initiated in 1963.

Bolt Beranek and Newman in a comprehensive and well-documented report have set forth specific guides that will help state highway department engineers determine the most appropriate means and units for measuring and evaluating highway noise for a number of common traffic situations. These guides are presented in easy-to-use tabular and graphic form. They are supplemented by a computer simulation model that allows the engineer, designer, or researcher to predict—under fixed conditions of vehicle speed, truck mix, vehicular volume, and distance from the highway—the vehicle noise levels for any existing or planned highway situation for freely flowing traffic.

In an effort to determine individual reaction to vehicular noise the researchers conducted home interviews involving more than 300 respondents. Through the use of the home interview survey techniques these researchers derive relationships between expressed annoyance with highway noise and the residents' socioeconomic class, physical noise levels, highway landscaping, and attitudes toward highways in general.

This effort was by no means designed to solve all of the problems in the field of highway noise, and it is anticipated that additional highway noise research will be conducted by the NCHRP. Significant studies of the noise created by trucks are presented in the complementary *NCHRP Report 75,* "Effect of Highway Landscape Development on Nearby Property," and legal problems involving highway noise are given in NCHRP Project 11-1(7), "Valuation and Compensability of Noise, Pollution, and Other Environmental Factors." As for the work reported herein, improvements could be made to the traffic noise simulation model to allow it to handle more complex situations and to include the variable effects of shielding structures and topography.

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ACKNOWLEDGMENTS

The study reported herein was conducted by Bolt Beranek and Newman, Consulting Engineers, in connection with NCHRP Project 3-7. For the research agency, Welden E. Clark acted as Principal Investigator, with William J. Galloway and Jean S. Kerrick assisting.

Programming of the traffic noise simulation was performed primarily by Craig Fletcher. Investigation of existing vehicle noise ordinances, and assistance in selection of interview sites was provided by Joyce Herman. Field measurements of noise used to validate the simulations were performed by Ronald Burns, Burt L. Freezor, Stewart Ferguson, Robert E. Galloway, and Jon P. Pettijohn.

The field interview to assess residents' reactions to their noise environments was pre-tested by Caroline Whorf and Inga Hoffman, who made valuable suggestions leading to revision of the interview schedule. Additionally, Mrs. Hoffman participated in the training of the other interviewers: Geraldine Shick, Kent Farnsworth, David Goodkin, Wilbur Mellema, and Philip Rubin.

Thanks are due Dr. Virginia A. Clark, Department of Biostatistics, University of California, Los Angeles, for advice in the statistical comparison of the various noise measures, and for assistance with the simulation model.

HIGHWAY NOISE

MEASUREMENT, SIMULATION, AND MIXED REACTIONS

SUMMARY

To the confusion of unwanted sound which is called highway noise, the present study attempts to bring order and to expand the knowledge of noise and of the reaction of people to noise.

Two major studies formed the basis for a theory of traffic noise from which a simulation model was built, and computers were then put to work describing the noise of different highway situations. In addition to the model, a second innovation in the present work was a detailed interview with people living relatively near a freeway or highway. Those interviews formed the basis for predictions about residents' expressed annoyance with noise.

The two studies basic to the simulation model involved first comparing various measures of sound, and deciding upon a simple, yet satisfactory physical measure of the level of sound, and then the measuring of noise produced by various kinds and classes of vehicles.

A physical measure of sound was judged acceptable if, through group judgments, it proved statistically equivalent to psychologically derived measures. Thus, physically measured sound was related to sound heard as different by human respondents. Four psychologically derived measures of sound were compared with two physical measures.

The physical measure of noise—sound level in decibels as measured on the A scale of a standard sound level meter—was selected as being statistically indistinguishable from the best psychologically derived measures in its reliability as a predictor of human response to vehicle noise. Most of the noise level results described in this report are expressed in terms of this measure, commonly referred to as "dBA."

Noise from individual motor vehicles has two major components: engine-exhaust, and tire-roadway interaction. By and large, most modern passenger cars as produced by the manufacturer generate as much noise by tire-roadway interaction as by engine-exhaust under normal operating conditions. Acceleration, however, produces more engine-exhaust noise.

Large diesel trucks represent a relatively small proportion of total traffic on urban highways, often 5 percent or less. They are, however, significantly noisier than cars. A high proportion of diesel trucks use reasonably good muffling practices. The ultimately controlling factor on total noise output is that produced by tire-roadway interactions. Assuming maximum muffling, mechanical noise control, and normal tire tread designs, a large diesel truck-trailer combination would be expected to produce 10 to 15 dB higher noise levels than a passenger car at the same road speed simply due to the relative contact areas of the tires with the road.

A survey of difficulties involved in the legislative control of vehicle noise suggests that only extreme and deviant noises can be controlled—such as noise produced by faulty mufflers. Both the objective measurements reported and the simulations undertaken here indicate that deviant noise sources are minor in their contribution to total highway noise.

Following the analysis of noise measures and of measured noise for various vehicles of various types, a computer simulation model was evolved which allows the engineer, designer or researcher to set the following conditions: average vehicle speed, number of lanes, density or flow of traffic, proportion of trucks to cars, and distance to the measurement site. Given those conditions, in any possible combination, computer estimates are made which are extremely close to those actually read from a meter. This simulation model enables the prediction of what vehicle noise will be for any existing or planned highway situation for freely flowing traffic.

Simulations made in the present study clearly show the effects of speed, of the proportion of trucks, and of traffic density on noise measured at different distances. At low speeds, and with truck traffic, wide variations in noise due to the intermittent peaks produced by trucks are found at a single site. But these variations decrease when speed and density are increased and truck traffic is decreased. In general, the simulations are used to obtain the time average noise level, and the noise level variations around this average, as a function of the these parameters. All simulations show the effect of traffic density and speed.

As might be expected, the range of noise levels around the time average decreases with increasing density of traffic. For an average density of 10 vehicles per mile, at 50 miles per hour, the time average noise level for passenger cars at a distance of 100 feet is about 60 dBA. The instantaneous noise levels normally distributed about this mean have a standard deviation of 4 dBA. Thus, 95 percent of the time (2 standard deviations) the instantaneous noise levels would be expected to lie between 52 and 68 dBA.

The addition of trucks to the passenger car mixture skews the time distribution of noise levels upward as the percentage of trucks increases due to the higher noise levels produced by individual trucks as compared to individual passenger cars.

It is important to observe that these results are aimed at describing the distribution of noise levels as a function of time. The maximum noise produced instantaneously by the passage of a single vehicle may be in excess of these values.

While these are general conclusions, specific guides are provided in the body of the report, allowing relatively precise noise determination for a number of common traffic situations. Thus, the planner or engineer can predict the effects of increasing density, speed, and trucks in a specific situation.

In interviews with more than 300 residents living within sight of a freeway, 70 percent of the upper socio-economic class residents living in an area of little freeway noise expressed annoyance, while only half of residents of the noisiest area did so. Yet the second area is almost four times as noisy as the first.

The interview study began with the assumption that living near a freeway has both advantages and disadvantages. Statistical analysis, however, indicated that residents judge their living situation in four distinct ways: convenience, attractiveness, intrusion (including odor and vibration, as well as noise) and necessity for handling the existing traffic volume.

When environmental features other than noise—landscaping, distance to freeway, visual dominance, and so forth—were considered, they were found to be only moderately related to voluntarily expressed annoyance with freeway noise. Predictions of spontaneous annoyance were actually not quite as good as predictions made from the interview data alone. Obviously, prediction of reactions must include consideration of both physical and psychological factors. Actually, 90 percent of those who did *not* express annoyance were accurately classified. It is clear that it is not only the actual noise level, but the total situation, including attitudes toward highways and freeways in general, which leads to expressed annoyance with noise.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

The over-all objective of the research is specified in a quotation from the original project statement:

> Questions related to highway noise levels and their effects on the users of adjacent property arise frequently in planning and design of highway improvements, particularly in urban areas. It is important to have means of evaluating probable noise levels for the various classes of highways and the effectiveness of controlling highway noise through highway design features as well as to reduce noise production through legislation and enforcement of vehicle regulations.

The work is thus concerned with the physical (that is, the directly measurable noise produced by highway vehicles) as well as with the perceptions of that noise by, and concomitant responses of, urban residents.

An important point of possible confusion concerns the view of the role of this research. One might interpret "standards for highway noise" as relating primarily to statutory limits on noise production by individual vehicles or planning and design criteria to protect communities from undue traffic noise intrusion. The latter view is supported by the following:

(1) *Technological.*—The level of muffling of engine exhaust noise on new vehicles and on vehicles operated by responsible parties appears to be a sensible engineering compromise between the ultimate attainable and other design and operating requirements. Further, tire-roadway noise and engine-exhaust noise are both important contributors to the total noise.

(2) *Legal.*—The effectiveness of statutory means for enforcement of noise standards is dependent on test procedures, equipment, officer training, court rulings, etc., in dealing with willful deviators. In the past, the courts have both upheld and disallowed citations from objective and non-objective statutes. The determination of reasonable objective levels to discriminate deviant vehicles which are too noisy from the normal vehicle population is relatively straightforward, and such levels are recommended in this report (Chapter Three).

(3) *Highway Location and Design.*—Major differences in noise intrusion into urban communities can result from design and route-determination decisions. Highway planners need information on the physical noise consequences of traffic flows and roadway configurations. Further, they need information on the probable effects on a neighborhood resulting from introduction of a new highway.

(4) *Rationale.*—Deviant vehicles are not the major noise source and, in any event, are generally recognizable and can be cited under present statutes, with some success. On the other hand, new highways must be located and designed without sufficient data on the probable normal noise consequences, because noise intrusions that are seemingly acceptable in some neighborhoods would be intolerable in others.

The present study has several major aspects. First, various physical measures of noise were compared, and a relatively simple physical measure was demonstrated to be suitable for subjective response evaluation. From these measures, from theoretical considerations, and from evidence collected in field studies, a simulation model of physical noise stimuli from freeways or highways has been generated so that designers and highway engineers may anticipate the noise which will result from a specific highway situation.

An interview study was designed to assess reaction to noise by residents living relatively near freeways or highways, in the Los Angeles area. These interviews were conducted in the attempt to determine general annoyance with highway noise expressed by residents living relatively near a freeway, and to attempt to relate this annoyance to objectively measured noise, to other features of the physical environment, and to place noise annoyance in perspective as it is seen as part of the larger problem of living near a highway.

Finally, the data developed in this work were related to some design features of highways such as traffic theory, grade location, road surface, and other parameters to indicate the relative effect of these highway design elements on the noise produced by freely flowing traffic.

RESEARCH APPROACH

The research undertaken in this report does not constitute a single approach to the study of noise: it encompasses a number of research approaches.

Previously collected data have been re-analyzed, both laboratory and field experiments have been performed, objective measurements were made in the field situation, and subjective reactions to the freeway have been obtained. Additionally, computer equipment has been utilized as a major aid to the research approach, to enable simulation of noise measurements which could not be taken in actual field situations, and to provide more sophisticated treatment of the interview data, enabling prediction from those data also. A review of legislative control has been made to aid in the construction of a design guide.

Concentration has been on the following lines of research: (1) data from experiments on human judgment of vehicle noise were reviewed and a thorough analysis was performed to enable the selection of a single measure of highway noise; (2) a detailed analysis of noise produced by different kinds of highway vehicles was undertaken to estimate the important components of highway-produced noise, and to develop generalized estimates of the noise produced by particular kinds of vehicles; (3) a model for the prediction of noise from traffic was extended and implemented on a computer to allow for extensive studies of the effects of changes in the parameters of noise generation and propagation; and (4) a field interview was designed for residents very near highways and freeways, which first enabled the respondent to express annoyance (or to fail to express annoyance spontaneously) with noise generated by the adjacent highway. A variety of predictive measures were then used to determine the extent with which expressed verbal annoyance could be anticipated.

This last study was undertaken on the assumption that spontaneously expressed annoyance is the first link in a chain of responses which may ultimately lead to more extreme forms of complaint. Finally, there has been an attempt to relate objective noise measurements to subjective annoyance in the field situation.

Both the simulation model and the interview techniques, relatively sophisticated and new in their respective areas, have been shown to produce impressive and useful results. First, a simulation model now exists which may be expanded to permit specification of other parameters or which may be used to predict various new traffic situations. Second, the interview approach has provided meaningful results in a single geographic area, and has demonstrated that those who live near freeways are not a single group. Also, it has suggested that there is a need for further study of the various freeway populations, freeway-adjacent residents of different kinds, and users of different kinds.

TERMINOLOGY

For the convenience of the reader, a "Glossary of Acoustical Terminology" is included as Appendix G.

CHAPTER TWO

FINDINGS

The findings from this research can be discussed under five topic headings:

Selection of a physical measure of noise.
Analysis of noise from individual vehicles.
Simulation of noise from traffic flows.
Reaction to traffic noise in a natural setting.
Review of attempts to control vehicle noise by legislation.

Important conclusions are presented in this chapter. Technical details are contained in a series of appendices.

SUMMARY

The noise produced by individual vehicles can be characterized quite accurately in terms of a measurable physical value—noise level in dBA. The noise from flows of mixed traffic can be estimated closely by computer simulation techniques, with accuracy comparable to field measurements. Although people can judge the relative strength of noises quite accurately when the noises are presented in an experimental setting, their expressed annoyance with traffic noise in their natural residential environments does not show a strong relationship with physical noise measures. People's expressed annoyance is found to be strongly affected by their frames of reference about freeways in general and about living near a freeway. Separate factors of judgment relating to convenience, intrusiveness, attractiveness, and necessity for the freeway have been demonstrated. Other physical characteristics of the environment, aside from noise level, are shown to be important variables influencing people's judgments, although the measures for these other environmental factors are still crude. Finally, indications are that attempts to control vehicle noise by objective noise level legislation have not been highly successful. Appropriate levels for limits for individual vehicles are suggested with the caution that the more important noise problems often stem from high-speed, high-volume traffic flows rather than deviant individual vehicles. Thus, the control of noise through highway planning is more likely to be fruitful than is enforcement of vehicle limits. This situation may change if clear, objective limits for vehicle noise can be adopted by a majority of statutory agencies and be rigorously applied to the occasional excessively noisy vehicle.

SELECTION OF A MEASURE FOR VEHICLE NOISE

It is believed that the A-scale noise level in units of dBA as measured with the A-weighting network of a precision sound level meter is the most practical measure of noise from today's highway vehicles. When applied to the noise from highway vehicles this measure correlates as well with human judgments of the acceptability of the noises as do the more elaborate methods.

Two criteria are important in the choice of a stimulus measure: (1) a high correlation between judgments of acceptability of the noises and values assigned to the noises by this measurement unit, and (2) a unit obtained as directly as possible from field measurements rather than from extended calculations.

The measures commonly used today for noise description tend to fall into two groups. The first group includes those attempting to represent as faithfully as possible the results of human judgments in laboratory situations. (Such measures as loudness level or perceived noise level are almost inevitably calculated from sound pressure level data taken in octave or ⅓ octave bands of frequency.) These calculation procedures generally preclude direct measurement in the field. The second class of measures is those that can be made directly at the measurement site with simple instrumentation. This includes measurements taken with a sound level meter on one of the several frequency weighting networks.

Statistical calculations have been performed with sets of noise source descriptions and judgments from panels of observers to determine the degree of correlation between each of the alternative measures and the sets of judgments. (See Appendix A.)

Of the simple objective measures of the noise only the A-scale noise level in dBA performs creditably. Of the calculated measures, several alternative methods for calculating loudness level and the method for calculating perceived noise level all performed creditably. Comparing the best of the two types in performance and considering the problems of field measurements, the A-scale noise level in dBA should be used for engineering descriptions of the noise from present-day highway vehicles. Perceived noise level stated in units of PNdB should be considered as the more precise measure in laboratory studies and where new noises of different frequency characteristics are encountered.

A major advantage to be obtained from use of the A-scale noise level is the ready availability of good instrumentation for field measurement. The situation was not always thus. In the mid-1950's, when the American Trucking Associations (ATA) sponsored studies of truck noise (*1, 2*), instrumentation was not as well developed, particularly microphones for precision field measurements. Those studies concluded that the A-scale measure did not perform as well as a calculated measure of loudness of the noise using an early form of loudness function based on pure tones. The voluntary standard of 125 sones at 50 ft for truck muffling was established using this early method of loudness calculation (*3*).

Analyses indicate that for the data of the earlier experiments, A-scale measurements, if made with presently available equipment, would correlate as well as the calculated loudness measure and would be a better choice because of simplicity. Further, the equivalent-tone-sone method of computing loudness used for the ATA voluntary standard has been superseded by later developments in the calculation of loudness level and perceived noise level (*4, 5, 6, 7*).

ANALYSIS OF NOISE FROM INDIVIDUAL VEHICLES

The major vehicle categories in the description of traffic noise must be the large trucks and passenger cars—the trucks are inherently very noisy sources even though standards of muffling and operation are generally good, and the cars represent a large proportion of the total traffic.

Passenger cars do not differ greatly as noise sources. This might be expected from the similarities among different models and the manufacturers' concern with good muffling practice. In contrast, trucks are a heterogeneous population of noise sources due to important differences in design of their engines and auxiliary equipment, and considerable differences in their size.

Other categories of vehicles demonstrate wide variation in noise source characteristics. Motorcycles are the major example of a class of vehicles whose noise performance could easily be improved. The noise produced by different models of motorcycles seems to bear little relationship to the size or power of the vehicle but rather to differences in muffling practice.

Noise from Passenger Cars

A characteristic noise spectrum shape has been generalized that is a good approximation to the frequency distribution of the noise produced by passenger cars of many models, ages, and manufacture over a variety of speed and road conditions. This generalized noise spectrum is an important basis for the method for determining noise exposure by simulation of traffic flow. The noise spectrum is relatively flat across the first six octave bands of frequency and drops off more sharply at 2,000 Hz and higher frequencies. (See Figs. B-4 and B-10.) Under normal operating conditions, the spectrum is found to be a composite of relatively equal contributions of noise generated by (1) the engine and the exhaust system, and (2) the tire-roadway interaction. (See Figs. B-3 and B-4.)

The measured data (Appendix B) show the effect of speed on passenger car noise. When the 50-mph condition is a base, the noise level can be expected to rise 3 dBA at 65 mph and drop 5 dBA for 35 mph cruise condition. For example, the noise level 50 ft to the side of a car passing at 50 mph is about 67 dBA. At 65 mph, the level would be 70 dBA, but at 35 mph the noise level would be 62 dBA.

When the noise produced by passenger cars is described in terms of the A-scale noise level in dBA, then the following empirically derived equation approximates the noise produced on typical pavements at various speeds:

$$\begin{aligned} L_{auto} &= 16 - 10 \log_{10}\left(\frac{d}{50}\right)^2 + 30 \log_{10} v \\ &= 50 - 20 \log_{10} d + 30 \log_{10} v \end{aligned} \qquad (1)$$

in which

L_{auto} = noise level, in dBA;

d = distance, in ft, to auto; and

v = speed, in mph.

At 50 mph this equation gives a noise level of 67 dBA at 50-ft distance. The slope of the speed dependence of the equation justifies theoretical considerations that the sound pressure should increase approximately as the third power of the vehicle speed (the equation as stated here takes account of the fact that noise level in dBA is a logarithmic function of sound pressure). (See Appendix B for limitations on use of the equation.)

The observed data for passenger cars indicate that this approximation is a good one for typical concrete or moderately rough asphalt roadways. The degree of roadway surface roughness is found to be an important factor in passenger car noise. Differences of as much as 5 dBA above and below the values given by the equation have been found for very rough and very smooth pavements, respectively. (See Figs. B-7, B-8, and B-9.)

Maximum acceleration conditions for automobiles produce noise levels of the order of 6 dBA above those for cruise conditions. (See Fig. B-5.)

Noise from Trucks

The diesel truck noise spectrum developed from measured data for use in the simulation studies results in an A-scale noise level of 82 dBA at 50 ft. It must be emphasized, however, that it should not be concluded that all trucks will produce 82 dBA at 50 ft on level roadways. The noise level measured at a given distance from the roadway will vary more from truck to truck than from car to car because of the greater variability in truck designs and muffling practices. (See Table B-2.)

For large diesel trucks, the principal noise source seems to be the engine and exhaust system, with tire-roadway interactions being less prominent. A generalized noise spectrum shape has been determined which peaks somewhat more in low frequencies than does the passenger car spectrum, due to the predominance of exhaust noise. (See Figs. B-12 and B-13.)

It is worth noting that the 82 dBA value used here for trucks is 15 dBA higher than that used for passenger cars at the same distance, or a factor of three times as noisy. (See Table B-1.) Another way of comparing trucks and passenger cars is that it would take 30 passenger cars having noise levels of 67 dBA to produce as high a total noise level as one truck at 82 dBA.

There is an effect of roadway grades on the noise produced by trucks, but the difference is only about 2 dBA between the average for samples of trucks on 3 to 5 percent up-grade and on level roadway. On the other hand, the acceleration of trucks from low speed on level roadways produces noise levels that are about 5 dBA higher than those generated under cruise conditions.

No clear-cut indication of the effect of speed on the noise produced by large diesel trucks can be found in the data. Indeed, there is reason to believe that the effects of speed are minimized because of the predominance of engine and exhaust noise over tire-roadway noise. Since trucks tend to operate at nominally constant rpm, engine and exhaust noise does not vary appreciably with vehicle speed under level roadway cruise conditions. (See Appendix B.)

The data do not show appreciable relationship between road surface and the noise from trucks, except for certain tread designs (*8*). It is probable that such a relationship will not be strongly evident for trucks because of the predominant engine and exhaust sources of noise, whereas the passenger car noise includes a greater component of tire-roadway interaction noise.

Noise from Other Vehicles

Some analyses of noise from motorcycles and sports cars indicate that these vehicles are, as a class, noisier than passenger cars (and indeed, in some circumstances noisier than trucks). However, no strong correlation can be found between the size or power of the vehicle and the noise it produces, indicating that the noise level differences come from large variations in muffling practice. The tire-roadway interaction noise from these vehicles is generally comparable to that from passenger cars. (See Fig. B-14.)

SIMULATION OF NOISE FROM TRAFFIC FLOWS

An earlier model (*9, 10*) has been extended for predicting the time history of noise produced by highway traffic, and implemented on a digital computer. The simulation model was implemented first on a Digital Equipment Corporation PDP-1 computer, and then updated and extended for use on an IBM System 360/30. The performance of the model has been validated in several ways, including direct comparison against the noise levels measured for several traffic situations, and by comparisons with the predictions of the previous model, independently validated in past years. (See Fig. 1.) Not only are dBA means and standard deviations approximately the same for measured and simulated data, but also histograms of dBA by percent of time are similar. (See Figs. C-2 and C-3.)

Figure 2 is a nomogram relating vehicle density, average speed, and traffic flow.

Without the use of such a simulation model, noise measurements would have to be made under a great variety of conditions in order to generalize relationships from measurement data alone. The difficulty with field measurements, aside from the time and expense, is that many of the conditions which should be explored cannot easily be found at sites where valid acoustical measurements are possible. Noise from other traffic flows, problems of reflections from nearby surfaces, and other difficulties limit the available measurement sites. Further, it is by simulation runs using values more extreme than those normally encountered in real traffic flows that some of the relationships can best be highlighted, and such analysis is only possible in laboratory simulation.

Simulation Results

First explorations with this computer-based simulation tool included the investigation of the effects of variation, one at a time, of speed, total vehicle flow, and distance from roadway. The results from these variations are as follows:

(1) The average noise level from freely flowing passenger vehicle traffic varies approximately with the third power of the average speed of the traffic. (See Fig. 3.)

(2) Increases in the total vehicle flow increase the average noise level and, in addition, reduce the fluctuation in noise levels. For traffic volume flows in excess of about 1,000 vehicles per hour, at a fixed average speed, noise level varies almost linearly with total vehicle flow. (See Fig. 3.)

(3) Increases in distance between the observation point and the roadway decrease the average noise level at approximately the first power of distance and decrease the

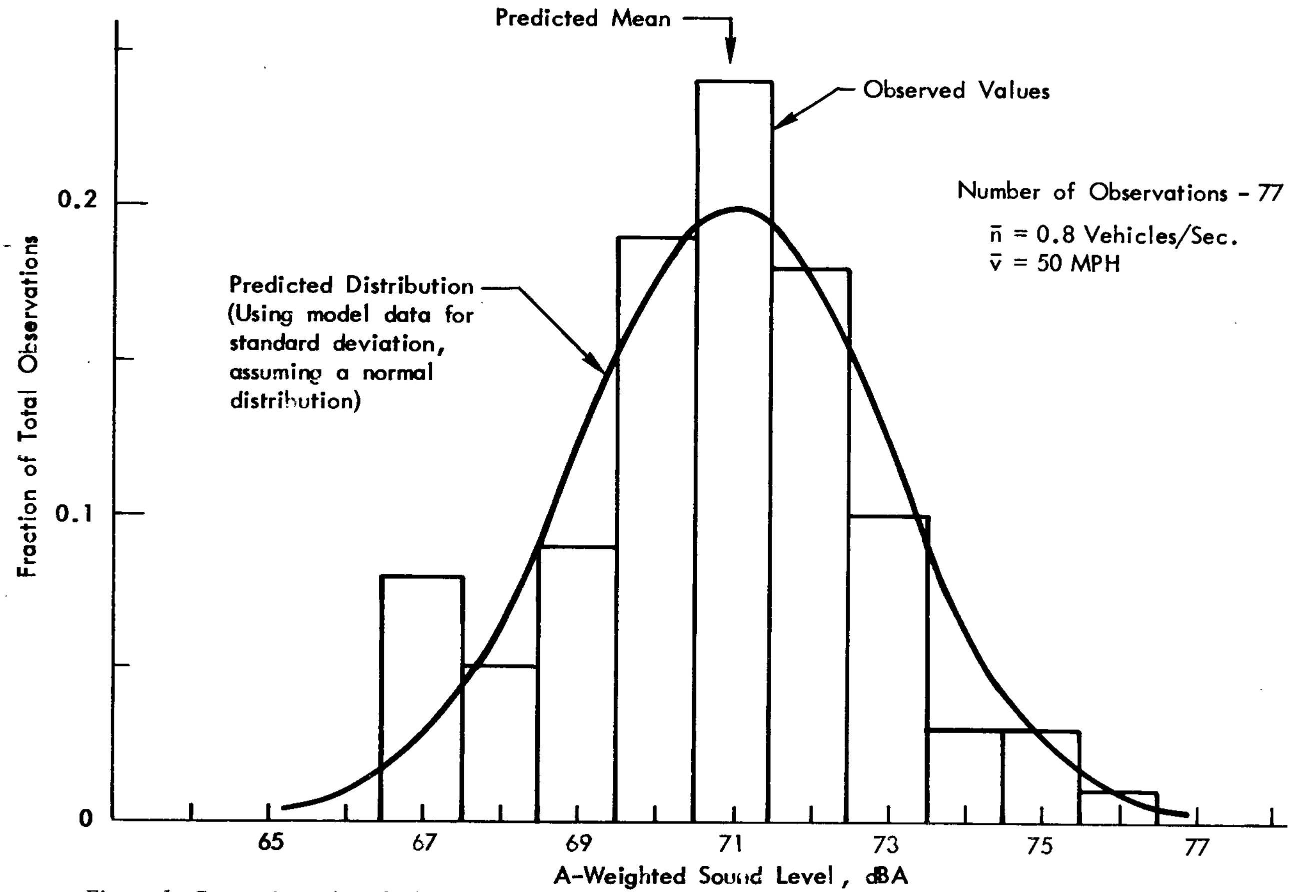

Figure 1. Comparison of prediction model with measured noise level for passenger cars.

fluctuations around the average noise level. (See Figs. 4 and 6.)

(4) The noise from multi-lane highways may be simulated by using total volume flow for all lanes for computation in the model. An effective distance to the observation point is determined by assuming all traffic to be located on a single pseudo-lane located at the geometric mean distance to the observer determined by the distance from the observer to the nearest and farthest lanes. For example, traffic on an eight lane highway would be considered to be traveling on a pseudo-lane located 2.8 lane widths in from the center line of the nearest lane. $[(1 \times 8)^{\frac{1}{2}} \simeq 2.8.]$

The simulation model includes capabilities for handling mixtures of several categories of vehicle noise sources in the traffic flow. Analysis of the effects of large diesel trucks and passenger cars in mixed flow shows that the average noise level and the amount of fluctuation both increase with a mixed flow over the values produced by passenger car flow alone. These increases are due to the 15 dBA higher noise levels produced by individual trucks. (See Figs. C-3 and C-4.)

A simplified analytical form for the simulation model can be used for passenger cars on a level highway at traffic flows above about 1,000 vehicles per hour. The mean noise level in dBA is given by:

$$\begin{aligned}\bar{L} &= 10 \log_{10} \frac{q \times 100}{d} + 20 \log_{10} \bar{V} \\ &= 10 \log_{10} q - 10 \log_{10} d + 20 \log_{10} \bar{V} + 20 \qquad (2)\end{aligned}$$

in which

q = traffic volume flow, in vehicles per hour;

d = distance, in feet, to pseudo-lane; and

$\bar{V}$ = average traffic speed, in miles per hour.

Thus for a traffic speed of 50 mph, $d = 100$ ft, and $q =$ 2,000 vehicles per hour,

$$\bar{L} = 10 \log_{10} (2{,}000) + 20 \log_{10} 50 = 67 \text{ dBA} \qquad (3)$$

The effect of truck noise superposed on passenger cars can be estimated by adding the following dBA values to the value of $\bar{L}$ calculated in Eq. 3.

If, in Table 1, 10 percent of the traffic of 2,000 vehicles per hour were trucks, the resulting average noise level would be $67 + 4 = 71$ dBA.

It is expected that the calculations will produce an answer within 2 dB of that obtained from the more detailed simulation results shown in Figures 3 through 6. For lower traffic flow values, the design charts should be employed.

Again, it should be emphasized that the calculation

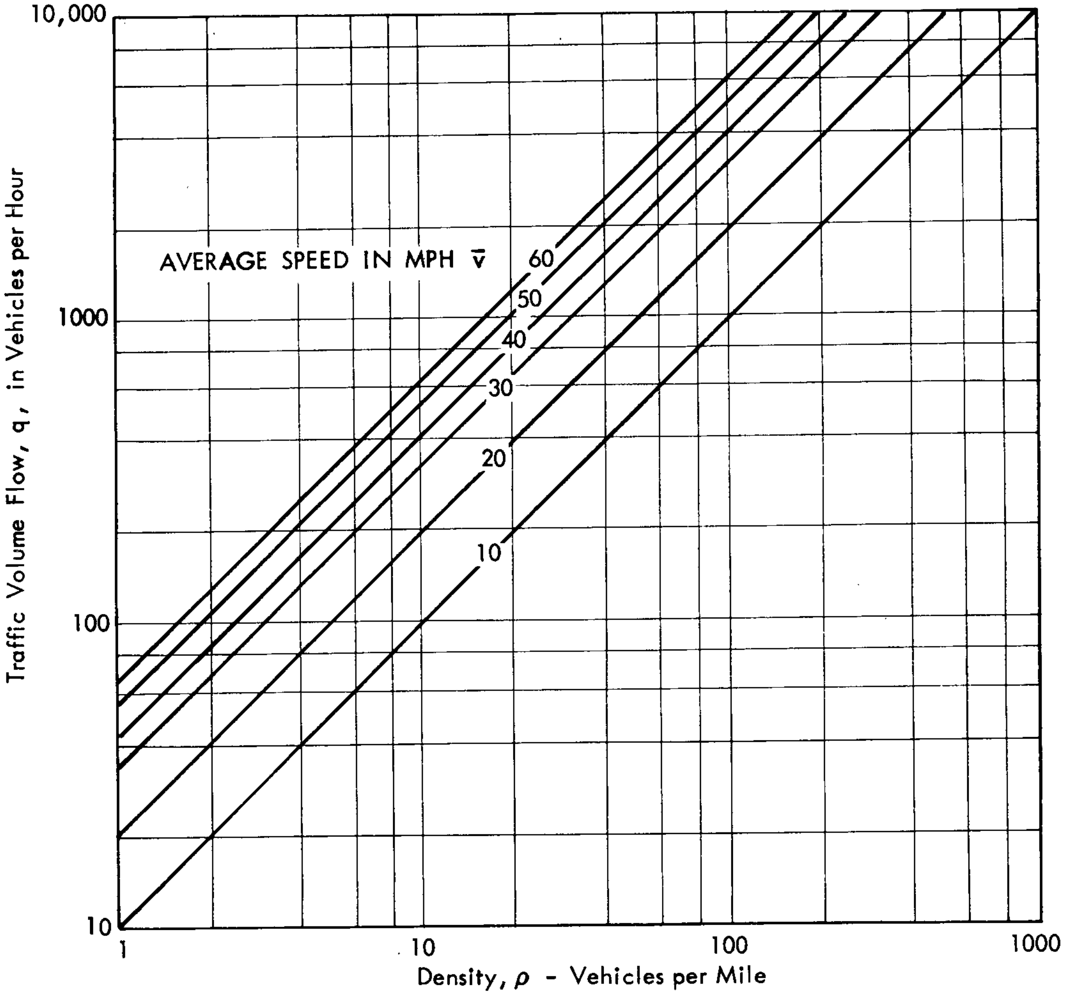

Figure 2. Nomogram relating vehicle density, average speed, and traffic flow.

yields the time average noise level, not the noise level of an individual vehicle. (See beginning of this section.)

An example of the predictive ability of the expression compared to a set of measured noise levels is shown in Figure 1. A distribution curve is also shown. This curve was computed by assuming a normal distribution having a a standard deviation as given by the simulation model in Appendix C.

REACTION TO NOISE IN A NATURAL SETTING

Reactions to Freeways in General

More than 300 adult residents, either living near a major highway or freeway, or being close enough to see one, without major intervening residences, were interviewed at five selected sites differing in measured freeway noise.

A pre-test suggested that users of freeways who do not live near them judge freeways or highways in general according to several major dimensions of judgment. Most important among these dimensions is a general attitudinal or evaluative one indicating that freeways are good, pleasing, and important, or conversely that they are bad, annoying, and unimportant. The second major dimension of judgment included a judgment of the noisiness or quietness of highways or freeways in general. These were discovered to be, for users, statistically independent judgments, so that any particular highway might be judged as good and quiet or good and loud.

The field interview, however, suggested that people who live near freeways have a different general orientation to freeways and highways in general. A special picture test, where a series of pictures of freeway scenes was judged on a series of seven-point scales defined by polar adjectives, was given in only two study areas. One study area, that was both economically most prosperous and most distant from the freeway (and also, most quiet), showed a similar general frame of reference to that of the users in the pre-test.

Residents in the other area, however (that with the highest noise levels), showed a completely different set of dimensions by which they judged highways and freeways, and the major dimension of judgment was that which included scales defined by both pleasing and quiet. The second major dimension they used was a judgment includ-

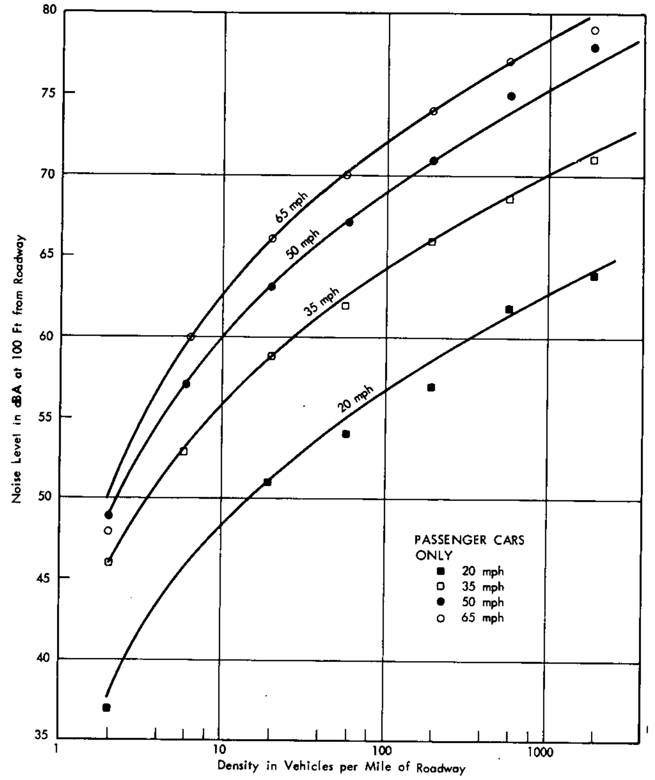

Figure 3. Curves for estimation of mean noise level in dBA at 100-ft distance from a lane (or single-lane-equivalent) of passenger car traffic, for four speeds.

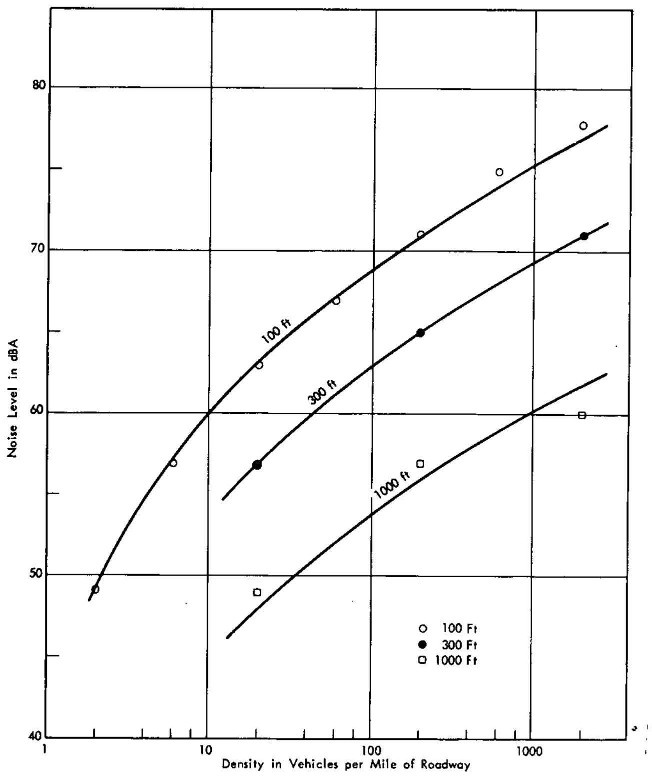

Figure 4. Curves for estimation of mean noise level in dBA at three distances from a lane (or single-lane-equivalent) of passenger car traffic at 50 mph.

ing goodness and fastness of the highway. Thus, respondents in that area appeared to differentiate between the pleasurable aspects of highways, which include the element of quietness, and the good aspects of the freeways which are associated primarily with speed.

The failure to find a generalized frame of reference within which most people judge highways or freeways, suggests that separate analyses must be performed for certain sub-sets of the population.

Reactions to Living Near a Freeway

On an *a priori* basis, five disadvantages and five advantages to living near a freeway were listed. Each respondent was asked the extent to which he objected to the disadvantages or the extent to which he appreciated or failed to appreciate the advantages.

This *a priori* selection or division of attributes into advantages or disadvantages failed to describe adequately individual responses made by people living near highways. First, two attributes which were considered by the investigators to be disadvantages to living near the freeway were not considered disadvantages by the respondents. Thus, most of the residents found lights very attractive and they found the general appearance of the freeway to be positive rather than negative.

In general, four major dimensions of judgment, accounting for roughly 60 percent of the variation in individual judgment of the attributes of living near a freeway, were found. The first dimension or factor of judgment included judgments of the convenience to work, recreation, and shopping.

Uniformly, convenience to recreation was most important for residents in each area. For males in each area, convenience to work was second highest as an advantage, and for females, convenience to shopping was second highest as an advantage to living near freeways. The second dimension of judgment includes the items already mentioned—lights and general appearance. The third dimension or factor of judgment is one labeled *intrusion*. This includes the items of odor, noise, and vibration, all of which are

TABLE 1

EFFECTS OF ADDING TRUCKS TO VEHICLE MIX

% OF TRUCKS IN TRAFFIC	ADDITIONAL dBA
0	0
2.5	1
5	2
10	4
20	8

objectionable to people living near freeways. Although, among all residents, noise was the annoyance most frequently mentioned spontaneously, when residents live close enough to a freeway to perceive disagreeable odor and vibration these are considered more intrusive than noise itself.

The fourth dimension of judgment is primarily a judgment that highways and freeways are necessary for the number of cars in a given area.

The tenth attribute, the ease of driving on a non-stop highway or freeway, showed no clear relationship to the others, being equally related to the general convenience factor and to the necessity factor.

Relationships Among Individual Reaction Measures

The single scale item asking for annoyance with the noise from their particular freeway location was not an adequate indicator of those who would spontaneously or voluntarily express annoyance with noise. However, taking all four interview factors or dimensions of judgments of living near a freeway, 64 percent of those who expressed annoyance and those who failed to express annoyance were predicted. Actually, the same level of prediction was achieved by the use of only two dimensions in the judgments of freeways, one of them the judgment of *attractiveness* and the second the judgment of *intrusion*. The judgment of intrusion, utilizing three judgments, rather than a single judgment, enables more precise and sensitive measure of general annoyance with the freeway. It is interesting to note that over the total sample, judgments of unattractiveness were not related to judgments of intrusion or annoyance, but when they did occur together in a single individual the probability that that individual would also express annoyance was greatly heightened. These relationships are associations, and no cause and effect statements can be made, but it is known that even when the same small stretch of freeway is being judged, those who find it least attractive are most likely to complain about both noise and lack of attractiveness.

Physical Properties of the Environment

Measures were taken of the distance from the interview site to the actual highway and the actual noise level was measured outside of the house. Also, the length of exposure to that particular freeway was ascertained by questionnaire. A sampling from the assessor's office gave a median property value for sub-sets in the major sample areas, and an attempt was made at coding other environmental features such as visual dominance (the amount of freeway seen by the respondent), intervening features, a surface street or an open buffer area, and landscaping.

These physical features separated statistically into two different factors or dimensions. These factors indicate the following relationships: when a house is far from the highway, that highway has less visual dominance, there are more intervening features between the house and the highway, and the median property value is higher. Certainly none of these relationships is surprising, except that the median property value may only represent local conditions.

The second dimension of interrelationships among physical features combined the attributes of noise, lack of landscaping, and long exposure. For the sample set considered, at those locations where measured noise was highest, there was no landscaping, and residents of the area were more stable, having lived there longer. No causal relationship between these factors should be inferred in extrapolating to other sites.

That neighborhood having the highest sound levels was a lower socio-economic area where little attention had been paid to landscaping. Again, these are observed relationships or associations; but it might be noteworthy that these are the people who are least likely to exert political influence in the matter of highway location or maintenance, and, indeed, are the people least likely to complain about features of the highway or freeway. By far the most noise complaints came from the quietest area, the area of highest socio-economic status.

Attempts at predicting expressed annoyance with freeway or highway noise by using physical features including measured noise were statistically significant, but not of much practical importance.

This failure to find a relationship between measured noise and subjective annoyance has been reported elsewhere (*11*). In the present instance, the mean measured noise levels for those who did express annoyance were only 1 dBA higher than the mean measured noise levels for those who did not express annoyance.

Most importantly, however, in one area where attitudes were tested toward freeways or highways in general, as well as dimensions of judgments related directly to living close to a freeway, it was possible to predict with amazing accuracy those who would voluntarily express annoyance. The measure of attitudes toward freeways or highways in general did not in itself predict well, but it added significantly to dimensions of judgments about living near the freeways, so that using all of the available interview data for that particular area (excluding any physical measurements or demographic variables) 82 percent accurate prediction was achieved.

It appears that a set of particular values and judgments, usually unrelated, combine to provoke the individual into responding with annoyance to freeway noise. In general, those who expressed annoyance find the freeways much less attractive, much more intrusive, less quiet and pleasing, and much more dull. Those who are annoyed by noise find the freeway generally intrusive, and they view the highways and freeways in a generally less positive fashion.

ATTEMPTS TO CONTROL NOISE BY LEGISLATION

Most of the existing state and local legislation in the United States dealing with motor vehicle noise may be termed subjective. The majority of states and large cities employ elements of the *Uniform Vehicle Code* published by the National Commission on Uniform Traffic Laws, Washington, D.C. This code states, in reference to noise,

> Every motor vehicle shall at all times be equipped with a muffler in good working order and in constant operation to prevent excessive or unusual noise and annoying smoke,

> and no person shall use a muffler cutout, bypass, or similar device on a motor vehicle on a highway.

There is no statement in this code on an objective measure of permissible noise. Enforcement depends on the police officer's judgment of what is excessive or unusual noise. The wording obviously is subject to many interpretations, and this ambiguity has led the courts on some occasions to declare such legislation to be unconstitutional, although it has usually been upheld.

In the case of *Smith vs. Peterson* in the California Appellate Court (1955), the plaintiffs, engaged in the manufacture, sale and installation of mufflers, contended that the vehicle code was unconstitutional on the grounds that no reasonable standard was established by the requirement that every motor vehicle be equipped with a muffler adequate to prevent "excessive or unusual noise."

The court held, however, that the wording was sufficiently certain to inform persons of ordinary intelligence of the nature of the prohibitive offence and thus sufficient to establish a standard of conduct. It was further held that what is usual is now a matter of common knowledge and anything in excess of that is excessive and unusual.

On the other hand, in the *People vs. Sisson* (1958, Schenectady County, New York), a similar statute was declared unconstitutional because it failed to set up a standard sufficient to define a violation thereof and because it required too much interpretation on the part of law enforcement officers.

Again, in 1954, in the *People vs. Zanchelli* in Columbia County, New York, the court declared a statute invalid and a denial of due process of law because the phrase "unnecessary noise" did not constitute a sufficiently definite standard.

Dissatisfaction with the vagueness of the current statutes has promoted some interest in replacing them with legislation specifying the objective measurement of motor vehicle noise on a sound level meter.

To investigate the present status of such objective legislation for the control of motor vehicle noise, 16 cities across the United States were surveyed.* Questions were asked regarding the existence of objective motor vehicle noise legislation, procedures employed, problems encountered, and the effectiveness of the legislation in terms of compliance and enforcement.

Of the 16 cities, only three—Bloomington, Ind.; Cincinnati and Cleveland, Ohio—have objective noise ordinances.

The Bloomington, Indiana, ordinance specifies a top noise limit for all vehicles of 95 dBA measured at 20 ft from the right rear wheel.

Cincinnati's ordinance, passed in November 1958, is substantially the same, though slightly more lenient. It also specifies a maximum noise level of 95 dBA and a distance of 20 ft but does not require that the distance be measured from the rear of the car, where the maximum exhaust noise is normally found.

Police records indicate that only two citations have been made in Cincinnati as a result of the use of the sound level meter. Enforcement must be done on a selective basis since the city owns only one sound level meter. The effectiveness of the ordinance is also questioned by a member of the police force who suggests that the maximum noise level of 95 dBA is too high to control noise effectively in residential neighborhoods. In these areas there are many complaints about motor vehicle noise, but when tested it falls below the maximum limit.

The ordinance in Cleveland is considerably different. It specifies 95 dB (presumably on the C scale) measured not less than 5 ft from the source.

Two of the cities—Columbus, Ohio, and Milwaukee, Wis.—have had experience with objective motor vehicle ordinances, but in both places the statutes have been repealed.

Columbus reports that their ordinance proved unenforceable and cumbersome, and consequently it was repealed in 1958. The problem resulted from the difficulty of isolating the noise of one particular vehicle on heavily traveled streets.

In Milwaukee, on the other hand, city officials felt their objective ordinance was an effective method of handling complaints, but it had to be repealed in 1957 when the Circuit Court ruled it unconstitutional after appeal of a conviction. This ruling was based on the argument that it was a local ordinance, and that it was unfairly affecting the nonresidents driving through.

At present, it would appear that most of the other cities † are satisfied with their subjective ordinances, though the Assistant Director of Law of Akron, Ohio, indicates that the constitutionality of such statutes is in serious question. Although there have not yet been any court cases under the existing statute, the City Council of Akron has been apprised of its questionable constitutionality.

In addition to the experience of the cities, at the state level there has been some activity in the area of objective legislation for the control of motor vehicle noise.

At the present time, a bill is under consideration in Wisconsin (where Milwaukee's local ordinance was declared unconstitutional) which would establish objective limits for motor vehicle noise on a statewide basis. This legislation would also permit cities to pass noise legislation within the framework of the state law.

In July 1965, the State of New York passed legislation which defined excessive noise as anything above 88 dBA (plus 2 dBA tolerance) measured at 50 ft (plus or minus 2 ft) from the center line of the lane of travel. Measurements must be made at speeds of less than 35 mph. In practice there appear to be some difficulties in enforcement of the law. A member of the State Police reported that records for 1966 indicate that 335 manhours were expended in order to make 16 arrests (20 manhours per arrest). All of the citations in New York have involved diesel trucks. They feel that the noise limits are so high

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* In addition to direct contact with a number of city and state officials, information was sought on current activities in the area of objective motor vehicle noise legislation from such sources as the National Highway Users Conference, the Automobile Manufacturers Association, the Society of Automotive Engineers, Inc., the Council of State Governments, and the American Trucking Associations. Several of these sources noted the existing or pending legislation at the state level; none had information about activities at the municipal level. Since the demise of the publications *Noise Control* and *Sound* there is no good source of information on activity leading toward the official establishment of objective limits for motor vehicle noise.

† Akron, Ohio; Baltimore, Md.; Beverly Hills, Calif.; Chicago, Ill.; Memphis, Tenn.; Minneapolis, Minn.; New Orleans, La.; Philadelphia, Penna.; St. Louis, Mo.; Washington, D. C.

that they automatically exclude all cars, and even motorcycles, from enforcement. (The constitutionality of that law has not been tested as all violators have pleaded guilty.)

Subsequent to the preparation of the first draft of this report, the California legislature adopted Section 23130 of the Vehicle Code which reads as follows:

Vehicular Noise Limits

(a) No person shall operate either a motor vehicle or combination of vehicles of a type subject to registration at any time or under any condition of grade, load, acceleration or deceleration in such a manner as to exceed the following noise limit for the category of motor vehicle based on a distance of 50 ft from the center of the lane of travel within the speed limits specified in this section:

	Speed Limit of 35 mph or less	Speed Limit of more than 35 mph
(1) Any motor vehicle with a manufacturer's gross vehicle weight rating of 6,000 lbs or more, any combination of vehicles towed by such motor vehicle, and any motorcycle other than a motor-driven cycle	88 dBA	92 dBA
(2) Any other motor vehicle and any combination of vehicles towed by such motor vehicle	82 dBA	86 dBA

(b) The department shall adopt regulations establishing the test procedures and instrumentation to be utilized.

(c) This section applies to the total noise from a vehicle or combination of vehicles and shall not be construed as limiting or precluding the enforcement of any other provisions of this code relating to motor vehicle exhaust noise.

(d) For the purpose of this section, a motor truck, truck tractor, or bus that is not equipped with an identification plate or marking bearing the manufacturer's name and manufacturer's gross vehicle weight rating shall be considered as having a manufacturer's gross vehicle weight rating of 6,000 lb or more if the unladen weight is more than 5,000 lb.

(e) No person shall have a cause of action relating to the provisions of this section against a manufacturer of a vehicle or a component part thereof on a theory based upon breach of express or implied warranty unless it is alleged and proved that such manufacturer did not comply with noise limit standards of the Vehicle Code applicable to manufacturers and in effect at the time such vehicle or component part was first sold for purposes other than resale.

In Pennsylvania a bill has been introduced in the legislature which would set up a maximum noise limit of 125 sones for commercial vehicles and 70 sones for passenger vehicles.

The comments received from several of the city and state officials indicate that there are a number of questions on the enforceability and legality of objective legislation dealing with the control of motor vehicle noise. Some of the problems include:

(1) The ability to prove the noise measurement is that taken from a single specific vehicle.

(2) The cost of purchasing instruments, setting up measuring stations (if such are to be used), and training officers in the new techniques.

(3) The limited number of arrests actually made in relation to the man-hours consumed in enforcing the law as a result of leniency in setting maximum noise limits and/or in the restrictions placed on the traffic officers in making the measurements.

(4) The lack of uniformity from one jurisdiction to another which results in the same automobile being in violation of the law in one place and within the law in another.

CHAPTER THREE

INTERPRETATION, APPRAISAL, AND APPLICATION

In this chapter, the findings from research are related to problem areas in transportation and urban development. The emphasis is on application, because general interpretation and appraisal of the work is also provided in summary in Chapters Two and Four, and in detail in the six technical appendices.

As noted in Chapter One, the major concern is with noise from traffic flows rather than from individual deviant vehicles. Further, emphasis should be placed on applications to planning rather than on enforcement of noise statutes or highway system operations, because the potential for alleviation of noise problems is greater. Accordingly, this chapter is divided into three sections: planning for new highways; planning for new development along highways; and coping with problems of existing highway systems.

The material presented here is an attempt to translate current knowledge into working tools or guidelines for engineering use. The report exchanges from research to consulting style, and integrates and extrapolates research data, past data, and experience to offer guidance on traffic noise. The qualifications and cautions, the underlying relationships, and the further research needs are covered elsewhere in the report.

GUIDES FOR PLANNING NEW URBAN HIGHWAYS

The planners of an urban highway segment need to be able to estimate the noise the highway will produce and the impact of this noise on existing or proposed neighborhoods. Estimation of the physical noise levels and their fluctuation is relatively straightforward, and graphs are provided for this purpose. Estimation of the impact of the noise on urban inhabitants is less certain. Qualitative factors to be considered in relation to the highway/neighborhood interaction and to socio-economic setting are provided.

A useful technique in application of these guides is an analysis of probable changes—a *before* and *after* comparison as part of the planning effort. In this, estimates of the physical noise from current traffic (local streets, stop-and-go arterials, etc.) can be compared to estimates for the new highway. Then, any clues available about neighborhood response to the existing situation can be used to calibrate an estimate of the impact from a future highway.

Prediction of Noise Produced by Traffic Flows

From simulation studies, the graphs in Chapter Two for estimation of the noise produced by traffic have been derived. These graphs may be used for quick estimates of idealized situations where use of the computer programs for simulation is not feasible or warranted. They apply to highways which are level, at the same grade as the surrounding terrain. The effects of elevated grades or cuts are considered in the next section.

The figures all refer to traffic on a single lane or a *single-lane-equivalent* roadway. This single-lane-equivalent can be considered as a hypothetical lane carrying the total flow (ignoring the overlap of real vehicles). It should be considered as located at a position displaced from the closest lane to the observer by a distance equal to the square root of the number of lanes times the lane width. For example, on a four-lane highway the effective pseudo-lane would be at the location of the second lane closest to the observer. Table 2 may be employed.

For divided highways having significantly wide median strips, noise levels on the two sides should be treated separately, then their sum obtained logarithmically, as follows.

As an alternate to the single-lane-equivalent, lanes having quite different traffic characteristics can be estimated separately and the dBA values combined according to Table 3.

Thus, values for two lanes of 72 dBA and 74 dBA would combine to 76 dBA. This might be further combined with a third lane at 76 dBA for a three-lane estimate of 79 dBA.

The simulation model is most dependent on average vehicle density, for example, vehicles per mile. (See Appendix C.) This parameter is obtained from traffic flow data by dividing traffic flow, q, in vehicles per hour by the average traffic speed, $\overline{V}$, in mph. In the illustrations in Chapter Two the parameters are plotted against vehicle density. A nomogram relating vehicle density, average speed, and traffic flow is shown in Figure 2.

Figure 3 shows four curves relating average noise level in dBA to traffic density. The curves are plotted for speeds of 20, 35, 50 and 65 mph, for traffic of passenger cars only. The graph shows that, at 50 mph, the average noise level grows from about 60 dBA for 10 vehicles per mile (vpm) to 75 dBA for 1,000 vpm.

TABLE 2

PSEUDO-LANE LOCATION

NO. OF LANES	DISPLACEMENT AWAY FROM NEAREST LANE, IN LANE WIDTHS
2	1.4
3	1.7
4	2.0
5	2.2
6	2.5
7	2.7
8	2.8

TABLE 3

ADDITION OF DECIBELS

IF HIGHER LEVEL EXCEEDS LOWER BY	THE SUM EXCEEDS THE HIGHER LEVEL BY
10 dBA	0 dBA
5 to 9	1
2 to 4	2
0 or 1	3

In applying these data, due caution should be given to the practical limitations on vehicle density in freely flowing traffic. For example, consider the relationships (*12*):

$$q = \rho\overline{V} = \rho\overline{V}_o \log_e \frac{\rho_o}{\rho} \tag{4}$$

in which

ρ_o = 264 vehicles per mile (20-ft length); e.g., maximum packing density; and

$\overline{V}_o$ = 27 mph.

Thus, for maximum volume flow, $\log_e \frac{\rho_o}{\rho}$ equals unity, and ρ is about 100 vehicles per mile in a single lane. This obviously implies that $q_{\max}$ is $100 \times \overline{V}_o$, or 2,700 vehicles per hour. Since the experimental evidence is that this is an unstable situation, more practical working capacities of 1,500 to 2,000 vehicles per hour seem more appropriate. For example, the maximum stable volume flow at 65 mph would be obtained as follows:

$$V = \overline{V}_o \log_e \frac{264}{\rho}$$

$$\frac{65}{27} = \log_e \frac{264}{\rho}. \tag{5}$$

$$\rho = 24 \text{ vehicles/mile}$$

$$q = 24 \times 65 = 1{,}560 \text{ vehicles per hour}$$

(say 1,500 for practicality)

The conditions on a multi-lane highway scale upward by the number of lanes. Using these relationships, Figures 2 and 3 can be used to determine the average passenger car noise level for multi-lane highways under conditions of maximum volume flow, that is, $q = 2{,}700$ vehicles per hour per lane, $V = 27$ mph, or, as another example, the average noise levels for maximum stable flow at a speed of 65 mph. These examples are given in Table 4 as a function of the number of lanes on the highway. The effective one-lane-equivalent vehicle density is the one-lane value of ρ times the number of lanes.

Figure 4 shows the effect of distance on the noise from passenger car traffic. Curves are shown for distances of 100, 300 and 1,000 ft, and other distances can be interpolated. The decrease in level with distances greater than 300 ft is somewhat larger than the 3 dBA per doubling of distance noted in Chapter Two, due to increased air absorption built into the model. (See Appendix C.)

TABLE 4

NOISE LEVEL AT 100 FEET FROM VARIOUS TRAFFIC FLOW CONDITIONS

NO. OF LANES	$q_{\max}$ PER HR	ρ PER MI	dBA	MAX q AT 65 MPH PER HR	ρ PER MI	dBA
2	5,400	200	63	3,000	25	66
4	10,800	400	65	6,000	50	69
6	16,200	600	67	9,000	150	72
8	20,800	800	68	12,000	200	74

Thus, for cars alone, the graph shows a reduction of 15 dBA between 100 and 1,000 ft, while the 3 dBA per doubling of distance rule-of-thumb would suggest only 10 dBA. However, for traffic containing an appreciable fraction of trucks, the 3 dBA per double distance is more nearly true.

Figure 5 compares the noise from various car/truck mixes, as a function of total traffic density. The curves show that the average noise level at 100 ft from a mix including 20 percent diesel trucks is 6 dBA greater than for cars alone, or, subjectively, the mix is more than half again as noisy as for the passenger cars alone. (See Appendix A.)

Figure 6 provides information on the fluctuations of noise levels. The graphs estimate the standard deviation of the noise levels that would be experienced at intervals perhaps 10 seconds apart. As an aid in estimating the range of noise levels that might be experienced, assume that for densities greater than 20 vpm 95 percent of the noise level values will fall around the mean noise level ±2 standard deviations. For example, from Figure 3, at

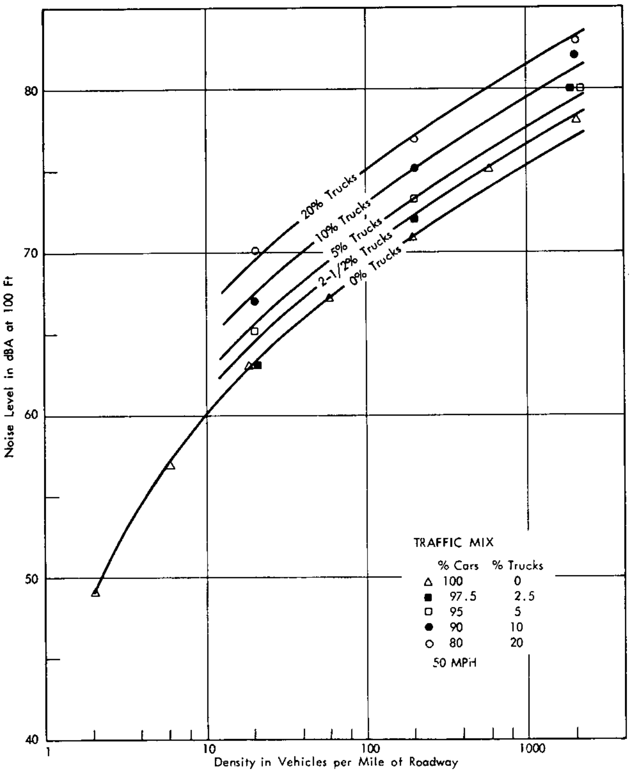

Figure 5. Curves for estimation of mean noise level in dBA at 100-ft distance from a lane (or single-lane-equivalent) of mixed car and diesel truck traffic.

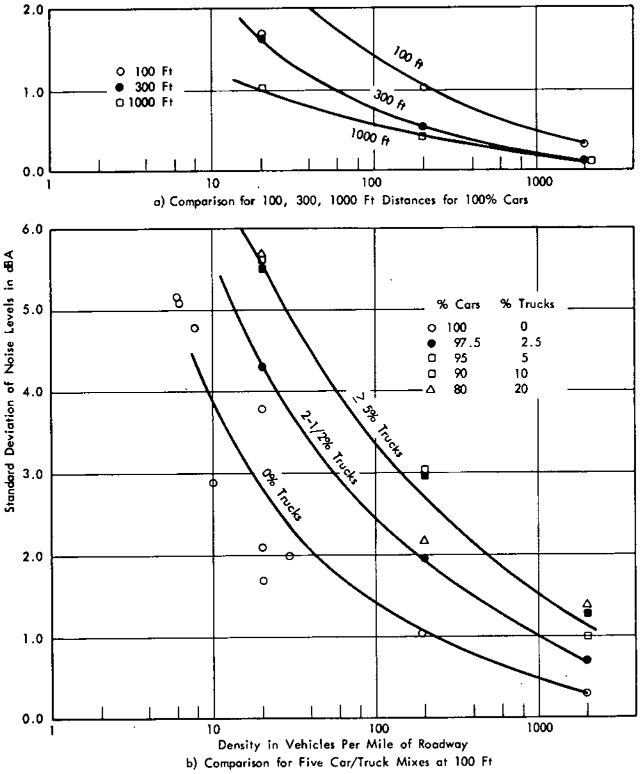

Figure 6. Curves for estimation of the standard deviation of noise levels in dBA resulting from a lane (or single-lane-equivalent) of traffic at 50 mph, for various mixes and distances.

a speed of 50 mph and a density of 100 passenger cars per mile, the average noise level at 100 ft is 69 dBA. From Figure 6, the standard deviation is 1.5 dBA. Therefore, it would be expected that for 95 percent of the time the noise levels would lie between 66 and 72 dBA.

For low traffic densities or for high truck mixes the distribution of noise levels tends to be unsymmetrical, or skewed, with a longer span above the mean and the assumption of a normal distribution should be used with caution. (See Fig. C-5.)

Effects of Elevated or Depressed Highways

Often a highway in an urban area is built on a grade above or below the elevation of the surrounding property. Such differences in grade provide some shielding of traffic noise, reducing the noise levels at the adjacent property. Computation of shielding on a theoretical basis is extremely complicated and applies only to a single source-receiver distance. In order to obtain design data for practical use in highway design, measurements of noise produced by traffic under conditions of elevated and depressed grades where the nominal change of elevation is typically 20 ft have been taken. All measurements were made adjacent to various 6- or 8-lane divided freeways, where lane widths were nominally 12 ft. These data were used to derive the design chart shown in Figure 7. This figure indicates the decrease in noise level with distance expected for the configurations described as well as for an on-grade situation.

The difference in dB between the on-grade and other configurations indicates the noise reduction obtained from shielding. For example, at distances of several hundred feet or more from the highway, the noise levels from a depressed highway are 7 dB lower than from a highway on-grade. For locations within several hundred feet of an elevated highway the noise levels may be as much as 5 to 10 dB lower than if the highway were on-grade. However, beyond 400 ft the elevated highway produces the same noise levels as if it were on-grade.

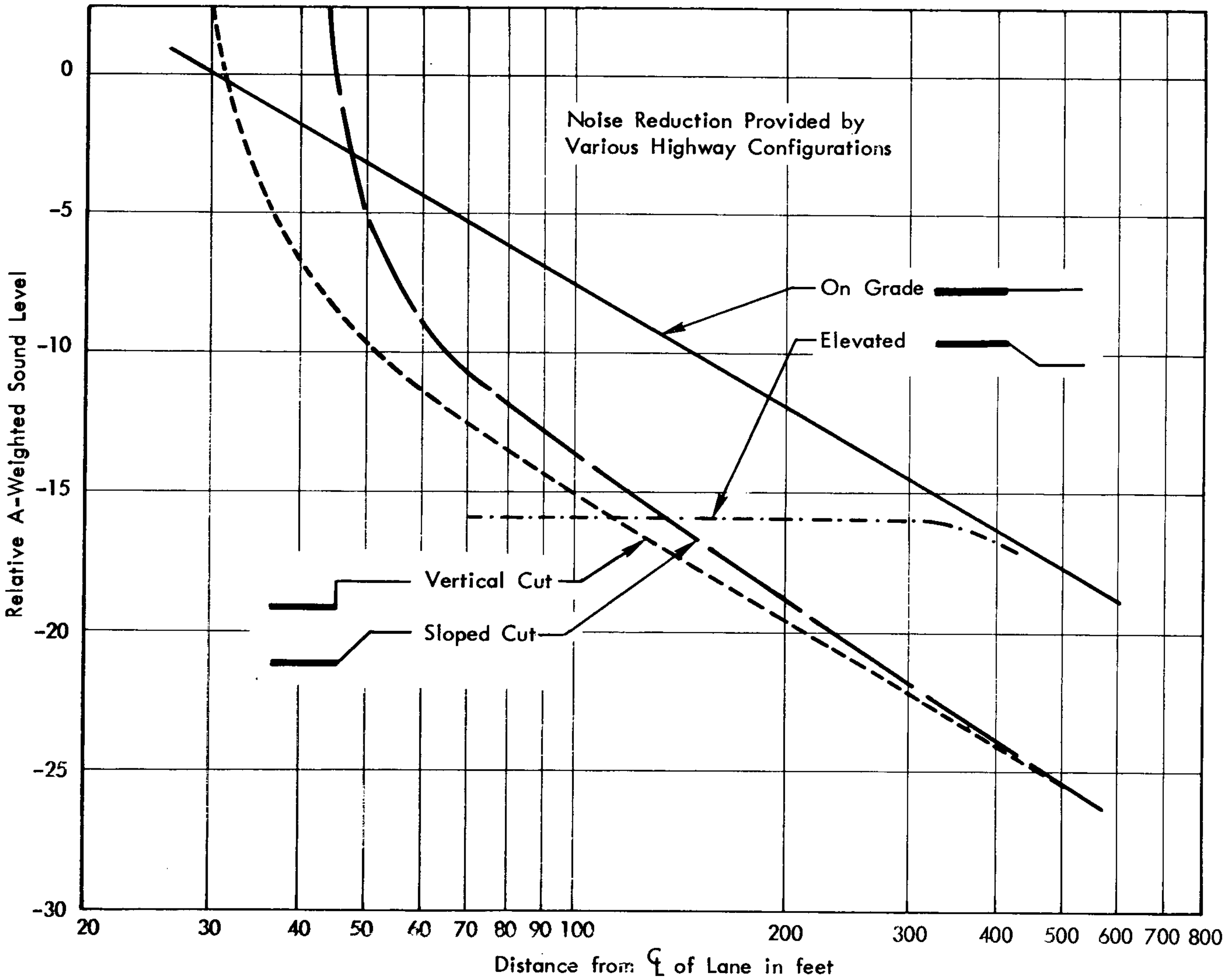

Figure 7. Noise reduction provided by various highway configurations.

Effects of Planting

Dense planting adjacent to a highway produces little physical reduction in noise level unless it is quite extended in the direction of the observer. A design value of about 5 dB per 100 ft of planting may be used if the trees are at least 15 ft tall and they are sufficiently dense that no visual path between them and the highway exists (*13*).

Prediction of Noise Produced by Individual Vehicles

For situations where the noise levels produced by individual vehicles are important (for example, at very low traffic densities) the data provided in Chapter Two and in Appendix B can be used directly. Appendix C provides discussion of air attenuation effects which should be considered for distances greater than 300 ft.

The Urban Highway as One Element of Neighborhood Environment

Unfortunately, prediction of people's reactions to traffic noise is not as straightforward as prediction of the noise levels. In studies of other kinds of noise intrusion (e.g., from aircraft flyovers), the researchers, and others, have found moderately direct relationships between noise level and reaction. However, the urban highway appears to be so pervasive a part of the neighborhood environment that people do not consider its noise apart from other aspects of the environment. Further, because the urban highway is so important in people's lives, judgments of annoyance with traffic noise are confounded with attitudes toward highways in general, and especially toward any highway that is part of the immediate neighborhood.

A good indication of this confounding of reactions to traffic noise with other variables is shown in the following data from interview studies:

Interview Area	Measured Traffic Noise Level (dBA) *	% of Respondents Offering Spontaneous Objection to Noise
1	58	67.1
2	77	50.7
3	63	33.9
4	64	50.9
5	67	40.0

* These are average noise levels in the vicinity of the respondents' homes at mid-day. Traffic noise levels change throughout the day as a function of density and vehicle mix, but all of the study areas experience qualitatively similar peak hour traffic. (See Appendix D and Table D-6.)

The spontaneous voiced objections are considered to be a relatively unbiased indicator of annoyance, since they reflect the salience of the respondent's feelings before his attention has been focused on (supposed) noise problems. In view of this circumstance, that people do not simply react in objective fashion to traffic noise, the best that can be offered at present is enumeration of physical environment factors that seem to be important to people, and of apparent relationships among noise and these factors, socio-economic status, life styles, and personal values.

It is quite clear that the generally higher socio-economic groups are most annoyed with freeway noise, even when that noise is minimal. There appears to be a definite split, however, in that middle and lower class do not differ that greatly from each other.

Respondents living in a relatively secluded area, where gardeners keep formal gardens well tended, and where native vegetation is abundant and pleasant, are highly annoyed by the freeway. They complain almost as much about (supposedly) depressed real estate values as they do about noise.

On the other hand, residents in more modest living areas, even though these areas are noisier, complain less about noise, and some actually are pleased that they can buy a nicer home because homes are (supposedly) cheaper near the freeway. To those residents, then, lowered real estate values are an advantage, not a source of complaint, and noise itself is taken for granted; it is not a source of annoyance.

Two major values, speed and perceived convenience, especially convenience to leisure activities, appear to be related to noise annoyance. In those areas where speed is considered good (even though it may also be annoying) annoyance with noise is low. Similarly, in all areas, the major advantage to living near a freeway is that it is convenient to leisure activities. (It is recognized that, in one case, leisure may be a trip to the beach on a hot day, while in another it may be a weekend trip to Palm Springs during the winter.)

For men, convenience to work is a secondary virtue, for women, convenience to shopping is second. This is true regardless of socio-economic level of the area.

Attractiveness is an important virtue, and one which mitigates against noise annoyance. But the present research indicates that attractiveness is in part an individual judgment. Why some people object to physical features which others fail to object to cannot be determined at present.

Several features of the physical environment are apparently important in people's judgments of urban highway environments. Features related directly to judged attractiveness include distance to highway, lack of visual dominance of the highway, and the presence of intervening features (even surface streets). Features relating to judged intrusiveness of the highway include lack of landscaping and high noise level.

It is important to note that some of the ways to improve residents' appreciation of highways as part of the urban environment are in contradiction to others. For example, the visual dominance of an elevated highway can be expected to reduce the judged attractiveness of a neighborhood, and thus increase the propensity for overt statements of annoyance by adjacent residents. On the other hand, the elevated highway provides some shielding, leading to lower objective noise levels, lower judged intrusiveness, and a lowered propensity for expressed annoyance. The quantitative tradeoff between these effects are not yet understood.

One final guideline from interview data suggests that judgments of intrusiveness of highways are directly related to years of exposure to the highway. Although the relationship is weak in the data at hand, it suggests that accommodation to the noise is perhaps a forlorn hope.

GUIDES FOR DEVELOPMENT ALONG HIGHWAYS

The noise problems facing the planner and designer of buildings or open-space activities adjacent to a highway are somewhat akin to those facing the highway planner. Thus, the noise estimation graphs provided in Chapter Two are directly useful, as are the suggestions for estimation of levels from individual vehicles.

Additional data that may be useful to the building designer include frequency spectrum information for the traffic noise at the building exterior, noise reduction data for the building construction, and criteria for allowable levels for intruding noise, for various indoor activities.

Use of the computer program for simulation of traffic noise provides a mean octave-band frequency spectrum in dB, as well as dBA values. For gross estimates, the relative spectra in Table 5 would be used for distances between 100 and 1,000 ft. Thus, if the noise level at 300 ft were 65 dBA, the designer would use the spectrum in Table 6 for noise levels at the exterior of a building. For individual vehicles, data from Appendix B can be used directly.

Noise reduction data, by octave band, for various types of building structures can be found in Beranek's *Acoustics* (*14*) or in other acoustics reference books. For typical residential housing, the design values for noise reduction of buildings shown in Figure 8 can be employed to determine inside noise levels (*15*). The values on the chart of noise reduction as a function of frequency (Fig. 8) should be subtracted from the noise level spectrum computed for outside the building in order to obtain the inside noise level spectrum.

For gross comparison purposes a relationship may be drawn between speech interference levels and traffic noise levels expressed in dBA. (See Appendix A.) Speech interference level denotes a kind of speech activity that is satisfactory for a particular noise condition. For outdoor conditions, a traffic noise level of 70 dBA corresponds roughly to a speech interference level (SIL) of 60. An outdoor traffic noise level of 70 dBA corresponds roughly to an indoor speech interference level of 40 to 45, for typical residential frame construction. Table 7 suggests the kinds of satisfactory speech activities for a range of outdoor traffic noise levels (such as might be estimated from Figures 3 through 6). Table 7 suggests average conditions. Communication would be worsened during noise peaks, and improved during traffic lulls.

For critical listening conditions (assembly places, concert halls, recording studios, and the like), a careful study of actual noise reduction by structures, and of the effects of peak noise levels is usually required. Detailed criteria for allowable noise levels under such conditions can be found in an acoustics reference text (*14*).

The contributions of other noise sources to the acoustic environment (for example, that produced by aircraft noise, sounds from industrial plants, air conditioning equipment, etc.) should also be taken into account when considering the impact of traffic noise on roadside development.

TABLE 5

dB VALUES FOR OCTAVE BANDS RELATIVE TO NOISE LEVEL IN dBA

OCTAVE BAND CENTER FREQUENCY (Hz)	dB
63	−1
125	+2
250	+1
500	−2
1,000	−5
2,000	−10
4,000	−18
8,000	−26

TABLE 6

TYPICAL NOISE LEVEL SPECTRUM FROM TRAFFIC

OCTAVE BAND CENTER FREQUENCY (Hz)	SPL
63	64
125	67
250	66
500	63
1,000	60
2,000	55
4,000	47
8,000	39

APPLICATIONS FOR EXISTING HIGHWAY SYSTEMS

Apart from usefulness for planning guidance, the work of this project leaves several implications for the management of highway systems.

Assessment of the Probable Effects of Traffic Flow Changes

The techniques and graphic guides discussed earlier in this chapter can be equally well applied to existing highway systems. By estimating the noise from current traffic activities and from anticipated changes, an indication can be obtained of the likelihood of negative reactions from people.

Further, by keeping a case history file of clues about reaction to traffic noise (complaint calls, letters, indignation meetings, evidences of unaffected activities) together with traffic flow information and noise estimates, an agency can build experience with local acceptance of highway traffic situations. Such documented experience is invaluable when problems arise.

Objective Limits for Individual Vehicles

The major concern with highway noise stems from traffic involving a flow of vehicles rather than from single, deviant vehicles. (Although, in some circumstances, the critical conditions may occur during times of low traffic density and low ambient noise in residential neighborhoods, as in

TABLE 7

NOISE LEVEL CRITERIA FOR SPEECH

OUTDOOR TRAFFIC NOISE LEVEL (dBA)	OUTDOOR SPEECH COMMUNICATION	INDOOR SPEECH COMMUNICATION
75	Raised voice at 1-2 ft	Normal voice at 3-10 ft
65	Normal voice at 2-5 ft	Normal voice at 10-25 ft
	Raised voice at 5-10 ft	Quiet voice at 5-10 ft
55	Normal voice at 5-15 ft	Satisfactory for conference at 15-ft table
	Raised voice at 10-40 ft	

pre-dawn hours.) Enough evidence is available, though, from this research and earlier work, to enable recommendations for objective noise level limits which will discriminate from the normal vehicle population the flagrant violators of acceptable muffling and noise control practices.

The recommended objective limits for single vehicles are as follows:

Maximum Noise Limits When Measured at a Distance of 50 ft From the Vehicle in Motion

Passenger vehicles other than motorcycles, trucks of less than 6,000-lb gross vehicle weight, buses of 15-passenger or less capacity—77 dBA.

Trucks over 6,000-lb gross vehicle weight, motorcycles, buses of more than 15-passenger capacity—88 dBA.

These objective limits are essentially the same as those submitted to the California Highway Patrol for their consideration in preparation of proposed legislation (*16*). Subsequent field measurements and simulation studies substantiate the appropriateness of the limits, as restated in terms of the dBA rather than PNdB.

These limits are intended to apply for conditions approximating normal level highway conditions. A testing procedure proposed by the research agency (*16*) is paraphrased as:

> When the vehicle is fitted with a manually operated gear box, with or without automatic clutch, the vehicle should approach a point 33 ft from a perpendicular to the microphone at a steady road speed which corresponds to an engine speed of three-quarters of the rpm at which the engine develops its maximum rated power as installed in the vehicle, and at such a gear ratio that the road speed approaches 30 mph as closely as possible. When the vehicle is fitted with a fully automatic gear box it should

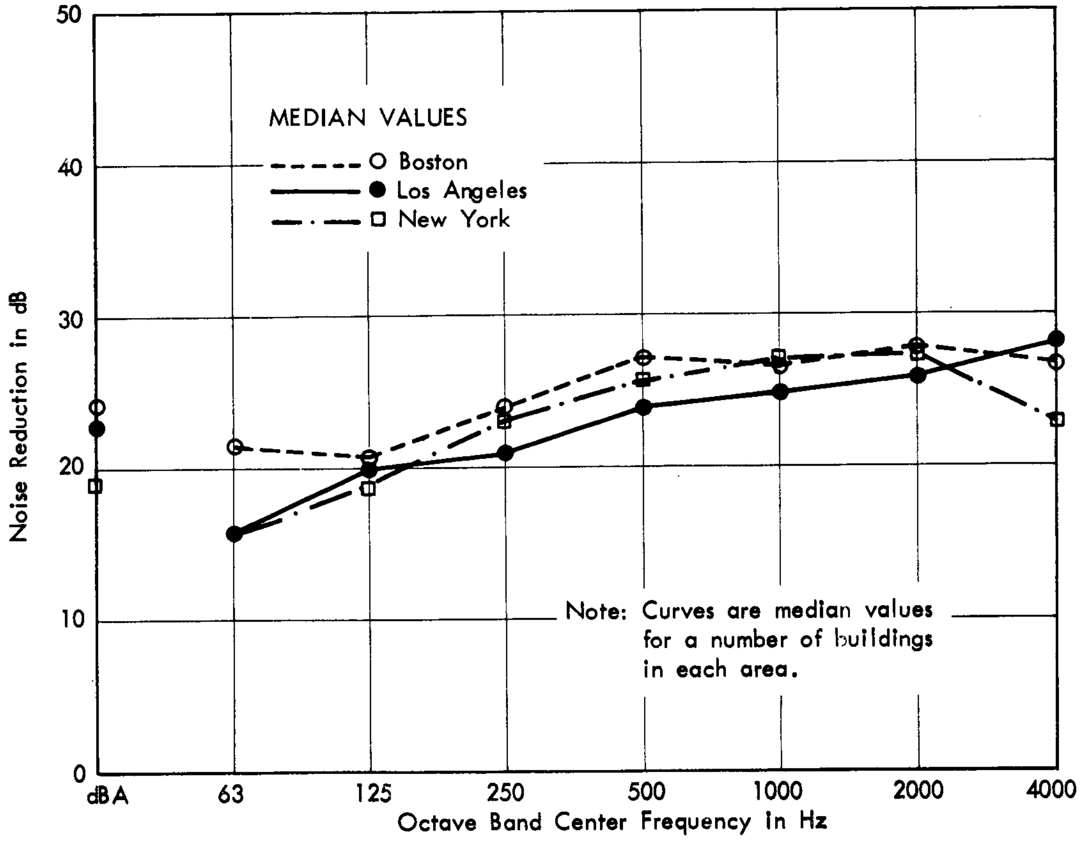

Figure 8. Typical noise reduction provided by residential buildings—windows closed, discrete traffic sources.

approach the same point at a steady speed of 30 mph, in the normal drive gear position.

When the front of the vehicle reaches the prescribed point the throttle should be fully opened and held there until the rear of the vehicle passes a point 33 ft beyond the perpendicular from the microphone position, when the throttle should be closed. The test should then be repeated with the vehicle traveling in the opposite direction.

The test could be performed with a properly calibrated sound level meter meeting the requirements of American Standard S1.4-1961, set to the A-scale weighting network.

All of these test conditions are consistent with, and deviate only in measurement distance (that is, 50 ft instead of 25 ft) from current recommended practice of the International Standards Organization (*17*).

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

In the course of the present research the noise produced by highway vehicles has been characterized, a unit selected for expression of that noise, and a method developed for prediction of the noise from traffic by means of computer simulation. The reactions to traffic noise of people living near highways have been investigated. The findings provide new insight into the complex of factors involved in people's reactions to the noise from urban highways, and to those highways, per se. Further, they provide directly usable planning guides for highway planners, engineers and administrators.

Inevitably, however, in any penetrating, application-oriented research, more questions are raised than can be answered with available resources of time and money. These findings concerning a set of separate, independent factors by which people judge urban highways as elements of their neighborhood environment open up important new possibilities for quantitative prediction of the impact of traffic noise, reactions to alternative highway configurations having to do with residential properties, the effect of landscaping, and many other planning aspects. This may constitute the most important work ahead.

Extensions of the traffic noise simulation model should allow attention to more complex traffic situations and to the variable effects of shielding structures and topography. Some further analysis with the model and computer program as they exist can extend the usefulness and scope of planning guides such as those of Chapter Three.

Finally, as more is learned about the ways that people view their environment and its assets and defects, prediction models can be developed that can estimate the propensity for overt and forceful actions for abatement of intrusions, rather than only indications of annoyance.

In the paragraphs that follow some specific topics for further research are suggested without attempting to order them by priority or resource needs.

FURTHER STUDIES OF TRAFFIC NOISE

(1) The noise from traffic should be simulated over time, considering the changes in density and other flow characteristics, to develop day-long and weekday vs weekend graphs of mean noise level and fluctuations. Differences between various urban highway sections and between different sides of a single section (allowing for unsymmetrical peak-hour flows) could provide useful data for further human reaction analyses.

(2) The parametric studies using the simulation techniques that provided the estimation curves in Chapter Two should be extended to provide more detailed data on the distribution of noise level fluctuations and the importance of peaks. Other simulations should explore the effects of density, vehicle mix, speed, and distance on the sample size (number of snapshots) needed for constant error of estimate.

(3) With slight extensions of the program, noise near on-off ramps, or at interchanges might be simulated as a function of the complexity of the situation (number of lanes, volume of cars accelerating or braking because of lane-changes, number and distances between on-off ramps, etc.).

(4) The simulation model should be extended to encompass the highway configuration parameters which affect freeway noise, and these extensions must be validated by field measurements. Most important are extension of the shielding effects of elevated and depressed roadway, shielding by topographical features (hills), and the effects on observers at different heights (multi-story apartments bordering a freeway). Plotting of contours of noise level which took these shielding effects into account would be a fairly straightforward extension of the computer program.

(5) The simulation program might be further refined to give estimates of the traffic noise levels inside certain basic types of architectural construction. It should be noted that those who complained most in the present interview study

not only lived in the quietest area, but also they lived in the most expensive homes, and thus the homes might be presumed to cut out more of the outside noise.

FURTHER STUDY OF THE RESPONSES OF PEOPLE TO HIGHWAY NOISE AND RELATED ENVIRONMENTAL FEATURES

(1) The present survey work should be expanded in several ways. Replications (including interview refinements) should be made with different kinds of people, and with people who are not as immediately adjacent to the freeways. Certainly, geographic considerations must enter into any generalized study of noise, in that outdoor living in southern California especially is likely to expose people to direct outdoor noise, unbuffered by buildings. If one considers a two-dimensional graph with socio-economic status (SES) along one axis and traffic noise level along the other, these present studies can be considered as one diagonal, proceeding from lower middle SES and high traffic noise to high SES and low traffic noise. It would be useful to fill in the other diagonal. It is possible that field work in one or more other cities (Chicago's Lake Shore Drive offers possibilities) might accomplish several of these goals.

(2) A series of smaller experiments should be carried out to determine the interrelationship of the various elements tapped in the present research and other related studies. The present research has suggested that any simple tabulation of the proportion of people who are annoyed may lead to underestimating the complexities of the noise problem. The attractiveness of the freeway is a judgment made completely independent of judgments of noisiness or intrusion. Yet, people who spontaneously express annoyance with freeway noise are also those people who do find freeways less attractive. Thus, further research should work both backward and forward from the present data. Working backward, schematically, an attempt can be made to predict those features in the environment, or those personal attributes in individuals themselves which lead them to find freeways unattractive, and those variables which make highways or freeways appear more or less intrusive.

There are a number of multivariate statistical techniques which can help to map the interrelationships, both environmental and personal, which lead to the decisions of convenience, attractiveness, intrusion and so forth. Further, it should be possible to tap the pool of respondents obtained by asking respondents in the present study if they would be willing to participate in further research. Here is a relatively small sample, but already a relatively large amount is known about these people and their environments. An important goal of these small studies should be the isolation and measurement of a set of environmental features (landscaping, visual dominance, etc.) that have both significance to residents and importance to highway planners. Other studies should explore additional style-of-life social variables, in that noise differentially interferes with different kinds of activities.

(3) Once an adequate set of physical environment variables is isolated, a cost/benefit type of analysis should be possible to illustrate and quantify the trade-offs that are possible between noise reduction by shielding, landscaping, elevation with attendant noise reduction but increased visual dominance, etc. Thus, one should be able to say, for example, that landscaping, although of little value in attenuating the physical noise, is worth as much in reduced human response as x dB of physical noise reduction.

(4) One of the more attractive possibilities for future research is that of attempting to relate laboratory judgments in a specific situation to generalized attitudes and annoyances in the field situation. It may well be that some people are truly more sensitive to noise (this is known to be true in laboratory tests of hearing acuity), but it may equally well be true that those who feel themselves to be inordinately sensitive to noise are not actually those who prove to be so in an experimental laboratory situation. This again represents an attempt to link physical measurement to personal characteristics and perceived personality correlates or self-image of the individual.

(5) As an adjunct to additional field studies, further research might be done to assess the ways in which individuals who are annoyed by noise, or individuals who simply perceive noise, attempt to protect themselves from it. In the present study, although no provision was made for collecting this information, some interviewers formed the impression that people living in the highest noise areas tended more often to create background noise or sound for themselves. It may well be, then, that the non-complainers who live in high noise areas are those who have successfully found ways to protect themselves from external noise annoyance. Thus, the television addict, or the hi-fi addict, may be relatively less annoyed by noise because he provides his own internal sound system. These systems for individual shielding may be as subtle (and probably unconscious) as humming to oneself, or as deliberately conscious as raising the volume of the television set.

Similarly, young adults with pets and children may have their own built-in shielding devices, where noise levels within the home compete actively with noise outside the home. Studies showing that interference with sleep produces the greatest noise complaints would suggest that daytime activities in themselves produce some kinds of shielding effects from noise. If, indeed, the noise level in a young family's home is sufficiently high, freeway noise at night may seem to provide a quiet rest period by comparison. This might suggest to developers that the kinds of living arrangements placed near a freeway, or a proposed freeway route, be the kind of living accommodations that a young family with a number of children might have. It might even suggest to landlords that they should encourage tenants to have pets or other background-producing appurtenances.

(6) Working forward, an attempt should be made to extend the annoyance measure so as to get closer to a measure of actual complaint or direct physical response to noise. Those who initiate negative actions about freeways or highways can be traced down; and those who respond either actively or passively to those complaints can also be accounted for. The characteristics of complainers can be examined in terms of their personal characteristics and self-images, as well as in terms of their positions on other

community issues. It would not be surprising, for example, to find that people who complain most about freeway noise, also complain about such diverse things as fluoridation of water, and community mental health clinics. Equally, they may complain about any tax-related matter and may perhaps, thus, be categorized in terms of decisions on other community matters.

Case studies of freeway route selection controversies, common in metropolitan areas, should help illuminate the patterns of overt action.

(7) A longitudinal study of great importance using one measure of overt response to highway noise (migration away from neighborhoods adjacent to newly built roadways) should prove especially rewarding. It should be possible to trace a sample of such migrants and interview them to ascertain the influence noise may have had consciously or unconsciously on their decision to move.

These suggestions for future research reflect the investigators' conviction that highway noise is neither an isolated nor a simple problem, and that it may well prove to have relationships with variables previously unsuspected. Indeed, even the present suggestions for research form a limited subset of the potential variables which might be considered in placing highway noise in proper and complete perspective with regard to today's total environment and man's responses to it.

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APPENDIX A

SELECTION OF A UNIT FOR SPECIFICATION OF MOTOR VEHICLE NOISE

Acoustical noise is defined as "unwanted" sound. It is generally composed of combinations of discrete tone and random pressure fluctuations covering the entire audible frequency spectrum. An accurate physical description of noise requires a careful frequency analysis of the intensity of components and a specification of the statistics of its randomness. Such an analysis is not only difficult and costly to obtain, but often is more detailed than necessary for many applications.

The acoustical engineer often obtains a satisfactory description by analyzing the sound to determine the sound pressure level (SPL) in each of a series of contiguous frequency bands covering the audible spectrum. The width of the frequency band utilized is determined by the relative importance of discrete tone sounds superposed on the random portions of the noise, and by the relative intensities of the low, middle, and high frequency components of the sound; that is, the shape of the spectrum.

Although the bandwidths of the filters used in frequency analyses can vary as desired, the most common are either one octave or one-third octave in width. The frequency range of interest is generally between about 20 and 10,000 Hz and a set of nine octave band filters can cover this range.

Although the acoustical engineer cannot generally work with a description of noise more coarse than that provided by an octave band analysis, he is often asked to provide a specification for noise using a single number rather than the series provided by frequency analysis. The sound level meter, a direct reading instrument which gives a single measure of the magnitude of a sound, has been developed for this purpose.

Because of deficiencies of a single number description applied to sounds of different character, several equalizing networks have been provided in the sound level meter to emphasize meter response to sounds of higher frequency, providing three weighting networks, labeled A, B, and C. The A network provides the most emphasis for higher frequencies and is supposed to have a frequency response roughly comparable to the inverse of the frequency response of the human ear at low levels of sound excitation. The B network provides somewhat less equalization. The C network provides, in effect, a uniform response over most of the audible frequency range.

SUBJECTIVE MEASURES FOR SPECIFYING NOISE

The hearing and discriminatory powers of humans form a complex system. The frequency response of the hearing mechanism and the ability of humans to extract varying characteristics of noise have generated extensive research into human reaction to noise and means for specifying this reaction. Of particular relevance to this present study is the work directed toward identification of the loudness or noisiness of sounds.

Two general areas of research provide information on noise reaction. By far the most extensive and scientifically acceptable is the psychologists' work on how an individual judges loudness and noisiness. To a lesser extent, experiments have been performed on groups of people to evaluate how they judge the acceptability of various sounds on category judgment scales.

Present research provides two categories of measures for subjective reaction to noise: first, measures obtained by psycho-acousticians through careful laboratory experimentation, and second, direct physical measures of noise found through experiments to provide good correlation with subjective judgments of noise.

The psycho-acoustician compares the loudness or noisiness of two sounds by analyzing the amplitudes of the sounds contained in a series of contiguous frequency bands extending over the range of audibility. Various methods of computation, developed from these experimental data, give a single-number description of the loudness or the noisiness of the sound. Two sounds are said to be equally loud or noisy if the appropriate computational method provides equal numerical values for each. These measures enable a single computation approach for a wide range of different sounds. While these techniques are valuable for comparing sounds of widely different character, they require careful analysis and relatively extensive instrumentation.

On the other hand, if one wishes to compare the relative noisiness of a number of sounds of the same general character (for example, one motor vehicle against another), a simple physical measure which does not require extensive computation may be used to measure subjective reaction if it is highly correlated to the amplitude of the sound. Thus, the psychologically derived measures, obtained from groups of observers, provide an acceptable, scientific, absolute base for comparison of any sounds. The simplified measures provide a relative base for comparing similar sounds. For any particular engineering use the simplified physical measure may be adequate if it provides a sufficiently high correlation to human response.

A physical measure of sound may be judged acceptable if found, through group judgments, that it provides a response measure statistically equivalent to that provided by psychologically derived measures. A number of these measures have been compared for two major experiments on the judgment of motor vehicle noise. The measures compared are as follows.

Psychologically Derived Measures

(1) *Loudness.*—the linear measure of loudness giving scale numbers approximately proportional to loudness. The unit of measure is the sone. The equivalent-tone computation of Beranek et al (*4*) has been employed.

(2) *Loudness Level.*—the measure of the strength of a sound derived from the sound pressure level of a 1,000-Hz tone giving an average judgment by normal observers of equally loud. This is a logarithmic quantity with the phon being the unit of measure. The loudness level of a sound is often calculated from sound pressure levels in specified frequency bands. Two systems have been employed in this study: one, LLs, due to Stevens (*5*) that uses octave frequency bands, and one, LLz, due to Zwicker (*6*) that uses one-third octave frequency bands. Both of these systems use equal-loudness contours based on frequency bands of noise.

(3) *Perceived Noise Level (PNdB).*—a measure purporting to rate the noisiness, rather than the loudness of a sound. The computational scheme of Kryter (*7*) yields a measure in *perceived noise level,* reported in units of PNdB. The computational approach is similar to the loudness level calculation of Stevens, with equal noisiness rather than loudness functions employed.

(4) *Speech Interference Level (SIL).*—a measure of noise bearing a direct relationship to the masking of speech according to Beranek (*14*). The SIL is reported in decibels and is the arithmetic average of the sound pressure levels in the octave frequency bands of 600-1,200 Hz, 1,200-2,400 Hz, and 2,400-4,800 Hz.

Physical Measures of Sound

(1) *Over-all Sound Pressure Level (OASPL).*—the sound pressure level measured by a uniform frequency response system. It is a measure of root-mean-square sound pressure in decibels with a reference base of 2×10^{-4} microbar. It is also referred to as dBC when read on the C-scale of a sound level meter.

(2) *A-weighted Sound Level (dBA).*—the value of sound pressure level in decibels measured by a sound level meter which has the frequency weighting network designated by A. This is an equalization circuit purporting to have approximately the inverse frequency response characteristics of the human ear at the 40-phon loudness level, and widely used in motor vehicle noise studies.

ANALYSIS OF EXPERIMENTS ON SUBJECTIVE REACTION TO MOTOR VEHICLE NOISE

Substantive experiments to evaluate the subjective reaction of humans to motor vehicle noise are quite costly, and therefore few in number. A number of listening tests have been performed from time to time with groups of people judging various types of vehicle noises. We have selected for further analysis two studies that are sufficiently comprehensive, with accessible basic data, to permit detailed analysis. An experiment described in 1951 by Andrews and Finch (*18*) reports judgments of objectionableness of commercial vehicle noise as a function of A-scale sound level readings. The basic noise data and subject rating scores from the experiment were not available and an analysis of their work is not included in this report.

Armour Research Foundation Studies

In 1953 Callaway (*1, 2*) at the Armour Research Foundation, now the Illinois Institute of Technology Research Institute (IITRI), conducted an experiment on subjective reaction to truck noise as part of a study for the American Trucking Associations (ATA). The results of this work led to the 125-sone specification for maximum truck noise employed by ATA (*3*).

In a subjective reaction experiment 15 observers rated the relative loudness of 100 truck noise spectra on a six-point scale. Truck noises were recorded on magnetic tape 50 ft from the side of a major highway. The recordings were reproduced in a semi-reverberant listening room over a loudspeaker system adjusted so that the noise levels in the room were within 2 decibels of their highway levels. The noise level data were then used to compute various measures to be correlated with the average subjective reactions of the observers.

The original ARF data were reported in terms of C-scale meter readings, and in loudness computed by the equivalent-tone method of Beranek et al (*4*). Because extensive work on loudness and noisiness computations has occurred since the ARF study, it appeared useful for this investigation to utilize the basic data from the experiment to compute relationships with more recent subjective measures. Permission was obtained from ATA to permit ARF to release the data in conjunction with a previous study for the California Highway Patrol (*16*). These results are reported here in more detail than previously available.

National Physical Laboratory—Motor Industries Research Association Studies

D. W. Robinson and his co-workers at the Applied Physics Division of the National Physical Laboratory in England have conducted two major experiments on subjective response to motor vehicle noise in the last few years. Both experiments were conducted to provide technical data for preparation of an International Standards Organization (ISO) recommended measurement procedure for assessing vehicle noise. In 1960, 19 observers sat at the side of a road making individual judgments on six-point scale of the noise produced by each of approximately 200 vehicles randomly selected as they passed the test position (*19*). Noise level measurements made at the same time were frequency analyzed in the laboratory and the results utilized to compute numerical values for various subjective measures. These measures were then correlated with the observers' average reaction.

A second experiment, Mills and Robinson (*20*), was performed in late 1960 in cooperation with the Motor Industries Research Association (MIRA). This experiment, run at the MIRA Proving Ground, provided a better distribution of vehicle types, more controlled operating conditions than the random observations of the roadway test, and more observers. It is the second experiment that was chosen for intensive investigation.

The MIRA experiment used 19 different production automobiles, light trucks, diesel trucks, and motorcycles. The vehicles were driven past a group of 57 observers at one of three operating conditions:

(1) Acceleration from 30 mph.

(2) Full throttle, with brakes applied to hold speed down to 30 mph.

(3) Constant speed of 30 mph in top gear.

All vehicles performed each operation at least once in both directions. Order of presentation of vehicles and operating conditions was randomized, with a total of 148 usable runs. A six-point rating scale was employed, with each observer rating each vehicle event.

The results of this experiment have been published only in terms of correlation of A-scale sound level meter readings in dBA. Dr. Robinson has performed some calculations with other subjective measures, and has kindly released the results of these calculations, along with his basic noise level and subjective rating data, so that new values could be computed of subjective ratings based on the newest forms of their functions, and to examine the usefulness of other measures.

Analyses of Results

Each of the observers in the previously mentioned experiments, after listening to a vehicle pass, was asked to mark his reaction to the sound of the vehicle on an open-ended category scale having descriptors ranging from "Quiet" to "Excessively Noisy" in the case of the MIRA experiment, or similar descriptors in the ARF experiment. The sound produced at the observers' position was recorded on magnetic tape.

In the MIRA experiment, the noise was analyzed to obtain sound pressure level in one-third octave frequency bands, as well as direct readings on the A and C scales. Thus, for each vehicle, the physical noise specification and a series of corresponding judgments by the observers were obtained. The noise data were the tabulated physical descriptions of the sound. For the MIRA data, the individual judgments of all 57 observers for each vehicle passage were received, transformed from the category scale into a numerical scale ranging from 0 to 10. The ARF judgment data available were the average judgments of the group of 15 observers, transformed into a numerical scale ranging from 0 to 6.

The first step in the analysis was to compute the average (mean) response of the 57 observers in the MIRA experiment to each vehicle. The distribution of individual judgments about the mean value showed a standard deviation for the entire group of judgments of about 0.97 units of the numerical rating scale. The standard deviation for the 57 observers' judgments of individual vehicle observations varied from 0.5 to 1.3. During the course of the tests, about one-third of the vehicle passages were repeats, enabling an analysis of reliability of subjective measurement. The standard deviation of individual judgment repeatability was about 0.82 units, or almost one-tenth of the numerical rating scale—Mills and Davidson (*20*).

The noise measurements from the 148 vehicle passes in the MIRA experiment were used to compute loudness level in phons by the revised method of Stevens (*5*) and by the Zwicker method (*6*). (Robinson has previously used an earlier Stevens form of calculation in his unpublished studies; the latest version is used here because it is now under consideration as a recommended procedure by the International Standards Organization.) The noise data were also used to compute perceived noise level in PNdB and speech interference level in dB.

Similar computations for the 97 vehicle noises of the ARF experiment were made of loudness level in phons by the Stevens method, perceived noise level, and speech interference level. The equivalent-tone loudness values in sones, calculated by ARF, were also used. No computation was possible for loudness level by the method of Zwicker (*6*) because data in one-third octave frequency bands were not available.

The sound pressure levels in octave frequency bands from the ARF data were also used to compute new values of noise level in dBA. (All computations of the various subjective measures as well as the new values for dBA in the ARF experiment were performed on a Digital Equipment Corporation PDP-1 computer. The abbreviation dBA (PDP) has been used to refer to the computed values of dBA.) At the time of the ARF experiment, sound level meters meeting the requirements of American Standard ASA Z24.3-1944 were used. These meters had relatively wide tolerances for microphones and circuitry. At the present time, sound level meters conform to the considerably more restrictive tolerances of American Standard ASA S1.4-1961. Meters having these requirements were used in the MIRA experiment. Values of dBA were computed from the sound pressure levels in octave frequency bands obtained from the MIRA experiment, and the computed values found to agree with the values read directly from the precision sound level meter, in general, by less than one decibel. The computed values of dBA for the ARF data are therefore more representative of the values which would be obtained today if the experiment were to be repeated.

With all these measures, scatter diagrams were plotted showing the correlation of average subjective rating with the various subjective measures. The data were also used to compute the linear regression of the subjective ratings on each of the various measures by the least-squares technique, together with the variances for each regression line. Last, correlation coefficients for each measure and the confidence intervals for these coefficients at the two standard deviations, or 95 percent level were computed.

Two sets of the scatter diagrams have been selected for illustration. The first set (Figs. A-1 through A-6) indicate the relationship between the average subjective ratings of the 57 observers for the entire complement of vehicles of the MIRA experiment, Robinson et al. (*19*), with overall sound pressure level in dBC, noise level in dBA, speech interference level in dB, perceived noise level in dBA, speech interference level in dBA, perceived noise level in PNdB, loudness level (Stevens) in phons, and loudness level (Zwicker) in phons. (Circled data points on the figures indicate two separate datum points of the same numerical value.) These figures show the ability of the individual subjective measures to predict the average subjective noise ratings obtained for an over-all assemblage of motor vehicles. The solid line is the least-square fit regression line; the dashed lines are the computed envelopes for two standard deviations from the regression line.

The second set of diagrams (Figs. A-7 through A-11) show how well one measure, noise level in dBA, predicts the average subjective rating of the noise from different classes of vehicles. These classes are the gas-engined vehicles of the MIRA experiment, the MIRA diesel trucks, the MIRA motorcycles, and the ARF diesel trucks. For the ARF diesels, two diagrams are shown for dBA as a function of subjective rating. The values of dBA computed are shown in Figure A-10; the originally reported values for dBA are plotted in Figure A-11 for the same subjective judgments.

The computed correlation coefficients with their confidence intervals are indicated on each diagram. The computed variances are also indicated. To facilitate comparison of the different measures, the entire set of correlation coefficients and related confidence intervals is plotted in Figure A-12.

CONCLUSIONS

The purpose of the analyses has been to identify the measures of vehicle noise which best predict the average subjective reaction of a group of observers. Perfect correlation of measure with reaction would be expected if the correlation coefficient were unity, i.e. 1.00. Any correlation coefficient having a value of less than 1.00 indicates an uncertainty in the ability of the noise measure to predict reaction. Comparison of one measure against another can be seen by referring to Figure A-12. The correlation coefficients and confidence intervals for all measures examined in this study are shown in this figure.

The acceptance of one measure as compared to another can be based on the relative relationships of the confidence intervals of the two measures. The confidence interval for a given correlation coefficient is based not only on the degree of correlation, i.e., magnitude of the coefficient, but on the variance of the data being correlated. A perfect correlation between a measure and subjective reaction would have zero variance, and thus a confidence interval of zero. The fact that there are differences in judgments of the same noise, that there are small errors in noise measurement, and that the number of observations is finite, all lead to a spread, measured by the variance. Although possibly small, the variance leads to an uncertainty in specifying the correlation coefficient. By computing confidence intervals for the coefficient, we can state, to the level of assumption indicated by the confidence interval, that the correlation coefficient lies within that interval. The 95 percent level has been chosen. Thus, it can be said with reasonable certainty that, if the experiment were repeated a very large number of times, in at least 95 percent of the experiments it would be expected that the true correlation coefficient would be within the interval specified.

Now, if the confidence intervals for the coefficients for the two measures were compared and the intervals overlap, it cannot be said with certainty that one of the measures is better than the other.

Examining the data in Figure A-12, there is little doubt that over-all sound pressure level in dBC is not an accurate predictor of reaction to motor vehicle noise. It can also be said that speech interference level is not a good predictor of reaction to diesel engine noise. On the other hand, there would be difficulty in selecting any one of the other measures as being better than the others on the basis of these experiments alone.

All other things considered, it is proposed for practical reasons that dBA be selected as the basic measure for motor vehicle noise at this time. If gas turbine engines producing substantial high frequency sound are extensively used in the future, it would be well to consider another unit. However, at the present time, noise level in dBA is the only measure having high correlation with subjective reaction that can also be read directly on a commercially available meter having standardized performance.

A further comment should be made concerning the American Trucking Associations' choice of the equivalent-tone-sone as a specifying unit for limiting truck noise. In the initial study by ARF, sones indeed provided somewhat better correlation that noise level in dBA. (The computation of confidence intervals for the data does indicate that some question exists whether there were significant differences, however.) Considering the variability of one sound level meter to the next at that time, and the rather broad performance requirements specified in the then existing sound level meter standard, it seems perfectly justified for the ATA to have chosen to use the sone method. To perform the measurements required to compute loudness in sones does require equipment of considerably higher

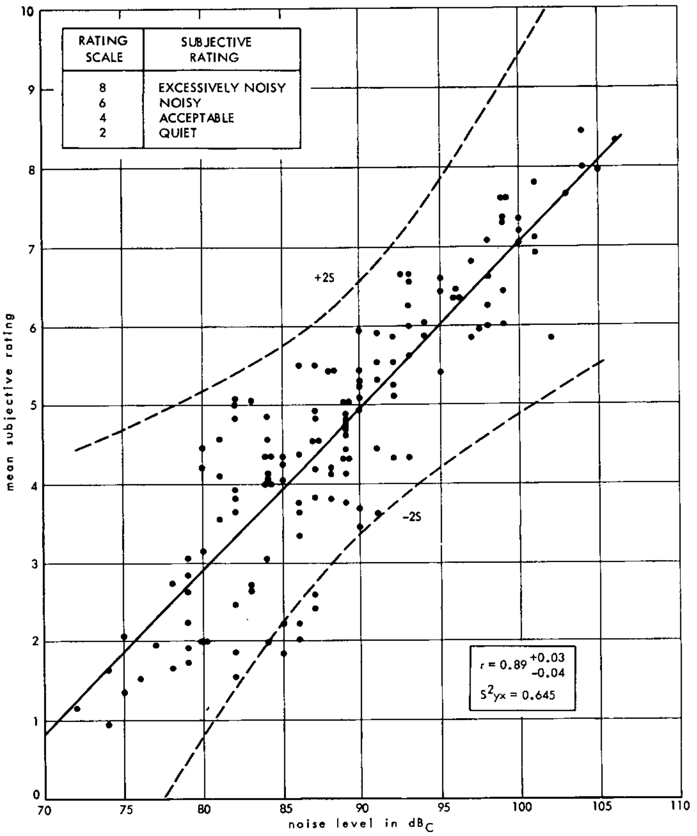


Figure A-1. Correlation of subjective ratings of noise from all vehicles in the MIRA experiment with over-all sound pressure level in dBC.

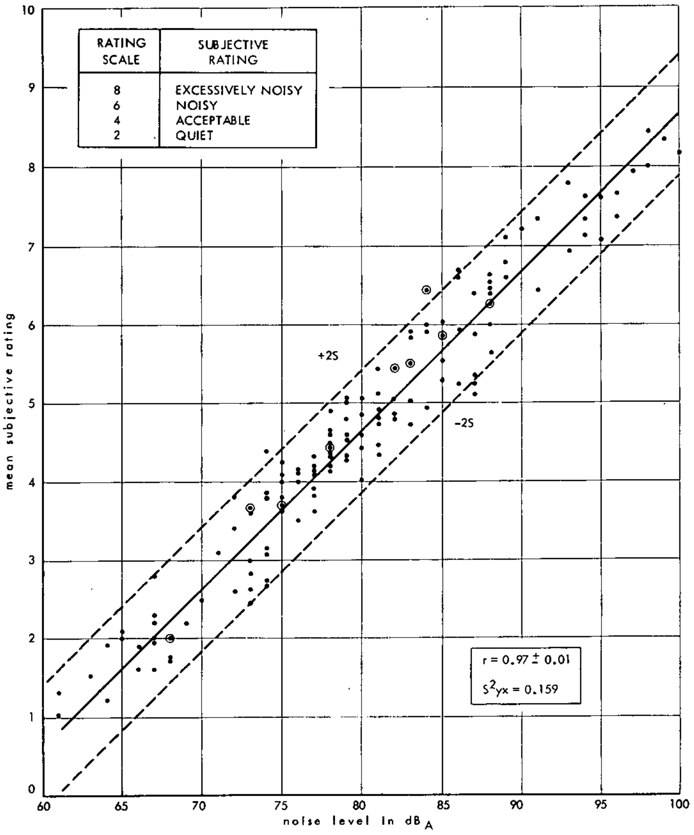


Figure A-2. Correlation of subjective ratings of noise from all vehicles in the MIRA experiment with noise level in dBA.

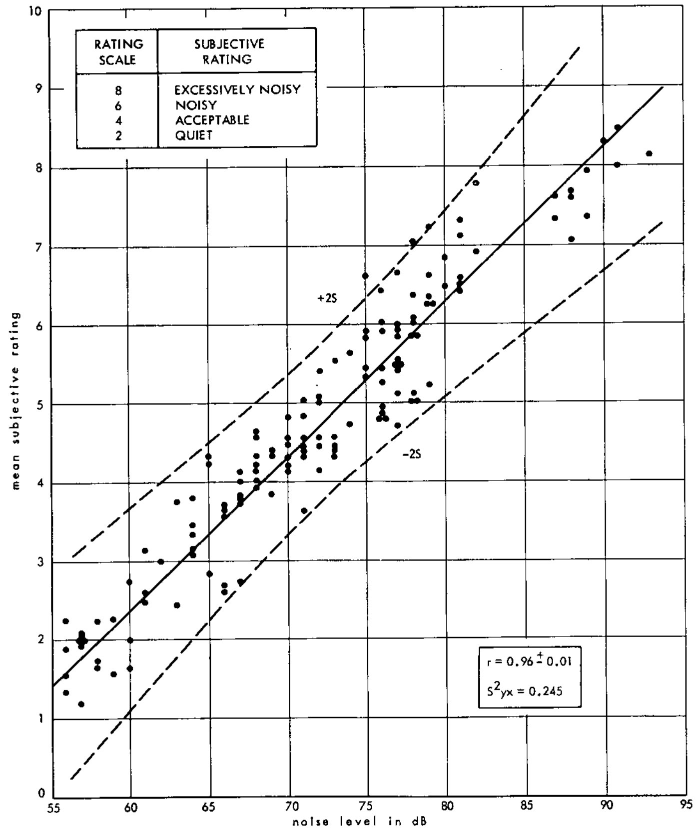


Figure A-3. Correlation of subjective ratings of noise from all vehicles in the MIRA experiment with speech interference level in dB.

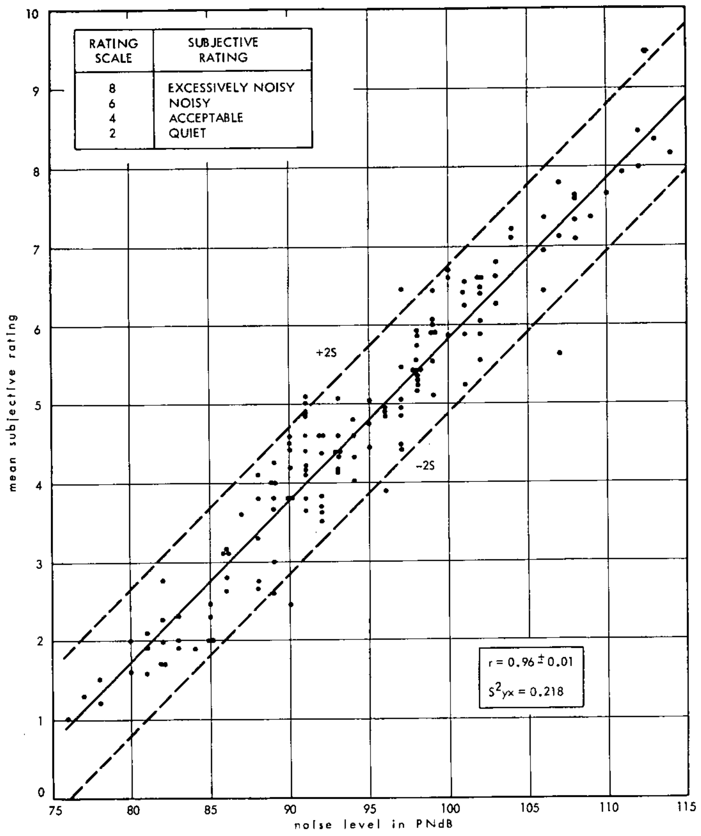


Figure A-4. Correlation of subjective ratings of noise from all vehicles in the MIRA experiment with perceived noise level in PNdB.

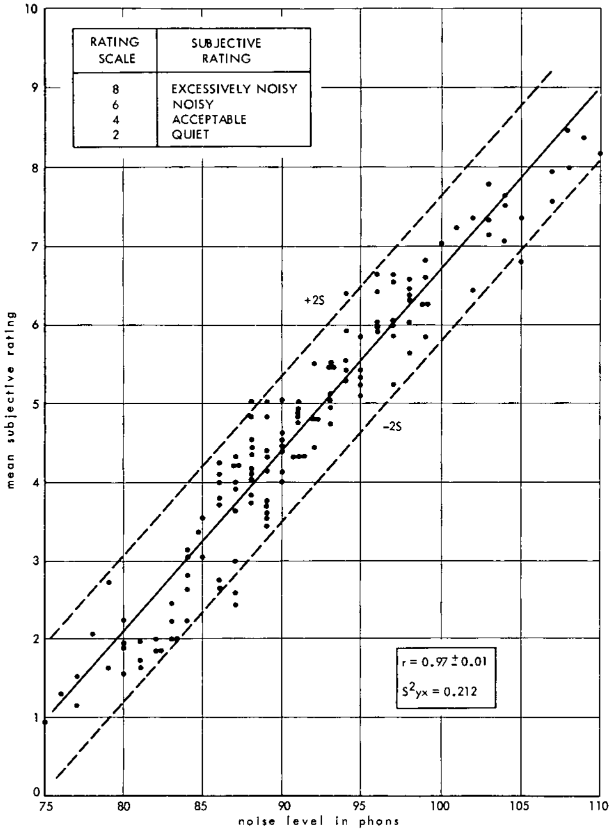


Figure A-5. Correlation of subjective ratings of noise from all vehicles in the MIRA experiment with loudness level (Stevens) in phons.

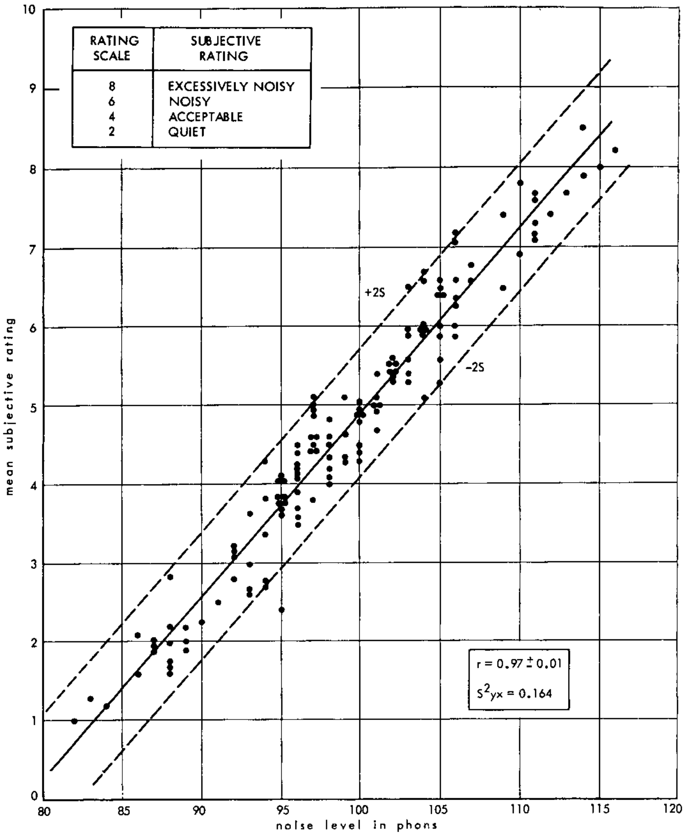


Figure A-6. Correlation of subjective ratings of noise from all vehicles in the MIRA experiment with loudness level (Zwicker) in phons.

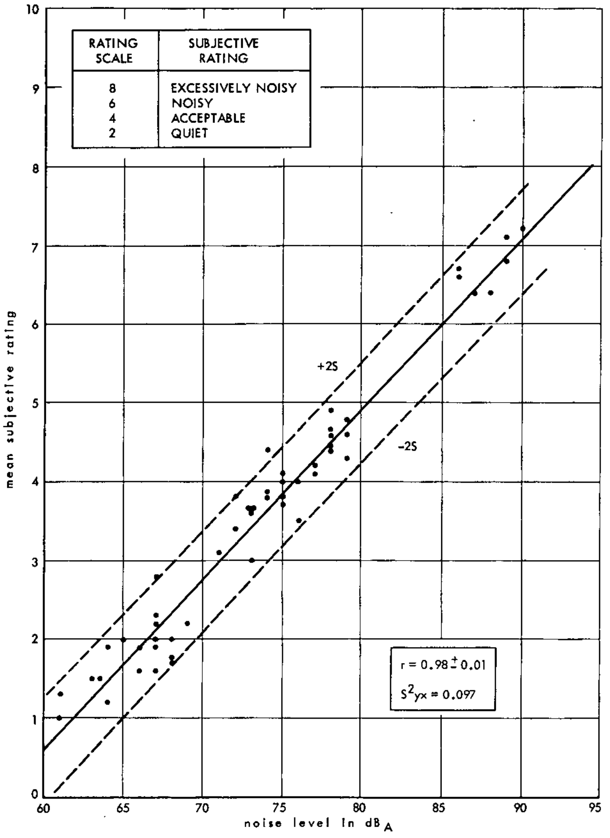


Figure A-7. Correlation of subjective ratings of noise from gas-engined vehicles (petrol) in MIRA experiment with noise level in dBA.

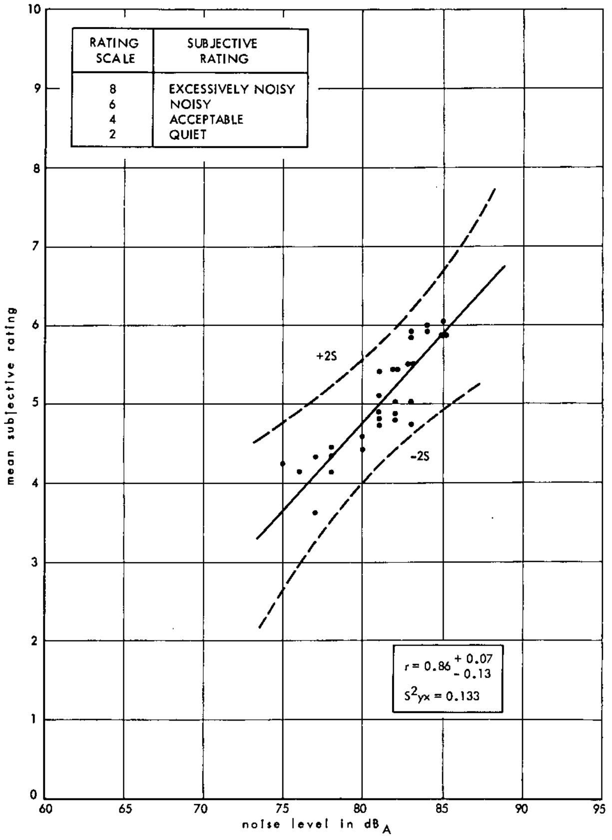


Figure A-8. Correlation of subjective ratings of noise from diesel-engined trucks in MIRA experiment with noise level in dBA.

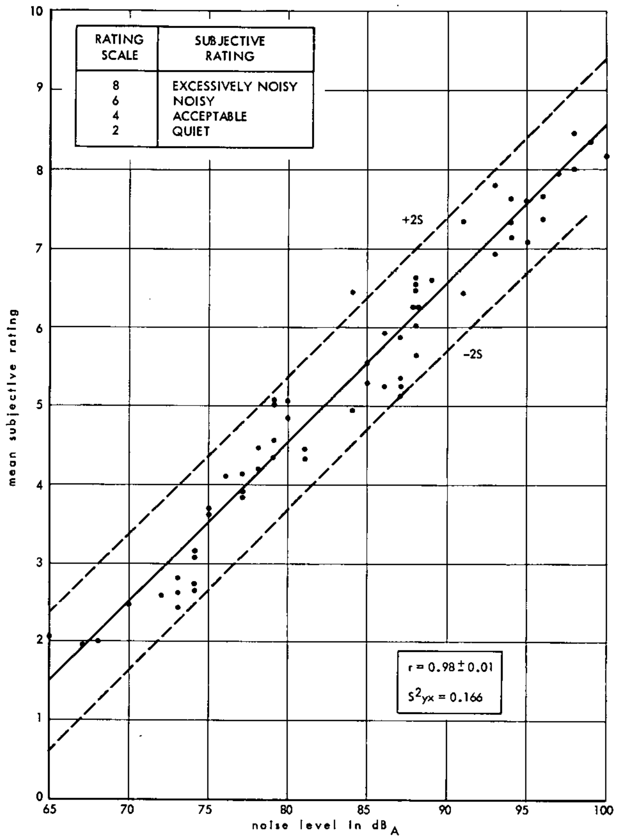


Figure A-9. Correlation of subjective ratings of noise from motorcycles in MIRA experiment with noise level in dBA.

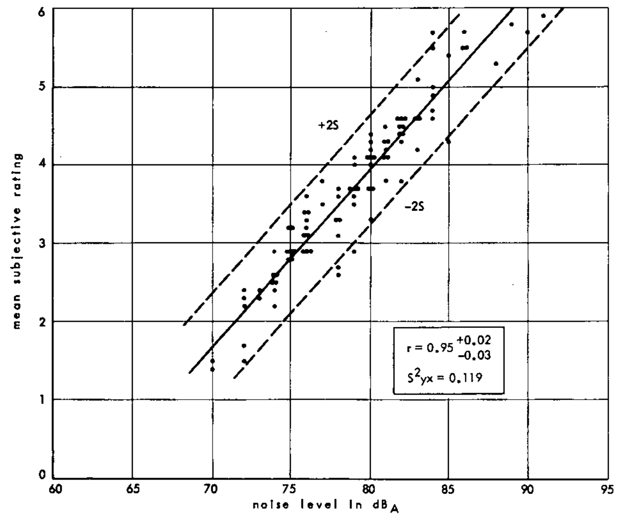


Figure A-11. Correlation of subjective ratings of noise from diesel-engined trucks in ARF experiment with noise level in dBA as computed from octave band sound pressure levels.

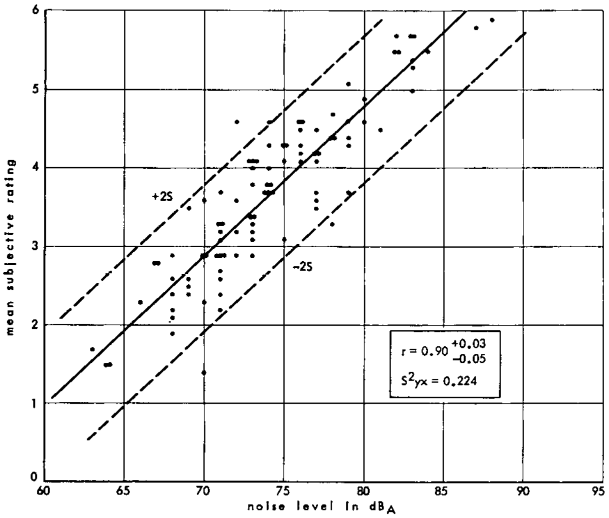


Figure A-10. Correlation of subjective ratings of noise from diesel-engined trucks in ARF experiment with noise level in dBA as reported by ARF.

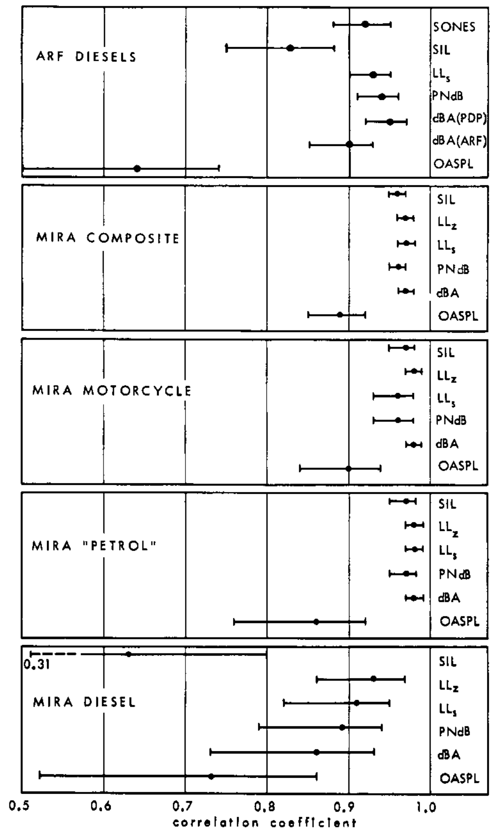


Figure A-12. Correlation coefficients and 2S *confidence intervals for various measures of subjective reaction to vehicle noise.*

precision than the old sound level meters. At the present time, however, there appears to be little justification for not changing to noise level in dBA; precision sound level meters are now in common use. Figure A-12 shows that dBA as now measured provides a slightly higher correlation coefficient than sones, although the confidence intervals do overlap. The much greater ease of measurement with a sound level meter is a real attraction.

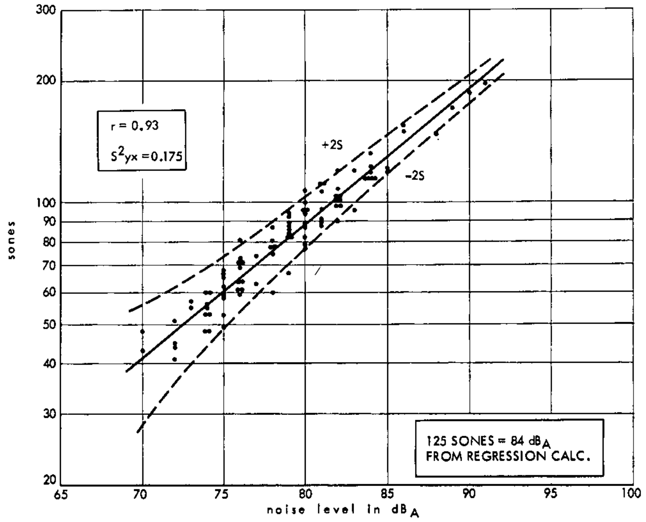


Figure A-13. Correlation of equivalent tone sones with noise level in dBA for equal subjective reactions in ARF experiments.

An indication of the relationship between dBA and sones for the ARF truck data is shown in Figure A-13. These data indicate that the equivalent-tone-sones for truck noise can be predicted with a high correlation by the noise level in dBA. The ATA 125 sone specification would correspond to a noise level of 84 dBA.

It is sometimes of use to talk about how much noisier one sound is than another. One can construct a table relating the quantitative differences between the noisiness of two sounds if the two sounds are similar in character. Table A-1 relates to motor vehicle noise as reported either in PNdB or dBA.

TABLE A-1

RELATION BETWEEN THE DIFFERENCE IN NOISE LEVEL OF TWO NOISES AND THEIR RELATIVE NOISINESS AS JUDGED BY AVERAGE LISTENERS

DECIBEL DIFFERENCE IN NOISE LEVEL OF TWO NOISES	RELATIVE NOISINESS OF NOISE WITH HIGHER LEVEL
0	Equal
5	1½ (50% >)
10	2 (100% >)
16	3 (200%)
20	4 (300%)

NOTE: This scale assumes the two noises have relatively similar spectrum shapes, durations, and meaning (e.g., both are motor vehicle noise).

APPENDIX B

ANALYSIS OF THE NOISE FROM INDIVIDUAL VEHICLES

Few live so far from urban development that they cannot hear, at some time of the day or night, the sounds of cars or trucks on the move. For many, the sound of moving traffic forms a continuous background noise on which other sounds are superimposed.

Noise is usually defined as unwanted sound, although some sounds from motor vehicles serve as warning signals. It is generally true that the cost of noise control measures becomes very high as those measures approach the limit of what is possible with given technology. Thus, the amount of noise control built into vehicles is in part determined by an economic compromise. To explore whether less noise might be achieved there must be an understanding of the various sources of noise and the major parameters of the noise-generating mechanism. Detailed noise control studies are properly part of the design process for vehicles, their engines and exhaust systems, and tires, and are not relevant to the present research. However, another important reason for analyzing the noise production for individual vehicles is to provide generalized descriptions of the noise generated by different categories of vehicles under different operating conditions. Such generalized descriptions are needed as data for estimating the noise characteristics of complex traffic flows and alternative roadway configurations.

SOURCES OF NOISE

There are two major sources of noise from motor vehicles in motion: the engine-exhaust system and the tire-roadway interaction system. Under some circumstances, intake noise at the carburetor opening constitutes a significant noise source, and the noise from cooling fans, valve lifters, superchargers, gear boxes, and many other parts is often detectable. Most modern passenger cars use good mufflers as factory equipment. Used cars, hot-rods, sport cars, motorcycles, and intermediate size trucks, on the other hand, often have inadequate mufflers. The extreme case is the truck or motorcycle with a straight exhaust pipe and either no muffler, or a rodded muffler.

Tire-roadway interaction noise is present for all motor vehicles in motion. For some vehicles and operating conditions, it is the dominant source of noise. For example, recent model passenger cars driven at high speed on a freeway radiate sound that is produced mostly by this tire-roadway interaction. Under some conditions, the sound from trucks is rich in tire-roadway interaction noise. Many characteristics of the tire, the roadway, and the vehicle suspension are important in producing this noise, although the specific mechanisms are not well understood or easily measured, as explained by Wiener (*21*). The amount of tread and the pattern of tread, the roughness of the roadway, whether it is wet or dry, the stiffness of the tire casing, the loading of the tires and the coupling between the tire and the vehicle body are all important in determining the amount of noise radiated.

Major Variables in Vehicle Noise Generation

In the macroscopic view necessary in studying the noise generation of vehicles by means of field measurements, a few variables are found important in describing differences in noise from one situation to another. These variables are the speed of the vehicle, the kind of road surface, and the load on the vehicle engine. The load may be interpreted as including the effects of acceleration (generation of more power from the engine than is necessary to maintain steady travel at the current road speed) and of up and down grades. This appendix deals with the effects of these variables on the noise generated by passenger vehicles and diesel trucks and arrives at some generalizations that are useful for describing the noise produced by highway traffic.

MEASUREMENTS OF VEHICLE NOISE

Choice of Measurement Sites

The measurements reported and analyzed in this appendix are of individual vehicles. Measurement sites were chosen to provide a clear run for the vehicle, a minimum of traffic interference, sufficient length so that the vehicle could attain steady state motion, and appropriate roadway surface.

There were no nearby buildings, signs or topographical features to reflect the sound from the vehicle and thus alter the noise level at the microphone. For most measurements the microphone was located 4 to 6 ft above ground and 25 to 100 ft to the side of the roadway. A distance of 25 ft is most satisfactory for passenger car measurements, especially at the lower speeds, because it assures that the sound from the vehicle will rise well above normal background noise. For large trucks, on the other hand, a distance of 25 ft is inadequate—the truck represents an extended noise source of greater dimension than the 25 ft. A distance of 50 ft was commonly used for controlled runs of trucks and up to 100 ft for measurements of random truck drive-bys.

In measurements of vehicles as they occur on lightly traveled roadways there has been an attempt to keep instrumentation and personnel inconspicuous to avoid distracting or alarming the drivers and causing speed or power changes.

Acoustical Instrumentation

It is possible to learn something of the noise produced by vehicles from direct measurements at the site with a sound level meter. Such a technique is quite reasonable as a tool for enforcement of noise limit ordinances, for example, if the instrumentation and its use are properly chosen. In order to provide meaningful data for detailed analysis of noise exposure, however, it is necessary to use equipment of laboratory precision and to pay special attention to frequency characteristics and proper calibration of the equipment. All of the measurements described in this appendix have been obtained with precision equipment: capacitor microphones, precision step-attenuators, and instrumentation quality tape recorders. Acoustical calibrations from secondary-standard acoustic sources have been introduced into the system at frequent intervals during measurement sessions and the resulting signals recorded along with the data. Illustrations of this equipment are shown in Figures B-1 and B-2.

All of the noise measurements on vehicles have been tape recorded. Tape recording is desirable for a number of reasons. It permits careful analysis of the contributions of different frequency ranges to the over-all noise level. It provides a record of the entire exposure and thus allows the analyst to decide whether the recording is impaired by other events. In some cases, the playback and analysis of the tape recording have been performed by a trained observer reading the output on a calibrated meter. In other cases the output in each frequency band of importance has been automatically plotted on a level recorder strip chart for a visual record.

Description of Available Data

The data used in the analyses to follow include measurements obtained within the past several years as a part of this study, as well as measurements obtained earlier. The data are identified in Table B-1, in two broad categories; (1) those of controlled experiments where test vehicles were driven over measurement sources at defined speeds, etc., and (2) samples of the vehicles occurring on certain stretches of roadway free of interference from other vehicle noise. The latter samples are called "random drive-bys" in the remainder of this report.

ANALYSIS OF NOISE FROM PASSENGER CARS

A study of the noise produced by passenger cars is important to this project for at least two major reasons. First, the traffic on urban highways consists mostly of passenger cars with a small proportion of miscellaneous trucks and other vehicles and a still smaller proportion of large diesel trucks. Although the passenger cars are not as noisy as other vehicles, they constitute such a large proportion of the total flow that their cumulative contribution to highway noise is important.

Second, the passenger cars represent a reasonably homogeneous category of vehicles in terms of the noise exposure. Differences from one make of automobile to another are not particularly important in the amount of noise produced or of its frequency characteristics. Although older cars tend to produce more noise than new cars because of deterioration of their muffler systems and the onset of rattles and mechanical noises, the population of passenger cars is heavily weighted toward relatively new cars in an urban community and thus presents a fairly uniform picture of noise source.

This characteristic of relative homogeneity in the category of passenger cars means that controlled experiments can be run on individual vehicles with considerable anticipation of success in extrapolating the results to the whole population. Further, the sample size necessary to derive a statistically stable indication of noise source characteristics is greatly reduced by the homogeneity of the base population.

Trucks, on the other hand, offer many alternatives of engine and body combination, and many basic differences in engine design and in ancillary equipment such as superchargers and engine braking systems that create large differences in the noise exposure. Thus, to get a representative sample of noise from a population of trucks is much more difficult.

Sources of Noise for Passenger Cars

The two major sources of noise for highway vehicles in general have been discussed earlier. For passenger cars the noise under normal operating conditions is a composite of contributions from the engine-exhaust system and the tire-roadway interaction system. The characteristic spectral shapes for passenger car noise as measured at a position 25 ft away from the vehicle at the side of the road are shown in Figure B-3. The narrow hatched band illustrates spectra measured for cars traveling at 65 mph. The upper edge of the band shows noise from cruise conditions, and the lower edge the noise created while coasting with the engine disengaged. The small differences between these two curves on the right hand side of the spectrum band indicate that the noise produced is primarily from the tire-roadway interaction which is independent of the engine operation. The somewhat greater differences between the two curves in the left half of the spectrum show that engine-exhaust system noises are important in this low frequency range at 65 mph during normal cruise conditions. The differences of 3 to 5 decibels suggest that one-half or more of the noise in the second, third, and fourth octave band comes from the engine-exhaust system.

The other banded area on Figure B-3 shows the range of spectra at 35 mph, from normal cruise condition at the lower edge of the band to maximum acceleration condition at the top edge. The large difference between these conditions across the entire spectrum indicates that engine-exhaust system noise predominates over the entire spectrum for conditions of maximum acceleration. For cruise conditions the noise is probably a composite of engine-exhaust and tire-roadway noise as it is for the 65 mph cruise condition.

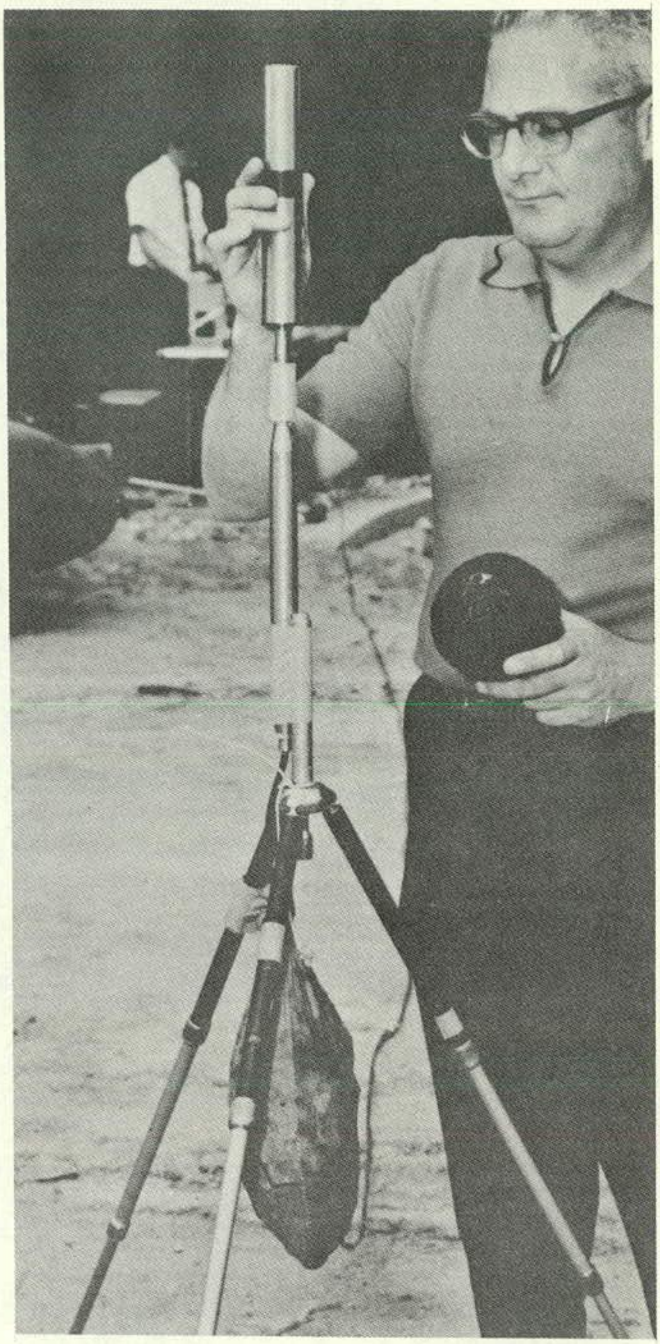


Figure B-1. Microphone used for field measurement of noise being calibrated with a secondary standard sound source.

Figure B-3 and many of the subsequent figures are plots of the sound pressure level in dB measured in each of 8 or 9 octave bands of frequency. The measured values are plotted at the geometric mean center frequency of the

Figure B-2. Precision sound level meter (lower instrument) and instrumentation tape recorder (upper instrument) used in field measurements.

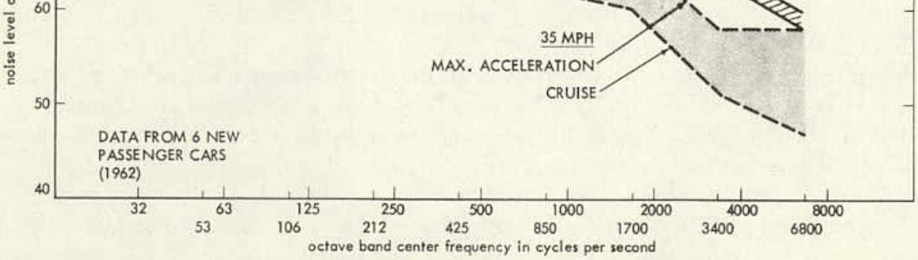


Figure B-3. Illustration of contributions from passenger car noise sources.

octave bands, as noted on the horizontal axis of the figures. Data taken in the past were analyzed with octave band filter sets meeting the old standards which were in use for many years. Those data are plotted at center frequencies of 53, 106, 212, 425, . . . Hz. Recent data are analyzed with equipment meeting the newer standard ASA S1.6-1960 and are plotted at center frequencies of 32, 63, 125, 250, . . . Hz. Because it is the shapes of the noise spectra that are involved in these illustrations, it was decided to plot the data as analyzed rather than to attempt conversions from one system of octave bands to the other.

Figure B-4 shows further the characteristic noise spectrum shape for cruise conditions of passenger cars. Noise levels are shown for a sample of 15 passenger cars at cruise conditions in the speed range from 43-57 mph, centered at 50 mph. The data for Figure B-4 are samples from Data Sets 7 through 9, Table B-1. Data for two other speed ranges, 23-42 mph and 58-72 mph, measured under the same conditions, illustrate essentially the same spectrum shape with slight differences in low and high frequencies. Thus, Figure B-4 can be considered to exemplify the spectrum shape encountered for vehicles in these three ranges of speed.

The individual spectra that go to make up Figure B-4 are not all exactly of the shape of the median spectrum. In some cases the contributions in the low octave bands may be in the upper part of the distribution whereas those in the high bands may be in the center or the low part of the distribution. On the average, however, this representation is a fair one for the noise sources as a class. The samples shown in Figure B-4 for the different octave bands of frequency have a standard deviation ranging from 2 to 4 decibels around the mean spectrum for the group. This distribution of individual measurements in octave bands for a limited speed range and similar roadway conditions is typical of the 120 or so spectra for random drive-bys of passenger cars which make up Data Sets 7 through 11 (Table B-1).

More insight into the relative contributions of engine-exhaust systems and tire-roadway interaction can be gained from study of Figure B-5. The upper graph illustrates the differences in spectra between cruise conditions and ac-

TABLE B-1

NOISE MEASUREMENT DATA FROM INDIVIDUAL VEHICLES

DATA SET	ROADWAY [a]	CONDITIONS AND SAMPLES
		(*a*) CONTROLLED EXPERIMENTS
1	A, B	Two station-wagon-type passenger cars of American manufacture (1963 and 1964) at controlled speeds of 30, 40, 50, and 60 mph.
2	C	Six new cars at speeds of 35, 50, and 65 mph, and for acceleration and coasting conditions.(*16*)
3	A	Controlled speed runs at 30, 40, 50, and 60 mph for two of the passenger vehicles used in initial formulation of the traffic noise model being extended in this study. (*9, 10*)
4	C	Diesel trucks under load conditions for level, up-grade, down-grade, and acceleration operation.(*16*)
5	—	Diesel truck tractor on a dynamometer stand at the maintenance headquarters of a trucking firm.(*16*)
6	C	Five new sport cars and four new motorcycles, controlled speed runs of 35, 50, and 65 mph, and acceleration conditions.(*16*)
		(*b*) SAMPLING FROM TRAFFIC
7	E	Random drive-bys of 22 passenger cars.
8	A	Random drive-bys of 12 passenger cars.
9	F	Random drive-bys of 7 passenger cars.
10	B	Random drive-bys of 39 passenger cars.
11	A	Random drive-bys of 43 passenger cars.(*9*)
12	G	Random drive-bys of 34 large trucks.(*10*)
13	H	Random drive-bys of 18 large trucks on 52 up-grades.(*10*)
14	I	Random drive-bys of 20 diesel trucks.
15	J	Random drive-bys of 20 diesel trucks on approximate 4% up-grade.

[a] Roadway surfaces: A, E= rough asphalt;
B= very smooth asphalt;
C, F, G, I, J= concrete freeway;
H= asphalt.

celeration conditions at 35 mph for the six cars of Data Set 2 (Table B-1). Each point represents the difference between the noise level in that octave band at cruise condition and at maximum acceleration condition for one car. The median line drawn through the points thus illustrates a relative spectrum for the change from cruise to acceleration conditions. The change is somewhat greater in the low frequency half of the spectrum than in the high frequency half, although quite significant throughout the whole frequency range. It is important to note that the distribution of the differences is quite large compared to the distribution of levels found in Figure B-4. Some engine noises that are not normally observed during cruise conditions become very significant at maximum acceleration,

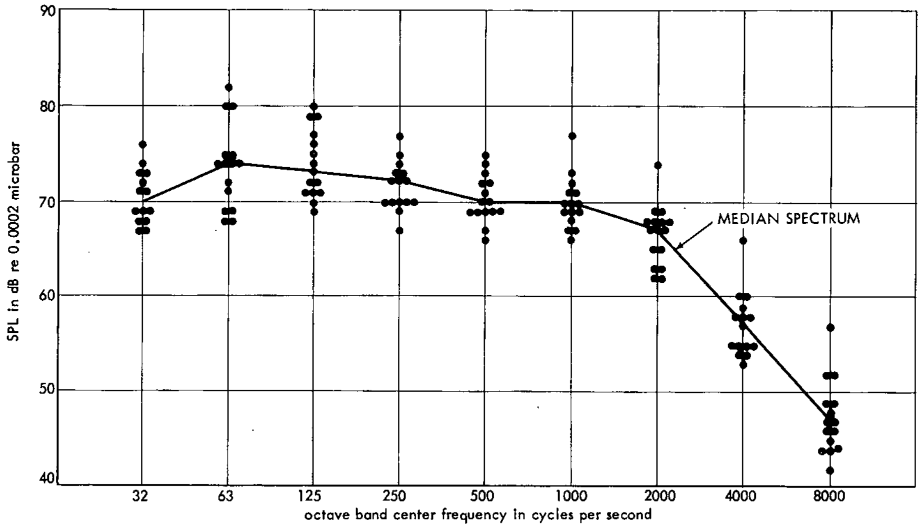
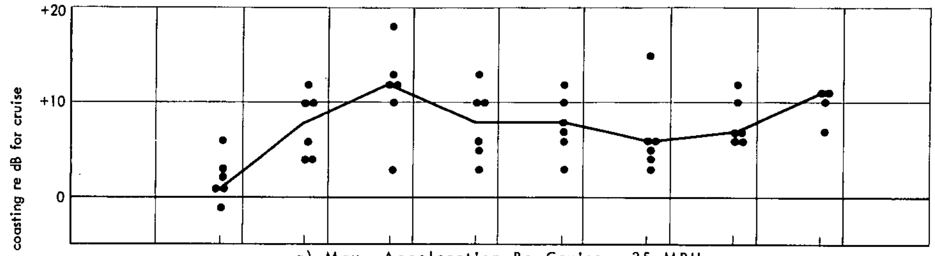
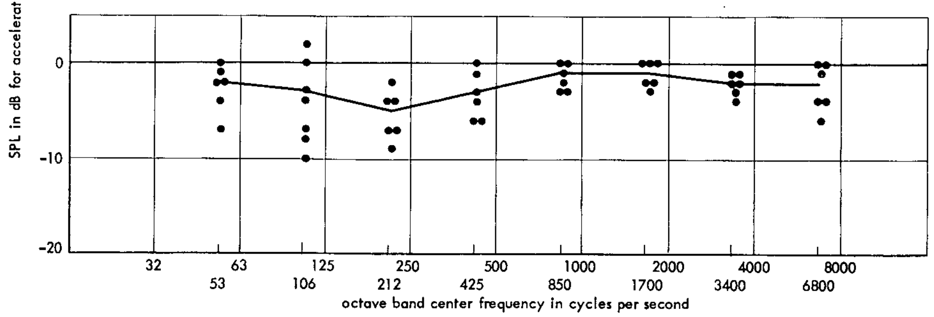


Figure B-4. Illustration of the distribution of noise levels for 15 passenger cars at cruise conditions.



a) Max. Acceleration Re Cruise - 35 MPH
6 New Cars (1962)



b) Coasting Re Cruise - 65 MPH
Neutral Gear, Engine Idling
6 New Cars (1962)

Figure B-5. Differences in noise spectra between (a) cruise and acceleration, and (b) cruise and coasting conditions for passenger cars.

such as noise generated at the carburetor intake. The character and magnitude of these sources vary considerably, depending on the equipment of the vehicle.

The lower graph of Figure B-5 shows the differences between cruise and a coasting condition with the engine disengaged. Again, the individual points represent differences for each individual vehicle. The median line drawn through the points represents the shift from cruise to coasting conditions for the six cars of Data Set 2 (Table B-1). The magnitude of the difference is considerably less than in the acceleration condition, suggesting, as discussed earlier in conjunction with Figure B-3, that the noise from the tire-roadway interaction represents a larger component of the total noise at 65 mph than in the 35-mph case.

The distribution of the measured levels shown in Figure B-4 accounts for measurement errors as well as differences between different vehicles. Replicated measurements undertaken as part of the controlled runs in Data Sets 1 through 3 (Table B-1) have indicated that 1- to 2-decibel differences from run to run are to be expected. Thus, the differences between cruise and coasting conditions for the higher frequency bands in the graph of Figure B-5 are not of major significance.

One concludes from Figures B-3 and B-5 that the difference between maximum acceleration conditions and cruise conditions is far larger than the difference from cruise to coasting conditions. (The fact that these data presented are for two different speed ranges confounds the comparisons somewhat but does not alter the basic conclusion.) This suggests that the major variations in noise exposure for individual vehicles are going to come in situations of stop and go driving, such as at intersections, rather than on the open road where accelerations are probably minor. This factor is much more important for trucks and for other vehicles than for passenger cars and is discussed later.

Effects of Speed

A good grasp of the major effects of speed changes on the noise produced by passenger cars can be obtained from Figure B-6. This figure illustrates, from Data Set 1 (Table B-1), a controlled experiment where a relatively new station wagon was driven at speeds of 30, 40, 50, and 60 mph past the measurement point. For the most part the noise spectra illustrate a consistent increase in all octave bands of frequency for each increase in speed. A merging of the 40 and 50 mph spectra in the low frequencies is possibly due in part to shifts in the spectrum from engine-exhaust system sources and in part to fluctuations in measurement. In other runs, for example Data Set 3 (Table B-1), repeated measurements made for each speed in each direction of travel tend to average out such discrepancies and thus show consistent increases in all bands with increased speed.

Figure B-6 for one vehicle on one type of surface is typical of data from Data Sets 1, 2, and 3 (Table B-1). These data encompass measurements on smooth and rough asphalt surfaces and concrete roadways, and measurements on passenger cars ranging in age from 1951 to 1964 models. An important point from all of these measurements is that there are no sharp changes in spectrum shape over the range of speeds measured, but rather small continuous changes which tend to average out over the entire data set.

In order to derive an expression for the dependence of the noise level on vehicle speed, one could analyze the data from runs such as shown in Figure B-6 for each octave band alone. However, since the spectra tend to retain the same shape over speed and for different vehicles, it is convenient to use a single measure of the noise level rather than a description in 8 or 9 octave bands. A suitable measure for this purpose is the A-scale noise level in units of dBA. The A-scale noise level is equivalent to that measured using the "A" weighting network of a sound

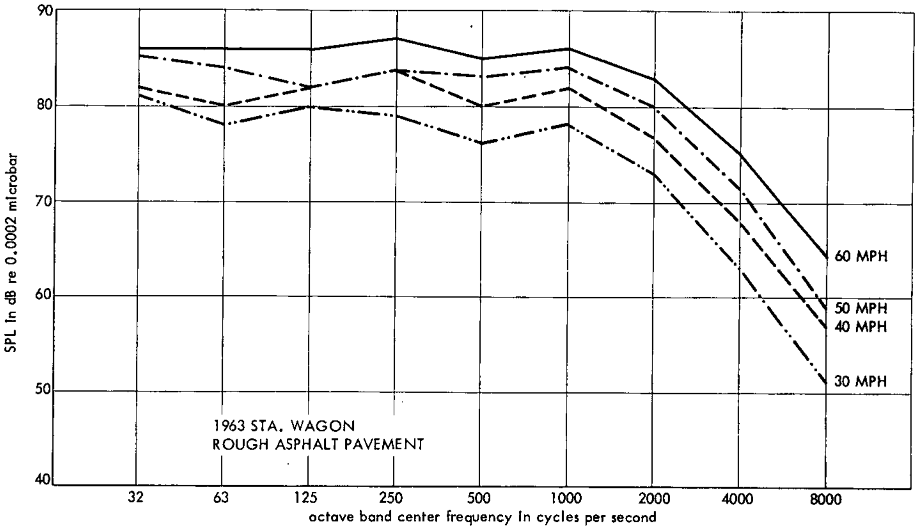


Figure B-6. Noise spectra for a passenger car at four speeds.

level meter that meets the requirements of American Standard ASA S1.4-1960. This measure of noise level and its usefulness for vehicle noise measurements are discussed in Appendix A.

Figure B-7 shows curves of dBA versus speed for controlled runs of two vehicles from Data Set 1 (Table B-1). Note that the lines, when plotted on semi-log graph paper, tend to be straight lines. Since dBA is in itself a logarithmic function of sound pressure, this straight line may be interpreted as a power function between sound pressure and speed. Theoretical considerations suggest a third power relationship for such noise source phenomena. To a first approximation it is reasonable for the noise power generated by passenger vehicles to be directly proportional to the power expended by the vehicle, and thus be proportional to the cube of vehicle speed. In order to develop a predictive model for the effect of speed on noise level, a least-squares fit of noise versus speed was computed, based on a 30-log speed relationship.

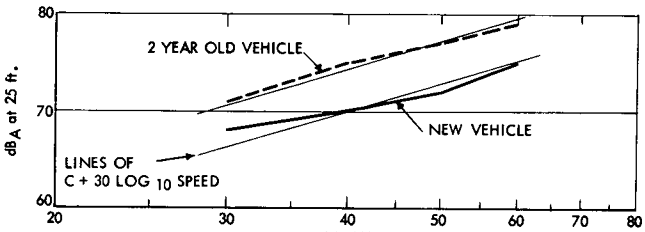
The experimental data illustrate that the approximation is reasonable, as is shown by the lines of proper slope for this third power relationship through each set of points on Figure B-7.

The controlled runs on individual vehicles illustrate the speed relationship, but do not constitute a sufficient sample from which to generalize the equation of this line because differences in the two vehicles (tires, alignment, muffler effectiveness, etc.) cause an offset between the two sets of points.

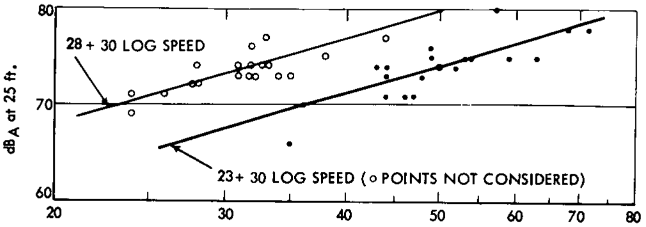
The data from the random drive-bys of Data Sets 7 through 10 (Table B-1) are plotted in graphs (b) and (c) of Figure B-7. The solid points in graph (b) are the combination of data from Data Sets 8 and 9, where the open points are data from Data Set 7. The data in graph (c) are from Data Set 10. Lines have been fitted to each of the three sets of points. For each set taken by itself the fit is reasonably good; for the three sets combined, no reasonable line of comparable slope can be fitted. Thus, it is apparent that there is an offset between the three sets of measurements and that each set alone fits the third power speed dependence.

Effects of Road Surface

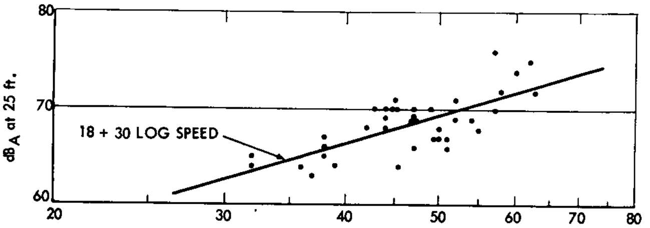
The illustrations in Figure B-7 show that measurements on different road surfaces lead to different collections of dBA versus speed points, each of which is internally consistent in terms of a third power relation on speed, but which are offset one from the other by about 5 dBA. Examination of these three road surfaces suggests an explanation for the differences. The surface for the open dots in graph (b) was a rough asphalt pavement with large voids, ½ in. or greater in diameter, prominent at the surface. The surfaces for the other points in graph (b) were a moderately rough asphalt surface and a rough concrete surface typical of freeway construction. The scale of roughness in these two is generally similar. The points of graph (a) were measured on a very smooth, nearly new asphalt pavement which was compact, with little surface roughness and voids of very small size in the surface. The samples for these three conditions are sufficiently large to justify a conclusion that the differences are attributable to the differences in roadway surface.



a) Controlled



b) Rough Pavements



c) Very Smooth Pavement

Figure B-7. A-scale noise level in dBA vs speed for passenger cars for (a) controlled runs on rough pavement, (b) random drive-bys on rough pavements, and (c) random drive-bys on very smooth pavement.

Figure B-8 illustrates further the difference between smooth and rough pavements. The data here, from Data Set 1, are plotted in such a manner that each point represents the difference between the rough pavement and the smooth pavement runs at one speed for one vehicle. The median line drawn through the collections of points thus represents the relative spectrum for the difference in going from a moderately rough pavement to a very smooth pavement.

Figure B-8 indicates that the difference between the two pavements is greatest in the neighborhood of 2,000 Hz. Comparisons with the data from a concrete surface suggest that the difference between very smooth asphalt and moderately rough concrete is greatest for frequencies higher than the 2,000 Hz. This is shown in Figure B-9, which illustrates the changes in the shape of the noise spectra for three different pavement conditions. The very smooth asphalt is seen to provide the lowest noise levels in the high-frequency bands; the rough asphalt provides much higher levels in this region, particularly at frequencies of 1,000 and 2,000 Hz; and the concrete pavement provides even higher levels, particularly in the frequencies above 2,000 Hz.

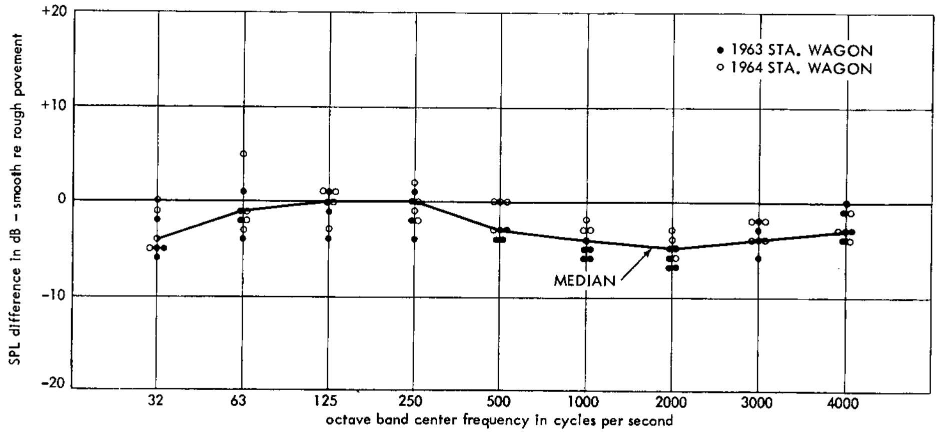


Figure B-8. Difference in noise spectra between rough and smooth pavements for two passenger cars (25-ft distance, 30, 40, 50, and 60-mph speeds).

Generalization

A major reason for these analyses is to provide representative noise spectra for different vehicle types that can be used in a computer-based simulation model to generate noise exposure descriptions for different highway configurations. One way of generalizing from these data on automobiles would be simply to average all of the available data. That approach would be unwise in the present instance because some pavement conditions are more typical of those to be found in urban highway networks than are others. Further, some of the deviant data are for relatively low speeds and thus less important in considerations of highway noise than are the data taken at higher speeds.

A generalized octave band spectrum for passenger cars at 50 mph and 50 ft is illustrated in Figure B-10. This spectrum has been derived from the data in Data Sets 1 through 3 and 7 through 11 (Table B-1) by weighting the various data sets together with judgment on the kind of roadways and speed ranges that should be considered.

It was previously stated that the frequency spectrum shape for passenger car noise does not show important changes over a wide range of vehicle speeds. As a consequence, a simplified technique for estimating passenger car noise can be described. The studies of speed *vs* dBA (see Fig. B-7) provide a model equation useful for determining the A-scale noise level:

$$\begin{aligned} L_{auto} &= 16 - 10 \log_{10} \left(\frac{d}{50}\right)^2 + 30 \log_{10} v \\ &= 50 - 20 \log_{10} d + 30 \log_{10} v \end{aligned} \qquad \text{(B-1)}$$

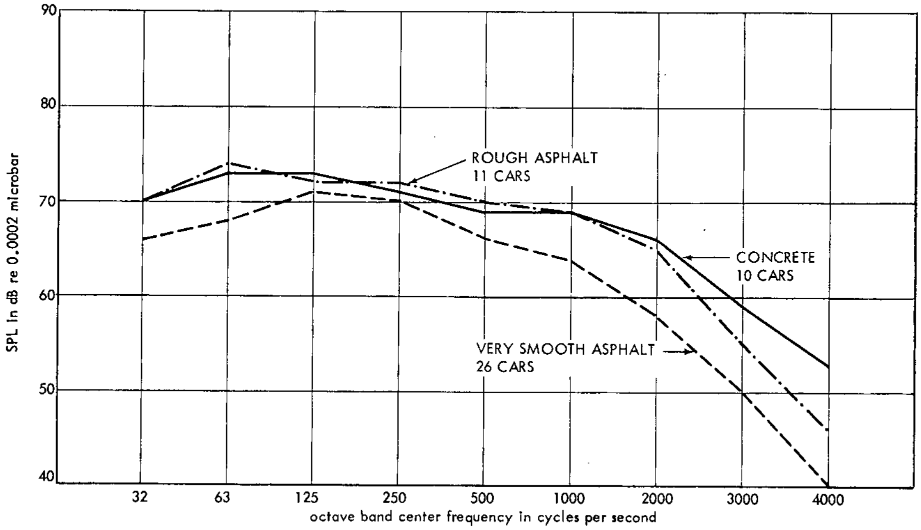


Figure B-9. Noise spectra for passenger cars on three roadway surfaces (25-ft distance, 43- to 57-mph).

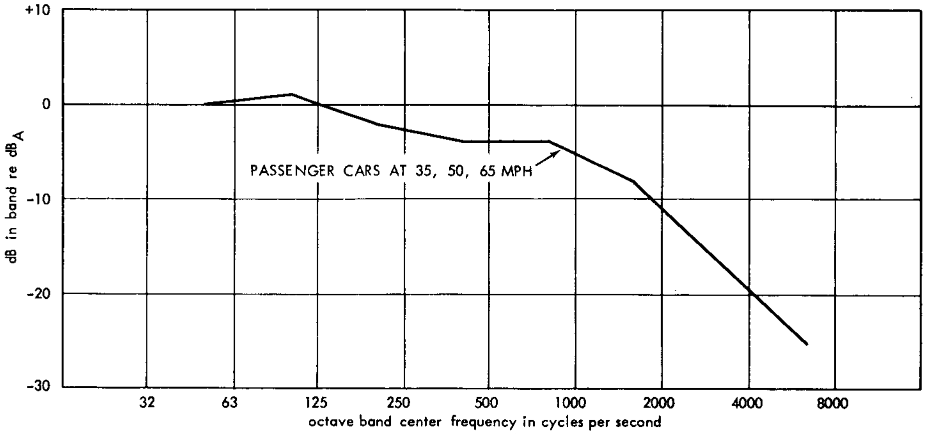


Figure B-10. Generalized relative noise spectrum and dBA estimation equation for passenger cars at 50 mph.

in which

L_{auto} = noise level, in dBA;
d = distance, in ft, to auto;
v = speed, in mph.

With the A-level determined by this equation, the relative spectrum of Figure B-10 can be used to determine the expected octave band sound pressure levels. Eq. B-1 should not be used for distances smaller than 25 ft. At greater than several hundred ft, attenuation due to the absorption of sound in air must be taken into account (Appendix C).

Because the spectrum differences for different surfaces are not extreme, variations in roadway surfaces could be accounted for by an offset in this dBA-versus-speed relationship, such as indicated in Figure B-7. Values of 11 and 21 for the constant (5 units above and below the value 16) would account for extremely rough and smooth roadway surfaces.

ANALYSIS OF NOISE FROM DIESEL TRUCKS

Large diesel trucks represent a relatively small proportion of total traffic on urban highways, often 5 percent or less. They are, however, impressive sources of noise and are usually clearly audible in the mixture with automobiles in traffic. The noise from diesel trucks must be considered seriously because these trucks are inherently much noisier than passenger cars, being on the order of 15 dBA higher in noise level. Other types of vehicles such as motorcycles are noisy largely because the standards of muffling of their exhaust noise are not comparable to those for passenger cars. With diesel trucks, as operated by major trucking lines, the opposite is true. The standards of muffling and mechanical condition are high; the trucks are noisier simply because they radiate relatively large amounts of acoustic power, because of their mechanical design configurations.

Sources of Noise for Trucks

In the earlier discussion of noise from passenger cars the illustrations in Figure B-3 were used to show that the characteristic spectrum shapes for passenger car noise are a composite of tire-roadway noise and engine-exhaust noise. For large diesel trucks the noise is again a composite of contributions from the engine-exhaust system and the tire-roadway interaction, but the engine and exhaust noise tends to be more dominant for most operating conditions. An illustration of the range of variations for engine-exhaust noise is shown in Figure B-11. Noise spectra are shown for a diesel tractor being operated on a dynamometer to simulate road conditions. Three different measured conditions are illustrated to show the effect of muffling on the exhaust noise. The top spectrum illustrates the noise with no muffler, but with a straight stack extending to the same point. The second spectrum illustrates the noise produced under similar operating conditions with a stock muffler of the type normally used by the operator on this truck. The lowest spectrum illustrates an experimental combination of two mufflers used to illustrate the practical limit of noise reduction through mufflers. Figure B-11 shows that the major improvement is made in going from a straight stack to the stock muffler, and only a minor improvement at other than low frequencies is made by employing an experimental and bulky collection of tandem mufflers. It should be noted that for any measure of the noise such as the A-scale weighting or perceived noise level, the differences between the stock muffler and the special tandem mufflers in the low frequency bands would not be significant. (See Appendix A.)

Some knowledge of the contribution of tire noise to the noise from diesel trucks in motion can be obtained from the lowest spectrum in Figure B-12, which shows the measurement of a diesel truck on a down-grade engine

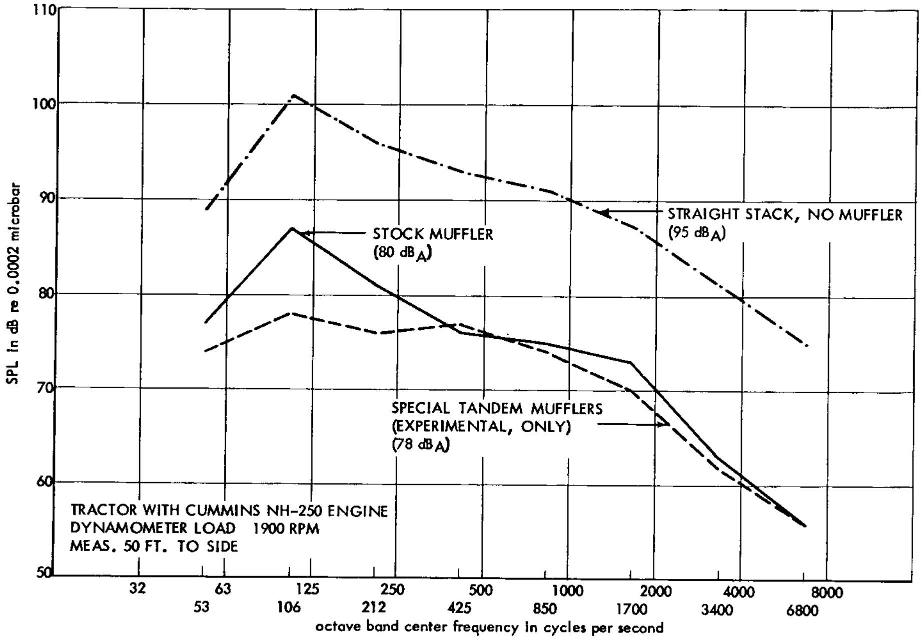


Figure B-11. Illustration of the effects of three exhaust configurations on the noise spectrum measured 50 ft from a diesel truck.

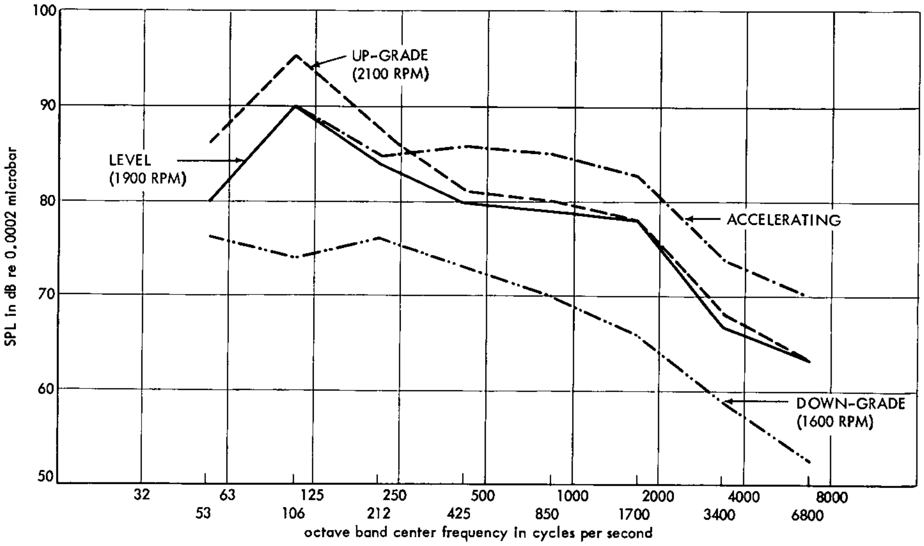


Figure B-12. Noise spectra at 50 ft from a loaded diesel truck for up-grade, level, down-grade, and acceleration conditions.

at idle. Comparisons with passenger car spectra indicate that this spectrum is within a few dB in the high-frequency bands of the tire noise for the passenger cars and thus is presumably tire noise, for the most part. Additional corroboration is afforded by the comments of the field observer during those measurements that the engine noise was essentially inaudible for the run. The data are from Data Set 4, Table B-1.

Effects of Operating Conditions, Speed, Grades, and Road Surface

As was true with passenger cars, the major effect of operating conditions on noise levels comes during acceleration. Figure B-12 shows the noise spectra measured 50 ft from a loaded diesel truck for a number of conditions. The accelerating condition is seen to produce noise levels of 5 to 7 dB above the level for up-grade conditions over most of the middle and high-frequency range. In this regard, it is probably the noise associated with acceleration that results in complaints about trucks on freeway approach ramps rather than the fact of the upgrade. Truck speeds do not vary over as wide a range as passenger car speeds. Further, the trucks have a large number of gear combinations allowing the driver to adjust the connection between engine and wheels so as to maintain essentially constant engine power output. For these reasons and others, the differences observed between level travel and up-grade travel are not large. For the truck noise illustrated in Figure B-12 the differences are as much as 6 or 7 dB in the lower several bands, but then become virtually insignificant.

A fact of the performance of reactive mufflers explains part of this similarity between up-grade and level conditions. As the engine is required to produce more power, the exhaust pressure rises. As exhaust pressure rises, the efficiency of a reactive muffler increases. Thus, the increased noise produced by greater engine power is somewhat offset by greater efficiency of the muffler.

Analysis of two series of truck noise measurements, Data Sets 12 and 13 (Table B-1), failed to disclose any appreciable effect of speed on noise levels (dBA). In contrast, it was shown in Figure B-7 that for passenger cars the noise level in dBA tends to vary with the vehicle speed. The tendency to operate trucks for constant engine power over a range of speeds and the relatively small contribution of tire-roadway noise to the overall truck noise probably account for the lack of speed dependence.

In an attempt to explore further the effects of up-grade vs level roadways for trucks, two sets of measurements were obtained on diesel trucks in normal traffic (Data Sets 14 and 15). Diesel trucks that were operating in freely flowing traffic were selected and were sufficiently separated from other noise sources to provide clean acoustic samples. The data include both two-cycle and four-cycle diesel trucks. The two samples were obtained at two sites on the same Los Angeles freeway at about the same time of day. This choice of time, and other observations, confirm that the samples of trucks are indeed comparable and representative of normal traffic.

Twenty satisfactory recordings were obtained for each position graded. Two samples have been analyzed and compared to test whether, in fact, the presence of a grade does increase the noise from the trucks.

In Table B-2 the sound pressure levels in eight octave bands for each of the truck samples are tabulated and summarized. A third set of carefully controlled (level roadway) diesel truck measurements from Data Set 4 is also tabulated in Table B-2. This illustrates the range of levels observed in each of the situations and suggests differences between the sets.

Analysis of the two series of level roadway measurements shows that they do not differ significantly. Thus, they have been combined into a level roadway group of 26 measurements for comparison with the up-grade measurements.

Comparison of the level and up-grade groups shows that the up-grade group produced significantly higher * noise levels, in the octave bands although the magnitude of the difference on A-scale value is only about 2 dBA because of the response of the A-weighting network. The differences arise primarily in the lowest two frequency bands, where the effect of engine power, speed, and gearing differences would be expected to show up.

Generalization

As was the case for passenger cars, the available data on trucks to arrive at a generalized spectrum for use in simulations cannot merely be averaged. As a generalized spectrum the mean spectrum has been chosen for 26 diesel trucks on a level roadway, from Table B-2. This spectrum is shown in Figure B-13. The A-scale noise level for this generalized spectrum would be 82 dBA at 50 ft.

The available data suggest that although the large diesel trucks tend to be similar in noise output at road speeds under cruise conditions, they exhibit large differences in both spectrum shape and level for acceleration, downgrade, and other conditions. Some of these are due to design differences in the various diesel engines and to superchargers, engine-driven brakes and other special equipment. An exhaustive study of the source variations and a detailed statistical sampling of the various source types is beyond the scope of the present studies.

NOISE FROM OTHER VEHICLES

Data on the noise from passenger cars and from large diesel trucks have been analyzed in some detail in previous sections. There are a number of other categories of vehicles that comprise some fraction of the traffic on urban highways. Five such categories might be described: motorcycles, sport cars, light trucks, larger gasoline-powered trucks, and buses.

Noise Characteristics of Different Vehicle Types

Two categories of vehicles that are often cited as prime offenders of noise restrictions are motorcycles and sport cars. Data have been obtained on both of these categories in Data Set 6 (Table B-1). Data for 65-mph cruise conditions for both are summarized in Figure B-14. In both cases the conclusions from the measurements are that no particular correlation exists between the amount of power developed, or the size of the vehicle, and the amount of noise output, but rather that the practice in muffling the exhaust level is highly variable for the manufacturers' products and much more variable in the hands of the users. In particular, the noise from acceleration of these vehicles is a problem, because of the low standard of muffling of exhaust noise.

The third category, that of light trucks, is not really greatly different from the passenger car category. Many of these embody passenger car engines in more rugged bodies.

An important difference might be in the standard of

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* The mean A-scale noise level for the up-grade group is higher than for the level group by 2.0 dBA, a difference that is significant at the 1% level of probability. Larger dB differences occur for the 63 Hz and 125 Hz octave bands but a precise significance statement is impossible because of dependence between the bands. The data also offer evidence for increased variance in up-grade measurements.

TABLE B-2

OCTAVE BAND SOUND PRESSURE LEVELS, DBA VALUES, AND GROUP SUMMARIES FOR THREE SETS OF DIESEL TRUCK MEASUREMENTS

	OCTAVE BAND SPL (dBA) FOR AN OCTAVE BAND CENTER FREQUENCY OF								
ITEM	63HZ	125HZ	250HZ	500HZ	1000HZ	2000HZ	4000HZ	8000HZ	ALL
1. Level roadway, $N=20$	79	82	80	81	76	75	64	51	
Data set 14	86	87	81	78	75	72	64	52	
	83	89	87	81	74	69	59	48	
	82	86	84	82	76	75	65	53	
	77	83	86	80	75	71	65	53	
	78	79	85	82	74	73	65	51	
	77	84	86	79	74	70	62	51	
	80	80	83	78	75	70	63	50	
	74	85	84	80	76	70	63	57	
	73	78	80	80	77	73	66	54	
	78	82	85	81	77	72	65	53	
	72	82	88	82	75	69	60	48	
	75	86	80	73	74	70	61	49	
	75	80	77	74	73	70	62	50	
	77	87	87	83	75	73	68	55	
	75	85	84	78	72	69	63	53	
	76	84	81	80	75	70	64	50	
	74	79	83	77	73	70	63	53	
	74	77	82	78	74	70	64	52	
	78	82	85	82	76	72	64	52	
Mean=	77.2	82.8	83.4	79.4	74.8	71.2	63.5	51.8	81.4
Variance=	12.56	11.08	8.36	7.00	1.75	3.50	4.26	5.14	2.69
2. Level roadway, $N=6$	81	89	85	81	78	72	65	59	
Data set 4	83	87	87	82	74	70	65	60	
	83	88	83	80	79	74	65	61	
	79	81	83	82	78	74	68	65	
	81	86	87	79	78	74	68	62	
	80	81	78	75	73	69	62	55	
Mean=	81.2	85.3	83.8	79.8	76.7	72.3	65.5	60.3	82.4
Variance=	2.57	12.27	11.37	6.97	6.27	5.89	5.10	11.07	5.11
3. Level roadway (combined) $N=26$									
Mean=	78.1	83.4	83.5	79.5	75.2	71.4	64.0	53.7	81.6
Variance=	13.03	12.01	8.66	6.74	3.22	4.09	5.00	19.72	3.26
4. Up-grade, $N=20$	77	88	80	79	76	76	64	53	
Data set 15	83	90	83	78	73	69	67	56	
	86	92	82	80	77	72	66	54	
	80	86	88	79	75	71	64	51	
	85	91	92	82	76	70	61	50	
	85	93	93	86	82	75	68	56	
	80	86	87	82	81	77	70	57	
	80	89	82	77	75	73	66	53	
	80	91	82	81	74	70	65	54	
	80	90	90	86	77	72	66	60	
	82	88	79	81	77	69	60	50	
	88	92	82	80	75	73	65	52	
	90	91	83	81	75	71	67	59	
	79	88	81	78	72	70	67	58	
	89	91	87	82	80	77	69	51	
	79	86	78	77	76	71	68	55	
	86	88	84	80	78	73	65	54	
	85	95	84	80	79	72	63	52	
	81	90	90	87	80	74	69	61	
	85	92	93	86	80	72	67	63	
Mean=	83.0	89.9	85.0	81.1	76.9	72.4	65.9	55.0	83.7
Variance=	13.79	6.03	21.89	9.25	7.46	5.92	6.66	14.05	6.76

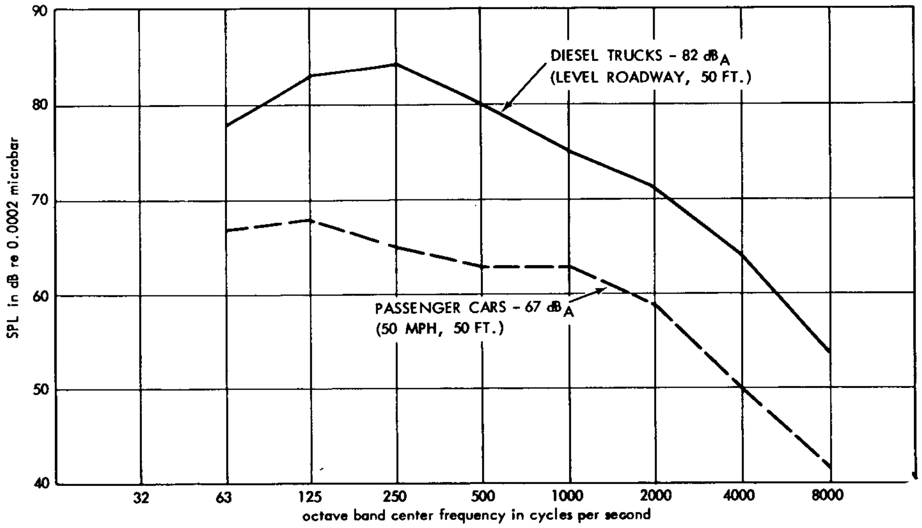

Figure B-13. Generalized noise spectra for diesel trucks and passenger cars at 50-ft distance.

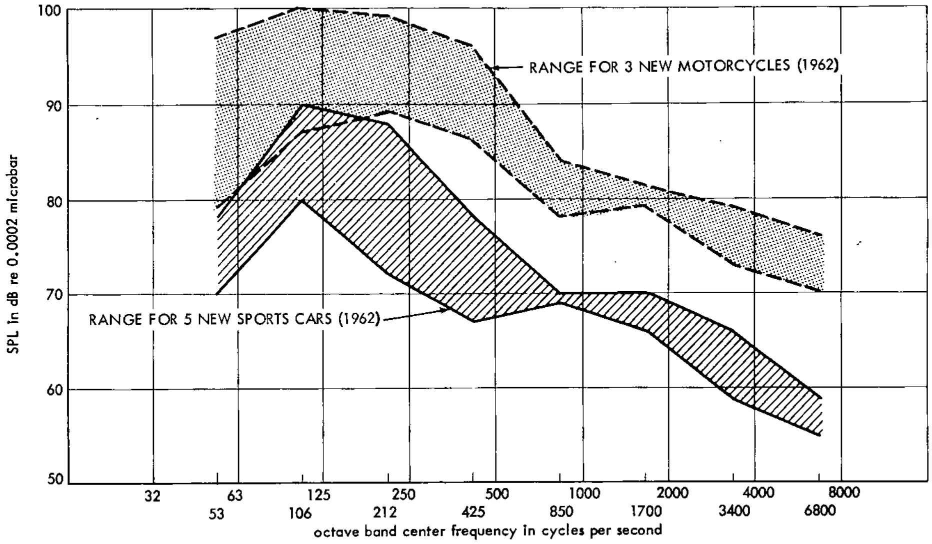

Figure B-14. Illustrative noise spectra for motorcycles and sports cars (25-ft distance, 65-mph speed).

muffling for vehicles which have been in use for several years. There is some evidence from previous studies (*16*) of greater tendency toward defective mufflers on used light trucks than on passenger cars.

The larger gasoline-powered trucks are a mixed category, including construction equipment, such as dump trucks, concrete trucks, and the large gasoline-powered delivery trucks common in urban transport. There is some evidence that the noise produced by these trucks lies somewhat below that produced by the diesel trucks, but no complete body of data is available at present.

The last category is that of buses, particularly the large diesel variety. These appear to be well muffled and well maintained. Their noise becomes noticeable primarily during acceleration in the close proximity of city street situations.

APPENDIX C

DEVELOPMENT OF A SIMULATION METHOD FOR DETERMINING THE NOISE FROM HIGHWAY TRAFFIC

This appendix summarizes the development of a method for predicting the noise at points near a highway from information on traffic characteristics. The method relies heavily on a simulation procedure in contrast to empirical estimation made directly from the study of field measurements.

Some of the reasons for employing the techniques of simulation may be emphasized by comparison with field measurement. Measurement requires observation and recording of relevant data at a time and place dictated by the phenomena under investigation. On the other hand, simulation can suggest those areas where observations would be most profitable, and further, situations can be simulated beyond the range of those observable to learn more about critical conditions.

Simulation allows analysis of more complex situations than can be represented by formulas alone. Although no simple formula relates traffic parameters exactly to traffic produced noise, the contribution of an individual noise source can be computed by formulas and a summation performed over a set of sources.

The present simulation model is extended from an earlier model for which computations were done by hand, Clark, Galloway, et al. (*9, 10*). Manual computation necessitated certain simplifying assumptions (e.g., that vehicles lie at the midpoints of fixed intervals along a straight line) which are unnecessary in a computer model. Input data for a simulation run consist of spatial information on roadway characteristics, distance to observation point, traffic flow characteristics, and noise levels produced by individual vehicles.

The roadway center line is described as a series of straight line path segments in a 3-dimensional coordinate system, allowing for approximation of horizontal and vertical curves. One to ten lanes are identified by specifying their effects from the roadway center line; thus, median strips and vertical separation of opposing roadways can be specified, although variations in vehicle spacing over the length of the roadway cannot be accommodated as yet. Observation points, one per simulation run, are stated in the same 3-dimensional coordinate system, so that observation positions can be above grade, on grade, or below grade. Traffic flow characteristics are expressed separately for each roadway lane, in terms of flow (vehicles per hour), mean speed (miles per hour), and the proportions of total flow represented by each vehicle category. Vehicle categories are defined by reference octave-band noise spectra, together with the reference distance and vehicle speed values.

A simulation run provides, as results, a set of n octave band noise spectra corresponding to momentary samples in time of noise from the total contributing traffic, hereafter referred to as snapshots. Summary measures (dBA and dBC) are also provided for each snapshot noise spectrum. An over-all summary for the entire run of n snapshots if also provided, consisting of minimum, maximum, mean and standard deviation values for dBA and dBC measures. (Most of the histogram figures in this appendix have been plotted directly from the computer output tabulations. For production uses of the simulation technique, alternative outputs such as direct graph plotting by computer and one-line graphical displays might be used.)

DESCRIPTION OF THE SIMULATION MODEL

Distribution of Sources Along a Roadway

For purposes of modeling the highway noise situation, vehicles can be considered as noise sources arrayed along a roadway lane with a characteristic density or flow rate. The limiting conditions of flow are on one hand a completely packed roadway with no moving vehicles, and on the other an empty roadway. Somewhere between, lies the condition of freely flowing traffic, which is the more common condition as well as being more amenable to mathematical analysis. A general discussion of traffic flow theory, with an extensive bibliography, is provided by the Highway Research Board (*22*).

Under the conditions of free flow, the cumulative exponential distribution closely approximates the time that would be observed between the passage of vehicles. The equation can be stated for computation as

$$t = \frac{\text{Ln}\,(1 - A(t))}{-M} \qquad \text{(C-1)}$$

in which $A\ (t)$ is a uniform random variable over the interval (0, 1), Ln the natural logarithm, and M the mean flow of vehicles per unit time. The time between successive vehicles is converted to a distance by multiplying by the mean speed of the traffic flow. Thus, a set of distances between vehicles is created that approximates the spacing for freely flowing traffic.

Figure C-1 portrays a simulated lane of traffic and a fixed observation point at some distance to the side of the roadway. The distance d_i represents one of the sample intervals between vehicles and the dashed lines represent the propagation paths, r_i, from each source to the observer.

A set of noise sources arrayed along a straight lane for which the observed noise level is calculated is termed a *snapshot* of highway noise conditions. Successive snapshots are not time-ordered, but are independent samples from a particular distribution of noise levels that is characteristic of given flow and speed conditions.

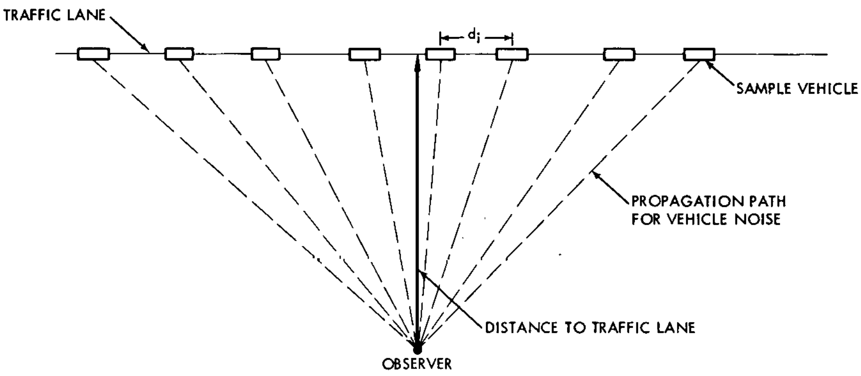

Figure C-1. Simulated lane of traffic.

Categories of Noise Sources

A model of traffic noise must cope with the fact that different classes of vehicles with widely differing noise source characteristics use the same roadway. (These differences are discussed in Appendix B.) In the present model, these differences can be accommodated by choosing a different noise spectrum* as a noise source description for each class of vehicles. It is possible to use a single noise spectrum to represent cars, another to represent heavy diesel trucks, and perhaps a third to characterize light trucks.

Additional variation in the noise source is possible through dependence upon operating conditions. As illustrated in Appendix B, accelerating vehicles are noisier than those maintaining constant speed. Even for a single category of vehicles and a single operating condition, there can sometimes be considerable variation. These variations within a class of vehicles can be accommodated by subdividing the class. For example, a reference spectrum 5 dBA above the normal might be used for some proportion of vehicles in an acceleration lane.

Propagation of Noise from Source to Observation Point †

The model must include the propagation loss over the path between the noise source and the observation point. The first and simplest effect is that of distance. For a sound source of uniform directivity, which vehicles approximate, the sound pressure level decreases by 6 decibels with each doubling of distance away from the source. Atttenuation from air absorption and scattering over the propagation path is also an important effect, more pronounced at high frequencies. Attenuation coefficients in dB/1,000 ft that are used in the computations for this appendix are as follows:

Octave Band Center Frequency	Air Attenuation (dB/1,000 ft)
63	0.0
125	0.0
250	0.3
500	0.6
1,000	0.6
2,000	1.2
4,000	2.4
8,000	5.2

Shielding effects of the roadway or other fixed features should be considered for many highway situations (see Figure 6). In addition, one moving source may shield another, as might be the case for a truck in the outer lane blocking the propagation path of several cars in its shadow. Such shielding effects can be approximated in the present model by means of a set of octave band correction constants. A more precise correction based on the geometry of shielding elements could be added into the model.

Summation of Levels

In the traffic noise model a reference octave band spectrum is chosen for each source, adjusted according to the distance from the observer and according to speed (where appropriate). The adjusted spectra for individual vehicles are summed band by band to accumulate a representation of the spectrum that would be observed at an instant for a given distance from all of the traffic lanes being simulated.

Finally, summary measures, noise level in dBA, and dBC are computed to obtain numbers characterizing the noise level for an instant of time. The set of octave band spectra, a dBA value, and a dBC value constitutes the noise description for a *snapshot* of the traffic. A simulation run consists of a selected number of these snapshots for a given set of traffic flow and roadway characteristics and one or more observation positions.

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* For the simulation model the noise spectrum consists of sound pressure levels, in 8 octave bands of frequency as specified in American Standard ASA S1.6-1960.

† A thorough discussion of the propagation of sound in outdoor conditions is presented by Wiener (*23*).

Another way of stating this is that, at any instant in time, the noise level contribution from a random distribution of vehicles having a mean flow of $\bar{m}$ vehicles per time is given by the following equation (written for dBA):

$$dBA = 10 \log_{10} \left\{ (2\pi W_o)^{-1} \sum_i \sum_j \sum_k T_k T_k^* \, N_{ij} \bar{W}_{ijk} \, \frac{r_o^2}{r_i^2} e^{-2a_k r_i} \right\} \qquad \text{(C-2)}$$

in which

dBA = decibels as measured on A-scale of a sound level meter

T_k = transfer function of the A-scale weighting network in the k^{th} band

T_k^* = complex conjugate of T_k

W_o = 10^{-12} watts per square meter

N_{ij} = number of vehicles at i^{th} interval of the j^{th} vehicle class

$\bar{W}_{ijk}$ = average sound intensity in watts per square meter in the k^{th} frequency band of a vehicle of the j^{th} class located at the i^{th} interval, traveling at mean speed $\bar{V}$ in meters per second, at a distance r_o

r_i = distance in meters from the observer to a vehicle at the i^{th} interval

a_k = air absorption in decibels per meter in the k^{th} frequency band

The simulation consists of computing this equation a number of times with random distributions of vehicles, each distribution having the same $\bar{m}$. The resulting histogram simulates the time distribution of noise levels expected from traffic having the characteristics employed in the computation.

IMPLEMENTATION OF THE MODEL AS A COMPUTER PROGRAM

The first implementation of the simulation technique by computer was done in the first year of the present study, using the PDP-1 computer. That preliminary implementation was described in the interim report project, and is not repeated here. The programs have been translated, generalized, and extended for the present version, described in the following section.

Program Organization and Equipment

The traffic noise simulation is programmed in Fortran IV to run on an IBM System/360 computer under control of the Disk Operating System (*24*). In its current form, the program requires approximately 44K (where K = 1,024) bytes of main storage including the system supervisor. It has been developed and run on a System/360 Model 30 computer, with 64K bytes of storage, two disk files, card reader and printer, and floating-point instruction set. The program, with only slight modifications and recompilation, could be run on larger System/360 computers or other computers having comparable Fortran facilities. Further, the program could be organized into several phases which overlaid one another and thus could be run successfully in machines of only 32K bytes of main memory. Thus, the present simulation model has wide potential usefulness for other research and for highway planning.

The program is organized as a control routine, HRBSIM, and 14 subroutines: CNTRIB, DBA, DBSUM, GETGAP, HRBINP, LFTPOS, MINDST, MOVE, RANDU, RUNSIM, RTPOS, TALLY, VSPEED, VTYPE. (Two of these, RANDU and TALLY, are subroutines provided in the Scientific Subroutine Package available from IBM.)

Although the earlier program version for the PDP-1 was organized for one-line input and graphical displays, this Fortran version has been programmed for batch-process computers. This has been done intentionally, so as to improve the applicability of the program for use by others.

Flow of Control

A simulation operation is begun by executing the main routine, HRBSIM. This control routine calls the subroutine HRBINP which reads control statements and data from an input card deck until it has read a run statement. The control program then checks the validity and completeness of the input data and posts any diagnostic messages. If the data are complete and valid, control is transferred to the subroutine RUNSIM for the bulk of the simulation run. This subroutine first calls subroutine MINDST to determine the perpendicular distance from the observation point to the described roadway center line. There are three nested loops within the RUNSIM subroutine which control a simulation run. The outer loop is an iteration through the required number of snapshots for the simulation run. The next inner loop is an iteration through all of the relevant lanes of traffic for a single snapshot. The innermost loop is an iteration through all of the vehicles which contribute to the noise level for a single lane for a snapshot. Subroutines CNTRIB, GETGAP, DBA, DBSUM, LFTPOS, RANDU, RTPOS, VSPEED, and VTYPE are used in these iterations. The subroutine TALLY is used to summarize the results for a series of snapshots constituting one simulation run.

Brief description of the procedure for one lane of one snapshot may clarify the working of the model. In one cycle of the innermost loop, four vehicles are selected, positioned along the roadway, and their contributions added to a noise level spectrum. The vehicles are positioned alternatively on left and right halves of the roadway (as seen from the observation point) at random intervals established from the lane density and a Poisson distribution of vehicles in time. (See Fig. C-1.) The positioning of vehicles takes into account the roadway center line (which may represent a curved path in both horizontal and vertical directions) and the offsets of the various lanes from this center line.

The vehicle class is selected at random from the distribution representing the proportions of different vehicle classes in the total traffic mix for that lane. Thus, vehicles of the different classes occur at random in the lane of vehicles, and according to their proportions in the specified mix.

Iteration continues in this inner loop for four-car groups until the last group has not contributed as much as one-half dB to the sum spectrum. At this point a further check is performed to assure that the noisiest class of vehicle, if chosen for this last position, would not have contributed significantly (by one decibel) to the sum spectrum. If the noisiest class could have contributed, the iteration is continued for another cycle when the test is performed again. This secondary test insures that noisy vehicles representing a small proportion of the total traffic mix are not biased out of the simulation.

For multi-lane simulations, the lane nearest the observation point is specified first, then the next one, etc. This insures that the longest span of traffic will tend to be simulated for the nearest lane, with simulations tending to be shorter for lanes farther away as they contribute less to the increasing sum spectrum.

When the series of snapshots constituting a single simulation run has been completed, the summary results are printed and control is returned to the main routine, HRBSIM. The cycle of input and computation is repeated as long as data and control cards remain in the input deck. Thus, a large number of simulation runs can be executed in a single computer session.

Input Conventions

The control and data card input formats have been designed as a compromise between maximum legibility and self-explanatory format on the one hand and the limitations inherent in the Fortran language on the other hand. Free-form English language statements might have been used (and often are in other computer work) but these would require special machine-dependent programming and would limit the universality of the entire simulation program over that obtainable with Fortran.

The control and data statements are grouped into five categories as follows:

(1) Control Statements: RUN, SNAPSHOTS, PUNCH, NOPUNCH, TRACE, NOTRACE, CLEAR.
(2) Geometry Data Input: PATH, OBSERV, LANELOG.
(3) Propagation Conditions Input: AIRATTEN, SHIELDCONST.
(4) Vehicle Classes Input: SOURCE.
(5) Traffic Characteristics Input: MIX, FLOW, SPEED, DENSITY.

The code corresponding to each of these card types is entered into the first two columns of the card. The values for the different variables are entered into the remainder of the card in a standard format. For a PATH card, for example, three coordinates (X, Y, Z) of a point along the roadway center line are entered.

Data values are entered in units convenient to the user—for example, mix of traffic percentages (e.g., 90 percent cars and 10 percent trucks). Flow is expressed in vehicles per hour, speed in miles per hour, and density in vehicles per mile.

Output

The output of a simulation run is an entry to each snapshot and a summary for the collection of snapshots. The individual snapshot entry includes the noise spectrum over all vehicles contributing to the snapshot, the number of vehicles by class and lane, and the span or distance between the extreme contributing vehicles for each lane. Summary information for the entire snapshot includes minimum, maximum, mean and standard deviation values for both dBA and dBC measures. A mean noise spectrum over all snapshots is printed, also. Finally, a tabulation of the distribution of dBA values in 1 dB intervals is printed, as data for a histogram of the simulation run.

Optional output is available through the use of a trace card. This optional output provides position and noise contribution information for each vehicle included in the snapshot. It is useful primarily as an exploratory tool for special traffic flow conditions or for modification of the programs.

Program Documentation

All subroutines of the program are thoroughly annotated and each is provided with a heading describing method, parameters, and other relevant data. Program listings and source program decks are available.

VALIDATION OF THE SIMULATION TECHNIQUE

There are several facets to the question of validation of such a simulation model. First is the question of the degree of theoretical validity. There is the correctness of the individual program segments. Finally, and most important, is the comparability of simulated with specific observed conditions.

Correctness of the Model

Two different physical phenomena are modeled in this work. One is the distribution of vehicles on a roadway and the other is the propagation of sound from a sound source to a remote observer. Research on the distribution of vehicles on a roadway has advanced immensely since the earliest work on this traffic noise simulation problem (*9*). The assumption of a Poisson distribution of vehicles along the roadway has been studied in detail and shown to be a good approximation for freely flowing traffic and a bad one for clustered situations (*22*). However, for purposes in distributing noise sources along a line in space, the assumption appears to be satisfactory. As an example, see Figure C-2.

For the situation of very dense traffic the differences in intervals predicted by one or another modeling assumption are not crucial to the noise contribution from the vehicles. On the other hand, for low densities where platooning may occur, the over-all noise production is well below higher flow conditions for the same roadway. Thus, it does not appear that more sophisticated models for the distribution of vehicles along the roadway would substantially improve the noise simulation procedure at this time.

The other physical phenemonon concerns propagation of sound from a source to an observer. Two major considerations in such a phenomenon are the directionality of sound radiation from the source, i.e., is sound radiated more efficiently in one direction than another, and the various mechanisms for attenuation of that sound as it travels to the observer. The model assumes that the source is non-directional—that is, that it radiates sound uniformly through the hemisphere above the ground plane. Data obtained during field measurements for this program, and previous studies, have shown this approximation to be a valid one for most vehicle noise. Departures from this non-directionality are not large or consistent from one vehicle to another and thus could not be easily accounted for in a simulation procedure.

The attenuation of sound in its travel through the lower atmosphere is governed by several factors. The most pronounced is the dispersion of sound as it radiates in all directions away from a point source (through the hemisphere). This dispersion, commonly known as inverse-square loss (since the decrease in sound pressure is inversely proportional to the square of the distance) is a well-established and easily computed effect. Further attenuation is caused by sound absorption in the atmosphere and by anomalies in the atmosphere which cause refraction and scattering of sound.

The absorption effects are generally well known through laboratory studies; the refraction and scattering effects are not as well understood. Considerable field and laboratory work has been done on these latter effects and past and very recent work has been reviewed in development and testing of the noise simulation model (*23, 25*). Conclusions on the atmospheric attenuation effects, from review of the recent research, are that the improvement in predictability of the attenuation between source and observer that can be achieved from careful attention to micro-meteorological data is not worth the added complexity. Thus, the model retains only a simple linear attenuation factor that specifies the attenuation in dB per 1,000 ft of propagation path for each octave band of frequency.

The final type of attenuation between source and observer is that caused by obstructions in the line of sight which act as partial barriers to sound. Simple approximations to the diffraction effect from such barriers are described by Wiener (*23*). It has not been possible to extend that work in this present study and, thus, the model is limited to conditions where the roadway is in sight of the observer. A simple approximation to shielding from sight can be obtained by applying an empirical attenuation curve to the results of the simulation. Examples of this approach are given in Figure 6 and Chapter Three.

The noise spectra for two classes of vehicles—passenger cars and diesel trucks—have been used in the simulation runs in this appendix. The standard spectra used are those derived in Appendix B. The speed corrections used in the model are also those derived in Appendix B. The correction used is 30 log $\frac{V_1}{V_0}$, where V_1 is the actual speed assumed for the lane and V_0 is the reference speed specified with the reference noise spectrum. No speed correction is used for the diesel truck reference noise spectra. (This is shown in the input data by a 0 value for speed for the truck reference spectrum card.)

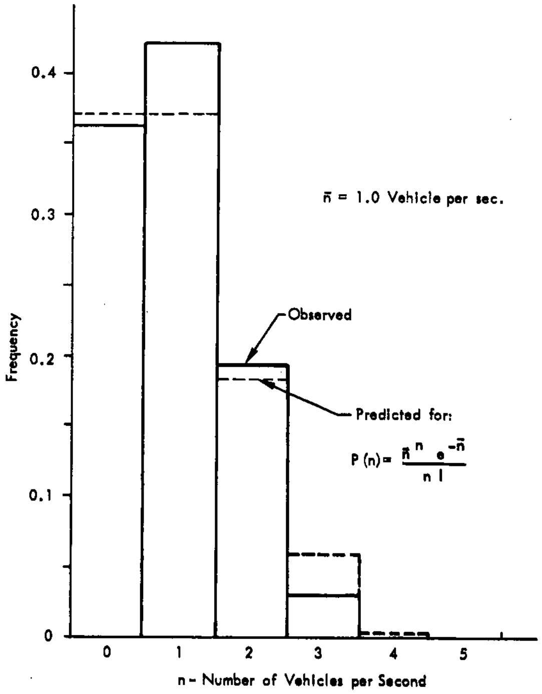


Figure C-2. Comparison of observed and predicted vehicle distribution in freely flowing traffic assuming a Poisson distribution.

Checking of Individual Routines

The computational subroutines for derivation of the inter-vehicle gap and for the calculation of the noise contribution at the observation point from a vehicle have been carefully checked to assure that the computations reflect the intent of the model. Other routines involved in the computation has been similarly checked with separate test programs.

Comparisons with Measured Conditions

The final task of such a simulation model is whether it will provide answers that compare well with actual observations for a range of conditions. Two comparisons are presented to illustrate the validity of the present model in a range of traffic noise conditions. The first is the comparison with heavy freeway traffic for an observation position close to a freeway. The second involves somewhat lighter traffic and two observation positions distant from the freeway. The second set of comparisons corresponds with average locations for sub-groups in interview Area 1, while the first comparison corresponds with the situation for interview Area 2.

Figure C-3 shows the comparisons for interview Area 2 traffic noise. Graph (a) of the figure shows a simulated traffic run and graphs (b), (c) and (d) show three actual measurements at different locations within Area 2, about 50 ft from the edge of the nearest lane of the freeway. All three measurements were made at mid-day with comparable traffic volumes by actual count. The traffic conditions for the simulated traffic run were based on these counts plus data from a more extended series of traffic counts through an entire day; they also represent mid-day conditions. Figure C-3 shows that the simulated and the three measured sequences all have approximately the same mean noise level in dBA and approximately the same standard deviation. Further, they have roughly similar histograms. It must be recognized that these are all samples from essentially random phenomena. Thus, the histograms for different samples will not compare exactly. The underlying distribution for traffic noise under these conditions should be a nearly normal (Gaussian) distribution and that fact is evident in the four histograms. For the measured noise distributions, the total freeway noise was tape-recorded at the observation position over a period of minutes for each sample. The notation of 40 snapshots on each of the measured data graphs refers to 40 momentary samples of the freeway noise taken from the recording at uniform intervals and analyzed in octave frequency bands. The separation between successive sample intervals was made sufficient to minimize serial correlation effects from the traffic stream and thus the snapshots from the measured data are akin to the snapshots derived from the simulation process.

Flow conditions for the simulation are as follows:

Lane	Flow (veh/hr)	% Cars	% Diesel Trucks
1 (nearest observ. pt.)	660	63.0	37.0
2	1,110	92.0	8.0
3	1,200	100.0	0.0
4	1,500	100.0	0.0
5	1,380	100.0	0.0
6	1,290	100.0	0.0
7	600	60.0	40.0
8 (farthest from observ. pt.)	720	50.0	50.0

The high proportion of trucks in the total flow is attributable to the mid-day measurement time. The day-long pattern of traffic for this freeway shows the customary morning and evening peak for passenger car traffic, while truck traffic is low during the peak car hours and builds to a maximum around mid-day.

The second comparison is shown in Figure C-4. In this figure, graphs (a) and (b) represent the simulated and measured conditions for the 750-ft observation point while (c) and (d) represent simulated and measured conditions for the 2,300-ft distance. Traffic conditions for the simulation are as follows:

Lane	Flow (veh/hr)	% Cars	% Diesel Trucks
1 (nearest to observ. pt.)	270	77.8	22.2
2	795	94.3	5.7
3	570	100.0	0.0
4	585	100.0	0.0
5	1,080	100.0	0.0
6	975	100.0	0.0
7	765	100.0	0.0
8 (farthest from observ. pt.)	645	65.0	35.0

Essentially, similar traffic flows were observed for the field measurements.

As with the previous comparison, the simulated noise level values agree closely with the measured values. At these distances, however, the simulated standard deviations are somewhat below those measured in field conditions. This difference is due to the fact that the freeway is on a slight grade at these measurement locations. Thus, some of the trucks included in the traffic flow would be traveling up-grade and creating slightly higher noise levels. Further, the variation in speeds due to interference from the trucks on the up-grade may contribute somewhat to the larger variation in the measured conditions. The differences between simulated and measured standard deviations are only marginally significant in the statistical sense. A simulation run including a third category of vehicles (trucks on the up-grade condition) would probably increase the standard deviation of the simulations to more nearly match the measured data.

The simulated noise spectra generally compare well with the measured noise spectra. At the large distances for Area 1, the spectra differ substantially only in the highest frequency band, indicating that propagation conditions at the particular time of the measurements are not identical with those assumed in the generalized air attenuation spectrum used for the simulation runs. Similarly, differences are noted in the lowest octave bands for traffic mixes including diesel trucks. These differences are not very important in the simulation results because the weighted-over-all summary value in dBA is affected most strongly by the mid-frequency bands of the spectrum.

These simulation results appear to be extremely good and suggest great usefulness for the simulation model. They represent a predictive capability comparable to what could be obtained from actual field measurements, and offer the capability of exploring future or hypothetical conditions.

INVESTIGATIONS OF TRAFFIC NOISE CHARACTERISTICS BY SIMULATION

Six aspects have been chosen of the variation in traffic noise as a function of flow and geometrical characteristics to illustrate investigations using the simulation model. These are shown in Figures C-5 through C-8. A brief description of each follows.

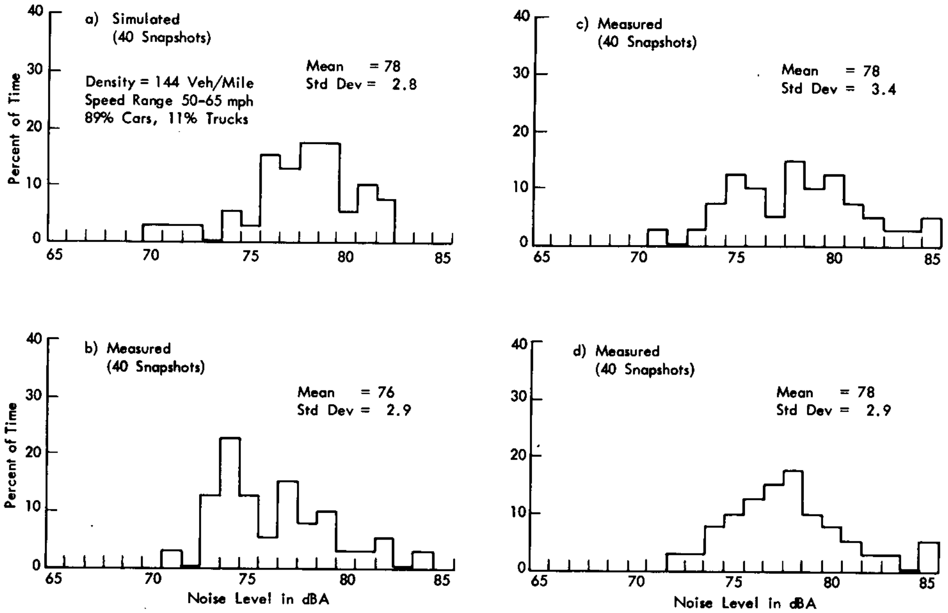


Figure C-3. Comparison of distributions of simulated and measured noise levels in dBA from an 8-lane freeway, for a distance of 50 ft from the edge of the nearest lane.

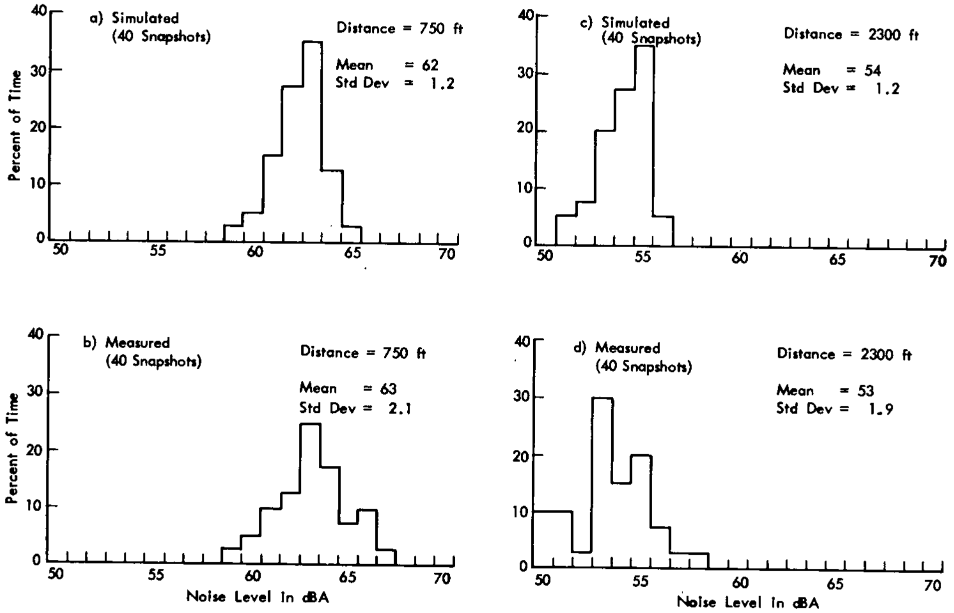


Figure C-4. Comparison of distributions of simulated and measured noise levels in dBA from an 8-lane freeway, for distances of 750 ft and 2,300 ft from the edge of the nearest lane.

Noise from Multi-Lane Traffic as a Function of Distance

For the traffic condition simulated in Figure C-3, an 8-lane freeway in heavy traffic conditions, three additional distances have been simulated. Figure C-5 shows the results of simulation runs at 50 ft, 100 ft, 200 ft, and 400 ft from the edge of the nearest lane of the 8-lane roadway. Two points are of particular interest. First, the mean noise level in dBA decreases with increasing distance from the roadway. The decrease is three decibels per doubling of distance, thus indicating that as a first approximation the roadway can be considered as a line acoustical source. The standard deviation, a measure of the fluctuation of the traffic noise levels, decreases also as distance from the roadway increases. With the greater distances, more vehicles are included in the simulation and thus the variations between vehicles and variations in spacing have less

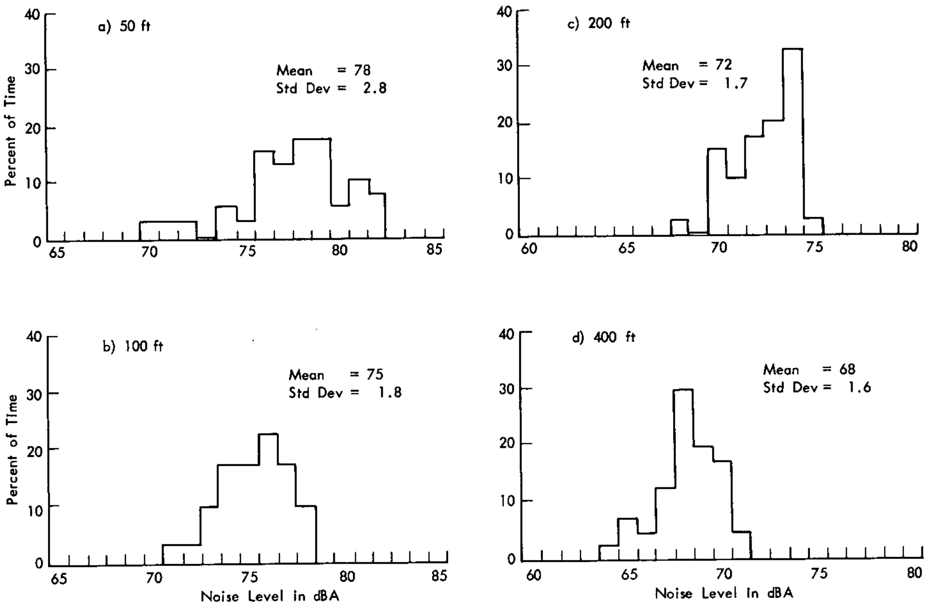


Figure C-5. Distribution of noise levels in dBA from simulated traffic of an 8-lane freeway, for 4 distances from the edge of the nearest lane.

effect on the total noise level. Other curves presented in the body of this report illustrate that at a distance of 1,000 ft from heavy traffic flows, the standard deviation of noise levels becomes very small (less than ½ dB). For these conditions, the noise from traffic is experienced as a steady hum.

Noise Level Distribution as a Function of Traffic Mix

Figure C-6 shows histograms for simulated traffic of passenger cars alone and traffic flows of 95 percent passenger cars and 5 percent diesel trucks. The comparisons show that the mean noise level increases as trucks are added to the traffic flow and, more importantly, that the standard deviation increases considerably as trucks are added. The comparisons of cars alone versus cars plus trucks are shown for three distances of the observation point from the traffic lane.

Noise Level Distribution as a Function of Distance

The six noise level histograms shown in Figure C-6 will serve to illustrate the effects of distance from the freeway to the observation point. The mean noise level is seen to decrease with distance in a similar fashion to that shown in Figure C-5. A generalization of the distance relationship is presented in Chapter Three.

Noise Level Distribution as a Function of Speed

The simulation runs illustrated in Figure C-7 show the effect of speed variations on the noise level output from a roadway. Three speed conditions are reproduced here, 35 mph, 50, and 65 mph. The mean noise levels are seen to increase approximately 4 dB between steps in speed. This is an approximate agreement with the 30 log (speed) relationship shown in Appendix B. There is no clear cut effect of speed change on the standard deviation of the simulated noise levels.

Noise Level Distribution as a Function of Density

The most important single variable shown in the analysis of traffic flow characteristics and their effect on noise level is the effect of traffic density. In Figure C-8, both the traffic flow (vehicles per hour) and the traffic density (vehicles per mile) are shown. The four histograms of Figure C-8 show the change in shape of the noise distribution and the shift of the distribution for changes in density. At the lowest density a straggly distribution is simulated (and measured), wherein individual vehicles often occur alone in a sample. As density increases, the distribution becomes more cohesive with a characteristic central tendency and symmetry. As the flow becomes very high, the distribution becomes very narrow (small standard deviation) and reaches the highest dBA levels.

Simulation Analysis for Development of Estimation Curves

A large number of simulation runs explored the effects of changes in flow or density, speed, vehicle mix, and distance from roadway on the traffic noise. Most of these have been organized to provide systematic variation of one or more parameters with the others held constant. For these analyses the power of the simulation technique is most apparent, since it would be nearly impossible, and certainly very costly and time-consuming, to obtain equivalent data through field measurement.

Summaries from these simulation studies of traffic noise behavior are presented in Chapter Three, as tools for estimation of traffic noise.

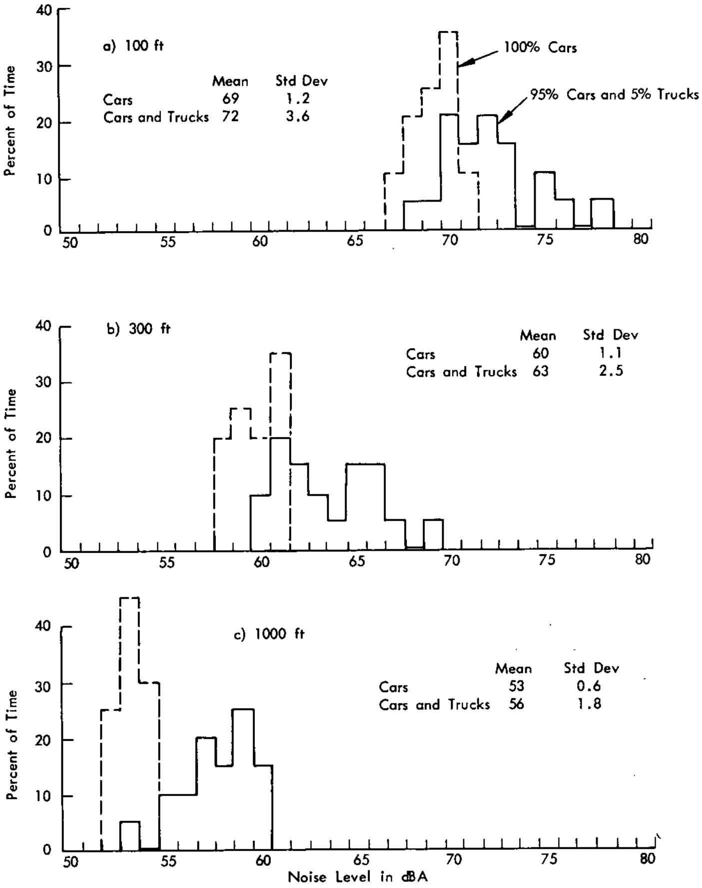


Figure C-6. Comparisons of the distribution of noise levels in dBA from simulated traffic of cars and diesel trucks.

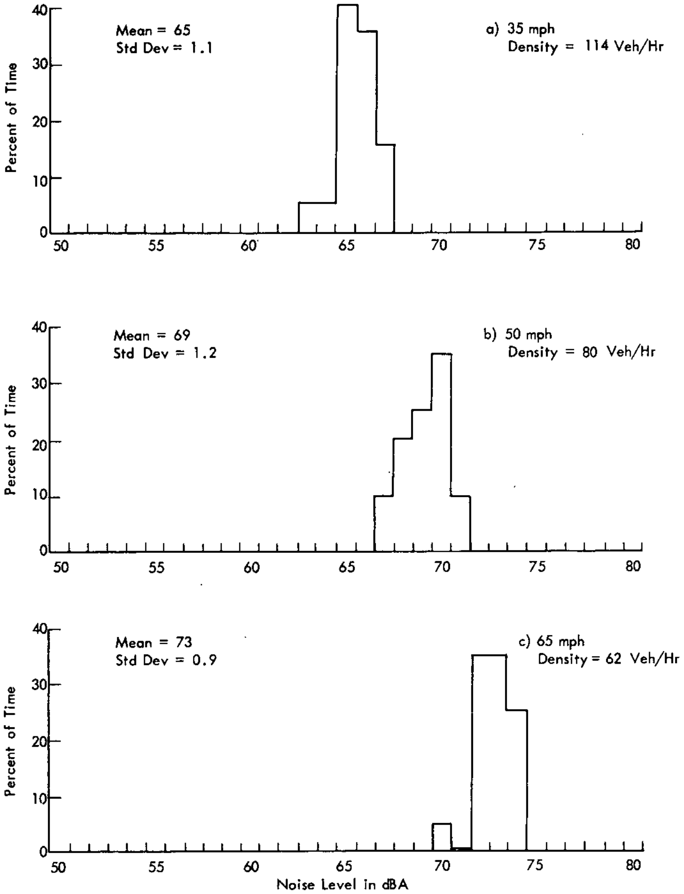


Figure C-7. Distribution of noise levels in dBA from simulated 1-lane-equivalent passenger car traffic, for 3-speed conditions at constant flow.

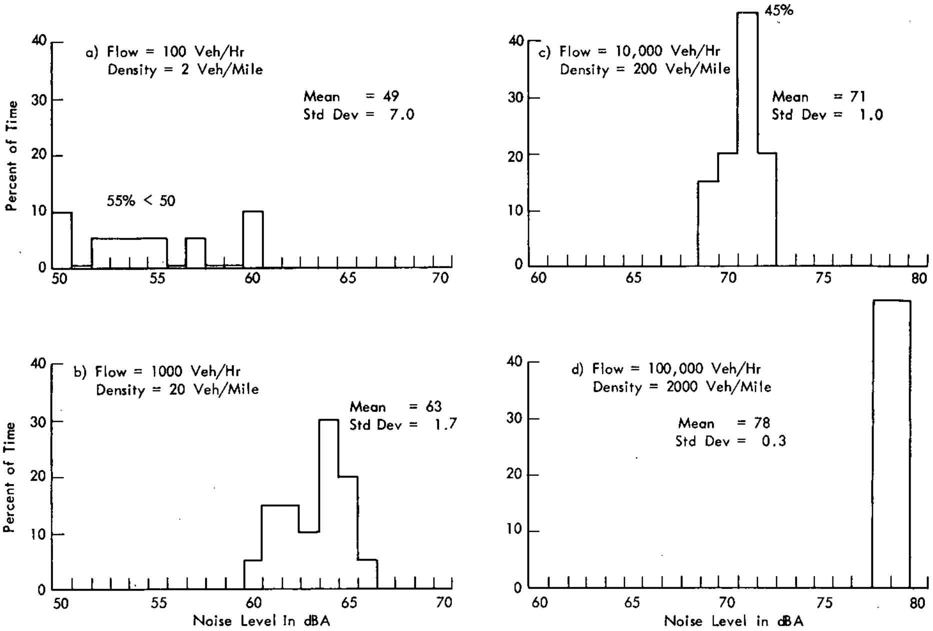


Figure C-8. Distribution of noise levels in dBA from simulated 1-lane-equivalent passenger car traffic, for 4 flow conditions.

APPENDIX D

DESCRIPTION OF SAMPLES AND THEIR PHYSICAL ENVIRONMENTS

The selection of the sites for the interview study was based on several criteria. The aim was to find neighborhoods satisfying the following conditions:

(1) A high degree of exposure to highway noise.

(2) Some range in socio-economic level. (The low socio-economic levels were not included because problems of interviewer selection and training to assure communication would have increased the survey cost and complexity out of proportion for this limited study.)

(3) Potential experience with highway noise over varying periods of time, as indicated by roadway completion dates.

(4) A variety of physical relationships between individual homes and traffic lanes in terms of distance from the right-of-way, land configuration, highway geometry, landscaping, and intervening physical features.

(5) A range of traffic levels and flow characteristics.

Twenty-five possible survey sites were investigated. Analyses of these areas resulted in the final selection of five neighborhoods (Fig. D-1) which represent a good spread in terms of geographic location as well as in the physical and socio-demographic factors previously mentioned. Figure D-2 shows the location of the five interview areas within the freeway system in Los Angeles County.

AREA 1—BEL AIR, SAN DIEGO FREEWAY

This is a prestigious hillside residential community in the western section of the City of Los Angeles. The homes in the interview area are built on the slopes of a canyon, from 150 ft to 300 ft above and at an average distance of about 1,500 ft east of the San Diego Freeway. They are, however, in a direct line of sight and hearing to the freeway. The relationship between the interview area and the freeway may be seen in two photographs in Figure D-1. One shows the freeway in the foreground with the homes located along the top of a ridge; another presents a view of the freeway taken from the interview area.

The homes range in value from $45,200 to $169,400, with a mean of $83,100 (Table D-1). Despite their high value, and partly because of the steep terrain, these homes are built on fairly small lots on narrow streets which follow the ridges. The third photograph of Area 1 indicates how close the homes are to each other and to the street. High land values in this area contribute 37.4 percent to the total cost of the homes (Table D-2).

This area has the highest percentage of professionally employed persons (25.9 percent) of all the interview areas (Table D-3). Over 85 percent have had some college education, 20 percent of them having completed college and 36.7 percent with post-BA degrees (Table D-4). Eighty percent are in the age groups from 35 to 54 years (Table D-5). This area had the lowest proportion of persons under 35.

The San Diego Freeway, which runs through the bottom of the canyon, is landscaped and elevated in design, although these factors are not very significant to the residents in the interview area because of the great distance between the houses and the right-of-way. The freeway was opened in this area just over four years ago. A good number of the homes predate the freeway, but many have been constructed since its opening.

This freeway carries a high volume of vehicles at peak commuting hours (150 cars per minute at 7:00 AM southbound from the San Fernando Valley to employment centers south of the Santa Monica Mountains and 113 per minute northbound just before 6:00 PM).

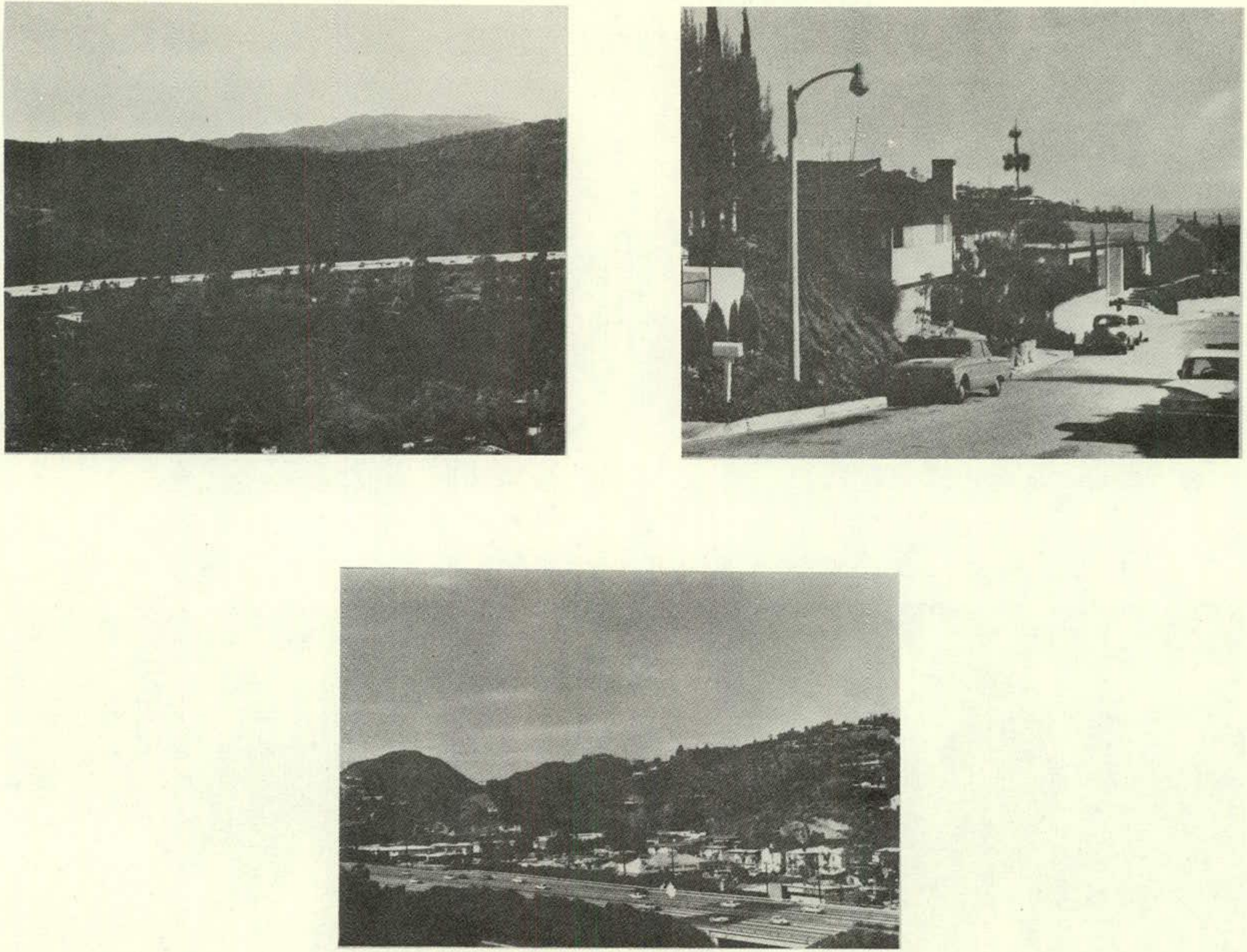
AREA 2—ALHAMBRA, SAN BERNARDINO FREEWAY

This is a community of modest homes in the San Gabriel Valley east of Los Angeles. Most of the homes are small stucco bungalows built some twenty years ago, but in portions of the area one finds older, wooden one- and two-story houses. There are some one-story duplexes and a few larger apartment house structures. Selected home values range from $9,400 to $19,200, with a mean value of $14,400 and a median of $16,000. This is quite low compared with a 1960 median of $15,900 for Los Angeles County as a whole when one considers the increase in property values in the past seven years. The land valuation accounts for nearly 45 percent of the total valuation, a higher ratio than Area 1.

Area 2 has the lowest proportion of professionally employed persons (2.9 percent) and the highest proportion of unemployed or retired persons (14.3 percent) of all the interview areas. It ranks first in the percentage of persons who have not finished high school; 5.7 percent have never attended high school and 34.3 percent have attended but not graduated. Only 22.9 percent have attended or graduated from college, the lowest percentage of all the interview areas. Compared with Area 1, this area has a considerably lower proportion of people in the middle age groups; 34.3 percent are over 55 years of age, the highest percentage of all areas. With 14.3 percent, this area has nearly as many persons 65 years of age and over as Area 4.

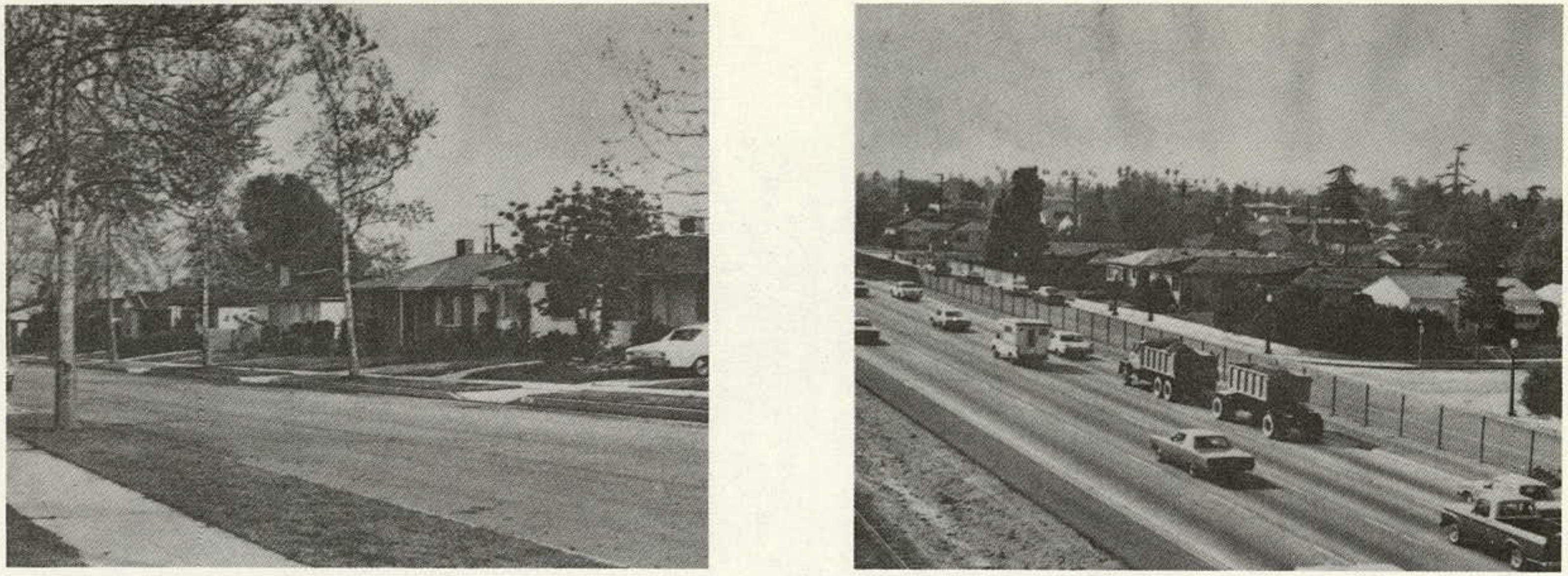
The homes lie on both sides of the freeway. Most of them face the freeway across a narrow access road, although some lots back directly on the freeway right-of-way. Residents complain that occasionally a car crashes through the fence into a yard or even into a house.

The freeway is on grade, separated from the interview

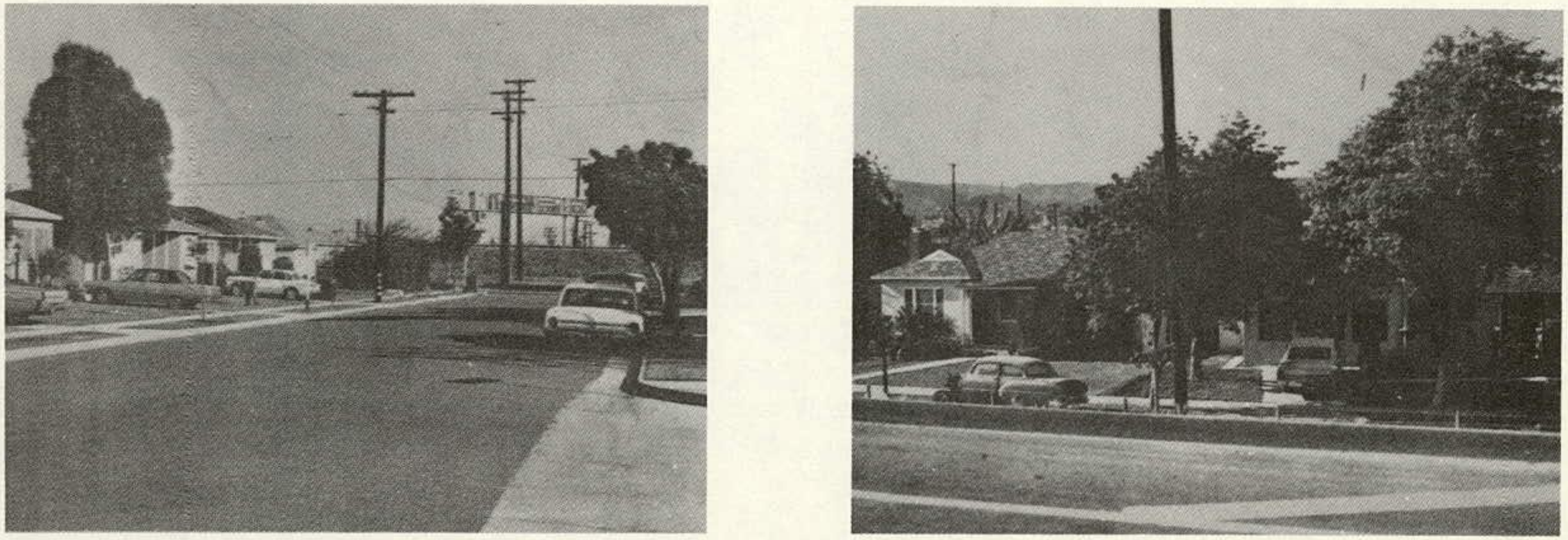


AREA 1

Figure D-1. Interview areas.

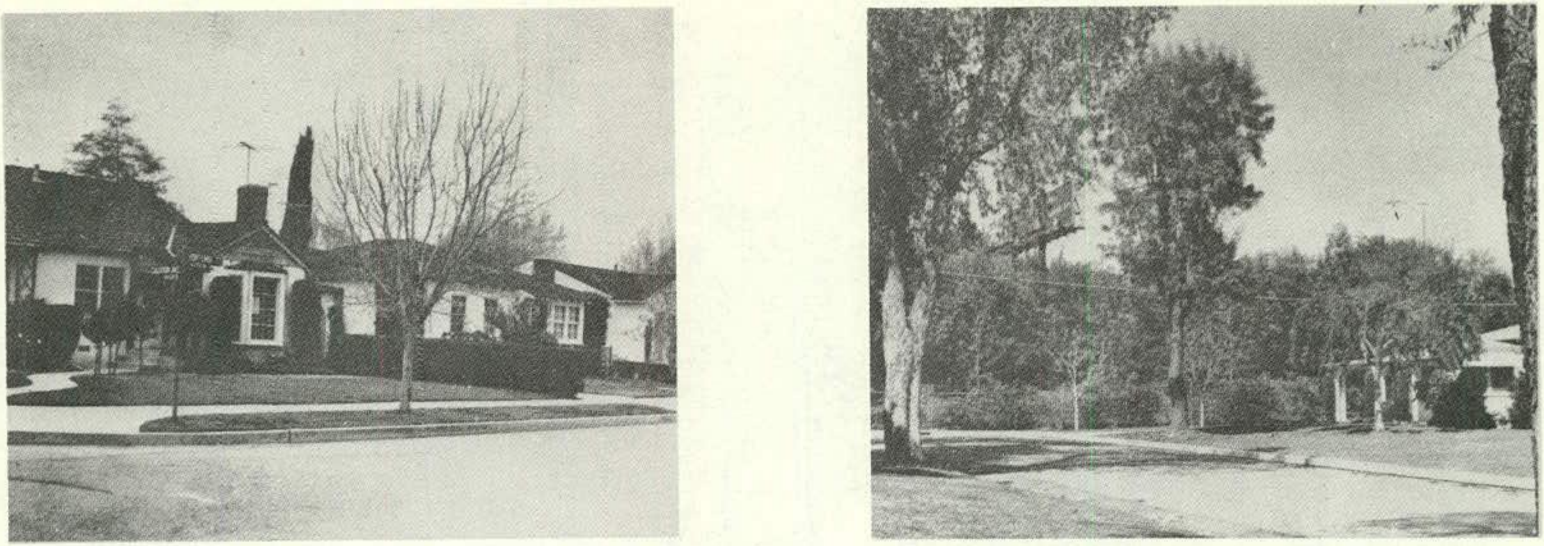


AREA 2

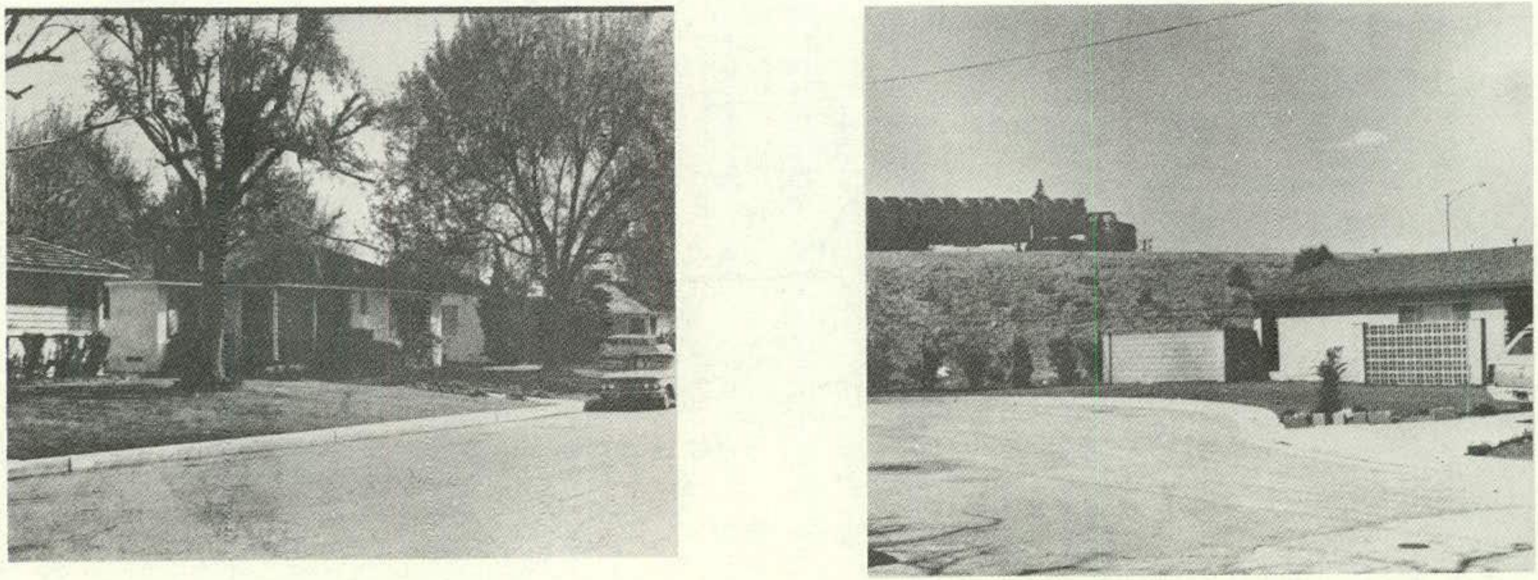


AREA 3

Figure D-1 (continued).



AREA 4



AREA 5

Figure D-1 (continued).

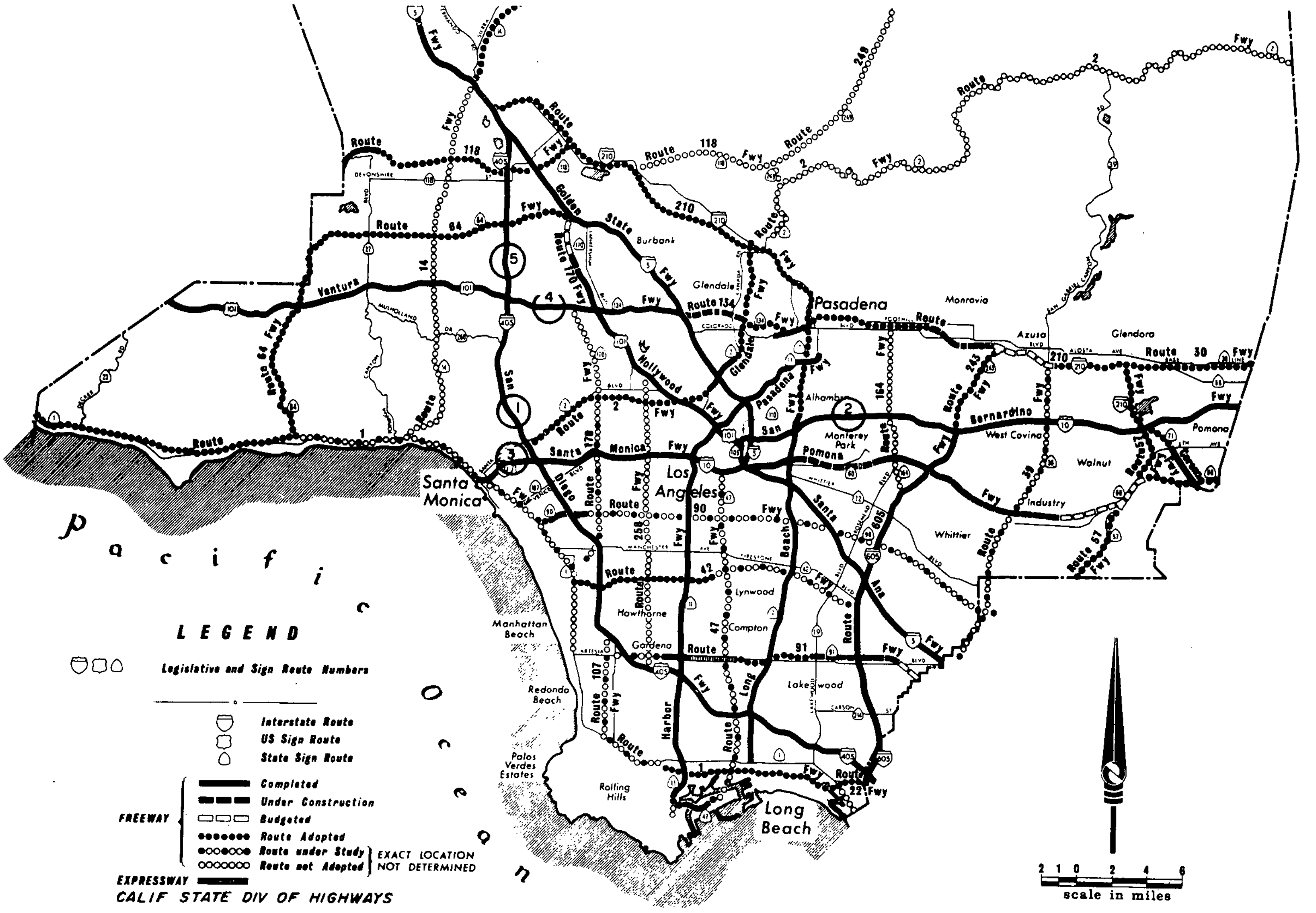


Figure D-2. Location of interview areas in Los Angeles County freeway system.

TABLE D-1

COMPARISON OF HOME VALUES IN THE INTERVIEW STUDY AREA (LAND IMPROVEMENTS)

AREA	VALUE ($) HIGH	LOW	MEDIAN (*N*=15)	MEAN (*N*=15)
1	169,400	45,200	71,100	83,100
2	19,200	9,400	16,000	14,400
3	24,000	14,200	17,200	17,500
4	33,100	10,600	20,000	20,400
5	40,600	10,400	16,800	21,100

[a] These figures are based on a sample of 15 properties in each study area from the records of the Los Angeles County Assessor. Since assessed valuation is at 25% of true market value, assessors' valuations were multiplied by 4.

TABLE D-2

COMPARISON OF LAND VALUATION IN THE INTERVIEW STUDY AREAS[a]

AREA	VALUE ($) HIGH	LOW	MEDIAN (*N*=15)	MEAN (*N*=15)
1	52,000	18,000	30,000	31,100
2	8,600	4,100	6,400	6,400
3	11,400	8,000	9,000	9,700
4	12,400	4,000	7,600	7,200
5	7,400	3,600	4,600	5,400

[a] These figures are based on a sample of 15 properties in each study area from the records of the Los Angeles County Assessor. Since assessed valuation is at 25% of true market value, assessors' valuations were multiplied by 4.

TABLE D-3

OCCUPATION OF PERSONS IN EACH INTERVIEW LOCATION

OCCUPATION GROUP	UNIT	AREA 1	2	3	4	5
1. Professional	%	25.9	2.9	3.6	17.9	12.1
	(*N*)	(7)	(2)	(2)	(19)	(7)
2. Skilled	%	3.7	2.9	10.7	9.4	13.8
	(*N*)	(1)	(2)	(6)	(10)	(8)
3. Semi-skilled	%	0.0	10.0	26.8	11.3	8.6
	(*N*)	(0)	(7)	(15)	(12)	(5)
4. Non-skilled	%	0.0	8.6	19.6	5.7	10.3
	(*N*)	(0)	(6)	(11)	(6)	(6)
5. Unemployed, retired	%	7.4	14.3	3.6	6.6	6.9
	(*N*)	(2)	(10)	(2)	(7)	(4)
6. Housewife	%	59.3	61.4	26.8	47.2	43.1
	(*N*)	(16)	(43)	(15)	(50)	(25)
7. Other	%	3.7	0.0	8.9	1.9	5.2
	(*N*)	(1)	(0)	(5)	(2)	(3)

TABLE D-4

EDUCATION OF PERSONS IN EACH INTERVIEW LOCATION

EDUCATION		AREA 1	2	3	4	5
1. No high school	%	0.0	5.7	1.8	1.9	1.7
	(*N*)	(0)	(4)	(1)	(2)	(1)
2. Some high school	%	6.7	34.3	26.8	7.5	10.0
	(*N*)	(2)	(24)	(15)	(8)	(6)
3. High school grad	%	6.7	37.1	30.4	38.3	33.3
	(*N*)	(2)	(26)	(17)	(41)	(20)
4. Some college	%	30.0	18.6	37.5	33.6	40.0
	(*N*)	(9)	(13)	(21)	(36)	(24)
5. College grad	%	20.0	4.3	1.8	10.3	3.3
	(*N*)	(6)	(3)	(1)	(11)	(2)
6. Post-BA degree	%	36.7	0.0	1.8	8.4	11.7
	(*N*)	(11)	(0)	(1)	(9)	(7)

area only by a chain link fence. There is no landscaping, with the exception of attempts in a few areas to train ivy over the fence. The houses nearest the freeway are only about 50 ft back from the outside traffic lane and they look directly onto the passing traffic, which contains the highest ratio of trucks of any of the freeways in this study. This is by far the noisiest of all the interview areas.

The freeway was opened in this area 13 years ago, and, thus, the residents have had a longer experience with highway noise than those in any other interview area. All of the home in the area predate the freeway. The San Bernardino Freeway is the major west-east route between Los Angeles and the rest of the United States, which accounts for the high percentage of truck traffic. It also serves as the major commuter route between Los Angeles and the San Gabriel and Pomona Valleys to the east, reaching, by traffic count, an estimated westbound peak of 120 cars per minute at 6:00 AM and an eastbound peak of 120 cars per minute at 5:00 PM.

AREA 3—SANTA MONICA, SANTA MONICA FREEWAY

This interview area lies 2 miles inland from the coast and some 12 miles west of downtown Los Angeles. It flanks the Santa Monica Freeway near its western terminus. The character of the neighborhood, its houses, and its residents are similar to what is found in Area 2. However, the elevated design of the freeway here affords more visual separation between homes and traffic than in Area 2. As may

TABLE D-5

AGE OF PERSONS IN EACH INTERVIEW LOCATION

AGE INTERVAL	UNIT	AREA 1	2	3	4	5
16-24	%	3.3	8.6	12.5	7.3	18.3
	(*N*)	(1)	(6)	(7)	(8)	(11)
25-34	%	6.7	14.3	21.4	17.4	28.3
	(*N*)	(2)	(10)	(12)	(19)	(17)
35-44	%	46.7	24.3	23.2	26.6	15.0
	(*N*)	(14)	(17)	(13)	(29)	(9)
45-54	%	33.3	18.6	23.2	18.4	28.3
	(*N*)	(10)	(13)	(13)	(20)	(17)
55-64	%	3.3	20.0	14.2	12.8	3.3
	(*N*)	(1)	(14)	(8)	(14)	(2)
65+	%	6.7	14.3	5.4	16.5	6.7
	(*N*)	(2)	(10)	(3)	(18)	(4)

be seen in Figure D-1, landscaping has not commenced in this area so the freeway appears more intrusive in the neighborhood than does the freeway in Area 4 where the landscaping is well established.

Most of the houses are one-story stucco bungalows built about 20 years ago, but there are also a few apartment structures. The homes range in value from $14,200 to $24,000, with a mean value of $17,500. The higher value of homes in Area 3 over Area 2 is largely a result of high land values to be found on the west side of Los Angeles. In this area land value accounts for 55 percent of the total property valuation, higher than any other interview area. As previously indicated, the houses themselves are comparable in appearance to the newer houses in Area 2.

Many Japanese and Mexican-Americans live in Area 3. Occasionally it was necessary to use interpreters during the interview study. This area is second to Area 2 in the percentage of persons who have not completed high school (28.6 percent), but a much higher proportion have attended college (41.1 percent). Only 3.6 percent are professionally employed; 37.5 percent are skilled or semi-skilled; 19.6 percent are non-skilled workers. This area has the lowest percentage of retired or unemployed persons (3.6 percent) and a significantly lower proportion of housewives (more working women) than any other area.

The freeway through this interview area is the newest of the freeways in all study areas. It was opened 1½ years ago. Partly for this reason and partly because this segment is so near the terminus, traffic is lighter than in any of the study areas. Only in Area 1, where the average distance from the homes to the freeway is 1,500 ft, is the noise level lower.

AREA 4—STUDIO CITY, VENTURA FREEWAY

Interview Area 4 flanks the Ventura Freeway in the San Fernando Valley. It is a pleasant, well-established middle-class neighborhood of single-family bungalows with some two-story apartments on the major streets. There is a greater range in home design and value of the single-family houses than in Areas 2 and 3, with a low of $10,600 and a high of $33,100. The mean home value is $20,400. The lower priced homes are generally comparable to those in Area 3, the difference in price reflecting the high land values in Area 3. In this area, land value accounts for 35.3 percent of the total value, compared with 55.4 percent in Area 3.

All but 10 percent of persons in the site have graduated from high school. Area 4 is second only to Area 1 in the respect that 18.7 percent have graduated from college or hold post-BA degrees. The percentage of professionally employed persons (17.9 percent) is second highest of all interview areas. In age characteristics, Area 4 is most like Area 2. It has the highest percentage of persons aged 65 and over (16.5 percent) and only 45 percent in the 35-54 groups (compared with 80 percent in Area 1).

Some of the homes in the area face away from the freeway, some present their sides to the freeway and a few face it across a frontage road. Where there is a road between the houses and the freeway, the distance from the houses to the first traffic lane is from 100 ft to 130 ft; in the case of houses abutting the freeway at the end of cul-de-sacs, the distance from house to first traffic lane is as little as 30 ft to 50 ft.

This section of the Ventura Freeway was opened to traffic seven years ago. It is a heavily used commuter route between the San Fernando Valley and the central portions of Los Angeles. Despite the heavy use, the elevated design of the freeway (averaging 16 ft above the level of the neighborhood) results in a considerable lowering of the noise level compared with that in Area 2 where the freeway is on grade. In addition, the heavy, well-established plantings of trees and shrubs provide an excellent visual traffic buffer. It may be seen in Figure D-1 that this freeway is not visually intrusive in the neighborhood, as are the freeways in Areas 2, 3, and 5. This well-landscaped effect is present throughout the study area.

AREA 5—VAN NUYS, SAN DIEGO FREEWAY

There is a greater range in home type and value in this study area than in any of the others, with the exception of Area 1. Table D-1 shows a low value of $10,000 and a high value of $40,000; but, as indicated by the mean value of $21,000, only a minority of the homes fall in the upper part of the range. For the most part, the homes resemble those in Area 3 and the newer homes in Area 2. It is largely an area of single-family bungalows, with a few apartment buildings on the major streets. The ratio of land valuation to total valuation is lower here than in any of the interview areas. The mean lot value of $5,400 is only 25.6 percent of the total mean value.

As suggested by the range in home values, this area is less homogeneous than Area 4. It has a higher proportion of persons who have not graduated from high school (11.7 percent) but a higher proportion of persons with some college education; a lower proportion of persons with an undergraduate college degree (3.3 percent) but a higher percentage with post-graduate degrees (11.7 percent). It is third highest of all areas in percentage of professionals

(12.1 percent) but second highest in the proportion of nonskilled workers (10.3 percent). Area 5 has the highest proportion of persons under 35 (46.6 percent) and shares, with Area 1, the lowest percentage of persons aged 55 and over (10.0 percent).

Some of the houses face the freeway across a frontage road; a very few at the end of cul-de-sacs are oriented with a side exposure; most of them abut the freeway right-of-way at the back of the property. The more expensive houses are concentrated in one block, facing away from the freeway on exceptionally deep lots.

This interview area is about 20 miles northwest of downtown Los Angeles in the San Fernando Valley; it is about 8 miles north of Area 1 on the San Diego Freeway. The traffic volume (in cars per minute) is similar in both study areas. The freeway segment passing this study area has been open for four years; the neighborhood was well-established before that time.

The freeway is elevated past most of the study area but descensd almost to grade in one section. Landscaping is barely started through most of this stretch, with the result that the freeway is an intrusive visual element in the community.

Table D-6 summarizes noise measures, distance, and configuration of freeway for each area.

TABLE D-6

NOISE MEASUREMENTS AT SELECTED FREEWAY LOCATIONS

AREA	SITE	MEAN dBA	STD. DEV.	DISTANCE FROM FRWY[a]	CONFIGURATION OF FRWY[b]	COMMENTS
1	Casiano Road	63.4	2.06	730′ East	150′ Below	Landscaping established
	Linda Flora Drive	53.4	1.95	2275′ East	300′ Below	Landscaping established
	Area-wide mean	58.4				
2	Ramona and Eighth	77.7	2.95	48′ South	5′ Below	Chain link fence—no planting
	Ramona and Fourth	76.2	2.91	48′ South	2′ Below	Chain link fence—no planting
	Ramona and Chapel	78.2	3.43	45′ North	5′ Below	Chain link fence—no planting
	Area-wide mean	77.4				
	Mark Keppel High School	68.8	2.85	22′ South	3′ Below	10′6″ cement block wall between frwy and microphone[c]
3.	Urban and Dorchester	60.5	2.41	57′ South	9′ Above	No landscaping
	Yorkshire and Virginia	62.9	2.75	80′ North	15′ Above	No landscaping
	Kansas and Virginia	65.5	2.38	60′ North	5′ Above	No landscaping
	Area-wide mean	63.0				
4	Sylmar Avenue	61.9	1.79	50′ South	11′ Above	Heavy trees and shrubs
	Hortense and Katherine	65.1	2.96	100′ South	11′ Above	Heavy trees and shrubs
	Kling and Wortser	64.2	2.45	30′ South	7′ Above	Heavy trees and shrubs
	Sarah and Gentry	65.0	2.02	100′ South	15′ Above	Heavy trees and shrubs
	Sarah and Beck	65.2	2.45	130′ South	11′ Above	Heavy trees and shrubs
	Area-wide mean	64.3				
5	Hart Street	65.0	3.42	75′ East	13′ Above	Partial landscaping
	Aqueduct and Haynes	68.8	2.73	90′ East	5′ Below	Partial landscaping
	Area-wide mean	66.9				

[a] Distance and direction of microphone from near edge of pavement.

[b] In relationship to microphone on 5′ tripod.

[c] Not included in area-wide mean.

APPENDIX E

DEVELOPMENT OF INDIVIDUAL REACTION MEASURES TO NOISE

Two initial decisions were made regarding the interview portion of the present study which served to differentiate this work from previous interview work regarding freeway or highway noise. First, it was decided that an attempt would be made to place noise in perspective to the total picture of living near freeways, including the advantages, as well as disadvantages other than noise.

Secondly, it was determined that the interview survey would be analytic rather than descriptive.

The first decision, to attempt to place noise in perspective, primarily influenced the introduction that interviewers gave to the problem and the general opening format of the interview schedule. Noise was not initially mentioned, and respondents were initially asked an open-end question which gave respondents no hint of the specific intent or interest of the investigators. Even when noise was brought up directly, it was embedded within other items, so that noise was never singled out as a variable until the end of the questionnaire.

The second decision, that the survey be analytic rather than descriptive, meant that attempts would be focused upon relationships, and on attempts at prediction. In contrast, a descriptive survey would involve the selection of different samples of respondents, or of a single sample considered a focal point of interest, and questions would be directed toward describing that population. In such a survey, it might be asked whether people are annoyed or not annoyed, whether they are upper, middle or lower class, whether they have had more or less than a high school education, and other similar kinds of questions. For the most part, such questions produce ordinal or rank order data, and the statistical techniques which may be applied to such data are extremely limited. It is possible to examine simple percentages, and arrange data in simple two by two, or *n* by *n* tables.

But, for statistical inference, interval data are necessary, and the intent of the present interview schedule was to attempt to develop scales of measurement which would be analogous to the interval scales developed in the actual physical measurements taken in other parts of the investigation. Thus, rather than simply attempting to place these people into categories, the present work attempted to devise measures which would allow the arrangement of people along a continuous scale. For that reason, the interview schedule contained a number of interrelated items in such a manner that the mathematical interrelationships between them could be examined, and, if possible, scales could be developed.

This may be considered analogous to the problem of perception of noises in the laboratory situation. In the laboratory situation, people might be asked whether sounds are loud or quiet, annoying or pleasing. Rather, it would be asked that individuals rate sounds along a series of continua instead of placing sounds in discrete interval categories.

It is well known, and has been demonstrated many times, that people can differentiate more or less finely any physical continuum of sensory input. Thus, within the perceptual range, individuals can discriminate among objects of different physical weights, different levels of illumination, as well as different qualities of sound, including noisiness versus quietness. In social measurement, however, the problem is not always that simple. Extensive use in the present study has been made of the statistical tool of factor analysis, for example. In the present study, relatively new techniques have been used, or old techniques adapted specifically for the present purpose, and remarkable success has been achieved in separating out general dimensions both of individual judgment, and of some properties of the physical environment. It has been possible to specify that a large proportion of the total variation is accounted for by these dimensions. Further, these measures have been used in actual prediction of response to the physical environment. The use of these statistical techniques to achieve certain properties of measuring instruments represents a generally sophisticated approach to the treatment of social data. This approach appears to have had marked success.

Of greater importance, however, the general approach has led the researchers to rely heavily on the spontaneous comments of people. In the case of social research, it is unfortunate that most people are apt to be cooperative. They tend all too often to give the responses which they believe the interviewer wants. It is axiomatic that when an individual's attention is called to some aspect of his physical environment, his perception is sharpened.

By deliberately not setting a frame of reference or calling attention to any specific elements, the researchers have attempted to assess individual reactions to noise from freeways or highways, as these reactions fit into the general reactions both to freeways themselves, and to the reactions of living near a freeway. For the first time in highway noise research, then, it is believed that the precision in social measurement which has previously been achieved in the measurement of objective, physical stimuli has been approached.

REACTIONS TO FREEWAYS IN GENERAL

The semantic differential, developed by Osgood and his associates (*26*), has been in general use as a measure of meaning for more than a dozen years. Recent research, however, has suggested that when a single class of stimuli is to be used (such as highways, for example) special forms of the differential give more adequate results, according to Berkowitz (*27*).

In the present study, the semantic differential was adapted by using sets of bi-polar adjectives which pertain especially to freeways or highways, as well as several reference scales from Osgood's original list (see Fig. E-1). In this case, the differential was used in conjunction with a series of photographs of highway or freeway scenes in an attempt to determine the general frame of reference within which people judge highways.

Some pictures were obtained from the California State Division of Highways, some were taken by interview staff members, in order to obtain a wide sample of freeway scenes, including scenes which appeared crowded and uncrowded, noisy and quiet, pleasing and annoying. A deliberate attempt was made to include photographs which were both quiet and pleasing, and quiet and annoying.

Forty volunteers, all freeway users but not people living near freeways, were asked to judge each of the 15 photographs on 19 adjective-pairs, with seven inervals of choice between each adjective-pair.

In this series of controlled associations to photographs, respondents were not directed specifically toward the noise problem, but they were given a chance to project noise to each photographed scene by a noisy-quiet scale item embedded in the list of bi-polar adjectives. Thus, they were asked to decide whether each photograph was "very noisy, moderately noisy, slightly noisy, neither noisy nor quiet, slightly quiet, moderately quiet, or very quiet," along with similar judgments on "pleasing-annoying," "fast-slow," etc. (See Fig. E-1.) A weighted mean on each scale for each picture was computed, and the average responses on each adjective pair were correlated, using photographs as replicates.

This analysis yielded an intercorrelation matrix, showing the association of each scale with all of the remaining 18 scales. The intercorrelation matrix was factor analyzed principal component method) and four factors or dimensions of judgment were extracted. Roughly 85 percent of the variance was explained, with about half of the total variance being explained by a general evaluative factor which included the adjective pairs pleasing-annoying, good-bad, interesting-boring, and restful-tiring. The second most important factor extracted, accounting for almost 20 percent of the total variation in judgment, was best described by the adjectives unimportant, quiet, rounded and soft. The third and four factors, accounting for a little more and a little less than 10 percent, respectively, of the variance were best described by the terms slow, heavy, and, for the fourth factor, unfamiliar.

Although the pre-test was used primarily to determine feasibility of this approach for the present study, and whereas it was used to select a smaller sample of both pictures and adjective pairs for the field study, it also provides information of interest.

It is not surprising to note that the first factor extracted was an evaluative or attitudinal factor. A review of 50 or so factor analytic studies of the semantic differential, with one exception, shows that the first factor of judgment of any set of stimuli is likely to be evaluative in nature, with the scales good-bad and pleasing-annoying having a high loading on that factor. (The single exception to that case may be found in a study of abstract art, where "movement" appeared more important than the pleasing or annoying qualities of the composition.) Usually two other factors are also found: a potency factor (strong-weak) and an activity factor (fast-slow).

(I) GOOD	:__:__:__:__:__:__:__:	BAD
HARD	:__:__:__:__:__:__:__:	SOFT
UNFAMILIAR	:__:__:__:__:__:__:__:	FAMILIAR
(I) EXCITING	:__:__:__:__:__:__:__:	DULL
DIRTY	:__:__:__:__:__:__:__:	CLEAN
REGULAR	:__:__:__:__:__:__:__:	IRREGULAR
(III) SLOW	:__:__:__:__:__:__:__:	FAST
NECESSARY	:__:__:__:__:__:__:__:	UNNECESSARY
HOT	:__:__:__:__:__:__:__:	COLD
(I) ANNOYING	:__:__:__:__:__:__:__:	PLEASING
HIGH	:__:__:__:__:__:__:__:	LOW
MODERN	:__:__:__:__:__:__:__:	OLD FASHIONED
(II) UNIMPORTANT	:__:__:__:__:__:__:__:	IMPORTANT
(II) QUIET	:__:__:__:__:__:__:__:	NOISY
ANGULAR	:__:__:__:__:__:__:__:	ROUNDED
BORING	:__:__:__:__:__:__:__:	INTERESTING
HEAVY	:__:__:__:__:__:__:__:	LIGHT
RESTFUL	:__:__:__:__:__:__:__:	TIRING
DARK	:__:__:__:__:__:__:__:	BRIGHT

Figure E-1. Adjective-pairs used in the pre-test, and selected for field study (Roman numerals) for use in the judgment of photographs.

It is important to note, however, that these factors or dimensions of judgment are independent or orthogonal to each other, and thus the presence of the scale quiet-noisy in the second factor rather than the first indicates that these judgments are not statistically related when freeway users are judging photographs. Thus a scene may be judged as either pleasing or annoying, and still be judged "noisy." For freeway users, then, the noise of a freeway is not associated with judgments of that freeway as unpleasant, bad or annoying.

The pre-test also demonstrated that photographs vary widely in the extent to which they are judged as pleasing or annoying, but that no freeway scene (even where the stimulus is a still photograph) is judged as quiet. At best, it is only judged as neither quiet nor noisy. However, average judgments of the 15 photographs on the two scales pleasing-annoying and quiet-noisy suggest that the investigators achieived a relatively wide range of photographs, adequate for sampling judgments toward freeways in general.

Because of the preponderance of scales or adjective pairs which fell into the first component or dimension of judgment, it seemed obvious that adequate measurement could be achieved by far fewer adjective pairs than were used in the pre-test.

The pre-test, using 19 adjective pairs and 15 photographs, took between 30 and 50 minutes to complete. For the field study, the test was shortened to include only eight photographs and six adjective pairs. The photographs were selected to tap the entire range of the pleasing-annoying spectrum, and the quiet-noisy spectrum. Again, an attempt was made to select photographs that would not automatically produce an association between judgments of annoyance and noise.

Figure E-1 gives the list of adjectives used in the pre-test, and indicates (by Roman numeral) the scales selected for the field study and the factor in which that scale appeared on the pre-test. Thus, three factor 1 scales (pleasing), two factor 2 scales (good), and one factor 3 scale (exciting) were selected for final use. Figure E-2 shows the pre-test rating for all 15 photographs on the pleasing-annoying and quiet-noisy scales. Those numbers circled indicate photographs used subsequently in the field test.

Figure E-3 shows profile differences to two pairs of pictures used in the pre-test. This figure illustrates the use of the picture test as a visual aid to determining judgments of particular highway or freeway situations.

THE PICTURE TEST IN THE FIELD SITUATION

In Area 1, the area first interviewed, all respondents were given the picture test immediately after answering the initial open-end question about the major advantages and disadvantages about freeways. It was discovered, however, that the picture test was unwieldy for use in the field, and that respondents did not appear to like it. Because its use in the present situation had not yet been empirically demonstrated, the investigators decided to sample respondents in Area 2, that area least like Area 1 both in socio-economic status and in measured objective noise level for the picture test, but to exclude that portion of the intervieiw schedule for the rest of the respondents.

In Area 1, 29 completed picture tests were given, and 56 in Area 2.

Initial screening of the data suggested that Areas 1 and 2 were different in their responses to the picture test. For example, when mean scores were taken for each picture on each scale for the two areas, and the average responses to each picture on good and quiet were examined, a rank order correlation of 0.13 was obtained for Area 1, and a rank order correlation between good and quiet for the freeway pictures of —0.69 was obtained for Area 2. The difference in correlations found in this preliminary screening suggested that the general goodness or badness of a photograph was not related to its judged noisiness for Area 1, but that it was indeed related for respondents in Area 2. (Results of the factor analyses done separately for Areas 1 and 2 demonstrate that people from the two areas do indeed judge scenes of freeways in quite different fashions.)

Area 1 used only two factors in the judgment of the photographs, making only those factors with a latent root greater than one. These factors closely approximated those found initially in the pre-test. Thus, all of the factor 1 scales from the pre-test were included in factor 1 for Area 1, although important-unimportant shifted from factor 2 to factor 1. Factor 2, for Area 1 included the quiet-noisy scale, as in the pre-test, and the fast-slow scale, which originally emerged as a factor 3 scale. It is not uncommon for the second and third factors to combine in this fashion, under two conditions: first, a combination may occur when a reduced set of scales is used, as in the present instance, or it may occur when the stimuli presented are less well differentiated for the respondents.

In summary, Area 1 shows a pattern of response to the picture test very similar to that obtained on the pre-test. This would suggest that those who live relatively far from the freeway, even when they are in a direct line of sight and hearing to that freeway, judge freeways similar to the way ordinary users judged them in the pre-test. (See Table E-1.)

Area 2 showed a quite different configuration with, as suggested earlier, quiet being negatively related to good, although the actual correlation coefficient is low. However, the basic factor structure, with three main factors, shows the first major dimension of judgment for Area 2 to include the scales quiet-noisy, important-unimportant, and pleasing-annoying. Thus, for Area 2, perceived quietness in a freeway is associated with its being pleasing and unimportant. The scales good and pleasing, which are usually highly associated, are *not* highly associaited for Area 2. For Area 2, a freeway is good if it is fast. Although cause-effect

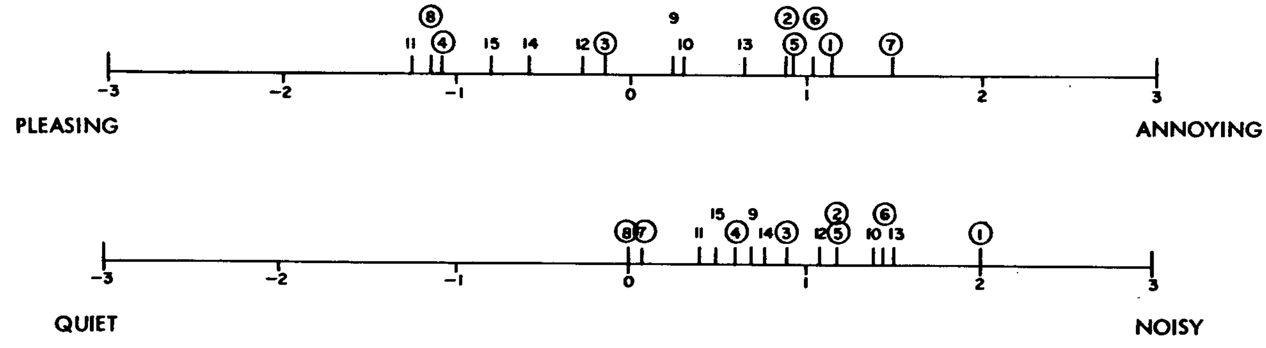


Figure E-2. Mean judgment on two rating scales for 15 photographs of freeway situation.

TABLE E-1

FACTOR LOADINGS FOR EACH SCALE OF THE PICTURE TEST FOR AREAS 1 AND 2

	AREA 1 ($N=29$)		AREA 2 ($N=56$)		
SCALE	FACTOR I	FACTOR II	FACTOR I	FACTOR II	FACTOR III
Good	0.89	0.26	−0.09	0.97	−0.04
Pleasing	0.90	0.24	0.78	0.57	0.19
Slow	−0.51	−0.60	0.36	−0.78	0.47
Quiet	−0.29	0.87	0.91	0.01	−0.26
Exciting	0.88	−0.30	0.11	0.29	0.94
Important	0.90	−0.26	−0.94	0.13	0.20
(Proportion of variance)	(.59)	(.23)	(.41)	(.33)	(.21)

statements cannot be made, these results would suggest an entirely different orientation toward freeways in general by the people in Area 2. They do not find speed pleasing, but they find it good. Unfortunately, the present study does not allow determination as to whether it is the fact of living closer to the freeway that determines the general frame of reference for Area 2, and gives it more and different dimensions than those for Area 1, or whether it is simply that a different kind of person lives in Area 2. It may well be that a self-selection process occurs whereby those people who value speed will select a living area like Area 2, simply because they find speed good, not because they find it pleasing. On the other hand, those who select a living area like Area 1 may select it because, for them, stimuli must be pleasing in order to be good. In any event, further research should attempt to avoid the confounding of kinds of people and distance to freeway that the present study could not avoid. In defense of the confounding, however, the investigators must point out that it is, in Los Angeles, quite difficult to find expensive homes located extremely close to a freeway.

Given the confounding, however, the observed differences can only be noted and it can be stated that there does not appear to be a general frame of reference within which residents living relatively close to freeways judge those freeways. In subsequent use of picture test data in this report, then, each area must be considered separately. Because a larger number of respondents was available in Area 2, only Area 2 factor scores were derived. For each individual, responses to the scales which appeared in each factor were summed for residents of Area 2.

The failure to find a single factor structure within which freeway photographs are judged does not, however, limit the usefulness of the technique. Evidence presented later in this section demonstrates the utility of the picture test in assessing reactions to freeways.

Figure E-4 presents the photographs used in the field test, and Figure E-5 shows mean differences in responses to the photographs by respondents in Areas 1 and 2.

REACTIONS TO LIVING NEAR A FREEWAY

After the initial open-end question, and after the picture test (if given), interviewers moved directly into questions about living near a freeway. To this point, any question or test was directed toward freeways in general, not specifically toward living near them.

Data from other surveys were examined, and a list of five common objections and five common advantages was compiled. These items admittedly differed in level of abstraction and generality. For example, odor and noise are quite concrete, and refer to specific attributes, while appearance is a much more general attribute, a higher level of abstraction, and difficult to objectively define. Nonetheless, these are the kinds of objections noted previously and it seemed worthwhile to include them in the present study. Because the interview schedule was formatted for direct input into the computer, a series of seven-point scales was again used to rate each attribute.

It is important to note that the interviewer called the respondent's attention to the fact that the attribute might be an advantage or a disadvantage; for example, "I want to list some of the major objections that some people have about living near freeways and see if you also have these objections."

Table E-2 gives the mean responses to each attribute for respondents in each of the five areas. Each mean judgment is based on the number of people sampled in each area.

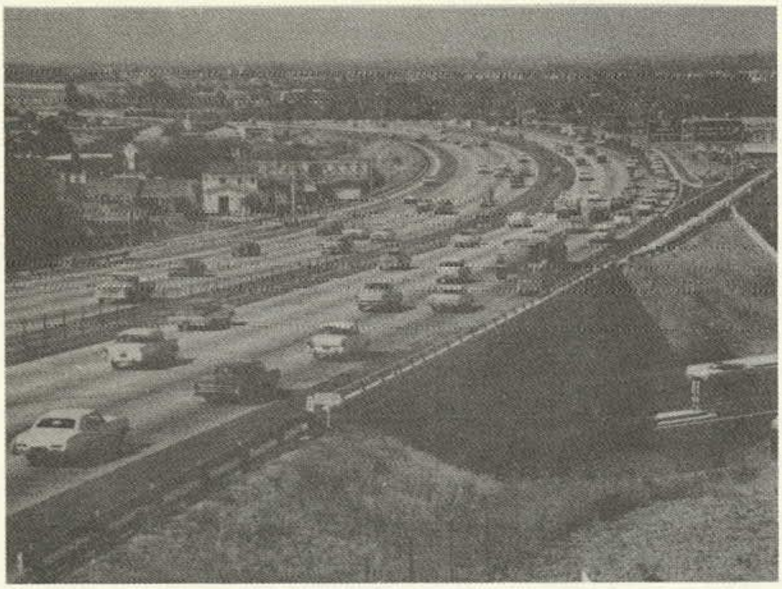
Two things are apparent and important to note about these mean responses. First, looking at the other category, one notes objections other than those listed, and in every case the additional objections are worse than any of those listed (the scale ranges from 1—very pleasant or unobjectionable—to 7—very unpleasant or objectionable, so that a high mean response indicates a highly negative rating).

In virtually every area, depressed real estate values were mentioned as an objection to living near a freeway. Additionally, in four of the five areas, residents were worried about the danger of cars running off the freeway and into homes or streets nearby and endangering the residents themselves. In three of the five areas, residents complained that living next to a freeway encouraged burglary, making get-away easy. (This complaint helps to explain why many residents were reluctant to answer the question about whether or not there were any large segments of the time during which they were routinely not at home.)

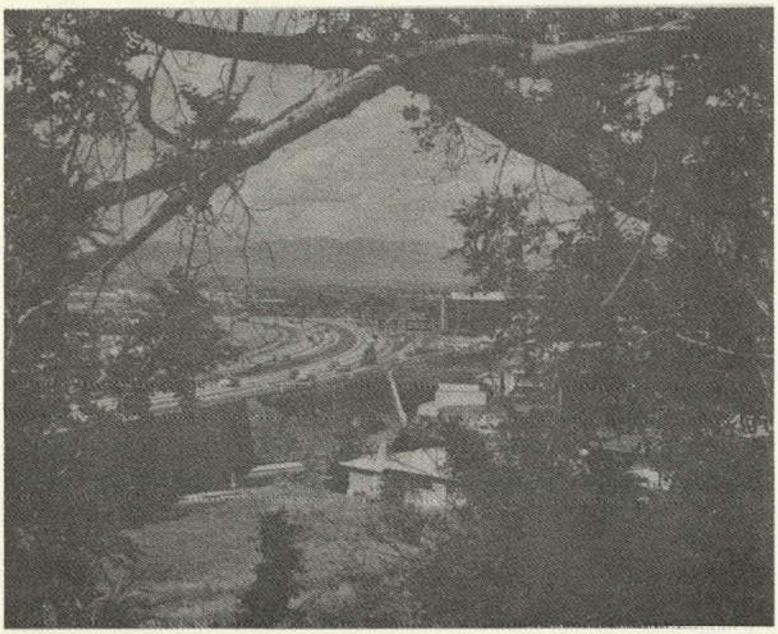
Some of the disadvantages were also perceived as advantages by other respondents. For example, while at least some people in every area complained of depressed real estate values, some residents in four of the areas suggested that one of the advantages of living near a freeway was that taxes were reduced, rent lower, homes easier to buy.

All areas complained of confusing and dangerous on-off situations, of dangerous driving situations on the freeway, but all were equally agreed that freeways were to some extent convenient, fast and necessary.

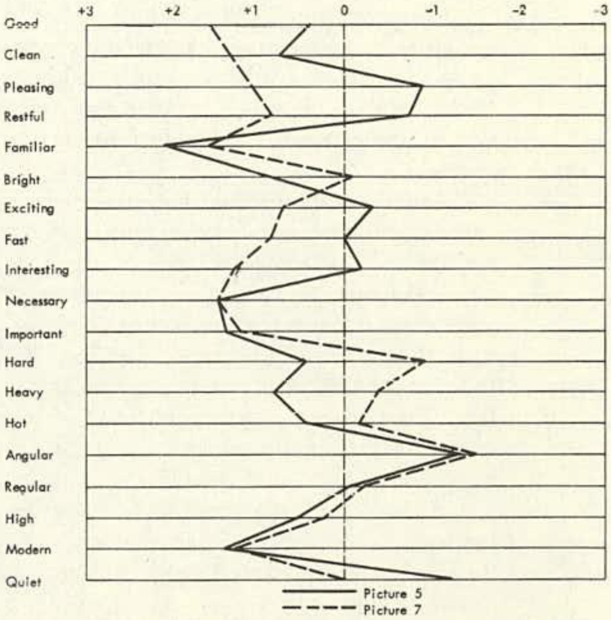
In addition to the presence of advantages or disadvantages which had not been listed and which respondents voluntarily gave, some mean scale responses were surpris-



PICTURE 5



PICTURE 7



PROFILES OF AVERAGE JUDGMENTS OF PICTURES 5 AND 7
(Pretest)

Figure E-3. Profiles of average judgments of pictures 5, 7, 2, and 11.

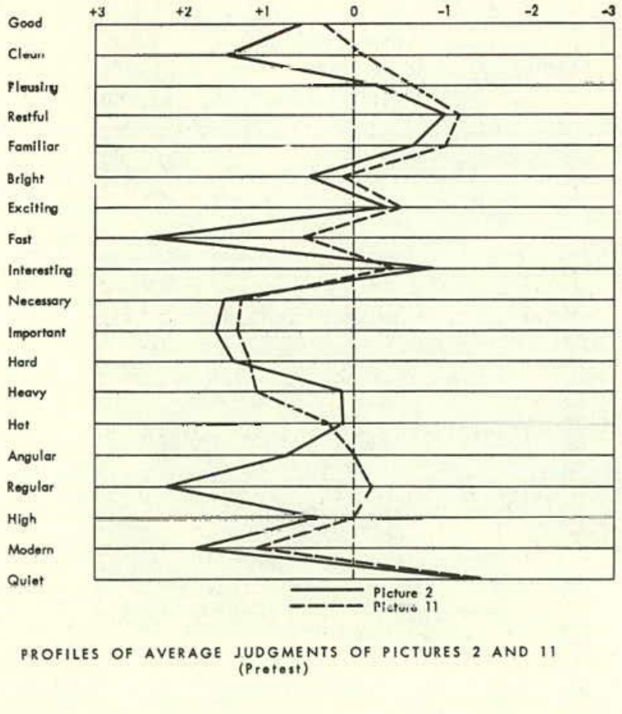
TABLE E-2

REACTIONS TO LIVING NEAR A FREEWAY

	AREA				
ATTRIBUTE	1	2	3	4	5
OBJECTIONS					
Odor	4.1	5.3	4.3	4.4	4.3
Noise	5.8	5.6	5.6	5.9	5.0
Vibration	4.1	5.5	4.3	4.8	4.3
Lights	2.5	1.9	4.2	3.9	4.0
Appearance	3.8	2.9	4.6	3.4	4.6
Other	6.1	6.6	5.7	6.4	5.9
(N)[a]	(30)	(69)	(56)	(110)	(60)
ADVANTAGES					
Convenient to work	2.8	3.7	2.8	2.4	3.4
Convenient to recreation	1.4	2.2	2.1	1.9	2.4
Convenient to shopping	3.2	4.9	2.9	3.0	3.4
Easier to drive	2.5	3.5	2.4	2.7	2.9
Necessary for number of cars	1.1	1.3	1.4	1.6	1.3
Other	1.0	1.6	0.0	2.5	2.5
(*N*)	(30)	(69)	(56)	(110)	(60)

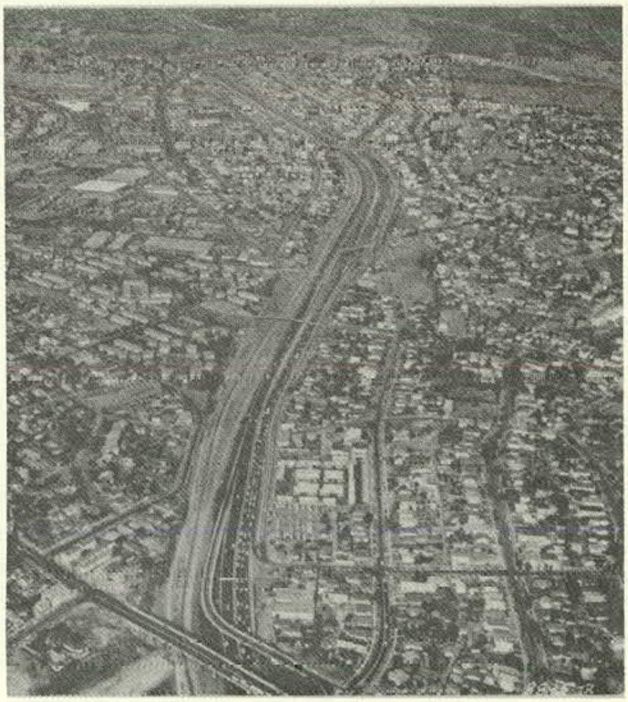
[a] *N* is the proportion responding in each area to *all* items.

ing. With the seven-point scale, ranging from 1 (positive) to 7 (negative), a mean of 4 would indicate a neutral position, suggesting neither advantage nor disadvantage, and indicating no objection. The mean responses to lights, for example, indicate that Area 2, although complaining most of odor and vibration, and complaining additionally of



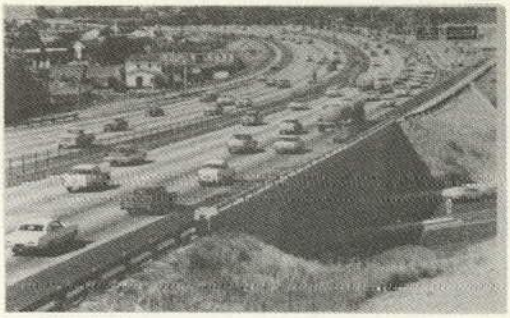
PROFILES OF AVERAGE JUDGMENTS OF PICTURES 2 AND 11
(Pretest)

PICTURE 2



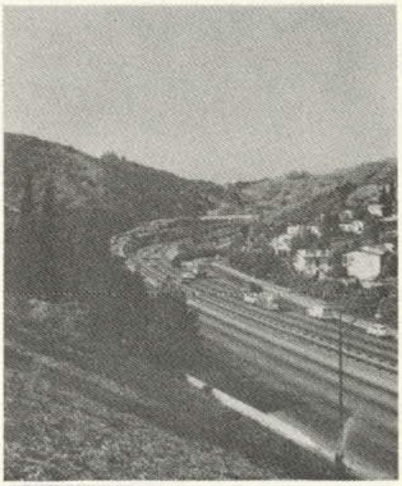
PICTURE 11

PICTURE 1.

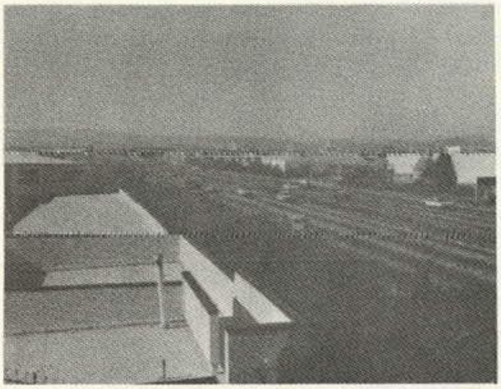


PICTURE 2.

PICTURE 3.



PICTURE 4.



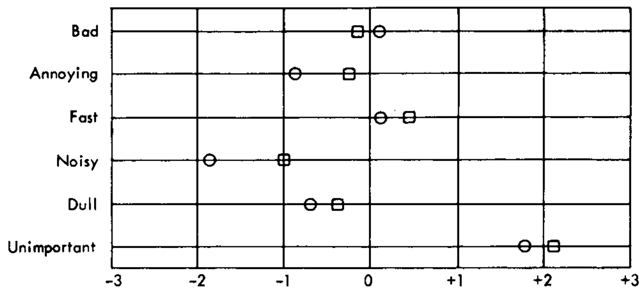
PICTURE 5.

PICTURE 6.

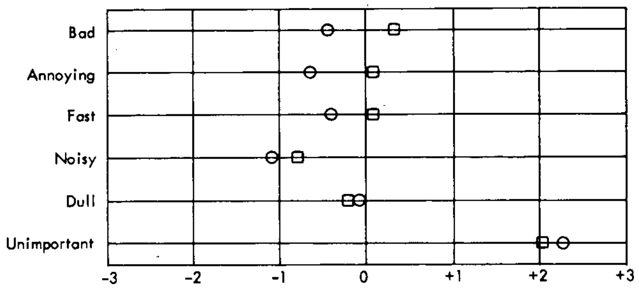
PICTURE 7.

PICTURE 8.

Figure E-4. Pictures used to determine attitudes toward highways in general.

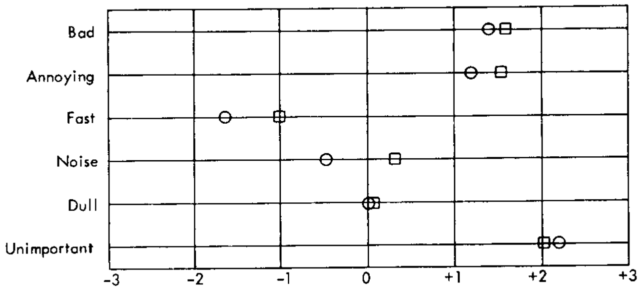


SEMANTIC DIFFERENTIAL RESPONSES TO PICTURE 1.

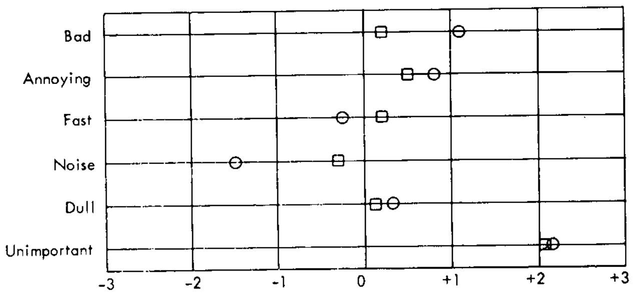


SEMANTIC DIFFERENTIAL RESPONSES TO PICTURE 2.

○ Area 1.
□ Area 2.

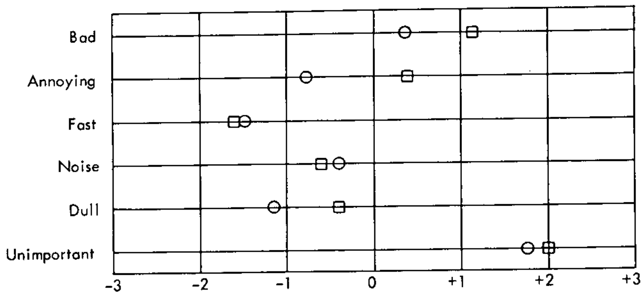


SEMANTIC DIFFERENTIAL RESPONSES TO PICTURE 3.

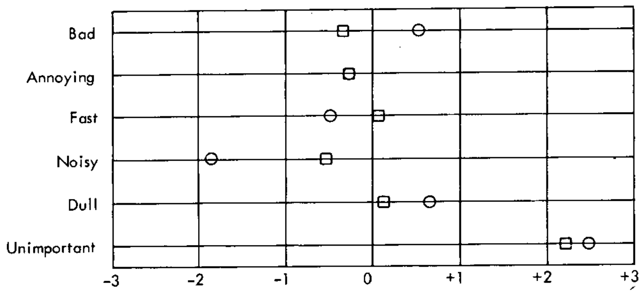


SEMANTIC DIFFERENTIAL RESPONSES TO PICTURE 4.

○ Area 1.
□ Area 2.

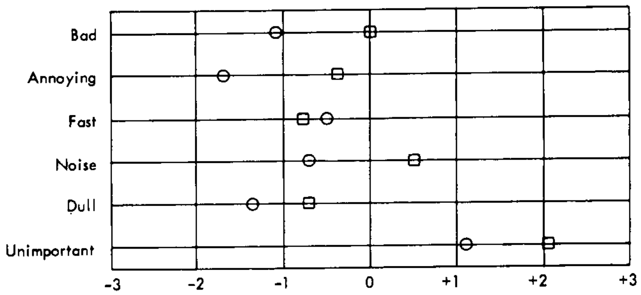


SEMANTIC DIFFERENTIAL RESPONSES TO PICTURE 5.

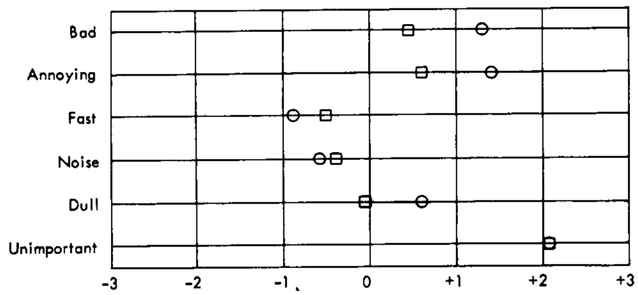


SEMANTIC DIFFERENTIAL RESPONSES TO PICTURE 6.

○ Area 1.
□ Area 2.



SEMANTIC DIFFERENTIAL RESPONSES TO PICTURE 7.



SEMANTIC DIFFERENTIAL RESPONSES TO PICTURE 8.

○ Area 1.
□ Area 2.

Figure E-5. Semantic differential responses to pictures 1, 2, 3, 4, 5, 6, 7, and 8.

noise, found lights generally quite pleasing. Area 1, not complaining about odor and vibration, but complaining strongly about noise, also found lights pleasing. In only one instance, Area 3, were lights judged even slightly unfavorably. Similarly, three of the five areas showed average responses to appearance on the positive side of the scale, with only Areas 3 and 5 finding appearance something to which they objected.

Because the a priori division of attributes into things about which people might object and things which people might see as advantages of living near freeways did not appear supported by the data, these data also were factor analyzed.

Because all respondents rated the same ten attributes (Table E-2), an attempt was made to find a general solution to the problem, rather than an area-by-area solution. Thus, rather than taking mean responses, responses for each individual to each of the ten items were used in the initial correlation matrix.

The factor analyses reported in the first part of this appendix were based on mean scores, having greater stability, and taking advantage of the central limit theorem. Using individual scores, on the other hand, it would be expected that much greater within-subject variance, and much less of the total variation among scores would be accounted for. Despite this expectation, however, a satisfactory solution, accounting for approximately 60 percent of the total variation among 310 respondents, was achieved (in contrast to roughly 80 to 95 percent of the variation accounted for on the picture test). Rather than two factors, which had been roughly categorized as disadvantages or objections, and advantages, four independent factors were found in the analysis of the ten items. Factor 1 included the three items relating to convenience: convenience to work, convenience to recreation, and convenience to shopping. The second factor, tentatively called attractiveness, included judgments of lights and appearance. Factor 3, tentatively labeled an intrusion factor, includes judgments of odor, noise, and vibration. Noise shows the lowest factor loading, suggesting that of the objectionable qualities of freeways listed, noise is the least intrusive. (See Table E-3.)

The fourth factor included primarily the item necessary for the number of cars. The ease-of-driving item initially placed in the advantage seequence, loaded about equally on factor 1 (convenience) and factor 4 (necessity).

It is clear that judgments made by residents living near a freeway do not fall simply into categories of advantages and disadvantages. In the present study, it was found that there were four independent dimensions of judgment, with at least one factor or dimension which was originally considered to be a negative aspect of living close to a freeway actually showing relatively positive mean scores in interview areas and, by statistical analysis, independent of the generally negative attributes of odor, noise and vibration. Lights and general appearance must clearly be considered different from those variables.

It should be emphasized that the care taken in pretesting the pictures presented as stimuli was not taken in the sampling of attributes for this portion of the interview schedule. It cannot be said that these are the only four factors by which people living near freeways judge those freeways. For example, had "danger" been added to the list, an added factor may have appeared to account for an additional proportion of the variance. Similarly, had any other attributes been added, they may have fallen into one of the existing factors, or they may have formed entirely new factors.

The present approach, however, of listing attributes, having them rated on seven-point scales, and utilizing factor analysis to discover the dimensions which people themselves actually use in their judgments of the freeway situation, appears to give reasonable results in terms of statisti-

TABLE E-3

FACTOR LOADINGS OF RESPONSES TO INTERVIEW QUESTIONS ABOUT LIVING NEAR FREEWAYS

CONVENIENCE	ATTRACTIVENESS	INTRUSION	NECESSITY	ATTRIBUTE
0.16	0.06	0.81	0.02	Odor
0.05	0.33	−0.68	0.22	Noise
0.07	0.01	−0.83	−0.04	Vibration
−0.08	0.85	−0.02	0.03	Lights
0.01	0.83	−0.11	−0.03	Appearance
0.76	−0.06	−0.03	−0.02	Convenience to work
0.76	0.23	−0.07	0.06	Convenience to recreation
0.71	−0.32	−0.21	0.08	Convenience to shopping
0.42	−0.28	−0.18	0.50	Ease of driving
−0.02	0.09	−0.01	0.92	Necessary for number of cars
(.25)	(.12)	(.12)	(.10)	(Proportion of variance)

cal explanation. It can easily be expanded to provide a more complete description of the ways in which people perceive certain attributes of the physical environment.

RELATIONSHIPS AMONG INDIVIDUAL REACTION MEASURES

The present study has four measures of individual reaction to noise in the field situation, varying in directness, in simplicity, and uniqueness to noise.

First, respondents were given the opportunity to voluntarily and spontaneously mention noise as a disadvantage to living near freeways. This measure, a measure of the salience of noise as a perceived disadvantage, has been taken as a dependent variable in order to enable examination of some of the properties of the other measures developed.

The justification for using this open-end question as a dependent variable is quite straightforward. It seems obvious that if people do not spontaneously complain of noise—if noise is so unimportant that they cannot recall it as a particular grievance, it seems unlikely that they will engage in any further or more extreme form of complaint. The converse, of course, is not true. Those people who spontaneously complain of noise may never go beyond the annoyance expressed on direct questioning about advantages and disadvantages of living near a freeway. It seems highly likely, however, that the proportion of people who engage in either community gossip, or more structured forms of community action, or of individual action involving actual complaint to local authorities, will be found among the group who spontaneously complain of noise. It was hoped that by examining people who did not spontaneously mention noise as an annoyance, most of the potential noncomplainants about noise would be eliminated.

The second noise measure is more direct but equally simple. Respondents were simply asked to rate the degree of annoyance or the degree of lack of annoyance with noise in their own particular situation. This scale permitted responses ranging from one (finding noise pleasant) to seven (strong complaint). This single question is roughly analogous to a single question of the perceived noisiness or loudness of an auditory stimulus presented in the laboratory, except that here it is being asked for an enduring and relatively stable judgment of noise on the average at the residence of respondents.

The third measure, taken for all respondents, is what is called intrusion, derived from the factor analysis described in the previous section, and combining the attributes of odor, noise and vibration. This measure, then, can be expected to be more stable (in that it includes more items) and more sensitive (in that a raw scale ranging from 3 to 21 may be obtained, rather than a scale from 1 to 7 *).

The fourth measure, which is for only a small subsample, is that which relates to freeways in general, and includes, for Area 2, judgments of pleasing or annoying and important or unimportant, as well as judgments of noise. This measure, too, is assumed to be both more stable and more sensitive than a single direct question, but it is less closely related to the immediate freeway situation at the respondent's home. Rather, it suggests the general frame of reference, including nonresidential situations, within which these respondents view freeways.

The present section describes the extent to which each of the measure enables prediction of the voluntarily expressed annoyance obtained in response to the open-end question.

Table E-4 gives the voluntary statements of advantages and disadvantages to living near a freeway. There is considerable variation by area in the extent to which people voluntarily mention noise as an annoyance, with Area 5 showing only 40 percent annoyance, and Area 1 showing more than 65 percent annoyance. For all areas, however, roughly half of the 315 respondents voluntarily expressed annoyance with freeway noise,† although a few others mentioned annoyance with noise because it served to protect burglars.

All respondents in the total sample were separated into two groups, the first failing to report annoyance of any kind with noise, or failing to mention noise at all in the first open-end question, and the second reporting some annoyance with noise, either general or specific. As indicated earlier, other interview variables were used in an attempt to predict whether any given individual would express annoyance or would fail to express annoyance.

The simplest and most direct index to the expression of annoyance is the rating of quiet-noisy in relation to their own freeway situation. Although respondents were given the opportunity of using a 1-7 scale, most of them used a 4-7 scale, indicating that few of them found living near a freeway quiet, though many of them found it neither quiet nor noisy. (It should be noted that a small proportion of people actually found the noise from the freeway an attractive feature of living near it; one respondent relatively distant from the freeway, for example, said that the freeway noise reminded her of the waves at the seashore.) Using the single scale, a variety of criteria may be used for predicting annoyance or lack of annoyance. It may be assume that those who find the freeway neither quiet nor noisy will not express annoyance, while those who express or perceive it as noisy in any way will express annoyance. On the other hand, it may be decided that only those with a given degree of perceived noisiness (moderately noisy to very noisy, for example) will express annoyance. But manipulation of the single scale failed to produce adequate prediction of annoyance. At best, less than 50 percent of the respondents were placed in the correct group, and, using the criteria that only those who found their freeway neither quiet nor noisy would fail to complain, resulted in roughly a 40 percent error. Clearly, then, perceived noisiness of the freeway rated on a single 7-point scale is a poor measure for the prediction of expressed annoyance. Some know it is not very loud, but they object to it anyway.

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* In practice, the average factor score has been taken, dividing by the number of scales entering into that factor, so that comparable measures may be obtained for each factor. In effect then, there is still a 1-7 scale, but with finer distinctions along that scale.

† In the preceding section, it was suggested that noise is less intrusive a factor than odor and vibration. Table E-4, however, shows that the highest proportion of complaints by respondents are made about noise. It is suggested that this higher proportion of annoyed residents reflects the fact that noise is more often present for those who live near freeways than are odor and vibration. It is suggested, however, that when odor and vibration are perceptible to residents, they are more intrusive than noise.

TABLE E-4

VOLUNTARY STATEMENTS OF ADVANTAGES AND DISADVANTAGES

COMMENT	AREA 1 (*N*=30)	AREA 2 (*N*=69)	AREA 3 (*N*=56)	AREA 4 (*N*=110)	AREA 5 (*N*=60)	ALL AREAS (*N*=315)
I. RESIDENT-ORIENTED CRITICAL COMMENT						
Disagreeable noise	66.7	50.7	39.3	50.9	40.0	49.8
Need better landscaping	43.3	18.8	37.5	6.4	36.7	24.1
Disagreeable dust and dirt	16.7	40.6	14.3	19.1	16.7	22.9
Depressed real estate values	23.3	17.4	7.1	7.3	6.7	11.1
Intrusion of trucks in residential areas	6.7	18.8	—	8.2	—	7.6
Disagreeable odor, fumes	10.0	10.1	1.8	4.5	—	5.1
Ugly; hate it; no advantages	10.0	1.4	8.9	2.7	6.7	5.1
Danger of cars hurtling off freeway	—	11.6	3.6	1.8	3.3	4.4
Proximity to accidents	—	11.6	—	2.7	—	3.5
Disrupted access within local community	—	—	8.9	2.7	1.7	2.9
Noise, easy get-away encourages burglars, etc.	—	2.9	—	0.9	8.3	2.5
II. RESIDENT-ORIENTED FAVORABLE COMMENT						
Like the view, appearance, landscaping	—	—	—	10.0	—	3.5
Like the freeway, no disadvantages	3.3	2.9	5.4	3.6	—	3.2
Reduces taxes, rent, buying price of home	—	4.3	—	0.9	3.3	1.9
III. USER-ORIENTED COMMENT						
Convenient, fast, necessary	70.0	31.9	51.8	30.9	30.0	39.4
Need more lanes, too crowded, especially at rush hour	16.6	11.6	10.7	17.3	8.3	13.7
On-off situations dangerous, confusing, slow	13.3	10.1	7.1	10.9	8.3	10.2
Need public transportation system	20.0	1.5	—	8.2	11.7	7.3
Dangerous to drive on	13.3	2.9	1.8	1.8	5.0	3.8
Need double deck freeways	3.3	—	1.8	5.5	1.7	2.9
Signing is confusing	6.7	5.8	—	1.8	1.7	2.9
Approximate socio-economic status	High	Lower middle	Lower middle	Middle	Middle	

The Prediction of Annoyance from Interview Factors

The four factors found in the test of reactions to living near a freeway were used as independent variables in a linear discriminant function analysis * using expressed annoyance as the dependent variable (*28*). Tables E-5 and E-6 describe the results of that analysis.

Using the four interview factors alone, 64 percent of the total group was correctly placed in either the annoyance or no annoyance group. The D^2 was large, and when converted to F was significant well beyond the 0.001 level, indicating that the analysis did indeed result in the selection of groups with significantly different average scores on the four factors. Table E-6, giving those mean differences, indicates that those respondents who voluntarily expressed annoyance found that living near a freeway is less convenient than for the no annoyance group, that the freeway is less attractive, that it is more intrusive.

In an attempt to increase prediction, three personal characteristics were added as independent variables to the interview factors. The accuracy of prediction was raised from 64 percent to 68 percent, suggesting that relatively little improvement was made by adding education, age, and the extent to which the respondent used the freeway for work. Again, however, when D^2 was converted to F, the F was highly significant, indicating that the two groups did indeed differ in their average educational level, average age, and average use of the freeway for work purposes. Those who expressed annoyance were better educated, were somewhat older, and used the freeway less often to get to work.

In general, then, between 60 and 70 percent of the expressed annoyances can be explained by reference to perceptions about living near the freeway and by selected personal characteristics of the respondent. This prediction is made entirely independent of the external noise level, or

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* For this analysis, a linear function, using the independent variables, is defined which separates respondents into groups on the dependent variable. For each respondent, answers to the independent variables are inserted into the function, and the respondent is then placed into a "predicted" group on the dependent variable. His "predicted" placement is then compared with his actual or observed placement. The analysis is such that the best function for classification is obtained, and errors of misclassification are minimum.

of any other pertinent environmental factors. In terms of error of measurement or prediction, the error is least where one would wish it to be least. For example, using only the interview factors alone would fail to predict 34 percent of those who actually express annoyance. Using the interview factors plus those few personal characteristic elements, only 29 percent of those who expressed annoyance were not predicted. Although these predictions are not yet impressive, they do suggest the usefulness of the technique, and the possibility that a large proportion of expressed annoyance about noise can be predicted without reference to environmental situations, including actual measured noise itself.

The Prediction of Annoyance with Freeway Noise for Area 2

It was assumed that attitudes toward freeways in general, as well as reactions to living near a freeway, are important variables in determining annoyance or lack of annoyance. Thus Area 2, where a relatively large sample of respondents taking the picture test was available, was examined separately. Tables E-7 and E-8 give the results of the discriminant function analysis done for Area 2 respondents for whom complete data were obtained. The analysis was performed in three ways. First, using only the picture test factors alone, 61 percent of the Area 2 respondents were correctly placed either in the annoyance or no annoyance group. Both the D^2 and the mean differences are relatively small, but, when the conversion to F is made, a statistically significant difference between means is found, indicating that two groups have been isolated which do differ significantly.

When the interview factors alone are used in the discriminant function, prediction is raised from 61 percent (picture test) to 70 percent. It appears obvious, then, that attitudes toward freeways in general do differentiate somewhat between the annoyance and no annoyance group, but that the interview factors, measuring reactions to living near a freeway, give a better single prediction.

The best prediction is achieved when both interview factors and picture factors are combined in a single discriminant analysis. In that case, 82 percent of the group was correctly classified. Actually, *90 percent of the group which expressed no annoyance was correctly predicted.* It seems obvious that while the factors in reactions to living near a freeway are most important in determining annoyance or lack of annoyance with noise, factors related to judgments about freeways in general can add significantly to prediction of who will be annoyed and who will not be annoyed.

TABLE E-5

DISCRIMINANT ANALYSIS—TOTAL SAMPLE

INTERVIEW FACTORS

$D^2 = 34.432$

df = 4,309

OBSERVED	PREDICTED No Annoyance	 Annoyance	 Total
No Annoyance	94 62%	57 38%	151
Annoyance	56 34%	107 66%	163
Total	150	104	314

Correctly Predicted: 64%

INTERVIEW FACTORS + EDUCATION,
AGE, HIGHWAY USE, WORK

$D^2 = 52.961$

df = 7,303

OBSERVED	PREDICTED No Annoyance	 Annoyance	 Total
No Annoyance	95 64%	53 36%	148
Annoyance	47 29%	116 71%	163
Total	142	169	311

Correctly Predicted: 68%

Again, those who express annoyance find that living near freeways is less convenient, their freeway is seen as less attractive (although it is the same freeway seen by the group which was not annoyed), and the freeway seen is more intrusive. There is relatively little difference in the extent to which the two groups see the necessity of the freeway in Area 2.

Freeways in general are seen by the group expressing annoyance as less quiet, pleasing and unimportant and as more dull than the group expressing no annoyance. There is no difference between the two groups, annoyed or not annoyed, in their judgments of freeways in general as good and fast. Both groups, on the average, find freeways in general neither good nor bad, fast nor slow, and, in view of the large mean differences observed on those scales alone, it must be concluded that each group contains a wide range of people perceiving the freeways as good and fast, and, bad and slow. In this case, the within-group differences are apparently large enough so that no between-group difference is found.

TABLE E-6

MEAN DIFFERENCES FOR GROUPS EXPRESSING ANNOYANCE OR NO ANNOYANCE WITH FREEWAY NOISE (MEAN FACTOR SCORES[a])

GROUP	CONVENIENCE	ATTRACTIVENESS	INTRUSION	NECESSITY	EDUCATION	AGE	FREEWAY USE: WORK
No annoyance	2.68	3.50	4.56	2.81	3.28	3.25	1.87
Annoyance	2.83	3.72	5.19	2.73	3.68	3.53	1.68

[a] Scores range from 1 (positive) to 7 (negative).

TABLE E-7

DISCRIMINANT ANALYSIS—AREA 2

INTERVIEW FACTORS:

$D^2 = 17.068$

df = 4,49

OBSERVED	PREDICTED No Annoyance	PREDICTED Annoyance	Total
No Annoyance	15 68%	7 32%	22
Annoyance	9 28%	23 72%	32
Total	24	30	54

Correctly Predicted: 70%

PICTURE FACTORS:

$D^2 = 3.337$

df = 3,50

OBSERVED	PREDICTED No Annoyance	PREDICTED Annoyance	Total
No Annoyance	15 68%	7 32%	22
Annoyance	14 44%	18 56%	32
Total	29	25	54

Correctly Predicted: 61%

INTERVIEW + PICTURE FACTORS:

$D^2 = 28.133$

df = 7,42

OBSERVED	PREDICTED No Annoyance	PREDICTED Annoyance	Total
No Annoyance	18 90%	2 10%	20
Annoyance	7 23%	23 77%	30
Total	25	25	50

Correctly Predicted: 82%

It has been noted that the picture test, designed to tap attitudes or dimensions of judgments about freeways in general, is not a popular test, and that it is somewhat difficult to use in the field situation. It is, however, perfectly feasible for use by well-trained interviewers who have established good rapport with the respondent. The Area 2 experience indicates that this is not in itself an adequate tool to predict annoyance with freeway noise. It appears to add greatly, however, to the prediction obtained when only reactions to living near a freeway are used. This increase in prediction, from 70 percent to 82 percent, indicates that its use is justified.

It should be noted that a relatively adequate degree of prediction of expressed annoyance with freeway noise has been used with interview data alone, ignoring wide differences in objective measured noise level. Common sense, however, would indicate that the objective noise level does indeed, however, have some impact, and this proposition receives tentative support from the fact that the interview factors alone predicted better for Area 2, where noise level may be assumed to be relatively constant for all respondents, than for the total group, where noise level varied greatly from one interview area to another.

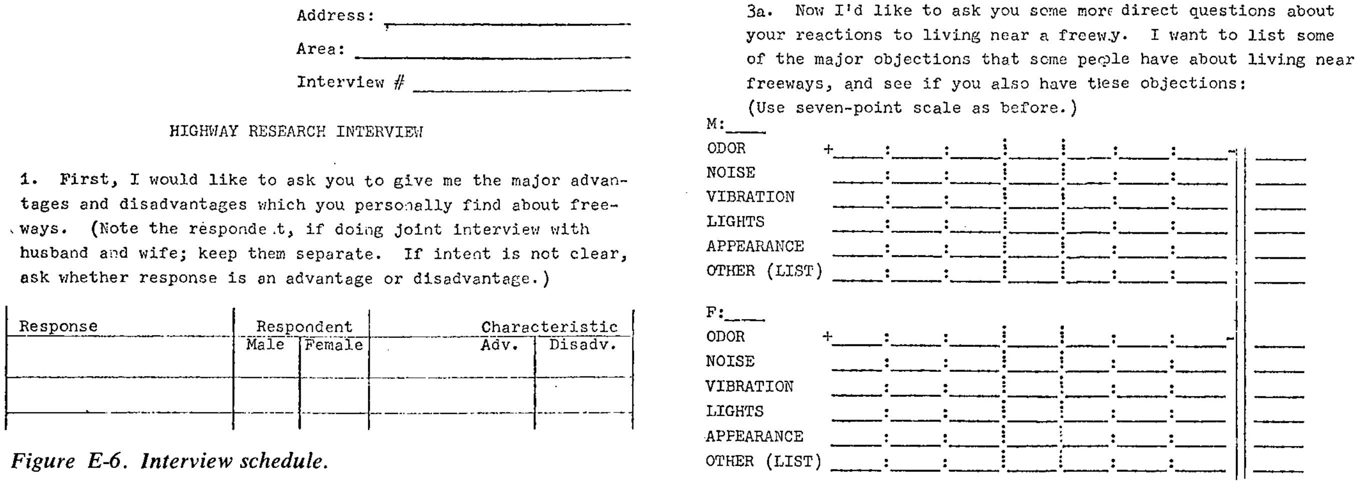
Figure E-6 shows a sample highway research interview form.

TABLE E-8

MEAN DIFFERENCES FOR GROUPS EXPRESSING ANNOYANCE OR NO ANNOYANCE WITH FREEWAY NOISE (AREA 2)

GROUP	CONVENIENCE	ATTRACTIVENESS	INTRUSION	NECESSITY	QUIET, PLEASING, UNIMPORTANT	GOOD, FAST	EXCITING [a]
No Annoyance	3.58	1.82	5.07	1.23	4.76	3.99	4.00
Annoyance	3.50	2.73	5.86	1.28	4.64	3.99	4.28

[a] Scores range from 1 to 7.



Address: ____________________

Area: ____________________

Interview # ____________________

HIGHWAY RESEARCH INTERVIEW

1. First, I would like to ask you to give me the major advantages and disadvantages which you personally find about freeways. (Note the respondent, if doing joint interview with husband and wife; keep them separate. If intent is not clear, ask whether response is an advantage or disadvantage.)

Response	Respondent		Characteristic	
	Male	Female	Adv.	Disadv.

3a. Now I'd like to ask you some more direct questions about your reactions to living near a freeway. I want to list some of the major objections that some people have about living near freeways, and see if you also have these objections:
(Use seven-point scale as before.)

M:____

ODOR + ____:____:____:____:____:____:____ - ____
NOISE ____:____:____:____:____:____:____ ____
VIBRATION ____:____:____:____:____:____:____ ____
LIGHTS ____:____:____:____:____:____:____ ____
APPEARANCE ____:____:____:____:____:____:____ ____
OTHER (LIST) ____:____:____:____:____:____:____ ____

F:____

ODOR + ____:____:____:____:____:____:____ - ____
NOISE ____:____:____:____:____:____:____ ____
VIBRATION ____:____:____:____:____:____:____ ____
LIGHTS ____:____:____:____:____:____:____ ____
APPEARANCE ____:____:____:____:____:____:____ ____
OTHER (LIST) ____:____:____:____:____:____:____ ____

Figure E-6. Interview schedule.

3b. Now what about some of the advantages of freeways:

M:____

CONVENIENCE TO WORK (speed, accessibility) +____:____:____⁝____⁝____:____:____- ____

CONVENIENCE TO RECREATION ____:____:____⁝____⁝____:____:____ ____

CONVENIENCE TO SHOPPING ____:____:____⁝____⁝____:____:____ ____

EASIER TO DRIVE ____:____:____⁝____⁝____:____:____ ____

NECESSARY FOR NUMBER OF CARS ____:____:____⁝____⁝____:____:____ ____

OTHER (LIST) ____:____:____⁝____⁝____:____:____ ____

F:____

CONVENIENCE TO WORK (speed, accessibility) +____:____:____⁝____⁝____:____:____- ____

CONVENIENCE TO RECREATION ____:____:____⁝____⁝____:____:____ ____

CONVENIENCE TO SHOPPING ____:____:____⁝____⁝____:____:____ ____

EASIER TO DRIVE ____:____:____⁝____⁝____:____:____ ____

NECESSARY FOR NUMBER OF CARS ____:____:____⁝____⁝____:____:____ ____

OTHER (LIST) ____:____:____⁝____⁝____:____:____ ____

3c. In general, would you say that the advantages of living close to the freeway outweigh the disadvantages?

(completely, moderately, slightly, no difference/don't know, slightly no, moderately no, completely no)

+____:____:____⁝____⁝____:____:____- ____

3d. Aside from the freeway, how much do you like living here, considering the neighbors and the general location?

+____:____:____⁝____⁝____:____:____- ____

4a. Now I'd like to ask a few personal questions of you about family education and occupation so that we can describe the kind of people we have talked to. (Phrase question to get both husband and wife information, regardless of whom you are interviewing.)

EDUCATION	Male	Female
No High School		
Some High School		
High School Grad		
Some College		
College Grad		
Post BA Degree		

4b. OCCUPATION Male Female

List in detail: ____________/____________

4c. How long have you lived in your present home?________

4d. What are/is your approximate age(s)?

	Respondent	
Interval	Male	Female
16 - 24		
25 - 34		
35 - 44		
45 - 54		
55 - 64		
65+		

5a. (For those who work?) In general, compared to most places of business, how noisy would you say it is where you work?

Male noisy____:____:____⁝____⁝____:____:____quiet
Female noisy____:____:____⁝____⁝____:____:____quiet

5b. On the average, would you say that with (television, radio, children, pets) around that your home is generally noisy or generally quiet?

(ask for R's rating, and record both if joint interview; on the third line, record your own impressions)

Male noisy____:____:____⁝____⁝____:____:____quiet
Female noisy____:____:____⁝____⁝____:____:____quiet
I noisy____:____:____⁝____⁝____:____:____quiet

6. Now, are there any large segments of time during which you are routinely away from home, at work, for example? (check if not at home during major portion of interval)

	Midnight-7am	7-9	9-4	4-7pm	7-midnight
Male					
Female					

7. Now I'd like to ask about car ownership and freeway use. How many cars do you have in the family? 1 . 2 . 3 . 4

7a. How many drivers are there? 1 . 2 . 3 . 4

7b. How often do you use the freeway?

	Transportation to					
	Work		Leisure Activities or visiting friends		Shopping	
Freeway Use:	M	F	M	F	M	F
Regular						
Occasional						
Rare						
Never						

8a. Now I've asked you a lot of questions without giving you a chance to give me many of your own personal views. Are there any things you would like to have us tell the Highway Research Board about your opinions and views of freeway construction? (record verbatim) ____________________

8b. If we need some additional help with our research, would you be willing to help us out again? yes_____
no_____

(If yes, ask for Name, Address, Phone)

Name: ____________________
Address: ____________________
Phone: ____________________

APPENDIX F

ANALYSIS OF RELATIONSHIPS BETWEEN PHYSICAL ENVIRONMENT AND INTERVIEW DATA

Ample evidence exists that people can judge the relative loudness of noisiness of sounds with good reliability. Laboratory work has resulted in well-defined functions for relating subjective, or perceived loudness and noisiness with increasing objective noise levels (*5, 6, 7*). Further, experiments with groups of people in quasi-natural settings (e.g., a group assembled for an experiment in a residence near an airport) suggest that, within limits, an absolute scale of subjective noisiness can be constructed for noises in certain contexts (*29*). Finally, analysis of case studies of neighborhood noise problems tends to show that higher noise levels for a given class of noise nuisance are correlated with higher levels of overt negative response. One might expect, then, to find a strong relationship between objectively determined traffic noise levels and responses to the intruding noise.

The data fail to show a simple, strong, or direct relationship between objectively measured noise and reactions to that noise by freeway-proximal residents in their natural settings. Two illustrations of that lack will suffice. First, if the percentage of residents giving a spontaneous objection to noise is compared in the five areas it is noted that 67 percent of the residents in the quietest area complained, but only 51 percent complained in the noisiest area. And yet the noisiest area, at 77 dBA, has nearly 20 dBA more traffic noise than the quietest area. (The noisier area is about 4 times as noisy, based on laboratory judgments of perceived noisiness.)

As a second illustration, a low correlation ($r = 0.23$) was found between a physical noise measure (dBA) and a subjective rating of intrusion (a factor consisting of judgments of noise, vibration, and odor as disadvantages to living near a freeway).

This lack of correspondence between physical measures of noise and supported human behavior correlates has plagued many attempts at explanation of noise problems. A partial solution has been found, particularly with regard to reactions to aircraft noise, in selection of correction factors that modify the estimated or measured noise stimulus. Such factors include both other physical measures (e.g., number of noise occurrences per day) and ratings descriptive of the residents or the entire community (e.g., previous exposure, economic ties) in attempts to account for response variations. The basic underlying assumption in those attempts is that physical noise is the primary stimulus.

The data indicate clearly that the objective noise level is not the single dominant characteristic of freeways for freeway-proximal residents. The data further suggest that people's judgments of other aspects of freeways are important, along with their judgments of noise as a disadvantage, in determining their proclivity for expressed annoyance.

There are basic differences between the freeway and aircraft noise situations. Most aircraft noise is louder and intermittent. Additionally, for all except a small portion of the population, aircraft contact is primarily contact with noise. In contrast, highways are in more general use, and they remain in a given visual situation. They are an integral part of the picture of the neighborhood, with many easily perceived attributes other than noise.

People's general attitudes toward freeways and toward living near a freeway are related to their attitudes toward freeway noise specifically, and complaints about noise may be a socially acceptable way to complain about freeways in general.

OBJECTIVE PROPERTIES OF THE PHYSICAL ENVIRONMENT

Lack of clear-cut and strong relationships between objective noise alone and expressed annoyance has prompted an attempt to find other physical correlates for the attitude factors isolated in the interview studies. Accordingly, seven variables which describe characteristics of the environment of the neighborhoods have been postulated:

(1) Distance from residence to freeway.
(2) Visual dominance of freeway.
(3) Noise level in dBA outside residence.
(4) Intervening features between freeway and residence.
(5) Landscaping of the freeway.
(6) Property value (land and improvements).
(7) Years of exposure to freeway.

Three of these are expressed by good interval-scale data:

(1) Distance in feet (determined by site measurement and map scaling).

(2) Noise level in dBA (measured at several spots in each area during mid-day, and extrapolated for distance variations within an area).

(3) Years of exposure (calculated as the shorter of freeway age and years of residence of respondent).

A fourth, property value, is measurable along an interval scale, but only mean values for the five areas were used. The other three variables were used as nominal scales:

(1) The code for visual dominance ranged from 0-3, with 0 for a freeway invisible behind a cut or general topography, 1 for the freeway depressed below the dwelling units, 2 for the freeway level with the dwelling units, and a code of 3 for the freeway elevated above the dwelling units.

(2) Intervening features were coded from 0-2, with 0 for no intervening features, 1 for a surface street or on-ramp, and 2 for an open buffer area (natural or landscaped). (It will be seen that the coding of intervening features may appear to be overlapping with that of landscaping, but subsequent analysis suggests that it is indeed a different variable.)

(3) Freeway landscaping was also coded on a 0-2 scale, with 0 for bare ground or fence, 1 for partial, wild, or ground cover only, and 2 for fully grown shrubs, vines, and hedges.

Although it is generally unwise to attempt to factor analyze ordinal data, a factor analysis was attempted to determine whether or not a meaningful solution could be achieved. Table F-1 gives the results of that factor analysis, and suggests that the factors are not only meaningful, but that a two-factor solution provides an explanation of nearly 70 percent of the variance found in the interview site areas.

The first factor isolated from the physical environment variables includes property value, intervening features, distance, and, to a lesser extent, the lack of visual dominance. This factor accounted for over 40 percent of the total variation.

The second factor, accounting for not quite 30 percent of the variation, included the variables noise level, length of exposure, and, in inverse relationship, freeway landscaping.

TABLE F-1

FACTOR LOADINGS OF PHYSICAL FEATURES

FEATURE	FACTOR 1	FACTOR 2
Distance	0.82	—0.26
Visual dominance	—0.76	—0.47
Noise	—0.30	0.84
Intervening features	0.85	0.13
Landscaping	0.24	—0.55
Md. property value	0.89	—0.21
Length of exposure	—0.07	0.71

PREDICTION OF ANNOYANCE WITH NOISE FROM PHYSICAL ENVIRONMENT VARIABLES

Using the same previously used groups (those who voluntarily expressed annoyance with freeway noise and those who did not), discriminant function analysis was performed using only the physical environment variables. Separate analyses were done for the variables in factor 1 and in factor 2 (as noted in Table F-1) and for all physical environment variables together.

The result of these analyses are given in Tables F-2 and F-3. For either factor 1 or factor 2, only 54 percent of the total group was correctly put into the annoyance or non-annoyance categories. This would suggest that either factor 1 or factor 2 of the physical environment measures may be used to predict noise annoyance, although the level of prediction is not high. For one criteria for error, how-

TABLE F-2

DISCRIMINANT ANALYSIS—PHYSICAL FEATURES

FACTOR 1:
$D^2 = 20.879$
d.f. = 4,305

OBSERVED	PREDICTED No Annoyance	 Annoyance	 Total
No Annoyance	93\63%	54\37%	147
Annoyance	89\55%	74\45%	163
Total	182	128	310

Correctly Predicted: 54%

FACTOR 2:
$D^2 = 4.137$
d.f. = 3,307

OBSERVED	PREDICTED No Annoyance	 Annoyance	 Total
No Annoyance	71\48%	76\52%	147
Annoyance	66\40%	97\60%	163
Total	137	173	310

Correctly Predicted: 54%

FACTOR 1 +
FACTOR 2
$D^2 = 26.609$
d.f. = 7,302

OBSERVED	PREDICTED No Annoyance	 Annoyance	 Total
No Annoyance	82\56%	65\44%	147
Annoyance	65\40%	98\60%	163
Total	147	163	310

Correctly Predicted: 58%

TABLE F-3

MEAN DIFFERENCES ON PHYSICAL FEATURES FOR GROUPS EXPRESSING ANNOYANCE OR NO ANNOYANCE WITH FREEWAY NOISE

(MEAN FACTOR SCORES[a])

GROUP	DISTANCE (FT)	VISUAL DOMINANCE	NOISE	INTERVENING FEATURES	LANDSCAPING	MD. PROPERTY VALUE	LENGTH OF EXPOSURE
No annoyance	215.92	2.57	64.40	0.48	0.95	21.85	3.57
Annoyance	199.70	2.44	65.46	0.58	1.03	27.47	4.14

[a] Scores range from 1 (positive) to 7 (negative).

ever, that of predicting noise annoyance and finding none, the second factor gives a better solution. This might well be expected from the fact that the objective noise level is included in that solution. It is somewhat surprising, however, that such measures as distance from freeway, visual dominance, intervening features, and property values actually predict a correct total percentage as well as does the factor including the objective noise.

When all physical features are included in the discriminant function, the prediction is increased by only 4 percent, bringing to a total of 58 percent correctly classified as being annoyed or not annoyed by freeway noise. In terms of predicting those who actually are annoyed, however, this solution is little better than the prediction arrived at by a description of the physical environment features classified as factor 2 features alone.

In general, many who complain live in an environment which is slightly more noisy, they actually have more landscaping, and have lived longer near the freeway. Additionally, they live somewhat closer to the freeway, the freeway is slightly less dominant visually, there are more intervening features, and there is a relatively large upward difference in the median property value of those expressing annoyance.

TABLE F-4

DISCRIMINANT ANALYSIS—PHYSICAL FEATURES AND INTERVIEW FACTORS

INTERVIEW FACTORS - ATTRACTIVENESS AND INTRUSION:

D^2 = 34.769

d.f. = 2,307

OBSERVED	PREDICTED		
	No Annoyance	Annoyance	Total
No Annoyance	98\67%	49\33%	147
Annoyance	62\38%	101\62%	163
Total	160	150	310

Correctly Predicted: 64%

ALL PHYSICAL FEATURES PLUS ATTRACTIVENESS AND INTRUSION:

D^2 = 65.827

d.f. = 9,300

OBSERVED	PREDICTED		
	No Annoyance	Annoyance	Total
No Annoyance	104 71%	43 29%	147
Annoyance	52 32%	111 68%	163
Total	156	154	310

Correctly Predicted: 69%

The picture of the non-complainer is of one who apparently sees more intangible benefits from living near a freeway, or more benefits not measured by this study. The non-complainers live farther from the freeway, they have lived near the freeway for a shorter period of time and they live in homes of much lower property value. They have less landscaping, less intervening features, but only slightly less average noise as measured.

It is recognized that some of these variables which have been classified as environmental features are quite roughly measured. It is also probable that there are features of the physical environment relating to annoyance or lack of annoyance which have failed to be tapped. Taking all physical features together, only 58 percent accuracy was achieved in prediction, as compared to 64 percent accuracy obtained by using only the four interview factors discussed previously.

Spontaneous expressions of annoyance have been predicted with 64 percent accuracy using the four interview factors of convenience, attractiveness, intrusion, and necessity (see Appendix E). Taking data for the total sample, it is found that two of these four factors actually predict as well as all four of the factors. Using only attractiveness and intrusion, as indicated in Table F-4, about 64 percent can be accurately predicted.

Using physical features of the environment, including actual measured noise, 58 percent accuracy was achieved in prediction (see Table F-2). If the judgment factors were combined, attractiveness and intrusion, and the seven physical environment factors, prediction level would be raised only to 69 percent, as indicated in Table F-4. The fact that these two sets of factors do not predict very much better together than separately suggests that the interview factors actually reflect characteristics of the physical environment.

It seems probable that by also taking into account a composite socio-economic or demographic factor, these predictions could be improved, but at present there is not such a single factor constructed. Ideally, one would like to be able to predict from various combinations of physical environment, demographic data, and interview data, so as to be able to handle future planning problems.

APPENDIX G

GLOSSARY OF ACOUSTICAL TERMINOLOGY

AMPLITUDE—The strength or magnitude of a sound wave.

AUDIBLE SPECTRUM—The frequency range normally associated with human hearing. For noise control purposes, this range is usually taken to include frequencies between 20 Hz and 10,000 Hz.

DECIBEL—A logarithmic unit which indicates the ratio between two powers. A ratio of 10 in power corresponds to a difference in 10 decibels. The abbreviation for decibel is dB.

dB—See decibel.

dBA—The sound pressure levels in decibels measured with a frequency weighting network corresponding to the A-scale on a standard sound level meter. The A-scale tends to suppress lower frequencies, e.g., below 1,000 Hz.

dBC—The sound pressure levels in decibels measured with a frequency weighting corresponding to the C-scale on a sound level meter. The network provides essentially a uniform response over the audible frequency spectrum.

EQUIVALENT-TONE-SONE—Loudness of a noise in sones computed by equating to the sound pressure level of a noise measured in frequency bands the loudness of a tone judged equally loud as the noise. (See Appendix A.)

FREQUENCY—The rate of change of a variable such as sound pressure with unit time. The unit of frequency is called the Hertz, abbreviated as Hz, or the cycle per second.

FREQUENCY BAND—An interval of the frequency spectrum defined between an upper and a lower cut-off frequency. The band may be described in terms of these two frequencies, or, preferably, by the width of the band and by the geometric mean frequency of the upper and lower cut-off frequencies, e.g., an octave band centered at 500 Hz.

Hz—The abbreviation for frequency in Hertz.

INVERSE FIRST POWER—The diminution of sound amplitude due to geometric effects as the observation point increases in distance from an infinite line or cylindrical source. The sound pressure level SPL_1 at distance r_1 is related to the sound pressure level SPL_2 at distance r_2 by the equation:

$$SPL_1 - SPL_2 = 10 \log_{10} \frac{r_2}{r_1} \qquad \text{(G-1)}$$

which indicates cylindrical divergence.

INVERSE SQUARE—The diminution of sound amplitude due to geometric effects as the observation point increases in distance from a point source. The sound pressure level SPL_1 at one distance r_1 is related to the sound pressure level SPL_2 at a second distance r_2 by the equation:

$$SPL_1 - SPL_2 = 10 \log_{10} \frac{r_2^2}{r_1^2} \qquad \text{(G-2)}$$

which indicates spherical divergence.

LEVEL—An adjective used to indicate that the quantity referred to is in the logarithmic notation of decibels, with a standardized reference quantity used as the denominator in the decibel ratio expression.

LOUDNESS—The intensive attribute of an auditory sensation, measured in units of sones. By definition, a pure tone of 1,000 Hz, 40 db above a normal listener's threshold, produces a loudness of 1 sone.

LOUDNESS LEVEL—The loudness level of any sound is defined as the sound pressure level of a 1,000-Hz tone that sounds as loud to a listener as the sound in question. Described in units of phons.

NOISINESS—Analogous to loudness, but referred to a frequency weighting function in which observers judge the unwantedness or unacceptability of the sound as compared to a reference standard consisting of an octave band of random noise centered at 1,000 Hz.

OCTAVE—A frequency ratio of 1:2; e.g., 500 to 1,000 Hz. In noise control work, the audible spectrum is often described by a series of contiguous octave frequency bands.

ONE-THIRD OCTAVE—A frequency ratio of 1:1⅓. Three contiguous one-third octave bands cover the same frequency range as one octave band.

PERCEIVED NOISE LEVEL—A measure of the "noisiness" of a sound. Computed from an analysis of the sound pressure levels in octave or one-third octave frequency bands of the noise. (See Appendix A.) The unit of perceived noise level is the 'PNdB.'

PHYSICAL MEASURE OF SOUND—Any quantity describing a sound which can be read directly on an electrical instrument, e.g., sound pressure level.

PSYCHOLOGICAL MEASURE OF SOUND—Any quantity describing a sound which can be measured by subjective judgments of the sound. Usually computed from some empirically derived rule which uses sound pressure level in frequency bands as input data. Examples are loudness, perceived noise level, etc.

SONE—The unit of loudness.

SOUND LEVEL—A corruption of the term "sound pressure level."

SOUND PRESSURE LEVEL—The root-mean-square sound pressure, P, related in decibels to a reference pressure.

$$\text{Sound pressure level} = 10 \log \frac{P^2}{{P_{\text{ref}}}^2} \qquad \text{(G-3)}$$

in which $P_{\text{ref}} = 0.0002$ microbar.

Abbreviation: *SPL*—The value read directly from a sound level meter.

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