NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT 173

HIGHWAY NOISE
GENERATION AND CONTROL

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **173**

HIGHWAY NOISE
GENERATION AND CONTROL

BOLT BERANEK AND NEWMAN
LOS ANGELES, CALIFORNIA

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:
- HIGHWAY DESIGN
- ROAD USER CHARACTERISTICS
- URBAN COMMUNITY VALUES

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1976

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.

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The Transportation Research Board of the 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.

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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.

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FOREWORD

By Staff

Transportation Research Board

This report will be useful to highway designers, planners, researchers, and administrators because of its coverage of many aspects of the highway noise problem. It contains findings from a number of related studies performed in the fourth phase of NCHRP Project 3–7. These were conducted partly to support the development of new procedures for predicting and evaluating highway noise levels. They include studies of the description and control of noise at the source and at the receiver, studies necessary to formulate a model for noise level prediction, and studies of the economics of various highway noise reduction strategies.

Awareness by the NCHRP sponsors of community problems caused by highway noise was responsible for initiation of NCHRP research in this area several years ago. Since 1964 there have been four separate phases to Project 3–7; the results of the first three phases have been presented in previous reports. *NCHRP Report 78,* "Highway Noise—Measurement, Simulation, and Mixed Reactions," concerns the selection of appropriate means and units for measuring and evaluating the impacts of traffic-generated noise. *NCHRP Report 117,* "Highway Noise—A Design Guide for Highway Engineers," presents the results of the second phase, whose objective was to prepare a predictive technique for calculating the highway noise levels that could be associated with new highway designs. The design guide that evolved also permits the evaluation of design changes aimed at ameliorating noise impacts. In the third phase, the objectives were to measure the effectiveness of highway design treatments for noise reduction under various traffic and environmental conditions. This made it possible to improve the predictive methods presented in *NCHRP Report 117,* and the results were published as *NCHRP Report 144,* "Highway Noise—A Field Evaluation of Traffic Noise Reduction Measures."

The present report describes and presents the findings from the bulk of the research studies conducted in the fourth and concluding phase of Project 3–7. Other results from the project can be obtained elsewhere. First, the revised highway noise design guide procedures are presented in *NCHRP Report 174,* "Highway Noise—A Design Guide for Prediction and Control." Next, a 19-minute color film entitled "Quiet Highway Design" was produced as a project task; it can be obtained on a loan basis upon request to the Program Director, National Cooperative Highway Research Program, 2101 Constitution Avenue, N.W., Washington, DC 20418. Lastly, a study of the social impacts of time-varying traffic noise, which has not been published, has been summarized in *NCHRP Summary of Progress Through 1976,* copies of which may also be obtained upon request.

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ACKNOWLEDGMENTS

The research reported herein was conducted under NCHRP Project 3-7 by the Los Angeles office of Bolt, Beranek and Newman, Inc., Acoustical Consultants, with B. Andrew Kugler as Principal Investigator. It constitutes the major portion of the background effort leading to development of a companion publication, *NCHRP Report 174,* "Highway Noise—A Design Guide for Prediction and Control."

The assessment of vehicle noise sources and reduction technology was the responsibility of Peter E. Rentz and Dr. Larry D. Pope, Supervisory Scientists, BBN.

The investigation of highway noise propagation and traffic noise models was the responsibility of Mr. Kugler and Grant S. Anderson, Supervisory Consultants; Dr. Daniel E. Commins, Senior Consultant; and Allan G. Piersol, Supervisory Scientist, all of BBN. Special thanks are extended to Dwight E. Bishop and Charles E. Dietrich for their contributions to the truck noise evaluation phase and to R. Peter Costello for his assistance in the data acquisition and reduction phase.

The evaluation of community measures to control highway noise was mainly accomplished by Salvatore D. Pecora, Senior Consultant, BBN, and Mr. Piersol, with the assistance of Kazimierz Niemiec.

The economic trade-off studies of various highway noise-control strategies were under the direction of Mr. Piersol, who was assisted in this task by Robley Winfrey, Consultant (Highway Economics and Finance), Arlington, Va. Special thanks are extended to Kenneth D. Bandow, California Department of Transportation, for his assistance in the economic studies.

Grateful acknowledgment is extended to the many individuals and agencies contributing time and effort to the execution of this project. Special thanks are given to the California, Colorado, Connecticut, Illinois, Kentucky, Michigan, New York, and Texas departments of transportation or highways for their assistance during the truck noise measurement and highway cost evaluation phases of the project.

HIGHWAY NOISE

GENERATION AND CONTROL

SUMMARY

The research results presented here are a product of the long-term investigation of highway noise problems that has been carried out under the National Cooperative Highway Research Program. This report describes four studies that led to or are otherwise related to the development of the revised highway noise prediction procedure described in *NCHRP Report 174,* "Highway Noise—A Design Guide for Prediction and Control." The four studies pertain to noise sources, noise propagation, community noise abatement measures, and economic evaluation of noise reduction strategies. The findings are summarized in the following according to these subject areas.

Description and Control of Motor Vehicle Noise Sources

Motor vehicle component noise sources can be described sufficiently to enable the generation of total vehicle noise models. Through assessment of feasible and cost-effective noise-reduction procedures for each noise-producing component (engine casing, exhaust, fan, intake, tires, and transmission and differential gearing), the noise-abatement potential for trucks, automobiles, and motorcycles can be determined and inherent added vehicle costs estimated. Substantial agreement of predicted feasible and cost-effective abated vehicle noise levels with levels achieved in demonstration quiet vehicles is shown. The technical feasibility and economic impact of proposed and scheduled city, state, and federal noise regulations is interpreted in terms of vehicle component noise levels and abatement potential.

The noise of single motor vehicles can be precisely described with the models developed herein in terms of configurational characteristics and operational parameters. Modeling of individual vehicle mechanical and tire noise can lead to highway traffic noise models and computer programs that not only are more accurate, but that also could include road surface characteristics, tire population statistics, and noise-reduced vehicle statistics as model-improving inputs.

In terms of the Society of Automotive Engineers (SAE) acceleration pass-by 50-ft maximum A-weighted sound levels, in decibels, findings indicate the following:

1. Reduction of diesel truck noise below the 80-dBA level scheduled by California for 1978 appears possible with an additional initial cost (in 1974 dollars) to the operator of from $400 to $700.
2. Achievement of a 75-dBA truck to meet the scheduled Chicago ordinance 1980 levels and the Environmental Protection Agency (EPA) best possible current technology target will increase the initial cost (in 1974 dollars) into the $1,400 to $2,200 range (technical feasibility of a 72-dBA truck has been demonstrated).
3. Additional initial costs of a 70-dBA truck to meet the California scheduled 1988 level is going to be extremely expensive in terms of initial operator costs, using best possible current technology.
4. California (1978), Chicago (1980), and proposed EPA limits of 75 dBA for automobiles are achievable at moderate initial costs (in the range of $100).
5. Achievement of the 70 dBA scheduled by California for 1988 is going to be very expensive (costs cannot be estimated) and may be attainable only with major configurational changes and, perhaps, engine performance degradation.

6. Reduction of motorcycle noise to 80 dBA (California, 1980) appears to require significant and undetermined modifications. Even small-displacement engines (250 cc and less) will have trouble meeting 80 dBA (81 dBA can be obtained with improved muffling). A level of 75 dBA, as proposed by the EPA, may require radically different designs. The scheduled California 1988 level of 70 dBA appears beyond technical feasibility.

Highway Noise Propagation and Traffic Noise Models

Chapter Three covers five individual studies providing basic information needed to formulate a model for the prediction of highway traffic noise levels. The first study is concerned with the free-field propagation of highway traffic noise; specifically, the rate at which traffic noise diminishes with distance from the highway. Carefully planned field surveys show that the propagation loss for traffic noise over clear and flat terrain varies from a 3-dB decrease per doubling of distance to a 4.5-dB decrease per doubling of distance, depending on the ground cover. For example, the 3-dB rate would apply to a freshly plowed field, whereas the 4.5-dB rate is more appropriate for park land. Related issues, such as the variation in the propagation loss with observer height, traffic volume, and the percentage level used to assess the noise intensity, are clarified by the results.

The second study assesses a previously recommended procedure for predicting noise attenuations due to three types of highway noise-reduction measures—a roadside barrier, an elevated roadway configuration, and a depressed roadway configuration. The procedure applies a conventional diffraction model for noise reduction, in which the traffic noise is assumed to be an incoherent line source with a wavelength of about 2 ft. Good agreement was found between predicted and measured noise reductions. Basic cost data for various types of highway noise-reduction constructions are also presented.

The third study concerns the directivity pattern of the noise radiated by passing vehicles in the plane normal to their axis of motion. Extensive field measurements were made to establish the directivity of vehicle noise over angles from 0° to 45° above the horizontal. Emphasis was placed on truck noise, although automobiles, buses, and even motorcycles were also evaluated. The results indicate that vehicle noise in general, and truck noise in particular, can be assumed with only minor errors to be omnidirectional (equally intense in all directions) over angles from 0° to 45° in the plane normal to the vehicle motion.

The fourth study investigated the peak drive-by noise levels and emission levels of trucks of various types in various regions. The findings of extensive noise measurement surveys in six states show that truck drive-by noise levels correlate with both the number of axles and the speed of the truck, although the speed dependence is weak below 50 mph. The most significant difference in the drive-by noise levels occurs between trucks with two axles (referred to as medium trucks) and trucks with three axles or more (referred to as heavy trucks). After correcting for number of axles and speed, the average drive-by noise levels of heavy trucks fall in a range of ±2 dBA from state to state. When averaged over all sites in the survey, the emission levels for trucks are about 82 dBA for medium trucks and about 90 dBA for heavy trucks.

The final study reviewed noise prediction methods. Comparison of the various methods pointed to the desirability of nomograph solutions used in conjunction with computer programs.

Based on the results of these five studies, and information presented in other parts of this report, a model for the prediction of highway traffic noise is formulated and presented. This model provides the basis for traffic noise predictions using the new design guide presented in *NCHRP Report 174*.

Community Measures to Reduce Impact of Highway Noise

The project also studied possible techniques for reducing highway noise impacts on neighboring communities by actions taken beyond the right-of-way. Three general categories of action are considered: (a) suppression of noise impact through proper land use and zoning, (b) reduction of interior noise in community structures through additional sound treatment, and (c) reduction of exterior noise in limited community areas through use of sound barriers. In all three cases, application of the noise control measures to both existing and future facilities is considered.

Specific land-use strategies included restricting the use of land bordering on the right-of-way to: (a) clear buffer zone; (b) structures that are normally unoccupied, such as warehouses and storage facilities; (c) structures housing activities that normally involve high self-generated noise levels, such as shopping centers and manufacturing facilities; and (d) properly sound-treated high-rise structures that might provide some additional noise reduction to the remainder of the community through shielding. The study indicates that application of such land-use strategies to existing communities probably would not be economically practical in most cases due to the high costs associated with acquisition of land in a developed urban community. However, all of the techniques have some merit for applications to future communities where the required zoning regulations could be imposed before the land is developed.

The building sound-treatment study evaluated the noise reduction that might be achieved inside community structures through modifications to existing buildings, as well as through changes in the design of future buildings. The types of structures considered are single- and multi-family dwellings, low- and high-rise hotels and commercial buildings, and various types of community service buildings such as schools, churches, auditoriums, and hospitals. The modifications to existing structures and changes in planned structures required to achieve 5, 10, and 15 dBA of noise reduction are detailed, with complete architectural descriptions. The capital costs associated with the recommended modifications and changes are also presented. The results suggest that up to 15 dBA of interior noise reduction is possible for all types of community structures through proper sound-insulating constructions. The required costs vary widely with the type of structure and its regional location, but are generally within reason.

The use of sound barriers within the community is considered for special applications, such as providing noise protection for a school playground. The results indicate that properly designed barriers can provide up to 15 dBA of exterior noise reduction in limited outside areas. Capital cost data are summarized for several types of barrier construction. Although they can be relatively expensive, barriers provide the only reasonable techniques for achieving substantial noise reductions in open areas of existing communities by actions taken beyond the right-of-way.

Economic Evaluation of Highway Noise-Reduction Strategies

The economic aspects of various techniques for suppressing the impact of highway noise are considered in three general categories: (a) reducing the noise at the source by quieting vehicles, (b) reducing the noise transmitted beyond the right-of-way by appropriate highway constructions, and (c) reducing the noise reaching the receiver by proper community land use and building constructions. Basic cost data in the form of capital, maintenance, and operating expenses for specific noise-reduction techniques in each category are estimated and outlined. Using these data, an equivalent uniform annual cost per mile of highway is computed. Finally, the noise-reduction potential of each technique is estimated, and its cost-effectiveness is calculated in terms of dollars per dBA of noise reduction. These evaluations are performed separately on techniques applicable to existing and future vehicles, highway construction, and community measures.

The results for vehicle noise-reduction measures indicate that the quieting of only heavy trucks would be more cost-effective than the quieting of all vehicles. However, the quieting of all vehicles would obviously provide a greater noise-reduction potential. The diversion of all heavy trucks to alternate routes more remote from the community might be a cost-effective strategy for existing situations under very limited circumstances. Among highway measures, the building of roadside barriers would be far more cost-effective than the construction of various elevated and depressed roadway configurations. Furthermore, barriers can provide as much noise-reduction potential as any other highway construction measure. The most cost-effective community measures are probably those related to land-use strategies; for example, zoning the land bordering on the right-of-way for structures that house activities least sensitive to intruding noise (storage facilities, warehouses, manufacturing facilites, etc.) Appropriate sound treatment of community structures can yield substantial interior noise reduction, but the cost per dBA is relatively high.

Based on various quantitative and qualitative considerations, the study results suggest the following broad conclusions. The quieting of at least the heavy truck portion of the vehicle population appears to be the most attractive strategy for achieving up to about 5 dBA of traffic noise reduction in the community. The building of roadside barriers is the next most attractive strategy, and can provide up to an additional 13 dBA or so of noise reduction. Land-use strategies also provide very attractive methods for reducing the impact of noise by moving sensitive activities away from highways. However, reduction of interior noise in community structures by proper construction treatment is a relatively unattractive alternative when compared to other options.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

RELATION TO PREVIOUS STUDIES

This report is the fourth in a series that has described highway noise research studies carried out under the National Cooperative Highway Research Program. The first report, "Highway Noise—Measurement, Simulation and Mixed Reactions" (*1*), presented the results of studies into means for measuring and evaluating highway noise; the second, "Highway Noise—A Design Guide for Highway Engineers" (*2*), provided a practical document to aid the highway designer in decisions related to highway noise problems; the third, "Highway Noise—A Field Evaluation of Traffic Noise Reduction Measures" (*3*), presented the results of field testing of different noise reduction design measures, such as barriers. This report presents the results of another series of studies also covering several aspects of the highway noise problem.

A general overview may first serve to introduce the objectives of the research reported here. Highway noise may be defined in the traditional terms of source, transmission path, and the receiver. It is generated by various components of automotive vehicles, including engine intakes, casings, and exhausts, as well as tires, cooling fans, transmissions, and aerodynamic sources. The resulting noise is a function of traffic and roadway parameters like traffic volume and speed, the proportion of automobiles to other vehicles in the traffic stream, and the roadway surface. Thus generated, the airborne noise signal is propagated toward the receiver in a complex manner. Propagation characteristics are complicated by highway geometry, obstructions, and terrain and environmental characteristics. All of these variables modify the noise field reaching the receiver. Finally, in determining the acceptability of highway noise, the receiver's subjective response to the intrusive noise must be considered. This response is a function of noise signal characteristics, the receiver's communications requirements, and the interference of intrusive noise above ambient noise levels.

The emphasis of past NCHRP studies has been on the transmission path and the receiver. The noise source itself was considered only in terms of the aggregate noise levels produced by traffic, rather than by analysis of its discrete components. In this project, tasks were directed toward noise sources as well as toward remaining problems associated with both the path and the receiver. Four separate areas of study are covered: (1) motor vehicle noise sources and their control; (2) noise propagation characteristics and reduction possibilities on the transmission path; (3) community measures to reduce noise impact; and (4) cost-effectiveness of different noise reduction measures.

NOISE SOURCE STUDIES

Background and Problem Statement

The highway designer must have the ability to predict noise associated with new highways. Therefore, he must be provided with predictive tools based on reliable noise source descriptions. These source descriptions can be the unrestricted averages typified by the procedures in *NCHRP Report 117* (*2*) and a similar model (*3*); they also may be restrictive, through the use of "quiet" motor vehicle models. The latter are applicable for highway design purposes if either state or federal governments impose quantitative noise level limits on individual vehicles.

The models provided in *NCHRP Report 117* (*2*) describe the composite noise environment produced by combinations of automobiles and diesel trucks under various traffic densities and speeds. The generic noise descriptions are typical of vehicles in operation in the late 1960's and are representative of "average" vehicle mechanical configurations, vehicle tires, highway surface textures, and vehicle operational practices. Inherent to the design procedure is the description of the composite noise produced at a reference distance by an "average" automobile or diesel truck, at various road speeds. The resulting models, based on these average conditions, produce unbiased traffic noise estimates. Various factors tend to ensure the success of this average vehicle description approach. A few states impose limitations on individual vehicle noise and most new vehicles comply with those regulations. Older automobiles are quite similar in their noise properties, with their overall noise having been reasonably constricted by individual consumer demands. Diesel truck noise is predictable, on the average, though individual noise-producing properties vary, primarily due to differences in muffling practice and tire tread design.

Highway design can be predicated on either the conservative estimate that motor vehicle noise will remain at present levels or on the assumption that motor vehicle noise source levels will be lower when the highway becomes operational. In the most conservative design, the highway engineer will estimate the noise from a highway that may not be in operation for from five to ten years, based on noise levels produced by unrestricted vehicles now in use. He knows that the various pressures of regional, state, and federal noise control programs can lead to restrictions on vehicle noise for new vehicles that may come into use before his designed highway reaches the operational state. However, he has little indication of how much lower vehicle noise levels can or will be in the future. Further, enforceable restrictions with significantly reduced levels may not come about without the active support of the highway engineer.

For the highway engineer to make a sensible assessment of future noise problems, he needs to understand the nature of the noise source mechanisms associated with different parts of motor vehicles, the quantitative potential for their control, and the cost for their control relative to noise control through highway design. It is not enough for him to argue for an arbitrary reduction in vehicle noise levels unless he is convinced that such a reduction is technologically feasible and economically reasonable. For example, an understanding of road surface-tire interaction noise would enable him to include noise considerations in the design of pavement surfaces.

In the past decade, analysis of the noise-producing elements of motor vehicles has received impetus from both vehicle manufacturers and independent investigators sponsored by government agencies considering the possibility of noise limitations. A reasonable understanding of the relative importance of noise from such components as engine intake and exhaust, fan, gearing, tires, and other mechanical elements is available. This information is scattered through published literature and in unpublished reports by manufacturers. Most of the data are for physical effects of noise control, with few vehicle cost data to accompany the results. Collection of this information and critical review of its consistency is in order.

There is other related published work. Two significant previous studies devoted to modeling individual vehicle noise sources and to the assessment of technical feasibility of highway vehicle noise abatement were performed by Serendipity Associates (*4*) for the U.S. Department of Transportation (DOT), and Wyle Laboratories (*5*) for the U.S. Environmental Protection Agency (EPA). Another important ongoing study is in support of the EPA's implementation of the Noise Control Act of 1972. Highway vehicle manufacturers are being queried in noise control and economic matters to assess the technical feasibility and economic penalties of candidate noise limits. The report, yet to be published (*6*), will supplement this study, especially in the economic area.

A second part of the problem is the projection of noise control possibility into practical estimates of the time period for its effect. The time lag for introduction of new designs into the motor vehicle industry and the attrition and replacement of older vehicles are major factors in projecting the reduction of vehicle noise into future time periods. The time span for such changes can be strongly affected by social pressures leading to general legislative action or economic pressures that restrict operations to quieter vehicles in urban locations.

Research Objectives and Approach

The major objectives of the study were twofold. The first was to collect and assimilate data regarding the present, state-of-the-art, quantitative description of the noise-producing properties of the individual mechanical components of motor vehicles which, when aggregated, lead to the composite noise produced by motor vehicles on highways. The second was to assess the technological and economic feasibility of reducing individual component noise and vehicle composite noise expected from future vehicles for highway use.

The variety of motor vehicles and the number and combinations of constituent components is too large to allow either noise prediction or assessment of noise abatement potential for any particular motor vehicle. However, source classifications can be rather broadly sketched in terms of basic power plant design: (a) the spark ignition (piston) engine for automobiles, pickups, and light and heavy utility trucks; (b) the compression ignition (diesel) engine for long-haul-type tractor-trailers, for single-chassis trucks, and for buses; and (c) the small air-cooled high-speed internal combustion engine, such as the motorcycle engine.

Noise sources considered herein are associated with three categories of vehicles: (1) automobiles, including passenger cars, pickups, and light utility trucks with gasoline engines; (2) diesel trucks (tractor-trailers), gasoline-powered heavy trucks (over 6,000-lb gross weight), and diesel-powered buses; and (3) motorcycles.

Noise source prediction and assessment of abatement potential involve not only the identification of quantifiable vehicle subsystems but also the determination of the lowest level of analyses useful to source level prediction. For example, tire tread and carcass design, roadway surface and condition, and vehicle speed are known to be important parameters in the tire noise generation process. If the mechanisms were completely understood, mathematical relations could be derived that would relate the radiated sound power to all of these parameters. However, experimental data are needed to quantify tire noise. Parametric dependence then follows from correlating the experimental data with the test variables.

The physical problem of noise generation is addressed because understanding the mechanisms of noise generation is inherent in assessing the noise abatement potential. Abatement potential depends on the ability to alter the characteristics of the noise source or the transmission path to the observer (or both). Often, predicting the sensitivity of generated or transmitted noise to alterations of the source or path can be done more accurately than can predicting the absolute strength of the source or the resulting levels at the observer after transmission. Sensitivity to an adjustment or change in the source or path may be analytically derivable to a relatively high degree of accuracy. Absolute levels at an observer, however, should be based on measured data if they are available. Because noise control is somewhat an art as well as a science, data obtained from demonstration programs prove invaluable. Fortunately, demonstration program data are available from an ongoing program to make large diesel trucks quieter.

Lastly, study efforts in the area of economics of vehicle noise reduction concentrate on a compilation of opinions regarding specific aspects of noise reduction costs and an assessment of the impact on over-all vehicle noise reduction costs as seen by the vehicle operator, including capital, operating, and maintenance expenses.

NOISE PROPAGATION AND PREDICTION

Problem Statement

Two essential steps in the establishment of standards for highway noise levels are: (a) determination of highway noise propagation characteristics and the efficiency of noise reduction measures, and (b) formulation of noise source models and noise prediction procedures. This set of study tasks was directed to providing certain answers in both areas.

Before the impact of traffic noise on a community can be assessed, it is clearly necessary to know how the noise propagates from the highway to various areas in the community. Noise propagation is influenced by many factors, including atmospheric conditions; however, two of the most important factors are: (a) the spreading loss of the noise from the traffic source, and (b) the excess attenuation provided by noise reduction measures associated with highway construction, such as elevated and depressed roadway configurations and roadside barriers.

Beyond the studies of source description and control that are a separate part of the total project, there is a need to formulate simple and practical models for highway noise sources that can be used in a general highway noise prediction model. To achieve this goal, two issues require further clarification: (a) the directivity of motor vehicle noise and (b) the variations in truck noise with speed, number of axles, exhaust location, and geographic region. Also useful to this end is a survey of the users of previous noise prediction procedures.

Research Approach

The approach taken in dealing with free field noise propagation studies was to collect and evaluate data measured along well-traveled highways at sites with various types of ground cover. The sites selected for survey, the data collection procedures, and data reduction techniques are described in Appendix N.

The study of highway noise reduction measures required no new field measurements. Instead, basic data acquired during a preceding phase of the project were employed for the desired evaluations. The noise reductions provided by the barrier and by elevated and depressed roadway sites were computed using the sound levels measured at various locations around the sites, assuming a propagation loss factor as determined for similar terrain during the current study. These computed noise reductions were then compared to the theoretical noise reductions predicted by the incoherent line source model. A related subtask was to collect basic cost data for construction of at-grade, elevated, and depressed roadways, and noise barriers, from selected state highway agencies. These data were assembled and provided for the separate cost-effectiveness studies.

The studies of vehicle noise directivity and truck drive-by noise did require field data. The noise directivity study approach was to take free field noise measurements with a vehicle microphone array that would permit determination of a directivity pattern for passing vehicles. The drive-by studies were pursued by collecting measurements of the peak noise levels of individual trucks together with data on their speeds, numbers of axles, and exhaust locations. The test sites for both studies, and the data collection and data reduction procedures, are described in Appendix N.

The user reactions to the procedures of *NCHRP Report 117* (*2*) were obtained by means of two carefully designed questionnaires. The first was concerned with an assessment of accuracy, the ease of implementation, and difficulties experienced with the design guide procedures. The second questionnaire solicited information on the availability and accessibility of computer hardware and software for executing the *NCHRP Report 117* procedures. Related to this effort, also, was a review of other traffic noise prediction methods used in the United States and Europe.

COMMUNITY MEASURES FOR NOISE REDUCTION

Problem Statement and Background

There are two general ways that can be pursued at the community level to reduce the impact of highway traffic noise. One involves elements of land-use planning and control; the second involves improved insulation of buildings from noise. Both approaches were investigated in this study.

Techniques associated with land use generally center around the insertion of a buffer zone between the highway and noise-sensitive community facilities. The buffer zone might consist simply of unused open space, where noise reduction is achieved only through the field propagation loss of the traffic noise. Such an approach is generally expensive in urban areas where land costs are high. A more logical approach, from the economic viewpoint, is to use the land forming a buffer zone for some purpose where noise is less annoying than it is in the heart of a residential community. For example, various types of commercial and industrial facilities (warehouses, shopping centers, manufacturing facilities) can operate efficiently in the presence of an ambient noise background significantly higher than that which would be tolerated in a residential area. Still another approach is to limit the use of land bordering the highway to sound-insulated high-rise structures that might provide some noise shielding for the remainder of the community. High-rise office buildings, or even apartment complexes, could be used for this purpose if their interior noise levels can be held to acceptable levels.

For highways passing through an existing community, there is an obvious problem associated with noise-reduction strategies based primarily on land use. It might be prohibitively expensive to rezone areas bordering on the right-of-way in a manner desirable from the viewpoint of highway noise impact. It follows that land-use strategies are most applicable to new community developments bordering on planned or existing highways.

A straightforward way to reduce the impact of highway noise on nearby community areas is to reduce the interior noise levels in occupied structures through more noise-resistant construction techniques. Because improved interior noise reduction can be achieved by appropriate modifications to existing structures, this approach is applicable to existing communities as well as to future community developments.

Additional sound treatment for community structures does have one serious limitation. It yields noise reduction only for individuals inside the structures. The technique obviously provides no protection for individuals on the streets, in yards, on playgrounds, and so on. A related strategy for protecting outside observers, therefore, is to build barriers around noise-sensitive facilities in the community. Such barriers would protect individuals out of doors within limited areas, as well as inside structures.

Objectives and Research Approach

The general objective of this study was to define various reasonable techniques and constructions for achieving a given degree of noise reduction at the community level, and to develop the capital costs associated with the required techniques and constructions. Only techniques that can be applied wholly beyond the highway right-of-way are considered. The principal goal was to provide quantitative data for use in the cost-effectiveness studies. As the techniques related to the improved sound treatment of structures and the shielding of structures by external barriers lend themselves to detailed evaluation, the emphasis in this study was heavily weighted towards techniques involving specific sound-treatment constructions. The evaluation of land-use strategies, on the other hand, is limited largely to a discussion of alternatives, because procedures and costs are often too nebulous to be adequately quantified.

In developing either recommended modifications to existing structures or designs for future structures required to achieve additional noise reduction, the following factors were considered:

1. Geographic location within the United States.
2. Types of structures of interest.
3. Basic construction materials and components.
4. Amount of interior noise reduction desired.

Appendix N identifies assumptions necessary to deal with these factors, which led to development of the cost figures used in the studies described in the following.

COST-EFFECTIVENESS OF NOISE-REDUCTION MEASURES

Background and Problem Statement

Because the basic purpose of highways is to provide for the movement of vehicles between, within, and through population centers, it is inevitable that at least some communities must endure exposure to the undesirable noise generated by the traffic of these highways. There has always been an interest on the part of highway engineers in suppressing the impact of traffic noise on nearby communities. The growing tendency to legislate restrictions on community noise levels, however, is rapidly escalating this desire to a mandatory requirement. It follows that there is increasing interest in the economic feasibility of various traffic noise control strategies.

The various strategies that might be pursued to suppress the impact of highway traffic noise on nearby communities may be broadly divided into the categories of the preceding three studies, as follows:

1. Strategies related to vehicle noise generation (reducing the noise produced by the source).
2. Strategies related to highway design (reducing the noise transmitted beyond the highway right-of-way).
3. Strategies related to community land use and building construction (reducing the noise reaching a receiver outside the right-of-way).

There are various alternative strategies within each of these primary categories. For example, if the designer chooses to achieve a desired noise reduction by a strategy related to highway design, he may have such options as depressing the highway, elevating the highway, or building roadside barriers.

The goal of this study task was to provide a basis for direct quantitative comparisons among various strategic options for a given mile of highway, independent of judgments concerning the value of noise reduction in one area versus another.

The basis for the cost-effectiveness comparison is in terms of "dollars per dBA." Of course, there are numerous factors other than cost that often influence the ultimate selection of a highway noise reduction measure. A few examples include:

1. The time required for the measure to become effective.
2. General safety.
3. Interaction with other environmental pollution problems.
4. The regulatory authority to impose the requirements of a strategy.
5. The aesthetic impact of the strategy.

Partial consideration of the first factor is introduced by dividing the evaluations into two distinct groups—noise reduction measures applicable to new vehicles and constructions only, and noise reduction measures applicable to existing vehicles and constructions. Other noncost-related factors are identified where appropriate in the discussions of various strategies, and broad qualitative assessments of their relative importance are included in the evaluations.

In summary, the problem was to (a) identify suitable noise control measures, (b) determine their effectiveness in noise reduction, (c) assess their costs, and (d) present the options available to the designer.

Research Approach

Due to the wide range of highway noise reduction strategies that can be envisioned, it is necessary to define clearly the specific strategies to be investigated. Such definitions, with appropriate background material, follow.

Noise Control Measures

Control measures can be applied at the source, on the transmission path, and at the receiver. The primary sources of highway traffic noise include diesel- and gasoline-powered trucks (light, medium, and heavy), buses, automobiles, and motorcycles. The heavy truck is generally the noisiest of the sources, whereas the automobile and light truck are the most common. In most cases, these three types of vehicles dominate the resulting average traffic noise levels. Hence, attention in this study is restricted to heavy trucks, light trucks, and automobiles. When applying the results of this study to typical traffic situations, medium trucks and buses can be grouped with heavy trucks and motorcycles can be ignored, with little error in the general conclusions.

Strategies that might be considered to reduce truck and automobile traffic noise at the source include:

1. Adding noise reducing equipment to all trucks and automobiles.
2. Adding noise reducing equipment to all heavy trucks only.
3. Diverting all heavy trucks to an alternate highway more remote from the community.
4. Reducing the traffic speed.
5. Reducing the traffic volume.

The first three strategies, which are believed to provide the most logical techniques for reducing vehicle noise, are considered in this study. Reducing traffic speeds could theoretically suppress traffic noise somewhat because tire noise, a major source of vehicle noise at highway speeds, varies approximately with the fourth power of vehicle velocity. However, it is believed that imposition of a mandatory speed limit of less than 55 mph solely for purposes of traffic noise control would not enjoy sufficient public support to make it a serious alternative to other traffic noise control strategies. A similar argument appears to rule out noise suppression by a mandatory reduction of the traffic flow to some volume below the capacity of the highway. There is one exception, however, as given by strategy 3. It is quite feasible in some cases to eliminate the flow of heavy trucks on a given highway and thus suppress traffic noise by diverting all trucks to an alternate route remote from the community.

Strategies for traffic noise reduction through highway design measures may be divided into five specific categories:

1. Depression of the roadway.
2. Elevation of the roadway on a fill.
3. Elevation of the roadway on a structure.
4. Construction of roadside barriers.
5. Resurfacing the pavement with a low-noise surface.

Of course, combinations of these five strategies can be employed in some cases. For example, roadside barriers could be used in conjunction with either an elevated or a depressed roadway. Note that the first three strategies involving elevated and depressed roadways are logical alternatives only for future highways. For existing highways, strategies 4 and 5 are the only practical alternatives.

At the community level, possible strategies that might be suggested for reducing traffic noise could include anything from forbidding highways near the community to issuing earplugs to all residents. However, if it is accepted that a highway must pass through the community, then the most logical noise reduction measures that might be taken outside the highway right-of-way would include the following:

1. Reduce interior noise levels in occupied structures by proper sound treatment of at least those occupied structures bordering on the right-of-way.
2. Zone the community to restrict the use of land bordering on the right-of-way to properly sound-treated high-rise structures that would serve as a partial noise barrier protecting the remainder of the community (for example, high-rise office buildings or apartment houses).
3. Zone the community to restrict the use of land bordering on the right-of-way to those structures and activities least sensitive to outside noise intrusion (for example, storage facilities, warehouses, manufacturing facilities, shopping centers).
4. Build noise barriers within the community to protect limited areas involving noise-sensitive outside activities, such as school playgrounds.

Of the four strategies listed, the first is the easiest to quantify in cost-effectiveness terms. The second strategy can also be quantified and evaluated for applications to future communities, and even to existing communities if it is assumed that appropriate zoning restrictions already exist. The third strategy is an excellent alternative for future communities, but probably would be impractical for existing communities if the land bordering on the right-of-way has already been developed. Even for future communities, the costs and benefits of the strategy are too nebulous to permit a meaningful evaluation.

The last approach (building barriers around noise-sensitive areas within a community) is a specialized measure that is not really competitive with other more general traffic noise control strategies. The best way to apply barriers as a general noise reduction measure is to build them along the roadside within the highway right-of-way. This technique is already covered under highway design measures.

Noise Reduction Estimation Procedures

If the various traffic noise reduction strategies are to be compared in terms of their costs and benefits, a necessary first step is to establish the noise reduction potential for each strategy. This is done assuming the fullest practical applications of current technology as summarized in other parts of this report. To make the ultimate cost-benefit models tractable, all noise reduction assessments are made in terms of "A-weighted sound pressure levels" (dBA), which provide a convenient numerical description of the potential abatement.

The procedures used for assessing the potential reductions at the source, within the right-of-way, and in the community are detailed in Appendix N.

Cost Estimation Procedures

When costs and benefits, or inputs and consequences, can each be measured in terms of dollars, the usual procedure for the analysis of the relative economy of the alternatives for attaining the objective is to calculate an equivalent uniform annual cost, net present worth of the cash flows, benefit/cost ratio, or rate of return (*8*). For the problem at hand, where noise reduction is the desired benefit, there is no available technique for placing market prices on the benefits received through a reduction in the dBA noise level within a community. The cost of inputs can be expressed in terms of dollars, but the consequences of the input dollars cannot be dollar priced. The procedure, then, must involve a cost-effectiveness analysis in terms of the dollar costs required to make a specific reduction in the dBA noise level. This cost can be normalized to dollars per dBA of noise reduction, but the total amount of noise reduction must also be stated because some strategies will provide more noise reduction than others.

The several alternatives for achieving a reduction in noise level need to be reduced to a common standard of measurement in order to make meaningful comparisons. A mile of highway length is the common factor normally used in comparing highway capital costs and highway operation and maintenance costs. The traffic is normally expressed in number of vehicles flowing per unit of time, usually a specific hour or a day of 24 hours. With these traditional units of measurement in mind, the analyses of cost-effectiveness will be made on a highway-mile as the basic unit. When the traffic stream is a factor in the analysis, it will be expressed in terms of vehicles per hour or vehicles per day for the one-mile section.

The basic cost evaluation technique used in the study is equivalent uniform annual cost. It should be noted that the cost terms employed represented the change in cost from assumed baseline conditions due to the noise reduction measure rather than an absolute cost. The procedure for applying this technique to the cost analysis for noise reductions through modifications of the vehicle, path, or receiver conditions is detailed in Appendix N.

The preceding comment about assumed baseline conditions brings up an important point. It must be emphasized that the breadth and complexity of the cost-effectiveness analysis requires use of numerous assumptions and simplifications to arrive at the desired quantitative results. In some cases, the needed simplifications tend to restrict the applicability of the research conclusions; for example, to make the vehicle noise reduction problem tractable, vehicle noise reduction potentials, although speed-dependent, are evaluated only at free-flowing highway speeds of 55 to 65 mph. Furthermore, specific values must be assumed for certain critical but volatile cost parameters, such as the money-time discount factor used to compute equivalent uniform annual costs. Finally, due to a lack of widespread service experience, some estimates of pertinent costs constitute little more than educated guesses, like the estimate of the average yearly maintenance cost for an automobile muffler giving increased noise reduction.

To minimize possible misunderstandings, all assumptions and simplifications are clearly stated and discussed as they are made. The users of this research are cautioned to consider all such discussions carefully before interpreting the results. Furthermore, users may find it desirable to adjust or modify the results, using data more applicable to their specific noise reduction problems. Hopefully, however, the basic cost-effectiveness procedures presented in the report are sufficiently clear to permit such modifications to be accomplished with minimal effort.

GLOSSARY OF SYMBOLS

Symbol	*Description*	*Units*
A	Area	ft² or in.²
A_p	Pipe area	ft²
AL_{lg}	Acceleration level	dB[a]
B_{ATN}	Automobile tire noise base value	dBA
B_{MTN}	Motorcycle tire noise base value	dBA
B_{TTN}	Truck tire noise base value	dBA
CPL	Cylinder pressure level	—
F_c	Fractional change in cavity volume	—
I.L.	Insertion loss	dB
K	Constant	—
L	Load	lb
L_p	Sound pressure level	dB[b]
L_{PA}	"A"—weighted sound pressure level measured at 50 ft	dB[b]
L_v	Fan forward speed correction	dB
M	Mach number	—
N	Engine rotational speed	rev/min
N_{er}	Rated engine speed	rev/min
N_f	Fan speed	rev/min
N_p	Propeller shaft speed	rev/min
P	Pressure	lb/ft² in. H_2O
P_r	Stagnation pressure ratio	—
P_s	Static pressure	lb/ft²
PWL_{rad}	Radiated sound power	dB[c]
Q	Volume flow rate	ft³/min
R	Temperature	°Rankin
R	Reynolds number	—
R_{rad}	Radiation resistance	lb-sec/ft
S_o	Strouhal number	—
T	Temperature	°F
T_r	Transmission ratio	—
U	Velocity	ft/sec
U_m	Mean velocity	ft/sec
U_{tf}	Fan tip velocity $= \dfrac{N_f \pi d_f}{720}$	ft/sec
U_v	Vehicle velocity	ft/sec
V	Velocity	miles/hr
V_e	Exhaust gas velocity	ft/sec
$<W>_t$	Time averaged sound power	ft-lb/sec
$<W_m>$	Mechanical stream power	ft-lb/sec
W_{NR}	Additional weight	lb
$Y(f)$	Transfer function	ft⁴/sec-lb
a	Acceleration	ft/sec²
b_c	Cylinder bore	in.
b_f	Fan blade width	in.
bhp	Brake horsepower	hp
c	Speed of sound in air	ft/sec
d	Diameter	in.
d_f	Fan diameter	in.
d_p	Plate hole diameter	ft
d_{tp}	Diameter of tail pipe	in.

Symbol	Description	Units
f	Frequency	Hz
f_c	Critical frequency	Hz
f_p	Peak narrow-band frequency	Hz
fhp	Friction horsepower	hp
f_o	Firing frequency	Hz
$g(g')$	Tread depth	ft (in.)
g_o	Acceleration due to gravity	ft/sec^2
$h(h')$	Thickness	ft (in.)
k	Constant	—
k_c	Ratio of specific heats	—
l	Length	ft
lb_m	Weight	lb
$\dot{m}$	Mass flow rate	—
n_c	Number of cylinders	—
n_f	Number of fan blades	—
n_1	Number of gear teeth	—
n_w	Number of cavities per tire width	—
p	Pressure	lb/ft^2
q	Number of revolutions per ignition	—
r	Compression ratio	—
r	Radius	ft
r_f	Fan ratio (N_f/N)	—

Symbol	Description	Units
$\check{s}(s')$	Circumferential distance between tread grooves	ft (in.)
s_c	Cylinder stroke	in.
t	Time	sec
t	Thickness	ft
t_p	Plate thickness	ft
v	Engine displacement	in.^{3}
v_{cc}	Engine displacement	cm^3
$w(w')$	Width of a single cavity or groove in tread	ft (in.)
$\overline{w}$	Turbulence perturbation velocity	ft/sec
x	Reactance	lb/sec-ft^3
δ	Dirac or Kronecker delta functions	—
ρ	Density	lb sec^2/ft^4
σ	Fractional open area	—
σ	Radiation efficiency	—
τ	Time interval	sec
$\phi_p(f)$	Spectral density function	(lb/ft^2)^2/Hz
Π	Mechanical power	hp
Π_{er}	Rated maximum engine power	hp
η	Acoustical conversion efficiency	—

[a] Re 1g. [b] Re 0.0002 dynes/cm^2. [c] Re 10^{-12} watt.

CHAPTER TWO

FINDINGS—SOURCES AND CONTROL OF MOTOR VEHICLE NOISE

This chapter presents the findings from investigation of three topics: motor vehicle noise source predictions, vehicle noise abatement potential, and economics of vehicle noise reduction.

SOURCES

Vehicle noise source prediction involves identification and classification of the physical entities producing noise. The significance of a component as a noise source depends on the maximum dBA sound pressure level * experienced by an observer located 50 ft from the center line of the vehicle path. This is in keeping with standardized tests for measurement of motor vehicle noise. Three particular tests are relevant: (1) Society of Automotive Engineers Standard SAE J986a, "Sound Level for Passenger Cars and Light Trucks" (an acceleration test for vehicles of less than 6,000 lb gross weight); (2) SAE J366a, "Exterior Sound Level for Heavy Trucks and Buses" (an acceleration test for gross vehicle weight of more than 6,000 lb); and (3) SAE J331, "Sound Levels for Motorcycles (Proposed)" (also an acceleration test). Thus, the interpretation of the phrase "vehicle noise source prediction" is actually "noise level prediction at an observer location," being inclusive in the sense that both source characteristics (sound power level, directivity, etc.) and transmission path characteristics are inherent.

To determine whether a physical entity is a significant noise source entity, data from measurement programs are required. Tables 1, 2, and 3 summarize noise source data from measurements taken during SAE acceleration tests. Approximately equivalent over-all noise for the three different types of vehicles is indicated.

Trucks

Table 1 identifies six major contributors to truck noise. Engine noise is noise radiated from the exterior surfaces of the engine casing (block, oil pan, etc.). Fan noise, exhaust noise, intake noise, transmission noise, and tire noise are all separable and may each also be uniquely identified with vehicle components.

* The abbreviation dBA is a colloquial expression for sound level A as measured on standardized sound level meters. The "A scale" weights the frequency spectrum approximately according to human ear sensitivity. This description of environmental noise has been found to correlate well with subjective response to noise. The reference sound pressure level is 0.0002 dynes/cm^2.

TABLE 1

HEAVY TRUCK EXPERIMENTAL NOISE SOURCE BREAKDOWN, SAE J366A ACCELERATION TEST

DATA SOURCE	NO. OF VEH.	SOUND PRESSURE LEVEL (dBA) MEASURED AT 50 FT							
		ENGINE	EXHAUST	FAN	INTAKE	TRANS	TIRES	OTHER	OVER-ALL
(a) Diesel-Powered									
Wyle (*5*)	11	83 (81–85.5)	82.5 (77–86)	81 (78.5–83)	75.5 (70–80)	—	—	—	87.6 (85.5–89)
Law (GM) (*62*)	11	80.2 (78.5–83.5)	83.4 (79.5–90.5)	80 (72–86)	74.9 (67.5–90)	—	—	—	87.2 (83–93)
Johnston (GM) (*64*)	9	81 (77–85)	80.6 (77–85)	80 (76–82)	—	—	—	—	85.5 (85–86)
Hillquist, Scott (GM, Chrys.) (*53*)	Typ	80.5 (77–85)	80 (76–83)	79 (73–82)	72 (70–75)	—	—	76.5 (70–81)	85.5 (83.5–88)
Cummins (*67*)	Typ	84.1	80.4	80	—	—	82		87.6
Scott (Chrys.) (*68*)	1	81	80	82	82.5	74.2	65–74	65	88
Freightliner (*32*)	1	84	83.5	81.5	74	80	68	74	88
IHC (*69*)	1	78	83	86	73	68	—	71	88
Jenkins (Cummins) (*70*)	Typ	84	80	80	74	73	—	67	87
Ringham, IHC (*71*)	Typ	81	84	82	75	—	—	80	88
Ronnhult (*79*)	Typ	81.5	80	79	68	—	—	—	85
Average		*81.5*	*81.7*	*81.1*	*74*	*75*	*68*	*75*	*87.4*
(b) Gasoline-Powered									
Johnston (GM) (*64*)		76 (75–77)	81 (79.5–83)	80 (77–82)					(85.5)

TABLE 2

EXPERIMENTAL NOISE SOURCE BREAKDOWN, SAE J986 ACCELERATION TEST

DATA SOURCE	SOUND PRESSURE LEVEL (dBA) MEASURED AT 50 FT								
	ENGINE	EXHAUST	INTAKE	FAN	TRANS	DIFF	TIRES	OTHER	OVER-ALL
Hillquist, Scott (*53*)	75	81	76	76	—	—	—	72	84
Stewart, GM (*88*)	73 [a]	81 [a]	72 [a]			—	—	—	82 [b] (76–86)
Vargovick (*57*)	76.5	81 [c]	—	—	—	—	60 [b]	—	80 [b] (74.3–82.3)
General Motors (*58*)	—	—	—	—	—	—	59.5		79.7 [d]
Wyle (*5*)	71	82	80	71	—	—	—	—	84

[a] 30 vehicles. [b] 4 vehicles. [c] 1 vehicle. [d] 8 vehicles.

Diesel Engine Casing Noise

Engine noise is conveniently broken down into two categories: combustion noise and mechanical noise. Combustion noise is noise radiated from the exterior surfaces of the engine owing to forces induced on piston and cylinder walls which, when transmitted through the engine structure induce vibrations of the radiating surfaces of the engine. Mechanical noise arises from many internal sources that contribute to the vibration of the casing. Examples are the crankshaft-flywheel system, flexural vibration of the block, valve and timing mechanisms, and fuel pumps and injectors (*9*).

In addition to combustion noise and mechanical noise, another identifiable source of engine noise is "piston-slap," which arises from the impact of pistons (laterally) on the cylinder walls. Ungar and Ross (*10*) have analyzed this noise-producing mechanism. It is presently felt to be important only in large diesels operating at low speeds.

The combustion process and the motion of internal mechanical components cause engine noise. Forces created during the combustion process are transmitted through the piston rod and crankshaft to the block. These forces are applied rapidly and thus a great deal of the energy is carried by high-frequency spectral components. This is especially true in diesel engines where a space fuel charge is ignited (as opposed to the propagating combustion wave of the spark ignition engine). In diesel engines combustion noise is approximately 15 dB higher than mechanical noise (*11*).

TABLE 3

MOTORCYCLE EXPERIMENTAL NOISE SOURCE BREAKDOWN, SAE J331 ACCELERATION TEST

	SOUND PRESSURE LEVEL (dBA) MEASURED AT 50 FT					
DATA SOURCE	ENGINE	EXHAUST	INTAKE	TIRES	CHAIN	OVERALL
Wyle (*5*)	78	86	82	69	—	88

The vibration of the exterior surfaces of the engine block induced by combustion forces (or motion of internal mechanical components) gives rise to sound radiation. The sound power radiated can theoretically be related to the vibration levels (the velocity or acceleration levels) of the engine block, oil pan, or valve covers. An area of the casing where the mean square acceleration is essentially uniform will radiate time average sound power $\langle W \rangle_t$ in an octave (or a one-third octave) band centered at frequency f of level

$$\langle W \rangle_t = R_{\text{rad}} \langle a^2 \rangle / 4\,\pi^2 f^2 \qquad (1)$$

in which R_{rad} is the radiation resistance of the radiating surface and $\langle a^2 \rangle$ is the space averaged mean square acceleration level over the area in the band centered at frequency f (the acceleration level is described as being "band-limited"). The radiation resistance is

$$R_{\text{rad}} = \rho c\, A \sigma \qquad (2)$$

in which ρc is the characteristic acoustic impedance of the air, A is the radiating area, and σ is the radiation efficiency.

For flat rectangular surfaces, the radiation efficiency is a function of the critical frequency of the casing component and of a nondimensional parameter lh/A, l being twice the total length of all stiffeners on the surface of area A plus the boundary length enclosing A, and h the thickness of the casing over the area. The critical frequency is that frequency at which the bending wavelength in the plate equals the acoustic wavelength in the air. For steel plates, this is

$$f_c \simeq 40/h \qquad (3)$$

when h is expressed in feet.

Combining Eqs. 1 and 2, the power radiated becomes

$$\langle W \rangle_t = \rho c\, A\, \sigma \langle a^2 \rangle / 4\,\pi^2 f^2 \qquad (4)$$

The acceleration level, AL, of the engine casing is related to the space average mean square acceleration by

$$\text{AL}_{1g} = 10 \log \langle a^2 \rangle / g_o^2 \qquad (5)$$

in which g_o is the acceleration of gravity. The radiated sound power level (referenced to 10^{-12} watts) can therefore be expressed by

$$\text{PWL}_{\text{rad}} = 140 + 10 \log \sigma + \text{AL}_{1g} + 10 \log A - 20 \log f \qquad (6)$$

This equation is to be applied to an area A over which the AL is essentially uniform and for which σ can be defined.

In deriving Eq. 6 it has been assumed that the block radiates because of flexural vibrations rather than by casing expansion, which is an acceptable assumption (*4*). Even though the radiation efficiency needs to be experimentally determined, the theoretical framework for understanding the radiation is reasonably well established. Maidanik (*12*) has shown that the radiation from a complex, stiffened, reverberantly vibrating structure is dependent on the mass, stiffness, and length of the reinforcing members (here this might be webs on the exterior block walls), the thickness of the structure (the radiation efficiency is higher at a given frequency for thicker walls), and the total radiating area.

To predict the combustion noise radiation levels on the basis of engine configuration and the operating parameters, the vibration levels of the casing must be related to the forces generated in the combustion process. A reasonable approach appears to be that given in the Serendipity report (*4*). The space averaged mean square acceleration in a band can be related to the narrow band spectral density of the exciting pressures, $\phi_p(f)$, through a transfer function (an admittance), $Y(f)$:

$$\langle a^2 \rangle = 4\pi^2 f^2 \textstyle\int_{\Delta f} |Y(f)|^2\, \phi_p(f)\, df \qquad (7)$$

When combined with Eq. 4, this gives the total radiated power in a band Δf in terms of the cylinder-head pressure spectrum,

$$\langle W \rangle_t = \rho c\, A\, \sigma \textstyle\int_{\Delta f} |Y(f)|^2\, \phi_p(f)\, df \qquad (8)$$

If it is assumed that $\phi_p(f)$ is slowly varying over Δf, this becomes

$$\langle W \rangle_t = \rho c\, A\, \sigma \langle |Y(f)|^2 \rangle_{\Delta f} \phi_p(f)\, \Delta f \qquad (9)$$

Further assuming that the frequency average of the square of the magnitude of $Y(f)$ is essentially fixed by the engine configuration and can be experimentally measured, a knowledge of $\phi_p(f)$ is sufficient to calculate the radiated power from combustion noise. Figure 1(a) illustrates the time history of cylinder pressure during an ignition cycle. For an engine operating at a speed of N (rpm), with q revolutions/ignition and n_c cylinders, this would be repeated in a time interval

$$\tau = \frac{60q}{N\, n_c} \qquad (10)$$

If the pressure histograms for all the cylinders were summed, the temporal force history acting on the engine block structure would be that shown in Figure 1(b). The model proposed for the excitation pressure waveform is a sawtooth of amplitude P with a fundamental period τ (Fig. 1(c)). Expressed in the terms of a Fourier series, the sawtooth is

$$p(t) = \frac{P}{2} + \sum_{n=1}^{\infty} \frac{P}{\pi n} \sin\ 2\pi n f_o t \qquad (11)$$

in which $f_o = 1/\tau$ is the firing frequency. The mean square pressure is

$$\langle p^2 \rangle = \frac{1}{\tau} \int_{-\tau/2}^{\tau/2} p^2(t)\, dt = \frac{P^2}{4} + \frac{1}{2} \sum_{n=1}^{\infty} \frac{P^2}{\pi^2 n^2} \qquad (12)$$

in which each term in the summation on the right-hand side

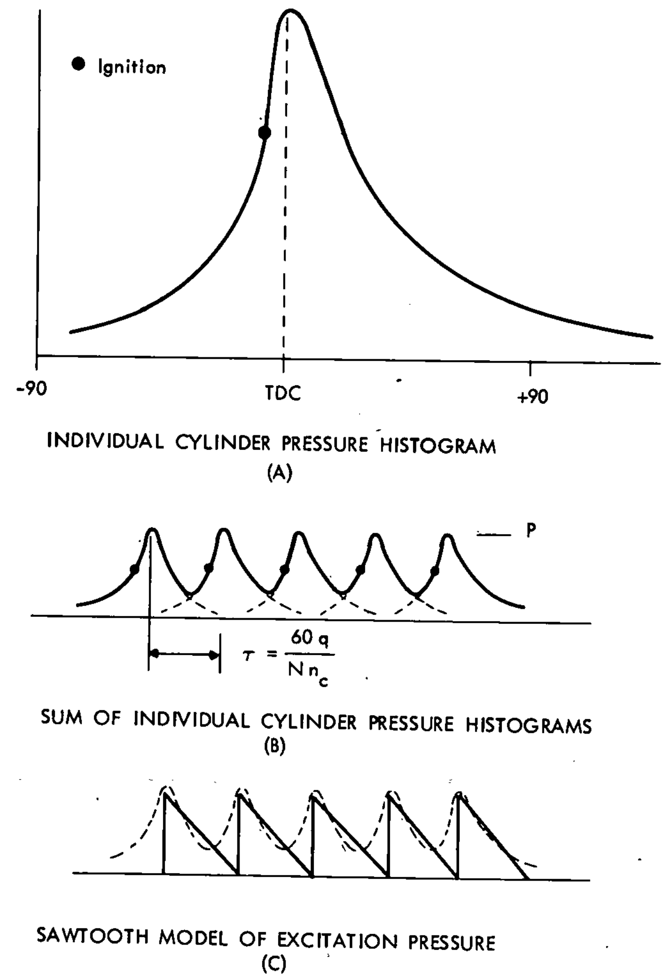


Figure 1. Cylinder pressures.

is the contribution of the spectral component n at frequency f (a multiple of the firing frequency f_o).

The spectrum can be expressed as

$$\phi_p(f) = \frac{P^2}{4}\delta(f) + \sum_{n=1}^{\infty} \frac{P^2}{\pi^2 n^2}\,\delta(f - n\,f_o) \qquad (13)$$

in which $\delta(f)$ is the Dirac delta function. Integrating over a bandwidth containing only one harmonic (that is, letting $f = f_o$), an "equivalent" continuous spectrum can be calculated (in the sense that the total mean square is obtained from an integration over frequency), as follows:

$$\phi_p(f) = \frac{P^2}{4}\delta(f) + \frac{f_o}{2}\left(\frac{P}{\pi f}\right)^2 = \frac{P^2}{4}\delta(f) + \phi_p'(f) \qquad (14)$$

The cylinder head pressure spectrum, CPL, is defined in terms of $\phi_p'(f)$ by

$$\text{CPL} = 10 \log \frac{\phi_p'(f)}{p_o^{\,2}} \qquad (15)$$

where $p_o = 2 \times 10^{-4}$ dynes/cm².

The Serendipity report (*4*) shows that for an idealized pressure-volume cycle the peak pressure is related to the indicated mean effective pressure, imep, through the relation

$$P = \frac{\text{imep}}{F(r,k_c)} \qquad (16)$$

where

$$F(r,k) = \frac{1}{1 - k_c}\;\frac{r^{1-k_c} - 1}{r + 1} \qquad (17)$$

r being the compression ratio and k_c the ratio of specific heats. For comparison purposes, consider the CPL of a Cummins 350-hp diesel at 2,100 rpm. The brake horsepower is 350, the friction horsepower between 50 and 70. The compression ratio is 14.3:1. The engine displacement, v, is 855 in.³ and it is a 4-stroke engine ($q = 2$). The indicated mean effective pressure is

$$\text{imep} = \frac{2.73 \times 10^{10}(\text{bhp} + \text{fhp})\,q}{N\,v}$$

$$\simeq 1.11 \times 10^{7}\ \text{dynes/cm}^2 \qquad (18)$$

The fundamental frequency is $f_o = \frac{N\,n_c}{60q} = 105$ Hz, and $F(r,k)$ calculates to be 0.107. This gives

$$\text{CPL} = 242 - 20 \log f \qquad (19)$$

Figure 2 shows a comparison of this estimate with a typical measured spectrum for similar engines (*13*).

A basic understanding of the dependence of engine noise on the combustion forces exists; however, owing to a lack of information concerning vibration transfer admittances and engine casing radiation efficiencies, it is not yet possible to predict engine noise (with any reasonable degree of accuracy) on the basis of the physical processes alone.

Estimation of Engine Noise Levels

Table 4 gives the dBA levels recorded at 50 ft during SAE acceleration tests to determine relative contributions of engine casing components of a Cummins NTC-270 CT turbocharged diesel engine at 2,100 rpm.

Figure 3 shows measured dBA levels for the three principal engine noise sources of the Cummins NTC-270 CT as a function of engine speed (*15*, Runs 247, 283, 291), as well as the sum of these three contributors and the estimated over-all engine noise. These data were obtained during static tests (as opposed to the data of Table 4, which came from SAE acceleration tests).

Both engine size and speed are important in diesel engine noise estimation. Priede (*16*) states that engine noise varies as the cube of engine speed and approximately as the 1.75 power of engine displacements. Engine noise spectra tend to peak between 250 and 1,000 Hz. Figure 4 shows the spectral data for the three components of Figure 3 at the 2,100-rpm point. Also shown is the resultant sound pressure level from all three components.

Figure 5, showing the sum of the three components when "A" weighted, indicates that the difference between the linear over-all level and the A-weighted level can be significant for engine noise sources.

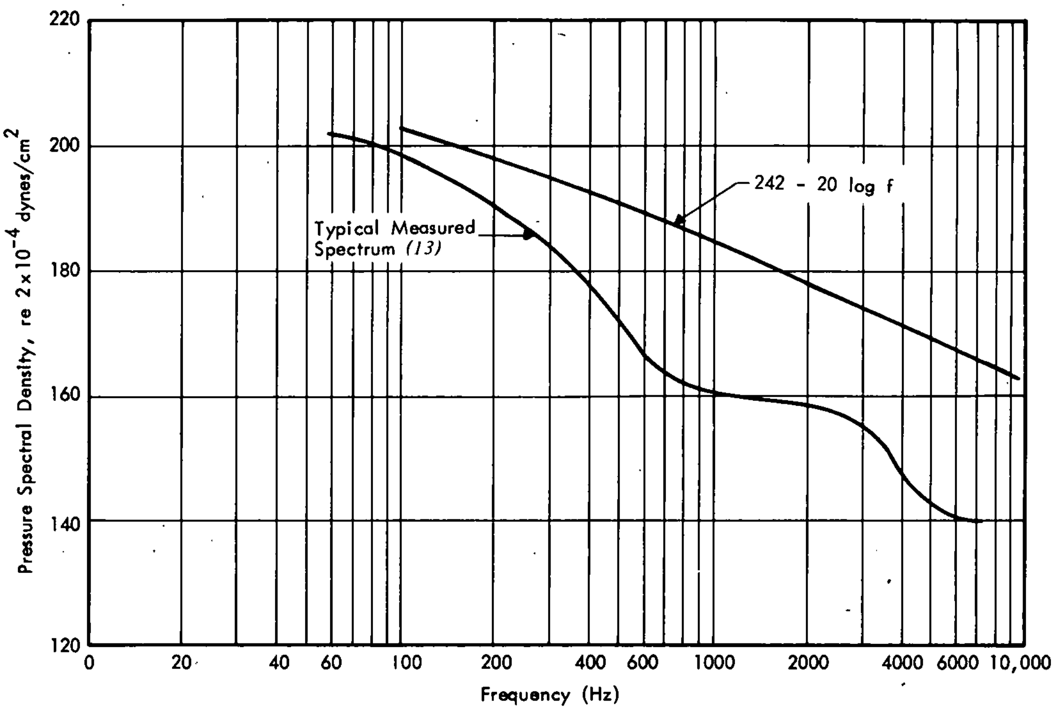


Figure 2. Cylinder pressure spectrum, CPL.

Engine Noise Models

For the purposes of this study, the interest in spectral data is only from the standpoint of being able to understand the physical processes. For purposes of noise models as required in *NCHRP Report 117* (*2*) or the *Manual for Highway Noise Prediction* (*17*), the over-all dBA value at 50 ft is sufficient. A number of noise models have been proposed by various investigators. In some cases, sound power levels (A weighted) have been specified; in other cases, dBA levels at 3 ft have been given. Most of these models are summarized in Table 5. All of the equations have been put in approximately the same form; that is, engine noise

TABLE 4

ENGINE NOISE SOURCES *

SOURCE	RADIATED NOISE AT 50 FT (dBA)
Intake crossover	55.6
Valve covers	65.9
Intake manifold	61.2
Rocker boxes and head	62.7
Left-hand block (upper)	61.9
Left-hand block (lower)	61.8
Right-hand block	66.0
Front	64.7
Bell housing	67.7
Oil pan	71.0
Exhaust manifold and turbocharger	67.3
Engine total	76.3

* Cummins NTC-270 CT diesel (*14*).

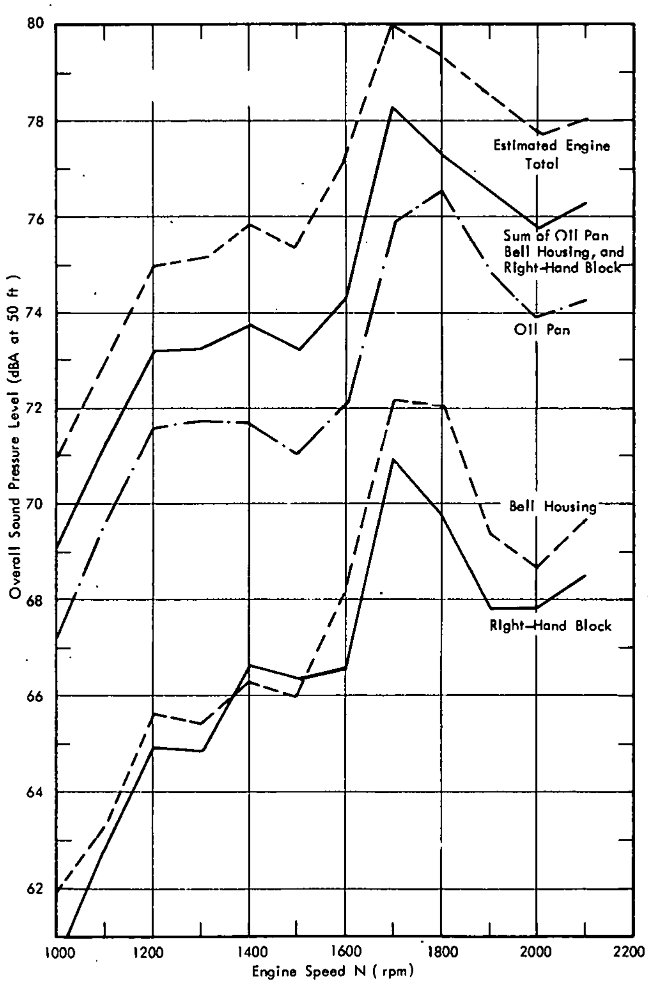


Figure 3. Noise sources for Cummins NTC-270 CT engine (15).

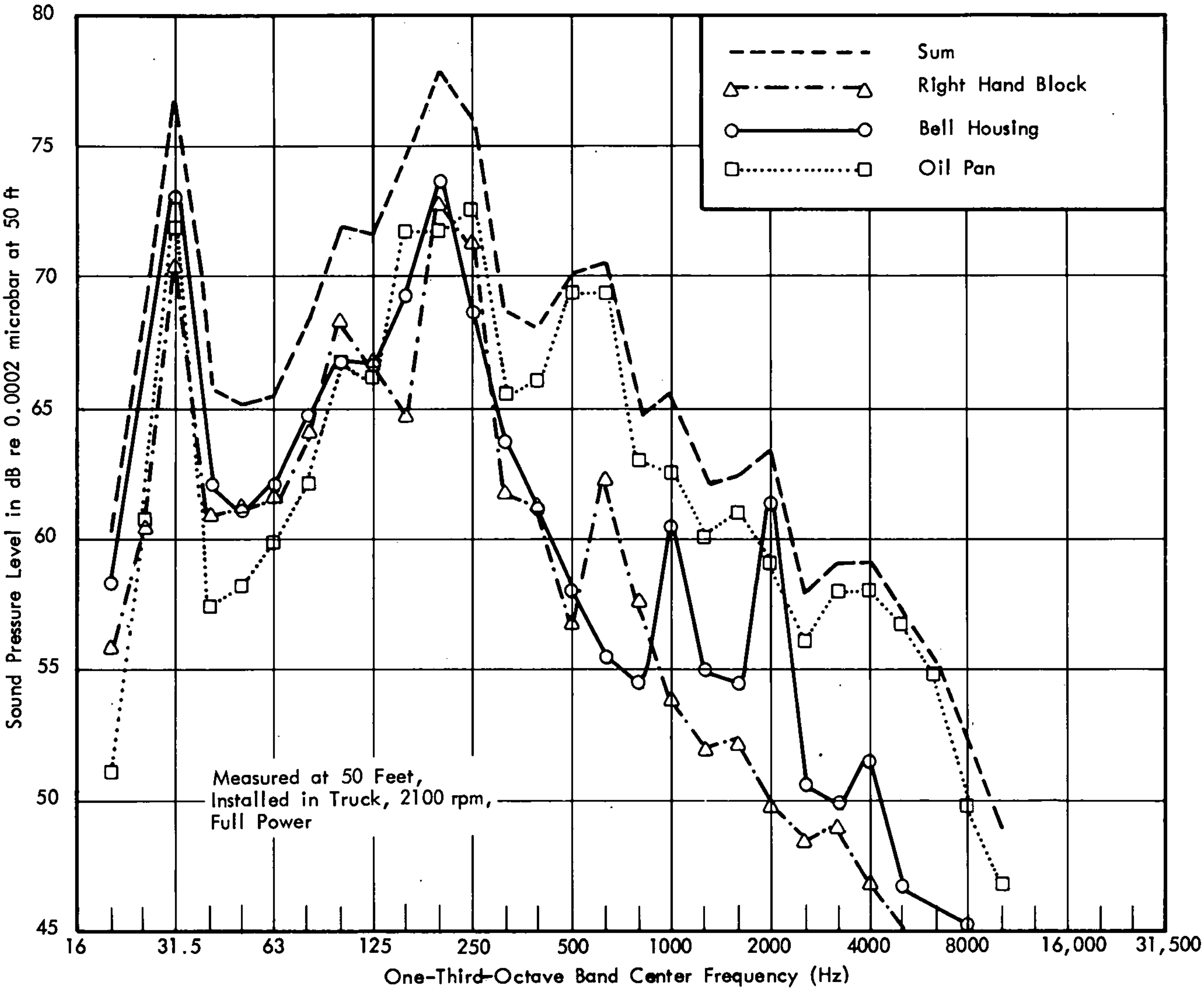


Figure 4. Noise spectra for Cummins NTC-270 CT engine (15).

power level predictions have been converted to 50-ft dBA level predictions by subtracting 32 dB and 3-foot dBA level predictions have been converted to 50-ft dBA level predictions by subtracting 19 dB. Further, all equations have been referenced to nominal engine characteristics and operational levels. The nomenclature is given in the "Glossary of Symbols" (Chapter One).

Figure 6 shows the calculated dBA levels as a function of engine speed for the NTC-270 CT engine previously considered along with the measured levels from Figure 3. The models are reasonable envelopes for this particular engine although nearly 5 dB too high at 2,100 rpm. This error is thought to be a result of the high torque rise characteristics of the engine (this is an engine characteristic whereby with fuel control the torque rises as engine speed drops, the engine delivering essentially constant horsepower). It can be shown, using the engine noise analysis of the Serendipity report (*4*), that with constant horsepower output a decrease in radiated noise can be expected as engine speed climbs. For the Cummins NTC-270 CT this region is from about 1,600 to 2,100 rpm. In addition, the diesel engine noise models are for engines standing alone and the data are measured with the engine in a truck. Reflection of the sound by the truck tunnel or hood would be expected to make the sound more intense in some directions; but absorption by the truck and road surfaces would tend to reduce the noise, especially in the higher frequency bands. The net effect is estimated to be a noise reduction of 1 to 2 dB.

Diesel Exhaust Noise

Unmuffled exhaust noise is the most severe noise source of a compression-ignition engine. Exhaust muffling has reached high levels of expertise, but Table 1 shows that engine exhaust remains a major contributor to diesel truck noise. Although mufflers can be designed to achieve practically any insertion loss, space requirements and weight limit their size. Regardless of muffler type (that is, dissipative, reactive, or a combination thereof), increased

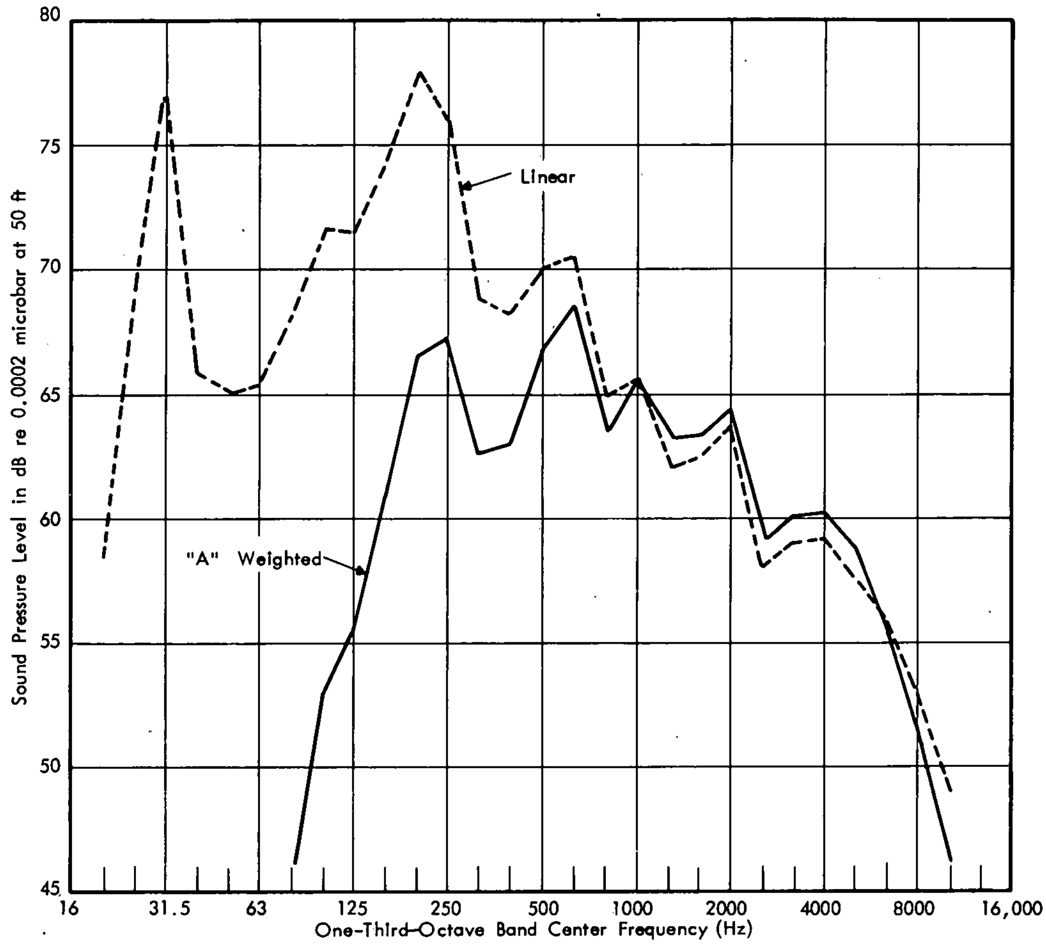


Figure 5. Linear vs "A"-weighted noise spectra for Cummins NTC–270 CT engine at 2100 rpm, full power.

muffling without increased size means increased engine back pressure, a critical limit on muffling.

Engine exhaust noise is caused by the discharge of the high-pressure cylinder gas. Exhaust noise perceived after transmission through, and emission from, an exhaust system is composed of (a) low-frequency components sharply peaked at the engine firing frequency and multiples thereof and (b) high-frequency spectral components associated with the turbulent mixing of the high-velocity gas as it passes through the exhaust system.

Figure 7 shows the one-third octave band spectra of exhaust manifold pressure for a Cummins NTC-350 diesel-powered truck operating at 2,000 rpm and 290 hp at the wheels. Also shown are the sound pressure levels in the 5-in.-diameter exhaust pipe, 3 diameters away from the turbocharger (*22*, Tests g, i). Figure 8 shows the unmuffled exhaust noise (dBA) at 3 ft from the stack pipe termination in the horizontal plane. The measured over-all level was 114.5 dBA. Assuming hemispherical spreading, the 50-ft levels would be 21 dB lower, or 93.5 dBA. This compares well with similar test data in which the maximum unmuffled exhaust from an NTC-350 (tailpipe only) was 93 dBA at 1,800 rpm (*23*, Table 9).

The generation of sound in an exhaust system is a very complicated and not well understood process. Sound generated near the exhaust valves (upon opening) is probably due to two different mechanisms: (1) turbulent mixing of the exhaust gases, and (2) the interaction of turbulence with complex shocks which of necessity will form to decelerate the fluid. It is probable that the "shock noise" dominates for the existing pressure ratios across the valves. The description of the shock noise for simple valve configurations (configurations not necessarily of the combustion engine type) involves a relation between the acoustic sound power $<W>_t$ and the mechanical stream power $<W_m>$ through an acoustical conversion efficiency, η:

$$<W>_t = \eta <W_m> \tag{31}$$

in which

$$<W_m> = \frac{1}{2} \dot{m} c^2 \tag{32}$$

$\dot{m}$ is the mass flow rate through the valve and c is the speed of sound at the throat. Above pressure ratios of about 3, the mechanical to acoustical conversion efficiency is

$$\eta = k_1 P_r^{0.56} \tag{33}$$

in which k_1 is a constant approximately 1.5×10^{-3}, and P_r is the stagnation pressure ratio across the valve. The spectrum has a haystack appearance, peaked near a frequency

TABLE 5

TRUCK ENGINE NOISE MODELS (dBA at 50 feet)

SOURCE	MODEL	EQ. NO.	REMARKS
(a) Diesel			
Hempel (*18*)	$L_{PA}=83+30\log\frac{N}{2000}-20\log\frac{N_{er}}{2000}+10\log\frac{\Pi_{er}}{250}$	(20)	4-stroke, mostly turbocharged
Serendipity (*4*)	$L_{PA}=84.2+30\log\frac{N}{2000}+10\log\frac{\Pi}{250}$	(21)	
Wyle (*5*)	$L_{PA}=k+30\log\frac{N}{2000}$	(22)	
Priede (*16, 19*)	$L_{PA}=k+30\log\frac{N}{2000}+17.5\log v$	(23)	
Waters (*20*)	$L_{PA}=83.5+30\log\frac{N}{2000}+50\log\frac{b_c}{5}$	(24)	4-stroke, naturally aspirated
Waters (*20*)	$L_{PA}=81.5+40\log\frac{N}{2000}+50\log\frac{b_c}{5}$	(25)	4-stroke, turbocharged
Waters (*20*)	$L_{PA}=90.5+40\log\frac{N}{2000}+50\log\frac{b_c}{5}$	(26)	2-stroke
Cordier and Reyl (*21*)	$L_{PA}=81.4+30\log\frac{N}{2000}+30\log\frac{s_c}{5}+5\log\frac{n_c}{6}$	(27)	
(b) Gasoline			
Priede (*16, 19*)	$L_{PA}=k+50\log\frac{N}{2000}+17.5\log v$	(28)	
Wyle (*5*)	$L_{PA}=k+50\log\frac{N}{2000}$	(29)	
Serendipity (*4*)	$L_{PA}=47.5+40\log\frac{N}{2000}$	(30)	

$$f_p = \frac{S_0\, c}{d} \tag{34}$$

where S_0 is the Strouhal number at the frequency f_p and d is the valve clearance. For pressure ratios in excess of 4,

$$S_0 \simeq k_2\, P_r^{-0.77} \tag{35}$$

where $k_2 \simeq 0.4$. Of course one recognizes immediate difficulties in utilizing these relations with engine valves (namely, the valve clearance changes as the valve opens and closes). To date no attempt has been made to predict exhaust noise from empirical methods such as described in the foregoing with any reasonable measure of success.

An additional modeling difficulty is that the exhaust manifold is intimately involved. Shocks may form in the manifolds owing to their configurations. For a standing (normal) shock in a duct, measurements have indicated (*24*) that the acoustic power generated by the convection of turbulence through the shock is

$$\langle W \rangle_t = \frac{1}{2}\,\eta\,\dot{m}\,U_y^2 \tag{36}$$

where U_y is the flow velocity immediately downstream of the shock, $\eta \simeq k_3\, P_r^{0.56}$, k_3 is approximately 3×10^{-3}, and P_r is the pressure ratio across the shock. The peak frequency of the spectrum is

$$f_p = \frac{S_0\, U_y}{\sqrt{A}} \tag{37}$$

where A is the cross section of the duct at the shock location and

$$S_0 \simeq 6 \times 10^{-7}\, R \tag{38}$$

where R is the Reynolds number of the flow downstream of the shock. Again the practical application of these empirical methods to the complex configurations of the exhaust manifold systems is beyond the state of the art. Further, in turbocharged systems the turbine tends to smooth out the flow from the exhaust manifold into the exhaust pipe.

Ultimately, one is faced with the fact that manifold and exhaust pipe spectra such as those of Figure 7 must be measured. However, it seems reasonable, based on the foregoing rudimentary analyses, that proper timing and sizing of exhaust valves and correct design of the shape and configuration of exhaust manifolds could effect noise reduction (*25*).

Before consideration of muffled exhaust noise, it must be stressed that unmuffled exhaust noise may vary greatly from engine to engine. Table 6 gives levels of unmuffled exhaust noise of different diesel engines. The Mack ENDT-675 and the Cummins NTC-350 are both turbocharged engines. The Mack and Cummins engines are 4-stroke and the Detroit Diesel engines are 2-stroke.

Muffled Exhaust Noise

Muffler performance is given in terms of an insertion loss; that is, the difference in sound pressure levels at a particular location before and after installation.

Simple muffler design is treated in reference works and published papers (*26, 27*). No attempt is made here to treat muffler design, except to note that there are two basic types of muffling and that practical mufflers often utilize both. The reactive muffler is a reflective device. Owing to impedance discontinuities, a simple cross-sectional area change in a duct will cause some sound energy propagating down a duct to be reflected. Dissipative mufflers literally convert sound energy to heat or to fluid turbulence. Absorption of sound is obtained by the motion of air particles within porous (glass fiber) insulation. In practical mufflers, another dissipative effect is the conversion of sound energy to fluid turbulence, obtained by passing the intense sound through a perforated plate. Just as the absorption coefficient of a "fuzzed" wall can be defined, so can the

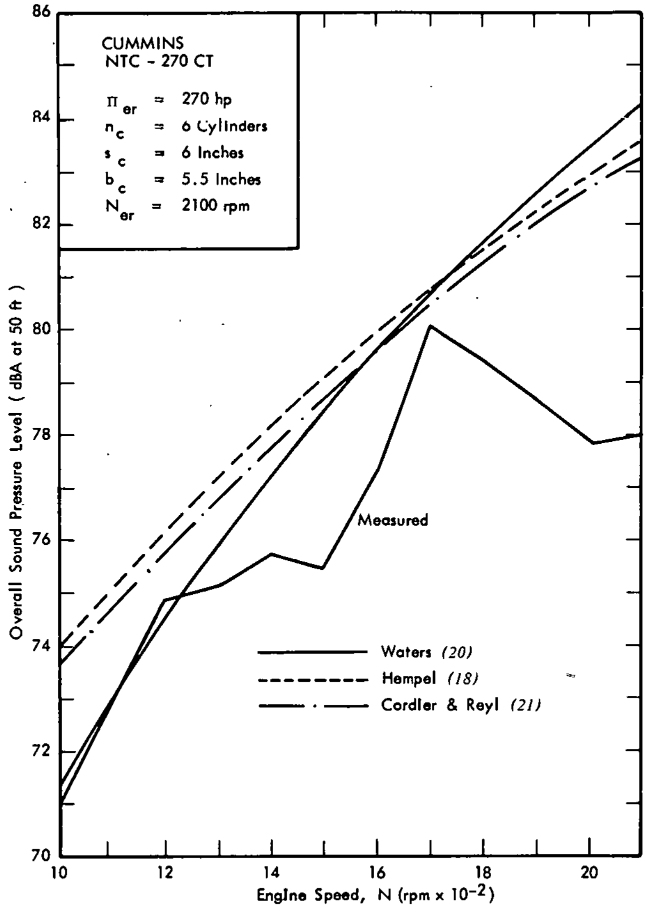


Figure 6. Comparison of engine noise models and measurements.

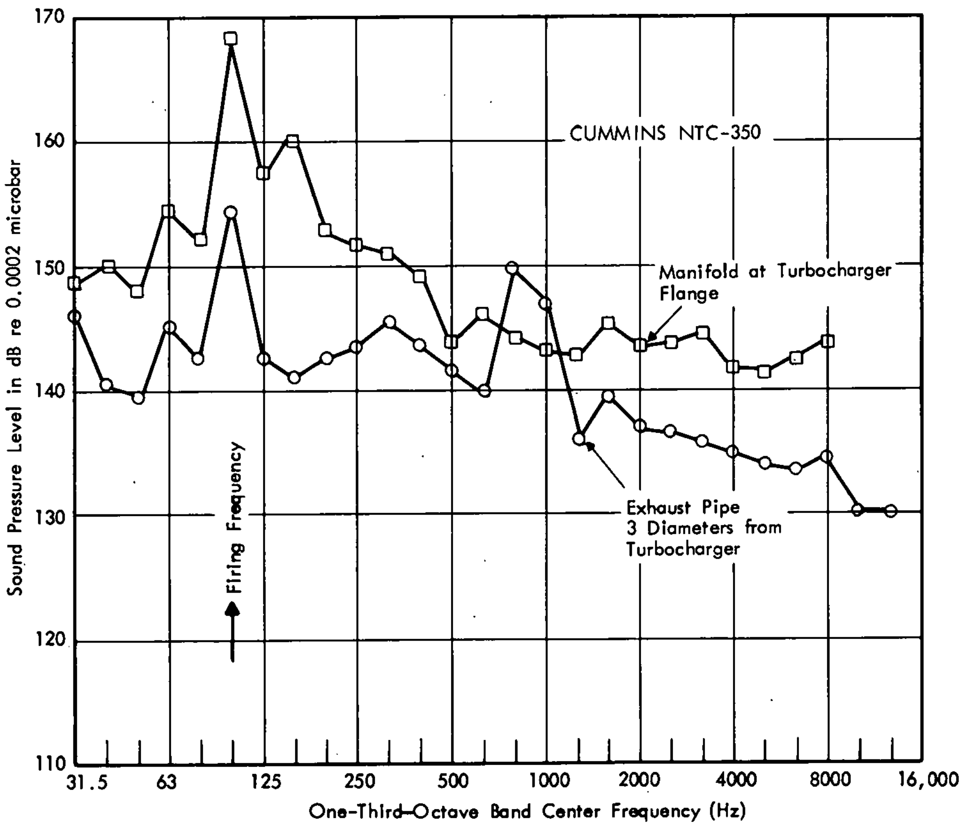


Figure 7. Typical manifold and exhaust pipe noise spectra (22).

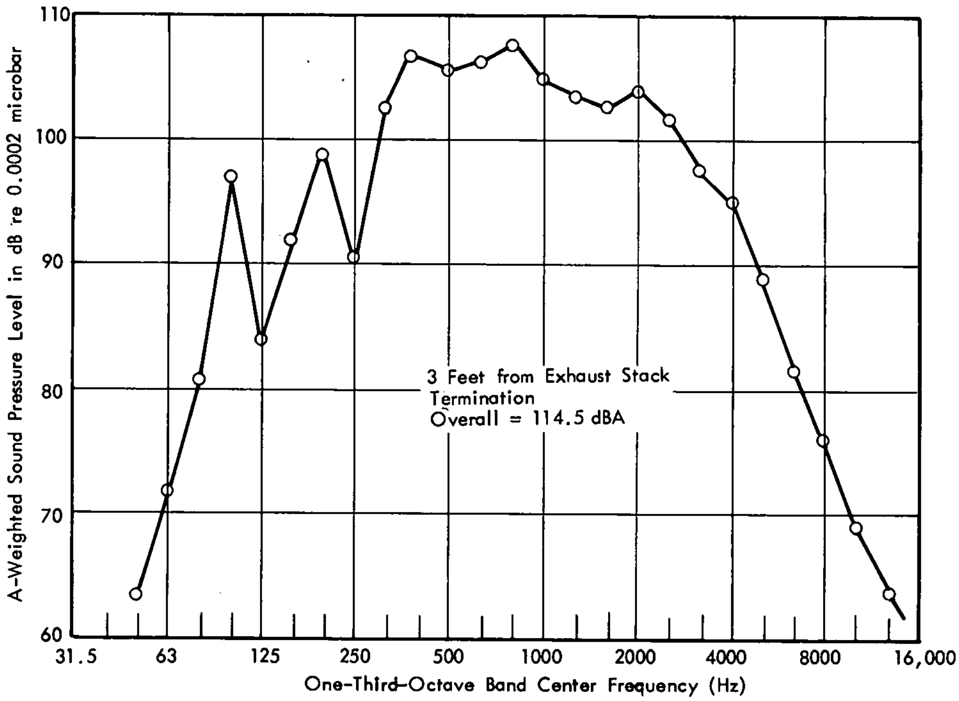


Figure 8. Unmuffled exhaust noise (22).

absorption coefficient of a perforated plate. For sound whose wavelength is greater than about four times the hole diameter (*28*),

$$\alpha \simeq \frac{4[(M/\sigma_1) - 1]}{[(M/\sigma_1 + 1)^2 + (X/\sigma_1)^2]} \tag{39}$$

where M is the Mach number of the flow through the holes in the plate, with $M/\sigma_1 > 1$,

$$\sigma_1 = \sigma(1 - \sigma^2) \tag{40}$$

σ being the fractional open area of the plate, and

$$X = x/\rho c \tag{41}$$

where x is the reactance of the fluid in the hole,

$$x \simeq 2\pi f \rho(t_p + 0.85\, d_p) \tag{42}$$

t_p is the plate thickness and d_p the hole diameter, and ρ and c are the fluid density and the speed of sound at the hole. In addition, sound is regenerated owing to the exhausting of the flow through the hole. Obviously, muffler performance depends on the changing velocities and temperatures (Mach numbers) of the exhaust gases throughout the muffler.

Although the principles of reactive and dissipative muffling are well known, practical muffler insertion loss can only be estimated crudely; and then more weight is given to past experience than to theoretical expertise. Historically, the best way to determine muffler insertion loss has been to build one and measure it. Under sponsorship of the U.S. Department of Transportation, Stemco Manufacturing Company of Longview, Tex., recently completed an extensive study of muffler performance (*23*). Table 7 gives the performance of various makes of mufflers on the engines listed in Table 6. In some cases, the same muffler was used on two or more different engines and it will be noted that the performance varied. The insertion loss in dBA is dependent on the spectrum of the engine exhaust noise. Figure 9 shows some typical muffler insertion loss spectra taken from the Stemco-DOT study.

TABLE 6

UNMUFFLED EXHAUST NOISE [a]

MAKE	MODEL	POWER RATING (hp) AT RATED SPEED (rpm)	EXHAUST NOISE (dBA) AT 50 FT AT OPERATING SPEED (rpm)
Cummins	NHC-250	250 @ 2100	95 @ 2100
Cummins	NTC-350	350 @ 2100	93 @ 1800
Detroit Diesel	6-71	238 @ 2100	105 @ 1900
Detroit Diesel	8V-71	318 @ 2100	104 @ 2000
Mack	ENDT-675	237 @ 1700	82 @ 2100

[a] Tailpipe only (*23*).

Muffler Insertion Loss Models

Muffler performance increases with size and with increased internal attenuating components such as internal baffling and chambers, insulation, and perforated liners and plates. Generally, the more complex the internal muffling elements the higher the back pressure. However, the Stemco data (*23*) show that muffler performance is not independent of the engine. In 1971 Cummins, Detroit Diesel, and Mack

TABLE 7
MUFFLER DATA SUMMARY [a]

ENGINE	MUFFLER MFR.	MUFFLER MODEL	DIAMETER (IN.) PIPE	DIAMETER (IN.) SHELL	LGTH. (IN.)	MFG. DATA (dBA)	MFG. DATA P_s (in. H_2O)	STEMCO DATA (dBA)	STEMCO DATA P_s (in. H_2O)	STEMCO DATA TEMP. (°F)	I.L.(dB)
NHC-250	—	Pipe	4	4	96	—	—	95	16	1230	—
	Donaldson	MPM09–0141	4	9	44.5	81	16.3	78.5	14	1230	16.5
	Riker	9XD405	4	9	44.7	86.2	30	74.5	31	1255	20.5
	Stemco	9349	4	9	44	75.5	23	76.0	21	1260	19
	Donaldson	MOM12–0154	4	10×15	26	79	27.2	77.0	32	1250	18
	Riker	94006	4	9×14	35	85.5	26	75.0	24	1200	20
	Stemco	9854	4	10	40.5	76	23	76.0	27	1230	19
	Donaldson	MTM10–0043	4	10⅛	36	80	22	81.0	23	1250	14
	Riker	94007	4	9×14	31.5	86	34	80.0	48	1260	15
	Stemco	9400	4	10×15	26	81	22	81.5	23	1230	13.5
NTC-350	—	Pipe	5	5	96	—	—	92.5	7	940	—
	Donaldson	MPM09–0161	5	9	44.5	80	17.5	80.0	12	910	12.5
	Stemco	9327	5	9	44	79	13.6	79.0	9	890	13.5
	Teck	505D9T	5	9	44.7	—	—	84.0	23	960	8.5
	Donaldson	MOM12–0131	5	10×15	26	82	31	79.5	21	1000	13
	Donaldson	MOM12–0108	5	10×15	26	80	33	80.0	34	1000	12.5
	Stemco	9401	5	10×15	26	—	—	81.0	28	970	11.5
	Teck	D179	5	10	26	—	—	87.5	35	1000	5
	Riker	9XD404	4	9	44.8	82.4	33	—	—	—	—
	Riker	94006	4	9×14	35	85.6	31	—	—	—	—
	Riker	94007	4	9×14	31.5	86.5	33	—	—	—	—
DDAD 6–71	—	Pipe	4	4	96	—	—	105	12	920	—
	Donaldson	MSM09–0142	4	9	44.5	82.5	41	80.5	51	1030	24.5
	Riker	9XD405	4	9	44.7	87	27	78	54	1020	27
	Stemco	9349	4	9	44	77	37	79	41	1000	26
	Teck	405D9T	4	9	44.7	—	—	86	58	960	19
	Donaldson	MOM12–0154	4	10×15	26	83	46	80	61	1030	25
	Riker	94306	3½	9×14	35	86	40	78	55	960	27
	Teck	D146	4	10	41.2	—	—	80.5	75	1030	24.5
	Donaldson	MTM10–0043	4	10⅛	27.7	83	35	81.0	41	940	24
	Riker	94307						83.5	94	1070	21.5
	Teck	D38	4	9	26	—	—	91.0	58	1020	14
Mack	—	Pipe	4	4	96	—	—	82	6	940	—
	Mack	ZME 336B	4					73	6	970	9
	Mack	ZME 355A	4					72	30	1000	10
	Stemco	9300	4	9	44	71	7.5	72.5	11	980	9.5
	Mack	ZME361–P5	4					70.5	23	960	9.5
	Mack	ZME361–P3	4					70.5	32	950	11.5
	Teck	419D	4	9	27	—	—	70.5	48	980	11.5
	Donaldson	MTM10–0043	4	10⅛	27.7	—	—	72	32	970	10
	Stemco	9400	4	9	44	—	—	74	31	950	8
	Teck	D 38	4	9	26	—	—	76.5	44	1000	5.5
8V–71	—	Pipe	4	4	96	—	—	104	27	—	—
	Donaldson	MPM0900141	4	9	44.5	—	—	83	57	870	21
	Riker	9XD405	4	9	44.7	86.6	49	80	94	840	24
	Stemco	9344	4	9	44	80	52	82	50	840	22
	Stemco	9344 & 9867	4	9	44	—	—	80	58	830	24
	Donaldson	MSM09–0146	3.5	9	44.5	78	38	82	45	880	22
	Donaldson	MSM09–0135						81.5	38	880	22.5
	Riker	9XD404	4	9	44.7	85.7	21	82.5	26	880	21.5
	Stemco	9350	4	9	44	78	42	80	44	880	24
	Donaldson	MOM12–0176	5	10×15	26	83	38	85	50	880	19
	Riker	94406	4	9×14	35	83	30	82.5	72	900	21.5
	Stemco	9416	4	10×15	39	77	52	81	60	880	23
	Donaldson	MOM12–0154	4	10×15	26	83	23	85.5	30	900	18.5
	Riker	94006	4	9×14	35	83.9	26	85	19	900	19
	Stemco	9416	4	10×15	39	—	—	81.5	12	880	22.5
	Donaldson	MTM10–0043	4	10⅛	27.7	—	—	88.5	20	870	15.5
	Riker	94007	4	9×14	38	85	20	45	20	900	—
	Stemco	9345	3.5	9	36	—	—	86	60	900	18

[a] Adapted from (*33*).

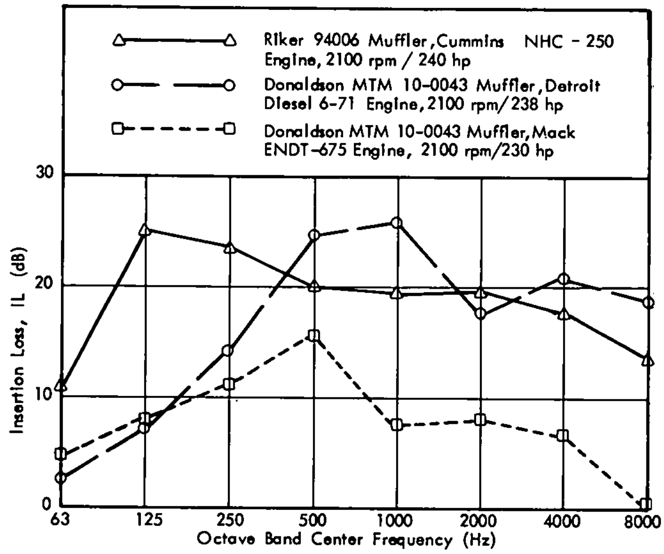


Figure 9. Typical muffler insertion losses (23).

engines represented 86 percent of all engines sold in the United States (*23*). Inasmuch as these data contain a highly representative cross section of various makes of mufflers, and inasmuch as the variation of over-all (dBA) insertion loss varies rather slowly from muffler to muffler for particular engine makes, the muffler insertion loss model ("A" weighted) is based on averages taken from Table 7.

$$\text{I.L.}_A = 22\delta_d + 17.2\delta_c + 10.7\delta_m \tag{43}$$

in which δ_d equals 1 for a 2-stroke engine and 0 for others; δ_c equals 1 for a 4-stroke, naturally aspirated engine and 0 for others; and δ_m equals 1 for a 4-stroke, turbocharged engine and 0 for others.

Unmuffled Exhaust Noise Model

From the Serendipity (*4*) and Stemco (*23*) reports,

$$L_{PA} = 97.5 + 10 \log \frac{\text{bhp}}{200} - 6\delta_m + 7\delta_d - 9\delta_m\delta_M \tag{44}$$

where δ_M equals 1 for a constant-power engine in the rated speed range and 0 for others.

Muffled Exhaust Noise Model

$$L_{PA} = 97.5 + 10 \log\frac{\text{bhp}}{200} - 15\delta_d - 17.2\delta_c - 16.7\delta_m - 9\delta_m\delta_M \tag{45}$$

Truck Fan Noise

Various contributing mechanisms have been postulated as being responsible for propeller fan noise. These mechanisms have been identified by Daly (*29*) and Sharland (*30*), among others, as follows:

1. *Steady blade forces* (*rotation noise*). There are two components, lift and displacement noise. Lift noise is due to the action of steady applied forces on the air and displacement noise to the displacement of the air about and around the passing blade. To a stationary observer, the resulting forces vary periodically with the blade passage frequency (rpm × number of blades) and its harmonics. This mechanism is not considered significant for automotive fans.

2. *Vortex shedding.* Vortices are discharged off the trailing edge of fan blades owing to the presence of a turbulent boundary layer near the trailing edge. The random discharge of these eddies into the free airstream generates broadband noise.

3. *Inlet turbulence.* Pressure fluctuations on the fan blades owing to turbulence of the inlet flow induce reactive forces on the air. The reactive forces have frequency components in the acoustic range and their presence can be detected at locations well removed from the blade owing to the resulting radiation. The noise is broadband.

4. *Interference noise.* Cutting of inlet wakes by the fan blades generates blade passage harmonics and frequencies associated with the number of wake-inducing elements (guide vanes, for instance). Impingement of fan discharge wakes on stationary obstructions generates blade passage harmonics.

Sharland (*30*) has presented analytical models for vortex noise and inlet turbulence noise. Noise from vortex shedding increases rapidly, varying as the sixth power of inlet velocity. However, interference and inlet turbulence noise are dominant, as shown by a comparison of the noise from a free-running fan and an installed fan (*31*).

Theoretical and experimental work has also been done to understand the basic process of noise generation by the interaction of flow with rigid surfaces. Current noise prediction techniques are summarized by Hayden (*31*) for the cases of (a) flow past a single discontinuity-trailing edge, (b) rigid body in disturbed flow, and (c) spoilers in confined environments. Analyses show that the noise sources for (a) and (c) are dipole, and the resulting sound power varies as U^6. Point dipole sources are also postulated for incoming turbulence, although deviations apparently exist. Although many of the underlying physical processes of fan noise generation are understood, empirical methods must still be employed to predict fan noise levels.

Fan Noise Data Base

Considerable truck fan noise data have been developed recently, mainly in the course of the DOT-sponsored quiet truck program. These data were usually measured with the fan being driven by an electric or hydraulic motor. Three typical spectra are shown in Figure 10. The data labeled "Reverberant" were taken in a reverberant room and corrected to 50 ft by hemispherical spreading (*32*). The other two curves were measured in the front and to the side of a truck in an open space (*15*, Run 552). Comparison of these curves shows a predominance of the blade passage frequency to the sideline, whereas high-frequency components are larger in amplitude in the front.

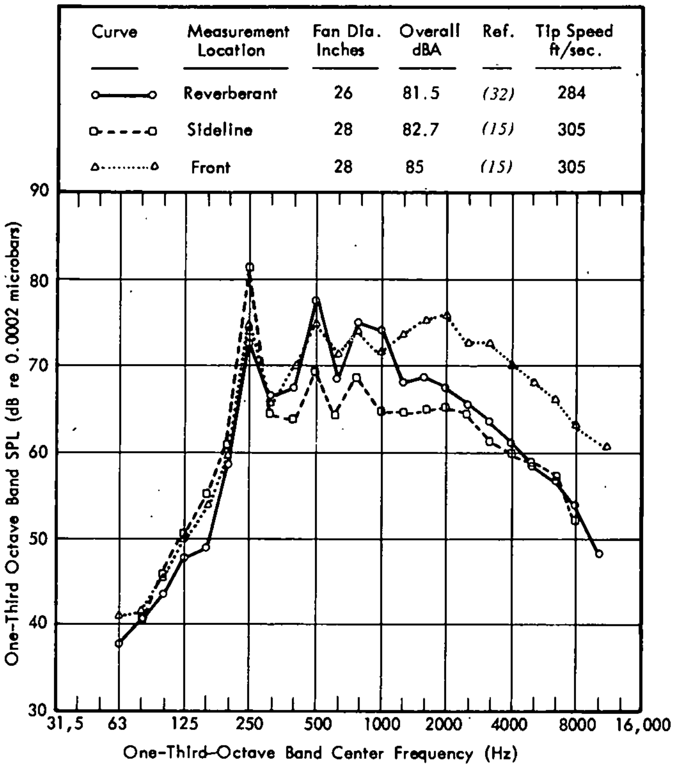


Figure 10. Fan noise spectrum at 50 ft, fan speed 2,500 rpm.

Fan Noise Models

Empirical noise models for fans have been developed under sponsorship of the heating and ventilating industry, the aircraft industry, the automotive industry, and the U.S. Government. Analytic models that were expressed in dBA or that could be "A" weighted were converted to sound pressure estimates at 50 ft and are presented in Table 8. The nomenclature is given in the "Glossary of Symbols" (Chapter One).

TABLE 8

FAN NOISE MODELS (dBA at 50 feet)

SOURCE	MODEL	EQ. NO.
ASHRE (*33*)	$L_{PA}=76.7+70\log\frac{d_t}{30}+50\log\frac{N_t}{2000}$	(46)
Daly (*34*)	$L_{PA}=76.1+72\log\frac{d_t}{30}+52\log\frac{N_t}{2000}$	(47)
Serendipity (*4*)	$L_{PA}=75.8+60\log\frac{N_t}{2000}+60\log\frac{d_t}{30}+10\log\frac{b_t}{3}+10\log\frac{n_t}{6}+20\log\frac{\overline{w}/U_m}{0.07}$	(48)
Wyle (*5*)	$L_P=k+60\log N_t$	(49)
Priede (*19*)	$L=k+(55\text{–}60)\log N_t$	(50)

The numerical similarity of the three quantified models is evident. The Serendipity model (*4*), however, accounts for the number and width of blades, and an index of the turbulence (the term 20 log $\overline{w}/0.07U_m$). The parameter $\overline{w}$ is the turbulence perturbation velocity and U_m is the velocity of the air flow into the fan. The ratio of $\overline{w}$ to U_m is shown in Figure 11 as a function of the distance from the obstructing (disturbing) object in the radiator and grille. Eq. 48 neglects the effect of vehicle forward speed. The

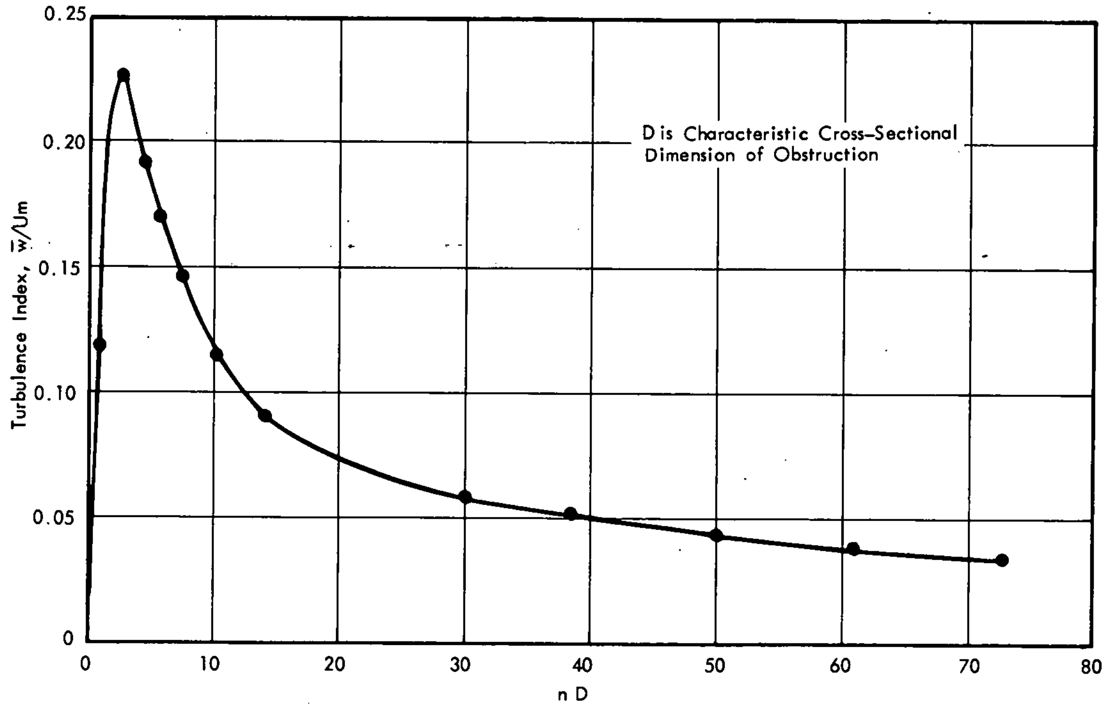


Figure 11. Variation of turbulence levels with distance from bluff objects in the radiator and grille (4).

appropriate correction is shown in Figure 12. For a representative fan tip speed of 200 ft/sec, the correction is 2.5 dB at 60 mph. The constant in Eq. 48 was calculated from octave band spectra on the basis of a fan tip speed of 200 ft/sec. Actual variations from this nominal value will result in small additional corrections. However, inaccuracy in estimation of the turbulence factor is considered a potentially greater source of error. Eq. 48 is considered the most accurate estimator of automotive fan noise. For trucks, selection of a turbulence index of 0.1 leads to estimates for the fans of Figure 10 of 81.2, 82.2, and 82.2 dBA, respectively. For automobiles, the nominal value of 0.07 has been shown to produce accurate estimates (*4*). Any particular configuration which has a "dirty" inlet or an excess of turbulent recirculation will exhibit higher noise.

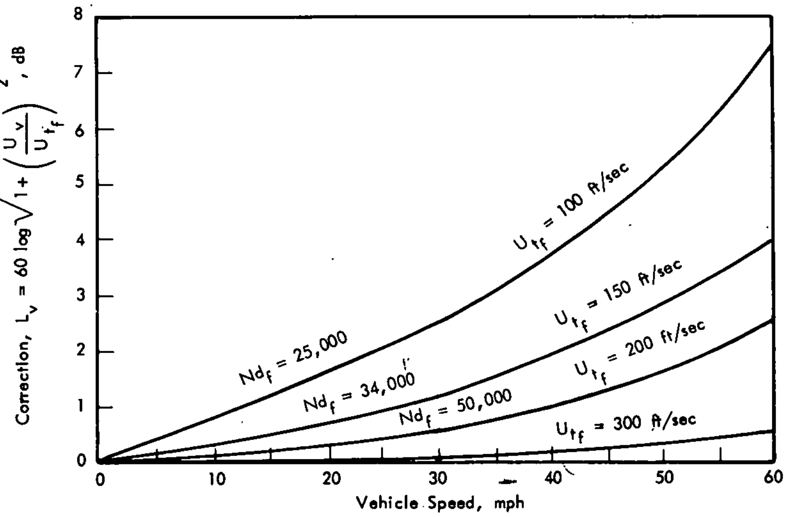


Figure 12. Vehicle forward speed correction to fan noise estimate as a function of fan tip speed.

Diesel Engine Intake Noise

Diesel engine open intake noise is generally less severe than engine casing radiation or engine exhaust noise, usually being 5 to 10 dB lower than either. Intake noise for naturally aspirated engines is due to the oscillating nature of the inlet flow. Turbocharged engine intake noise is quite different, owing to the presence of the compressor. Further, account must be taken of the effects of air cleaners and snorkels (vertical pipe between the air cleaner and the atmosphere) (*23*).

Figure 13 shows spectra of open intake noise (intake pipe but no air cleaner) for the engines of Table 6. Both the spectra and the over-all levels show considerable variability. Open intake noise can best be categorized according to engine type. Donaldson (*35*) has the following estimates for 50-ft levels for open intake induction systems: (a) turbocharged engines, 75-85 dBA; (b) naturally aspirated engines, 81-91 dBA; (c) blown engines (Roots Blower), 83-93 dBA. Figure 14 shows that the Stemco

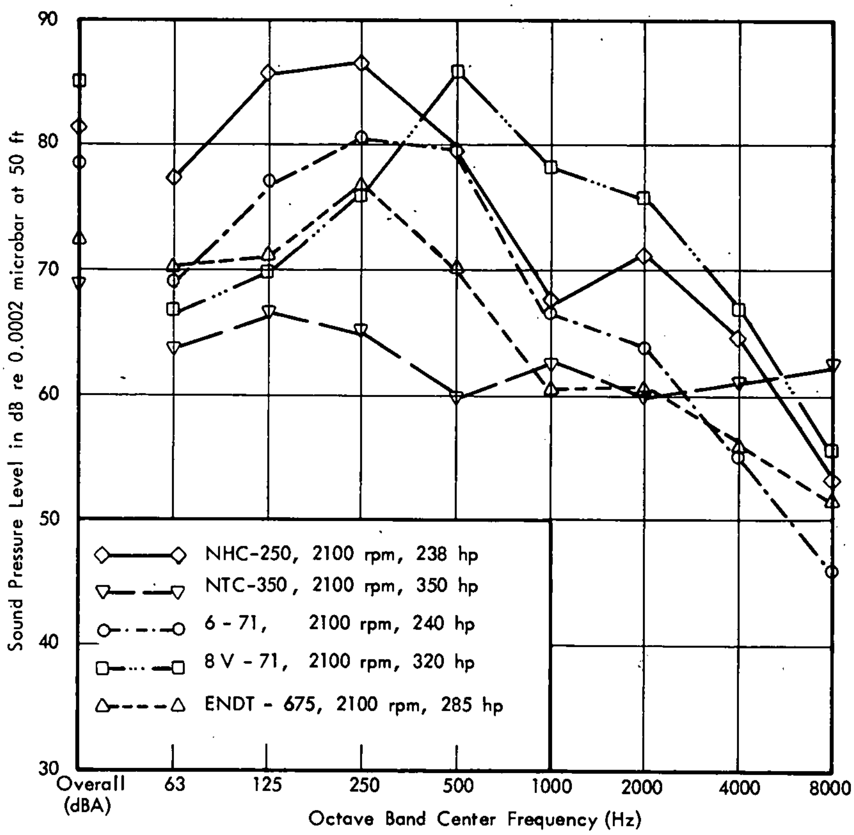


Figure 13. Diesel engine intake noise (open intake).

(*23*) data fall low within or below the Donaldson estimates.

Figure 15 shows some typical intake noise levels achieved with air cleaners installed. Donaldson (*35*) estimates for most air cleaner configurations (those without frontal intake) are: (a) turbocharged engines, 62-72 dBA; (b) naturally aspirated engines, 66-76 dBA; and (c) blown engines, 63-73 dBA. Snorkels usually reduce the 50-ft levels by 5 to 6 dBA (*23*).

Intake Noise Models

On the basis of the Donaldson (*35*) and Stemco (*23*) data,

$$L_{PA} = \left(75 + 5\log\frac{\text{bhp}}{250}\right)\delta_m + 81\,\delta_c + 83\delta_d - 13\delta_a\delta_m - 13\delta_a\delta_c - 20\delta_a\delta_d + 8\delta_a\delta_f - 5\delta_a\delta_s\delta_c - 5\delta_a\delta_s\delta_d \quad (51)$$

where δ_a equals 1 for an air cleaner installed and 0 for others; δ_s equals 1 for a snorkel on an air cleaner and 0 for others; and δ_f equals 1 for a frontal intake air cleaner and 0 for others.

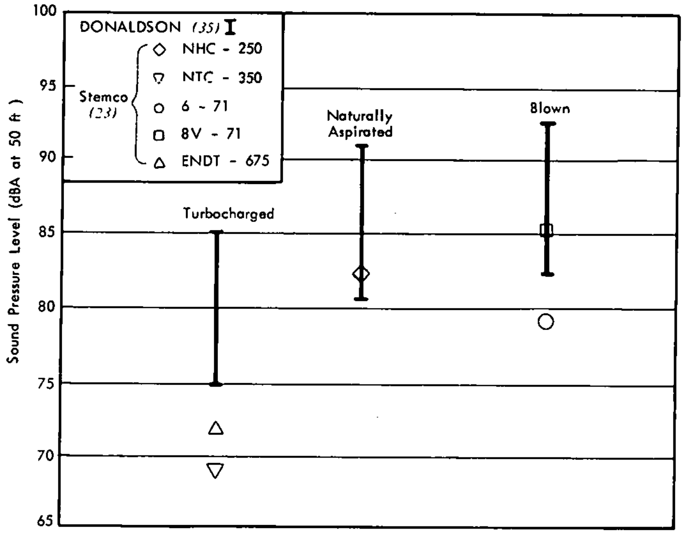


Figure 14. Open intake noise.

Tire Noise

Three underlying physical mechanisms that have been postulated to account for tire noise are (*36*): (1) air pumping, (2) casing vibration, and (3) aerodynamic sources (unsteady airflows). The first mechanism (monopole radiation) is regarded by Hayden (*37*) to be the principal noise producer for tires with tread grooves (pockets). However, Richards (*38*) has shown that tread vibration caused by the steady centripetal acceleration being modulated by the tread pattern or road surface can account for the radiated noise. Aerodynamic noise is considered insignificant by all authors.

Both air pumping and tread vibration models depend on velocity to the fourth power, which is in agreement with measured data. Hayden has shown that the sound pressure level at a distance r in feet from a tire owing to air pumping is

$$L_p = 68.5 + 20\log\left(\frac{g\,w}{s}\right) + 10\log n_w + 20\log F_c + 40\log U - 20\log r \quad (52)$$

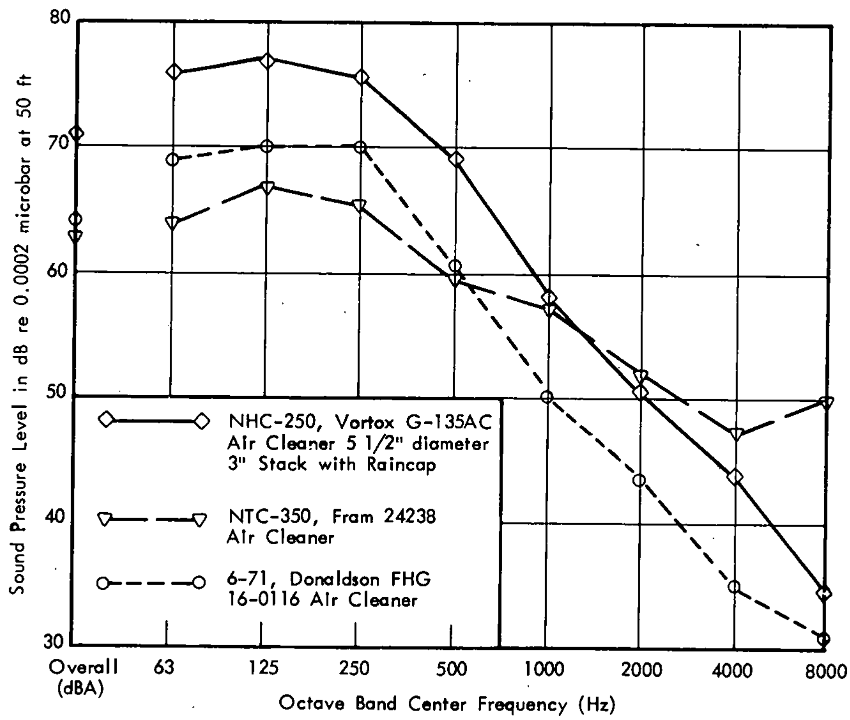


Figure 15. Diesel engine intake noise (with air cleaners) (23, 35).

where g is the tread depth in feet, w is the width of a single cavity or groove in the tread in feet, s is the circumferential distance between tread grooves in feet, n_w is the number of cavities per tire width, F_c is the fractional change in cavity volume, and U is the velocity in ft/sec.

For convenience, this equation is rewritten for the sound pressure level at 50 ft from the center of a traffic lane ($r = 47$ ft). In addition, the tire dimensions are expressed in inches, the velocity in miles per hour, and the parameters F_c, V, n, and $\frac{g' w'}{s'}$ referenced to nominal values of 0.1, 40 mph, 4, and 0.5 in., respectively:

$$L_{PA} = 64.1 + 20 \log \frac{g' w'}{0.5s'} + 10 \log \frac{n_w}{4} + 20 \log \frac{F_c}{0.1} + 40 \log \frac{V}{40} \qquad (53)$$

in which g' is the tire tread depth in inches, w' is the width of a single cavity or groove in the tread in inches, s' is the circumferential distance between tread grooves in inches, and V is the velocity in mph. This equation agrees well with measurements and in the 50-ft sound pressure level computed for representative values of passenger car tire dimensions (64.1 dBA is quite close to measured values).

Richards (*38*) has not developed a quantitative model relating tread and road surface irregularities to noise production. However, the results of a number of novel tests, such as running a car on a carpeted road, do give qualitative insight into the factors influencing noise production.

As Bender and Leasure (*36*) point out, the simple monopole model does not account for all of the noise phenomena of tires (directionality, deviation from V^4-dependence, or noise increase with wear). Nevertheless, Hayden's and Richard's work provides a basis for empirically modeling and understanding tire noise.

Tire Noise Data

All available published tire noise data were studied for self-consistency and correlation with test parameters. The dependence on the fourth power of velocity appeared to hold sufficiently well over the speed range from 35 to 65 mph to permit representation of the data in terms of tire-road surface combinations. The criterion used to judge the suitability of such a classification was whether or not the deviations from the best-fit V^4 line from 35 to 65 mph were small compared with the differences between tire-surface combinations. Typical values for these differences were ± 1 and ± 5 dB, respectively. A velocity of 40 mph was chosen as the normalizing speed. The peak "A" weighted sound pressure level at 50 ft from the center of the roadway, as measured with a "fast" meter response, was chosen as the measure of loudness.*

The source data were practically all measured at either 50 ft or at 25 ft from the center of travel of the test vehicle. Five dB was subtracted from 25-ft data to estimate 50-ft levels. This has been observed to be a more accurate correction than the 6 dB associated with hemispherical spreading for doubling of distance, or even the 6.6 dB attributable to going from 22 to 47 ft from the nearest tire (*39, 40*). The difference is due in part to the presence of noise from the other tires on the test vehicle. In the limit, a continuum of tires would constitute a line source and the attenuation would be 3 dB per doubling of distance from the source. The questions could be resolved through the testing of single tires (*41*). In addition, directivity and geometric considerations are involved.

Other special corrections were required for data that were measured under different circumstances. Colorado passenger car noise data (*42*) were measured while the test car was cruising by instead of coasting by. The propulsion noise was estimated to be 66 dBA at the 40-mph test speed, and all measurements were corrected accordingly. Other measurements were performed under the auspices of the SAE along a new highway near Lansing, Mich. (*43*). The roadside at the test site sloped away at approximately 7 deg. This declination was estimated to produce an attenuation of 2 dB, and the data were so corrected. The American Rubber Manufacturers Association's presentation to the EPA (*44*) described measurements made at 50 ft and 50 mph but with the slow meter response. The difference between slow and fast response is nominally 1 dB according to the Automobile Manufacturers Association, and this correction was added to their data.

Truck Tire Noise Data Base

The truck tire noise data are presented in Table 9. The tire treads are characterized as being either rib or cross-lug and by the code given in the particular reference. The treads are further identified by the footprints given in the NBS report (*39*) and shown in Figure 16.

The data are separated by type of pavement. Almost all of the available truck tire noise measurements have been made on either rough-textured asphaltic concrete pavement, which is assumed to be dense graded, or on new portland cement concrete pavement with a smooth cloth drag or light brush finish. This has apparently been done intentionally to minimize the number of variables. The levels given in Table 9 are the peak dBA readings for a loaded, single-axle truck passing 50 ft from the microphone at 40 mph.

Truck Tire Noise Modeling

The procedure used for selecting representative levels to characterize or model truck tire noise consisted first of grouping pavement-tire combinations that had obvious class similarities. These groups were neutral rib, new and worn rib, cross lug, and pocket retread tires, a total of seven groups.

The next step was to choose a number that was roughly the average of all the data in the group. The number was then compared with each data point in the group. If the difference was greater than 1 dB, methods of rationalizing the difference were attempted based on an apparent consistent bias in the levels in a particular reference, as with the ARM data (*44*), or on a particularly noisy or quiet tire, such as NBS (*39*) cross lug D and Tetlow's (*46*) cross

* Fast meter response corresponds to a time constant of approximately 0.2 sec.

TABLE 9

TRUCK TIRE NOISE[a]

REFERENCE	TIRE TREAD: DESCRIPTION	TIRE TREAD: NBS CODE	NOISE (dBA) AT 50 FT — ASPHALTIC CONCRETE: DENSE-GRADED, MEDIUM-COARSE FINISH	ASPHALTIC CONCRETE: OPEN-GRADED	PORTLAND CEMENT CONCRETE: NEW, SMOOTH, BRUSH FINISH	PORTLAND CEMENT CONCRETE: COARSE BROOM OR BURLAP-DRAG FINISH
ARM (*44*)	Smooth	—	62.9	—	63.9	—
NBS (*39*)	Neutral rib	A	70	—	67.7	—
ARM (*44*)	Neutral rib	A	64.3	—	65.2	—
NBS (*39*)	Rib B	B	71.5 (73.5)[b]	—	71 (75.5)	—
Firestone (*45*)	Rib, T-1, T-110	B	70–71 (73)	—	73	—
Tetlow (*46*)	Rib, worn	B	— (71)	—	—	—
SAE (*43*)	Rib R1, R6	B	—	—	—	69
NBS (*39, 47*)	Rib C	C	70.5 (71)	—	70.5 (72)	—
Tetlow (*46*)	Rib, new	C	70	—	—	—
SAE (*43*)	Rib R2, 3, 4, 5	C	—	—	—	66.5–70.5
NBS (*39, 47*)	Rib (retread) G	G	71 (75)[c]	—	69.5 (76.5)[c]	—
ARM (*44*)	Rib	—	65.7 (69.4)	—	68.2 (71.6)	—
ARM (*44*)	Rib RAA	—	—	—	—	70.9
NBS (*39, 47*)	Cross lug D	D	77.5 (79.5)[b]	—	80 (81.5)	—
Tetlow (*46*)	" " BD	D	74–76 (77.5–80)	—	—	—
SAE (*43*)	" " X7	D	—	—	—	— (76.5)
Tetlow (*46*)	" " E	D	71	—	—	—
SAE (*43*)	" " X3	D	—	—	—	71
NBS (*39, 47*)	Cross lug E	E	76 (80)	—	76.5 (79)	—
Tetlow (*46*)	" " A	E	77.5	—	—	—
SAE (*43*)	" " X9	E	—	—	—	— (75.5)
NBS (*39, 47*)	Cross lug F	F	75 (79.5)	—	75 (80.5)	—
Firestone (*45*)	" " T 200	F	75.3 (79.5)	—	—	—
Tetlow (*46*)	" " C, c	F	72.5 (80)	—	—	—
SAE (*43*)	" " X5, 11	F			—	70 (78.5)
Tetlow (*46*)	" " F	F/B	72	—	—	—
SAE (*43*)	" " X1	F/B		—	—	— (75.8)
NBS (*39*)	Cross lug (retread) H	H	76.5 (76)	—	75.5 (79)	—
ARM (*44*)	Cross lug	—	72 (73.6)	—	75 (80)	—
Tetlow (*41*)	" "	—	74 (79)	—	—	—
ARM (*44*)	" " XB, XC, 5XD	—	—	—	—	74.8
NBS (*47*)	Pocket retread	I	83.5 (84)	—	88 (88)	—
Tetlow (*46*)	" "	I	85	—	—	—

[a] 40 Mph; four-tire, single drive axle, loaded to 4,430 lb/tire. Speed dependence correction = 40 log $V/40$.
[b] New (worn) tire tread.
[c] Irregular tread pattern.

lug E. If the remaining differences were consistently low or high, the candidate number was changed and the process repeated. As a result of this process, the levels in Table 10 were selected as being representative of loaded, single-axle, truck tire noise as measured at 50 ft and 40 mph.

These levels are independent of road surfaces that are within the ranges of texture and acoustic properties of the surfaces used for the tests. This may exclude open-graded asphaltic concrete and pitted portland cement concrete. Parametric variation from the base values given in Table 10 depend on the following:

VARIABLE	DEPENDENCE (dB)
Speed (mph)	$40 \log V/40$
Load (lb)	$10 \log L/4{,}430$
No. of loaded axles	$10 \log N_{\text{axles}}$
Pressure (psi)	—
Torque (ft-lb)	—
Temperature (°F)	—
Wet road	—

The linear variation of tire noise with load is an approximation. The first NBS study (*39*) presented data indicating that tire noise varied according to the first or second power of load. However, the second NBS report (*47*) showed that unloading the single-axle test truck from 4,430 lb per tire to 1,530 lb per tire decreased the noise a maximum of 2 dB instead of the 5 dB predicted with the linear dependence assumption. Tetlow (*46*) observed a 15-dB decrease with halving of the load for the pocket retread tire, which corresponds to a 5.5-power dependence on load. These two apparent anomalies may be explainable in terms of different noise generation mechanisms. In any case, the linear dependence should be sufficiently accurate over small ranges, and the loaded truck noise estimate is both the most critical and the most accurate.

A limited number of wet-road measurements were made by NBS (*47*). The results showed a maximum of 3-dB difference between wet and dry pavements for the same tires. The trend was not consistent, however; some tires were noisier wet, others dry.

Tetlow (*46*) observed that neither tire pressure, torque, nor temperature effected a measurable difference in the noise.

The increase in the number of loaded axles has been the subject of considerable concern (*39, 41, 46*). The measured noise level at 50 ft has been observed to increase 2 or 3 dB when two loaded axles are tested. The 3-dB value is considered appropriate because the noise energy has been doubled.

The single-axle or dual-axle loaded truck tire noise prediction model is

$$L_{PA} = B_{TTN} + 40 \log \frac{V}{40} + 10 \log \frac{L}{4{,}430} + 10 \log N_{axles} \quad (54)$$

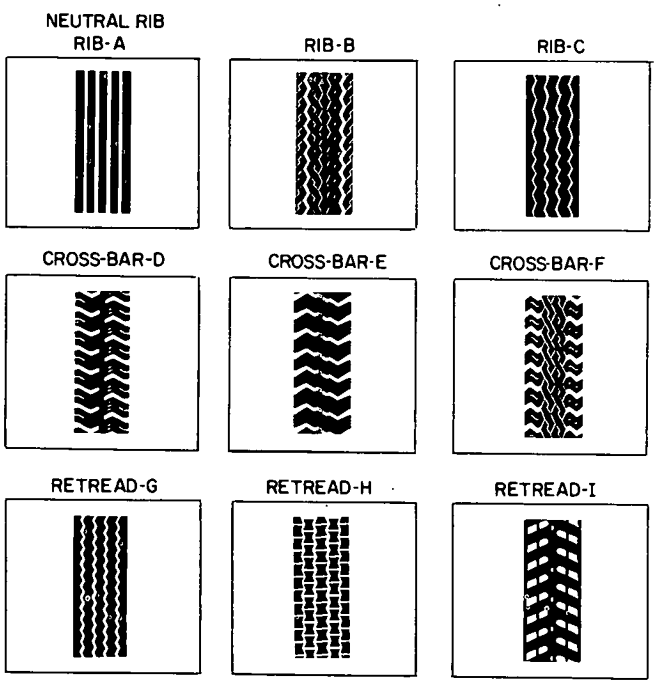


Figure 16. Test tire tread designs. These exact tread patterns represent 70 to 80 percent of the total truck tire population in use on the road today (39).

TABLE 10

BASE VALUES FOR TRUCK TIRE NOISE

	BASE VALUE, B_{TTN}	
TIRE TREAD	NEW	WORN
Neutral rib	69	—
Rib	70.5	73
Cross lug	75	79.5
Pocket retread	86	86

Other refinements are possible for situations where tire treads are mixed or in the case of truck-trailer combinations. The NBS study included mixed-matched sets of tires, from which the following guidelines have been deduced:

1. To estimate the noise due to only the outside tire of a matched set, subtract 1.5 dB from the loaded, four-tire, single-axle level.
2. To estimate the noise due to the inside tire of a matched set, subtract 6 dB from the loaded, four-tire, single-axle level.
3. To estimate the noise attributable to opposite-side tires, subtract 3 dB from the loaded, four-tire, single-axle level.
4. To arrive at an estimate of the noise of a mixed set of tires, add the individual contributions (Steps 1, 2, and 3).
5. For a second loaded axle, add 3 dB.
6. For separated axles, subtract 2 dB from the quieter set and add on a power basis.

The model was applied to 47 of the loaded tractor-trailer combinations measured in the NBS studies (*39, 47*). The mean error between the model predictions and measured values was calculated to be 1.3 dB and the standard deviation 2.2 dB. In eight cases with worn cross-bar-H tread patterns (estimated $B_{TTN} = 79.5$), large differences between measurements and predictions were observed. The actual measured value for worn H treads was 76 dBA (Table 9). These tires were therefore considered to be new. The model predictions were recalculated on this basis and compared with the measurements. The resulting mean and standard deviations of the errors were 0.4 and 1.6 dB, respectively.

Truck Transmission and Differential Gearing

Gear meshing is the major source of transmission and differential noise. Superimposed on the steady torque being transmitted by two meshing gears are perturbations caused by errors in tooth form and spacing and by nonuniform tooth stiffness. It is generally felt that geometric errors are the primary source of dynamic loads, except perhaps for spur gears. Vibrations induced in the transmission and differential housings are the source of sound radiation. This vibration is due to vibratory energy transmission through the shafting and to a lesser extent to sound radiation from the gearing. The excitation of torsional resonances of the shafts by dynamic torques (loads) having frequency components coincident with the shaft resonances is one of the major sources of gearing noise. Narrow-band analyses show that the dynamic load spectra exhibit prominent peaks at frequencies equal to the rotation rates of both gears, their harmonics, the gear mesh frequency and its harmonics, and at side-band frequencies equal to the gear mesh frequency plus or minus the rotation rate of the gears. Torsional resonances coincident with any of these frequencies are likely to induce high levels of sound radiation owing to forces transmitted through the bearings to the case. Case configuration and damping are also important (*48*). A technical discussion of gear dynamics is outside the scope of the present study. Nayak (*48*) has summarized most of the present body of past work regarding gear dynamics.

There are three primary steps involved in gear noise estimation:

1. Predict dynamic loads.
2. Predict vibration transmission to the casing.
3. Predict acoustic radiation from the casing and from the surrounding structure excited by vibration transmission from the casing.

Nayak notes that although the prediction of dynamic loads for spur gears is relatively well established, the same is not true for helical gears. The prediction of vibration transmission and casing radiation appears as if it might be best handled with statistical energy analysis techniques (*49, 50*), but empirical methods must be relied upon to achieve any reasonable level of confidence in noise predictions.

One of the basic problems in providing simple noise models for truck transmissions is that there may be from 5 to 13 forward gears obtained through one or two step reductions. Figure 17 shows a narrow-band analysis of noise from a Fuller Model RT-910 truck transmission in the range from 500 to 1,000 Hz in the 9th forward gear. Engine speed is 2,000 rpm and the brake horsepower being delivered is 290 (*51*).

The spectrum shows a predominant peak at 860 Hz corresponding to the meshing of the output gears in the main box (4 and 9 gears). Figure 18 shows a schematic of a truck transmission. The ratio of the engine speed N to the propeller shaft speed N_p is the transmission ratio, T_r. The number of teeth on the two pinions are n_1 and n_3 and on the bull gears n_2 and n_4. There are two mesh frequencies (four if the secondary box of the transmission provides additional reduction):

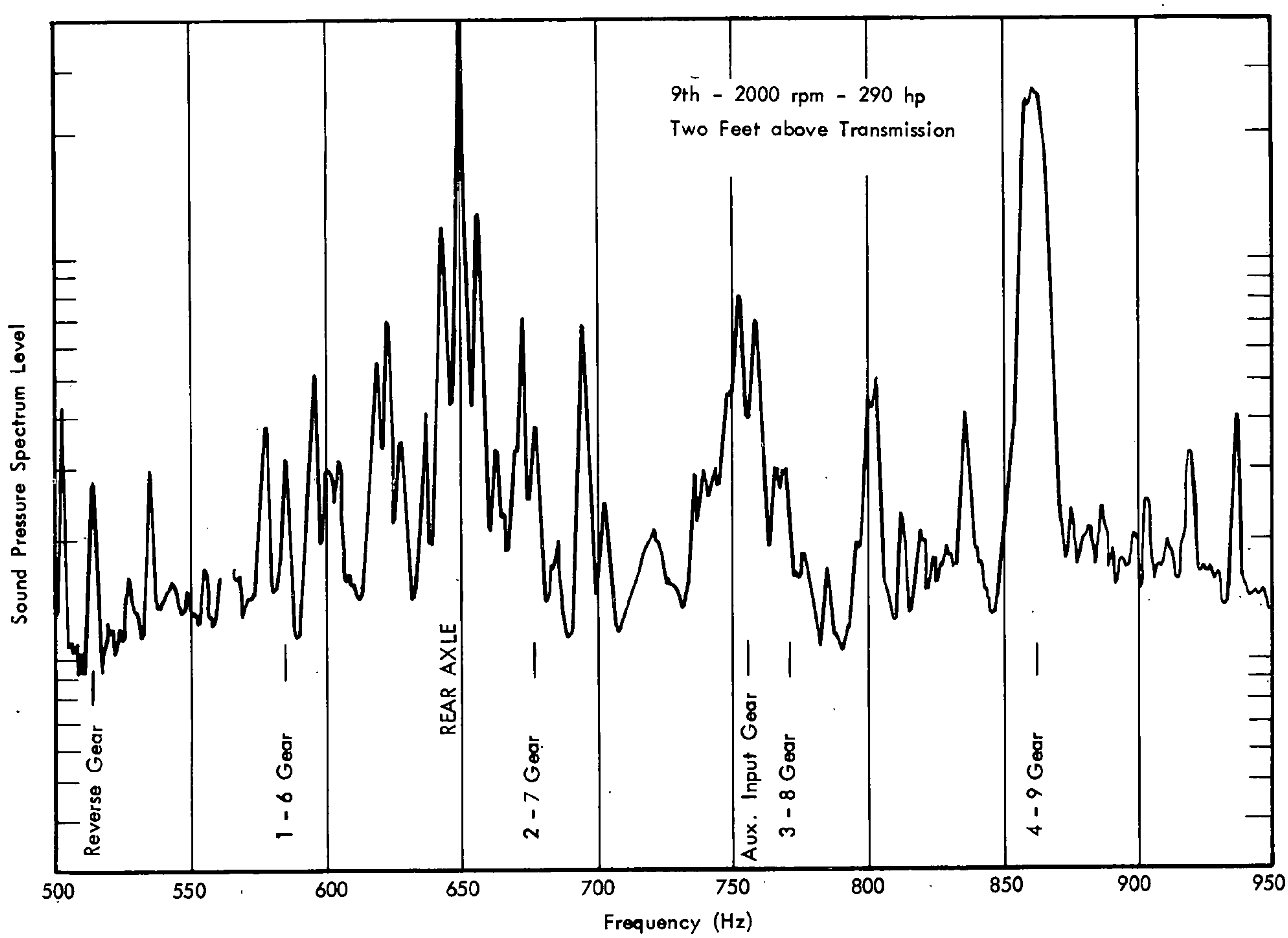


Figure 17. Transmission noise spectrum, Fuller Model RT-910 (51).

$$f_1 = \frac{N n_1}{60} \quad (55)$$

$$f_2 = \frac{N_p n_4}{60} = \frac{N}{T_r} \frac{n_4}{60} \quad (56)$$

For the transmission of Figure 17 in 9th gear, $T_r = 1.24$ and $n_4 = 32$ teeth. This gives a second mesh frequency of 860 Hz.

Table 11 shows transmission ratios for the Fuller RTO-910 transmission. The numbers of teeth on input and output pinions and bull gears in both the main and secondary boxes are given. From these data, the tooth contact frequencies can be calculated. For engine speeds governed between 1,500 and 2,100 rpm in 6th gear and above, the first mesh frequency in the main box would range between 699 and 980 Hz (there is no mesh frequency in the 10th gear). The second mesh frequency would range between 437 and 612 Hz in the 6th gear and between 647 and 906 Hz in the 9th gear. The radiated sound power is proportional to the delivered horsepower. For constant horsepower delivery, the effect of "A" weighting on the shifting mesh frequencies would cause an approximate 2-dB increase in the sound pressure level as engine speed is increased from 1,500 to 2,000 rpm.

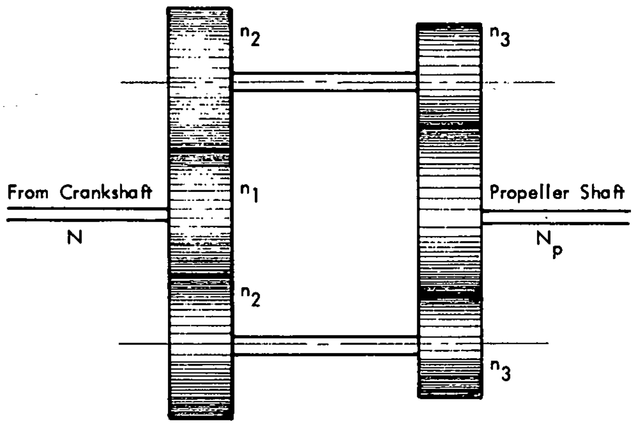


Figure 18. Truck transmission schematic.

Within a particular class of gears, the radiated power level can be expressed in the form

$$\mathrm{PWL_{rad}} = 10 \log \mathrm{bhp} + C \quad (57)$$

Zumbroich (*52*) made measurements on 78 different gears, including spur, helical, bevel, and planetary gears running at design load and speed. A regression line fitting all the gearing systems was

$$\mathrm{PWL_{rad}} = 10 \log \mathrm{bhp} + 80 \quad (58)$$

To obtain 50-ft linear sound pressure levels, 32 dB is subtracted for hemispherical spreading

$$L_p = 10 \log \mathrm{bhp} + 48 \quad (59)$$

To obtain dBA levels at 2,100 rpm, on the basis of the typical truck transmission spectrum peak in the 800- to 900-Hz range, 0.5 dB is subtracted

$$L_{PA} = 10 \log \mathrm{bhp} + 47.5 \quad (60)$$

To account for the effect of "A" weighting in the engine speed range from 1,500 to 2,100 rpm,

$$L_{PA} = 10 \log \mathrm{bhp} + 13.5 \log \frac{N}{2{,}100} + 47.5 \quad (61)$$

For a Cummins NTC-350 engine operating at 350 hp and 2,100 rpm, this would give a 50-ft level of 72.5 dBA. The standard deviation is approximately ±6 dB (*52*), which is quite large, but Table 1 shows that there is indeed a wide variation in measured levels.

Differential noise is normally of sufficiently low level to be ignored.

Other Truck Noise Sources

Two of the other noise sources are (1) aerodynamic noise generated by the turbulent air flow over the vehicle, and

TABLE 11

FULLER RT–910 TRANSMISSION

	MAIN BOX						SECONDARY BOX						
GEAR	DRIVE GEAR TEETH	DRIVEN GEAR TEETH	RATIO	DRIVE GEAR TEETH	DRIVEN GEAR TEETH	RATIO	DRIVE GEAR TEETH	DRIVEN GEAR TEETH	RATIO	DRIVE GEAR TEETH	DRIVEN GEAR TEETH	RATIO	PRODUCT OF RATIOS
10th	—	—	1.0	—	—	1.0	—	—	1.0	—	—	1.0	1.00
9th	28	40	1.43	37	32	086	—	—	1.0	—	—	1.0	1.24
8th	28	40	1.43	33	36	1.09	—	—	1.0	—	—	1.0	1.56
7th	28	40	1.43	29	40	1.38	—	—	1.0	—	—	1.0	1.97
6th	28	40	1.43	25	44	1.76	—	—	1.0	—	—	1.0	2.51
5th	—	—	1.0	—	—	1.0	28	32	1.14	15	42	2.80	3.20
4th	28	40	1.43	37	32	0.86	28	32	1.14	15	42	2.80	3.95
3rd	28	40	1.43	33	36	1.09	28	32	1.14	15	42	2.80	4.99
2nd	28	40	1.43	29	40	1.38	28	32	1.14	15	42	2.80	6.33
1st	28	40	1.43	25	44	1.76	28	32	1.14	15	42	2.80	8.04
Rev. hi	28	40	1.43	22	42	1.90	—	—	1.0	—	—	1.0	2.73
Rev. lo	28	40	1.43	22	42	1.90	28	32	1.14	15	42	2.80	8.72

(2) radiation from the vibrations of the cab and trailer body. The contribution of these sources and all others is indicated in Table 1.

Buses

A bus is essentially a quiet truck. The engines are enclosed and larger mufflers are used. Fifty-foot levels range from 80 to 87 dB at highway speeds (*5*).

Automobiles

Table 2 shows that engine casing noise, engine exhaust and intake, and fan noise are the major contributors to automobile noise in the SAE acceleration tests. Tire noise is quite low at the speeds attained in the tests. However, owing to its dependence on the fourth power of velocity, tire noise becomes significant at highway speeds. Transmission and differential noise are inconsequential.

Automobile Engine Noise

Automobile engine noise arises from the same exciting mechanisms (combustion, motion of internal mechanical components, and piston slap) as for the diesel. However combustion noise is significantly lower than for the diesel due to the smoother cylinder pressure histogram. Mechanical noise and combustion noise are of approximately the same level. The spectrum of engine noise is somewhat similar to that of a diesel engine. Eq. 30 is to be used to predict 50-ft dBA levels.

Automobile Exhaust Noise

Exhaust noise is generated by essentially the same physical processes discussed in connection with diesel exhaust noise. The spectrum contains a peak at the engine firing frequency, above which it rolls off at about 6 dB/octave. Figure 19 shows typical spectra of muffled automobile engine exhaust noise. As Hillquist (*53*) points out, the exhaust noise characteristics of Car B is quite different from that of Cars A and C. For the former the higher frequencies (1,000 Hz and above) carry the most acoustic energy, whereas the exhaust noise for Car B is most significant in the range of the firing frequency. The "hiss" associated with the high-frequency noise is partially due to the expelling of high-velocity gas from the exhaust pipe.

The total power radiated by a circular jet of area A with Mach number M is (*54*):

$$\langle W \rangle_t = K A \rho c^3 M^8 \tag{62}$$

where K is a constant approximately equal to 5×10^{-5}. The ratio of the narrow-band power spectrum at frequency f to the peak narrow-band level at frequency, f_p, is

$$\phi/\phi_p = [9(f/f_p)]^3/[5 + 4(f/f_p)^{1.5}]^3 \tag{63}$$

with

$$f_p = 1.8\, V_e/d_{tp} \tag{64}$$

where d_{tp} is the tail pipe diameter in inches and V_e the exhaust gas velocity in ft/sec.

Because

$$\int_0^\infty \phi(f)\,df \simeq \phi_p f_p \tag{65}$$

$$\phi(f) = \frac{K A \rho c^3 M^8}{f_p}\,\frac{\phi}{\phi_p} \tag{66}$$

The band levels are

$$W_{band} = \int_{\Delta f} \phi(f)\,df \tag{67}$$

The velocity of the exhausting gas is estimated to be (*4*)

$$V_e = 1.45 \times 10^{-3}\,\frac{vN}{d^2_{tp}} \tag{68}$$

By "A" weighting the spectrum (Eq. 66) and using the exhaust velocity expressed in terms of the engine parameters, Eq. 62 can be used to obtain 50-ft levels for exhaust hiss owing to turbulent mixing at the tail pipe exit

$$L_{PA} = 80 \log \frac{N}{2{,}000} + 80 \log \frac{v}{300} - 140 \log \frac{d_{tp}}{1.5} + 30.5 \tag{69}$$

The levels predicted from this equation for typical automobile engine speeds, displacements, and tail pipe diameters are significantly below the values given in Figure 18. Exhaust hiss apparently originates in the muffler-tail pipe system and is not the result of turbulent mixing at the tail pipe exit.

Muffled Exhaust Noise Model

Automobile muffler insertion losses are not unlike those for truck mufflers (Fig. 8) (*4*). As a typical value, an insertion loss of 17 dB is selected and the following is used (*53*, *55*):

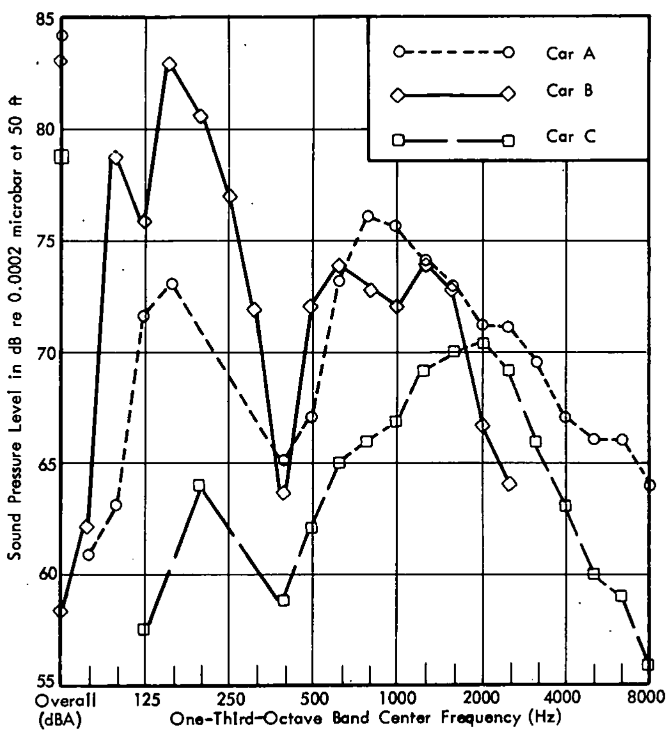


Figure 19. Typical muffled engine exhaust spectra (53).

$$L_{PA} = 77 + 10 \log \frac{bhp}{60} \quad (70)$$

Automobile Fan Noise

Automobile and truck fan noise arise from the same physical mechanisms. In general, automobile fans are smaller and have fewer blades. Water temperature controlled and viscous fluid clutches are sometimes used on automobiles to disengage the fan when ram air through the radiator is sufficiently high. Eq. 48 is equally applicable to either automobile or truck fans.

Automobile Intake Noise

It is apparent that during acceleration when the throttle valve is fully open (such as in the SAE acceleration tests) intake noise is higher than it is in the cruise condition where the throttle is only partially open and the flow is choked. In the first case, noise due to the periodic inflow into the engine caused by the opening and closing of the intake valves propagates freely through the intake. A mathematical treatment of wide-open throttle intake noise is presented in the Serendipity report (*4*). For purposes here, the following is suggested:

$$L_{PA} = 74\, \delta_A \quad (71)$$

δ_A equals 1 if the automobile is accelerating at or near wide-open throttle, and equals 0 otherwise.

Automobile Tire Noise

The automobile tire noise model used here places little emphasis on the effects of different types of treads and no differentiation is made between new and worn tires. Only the standard straight ribbed tire is considered in detail. Other types, such as smooth tires and snow tires, are considered in relation to the standard tread. In place of data showing variability with tread patterns (as was the case for truck tires), there is a proliferation of data for various pavements (Table 12). These data afford a broader picture in the other dimension, road surface texture. In addition to the 50-ft dBA levels given in Table 12, Foss (*56*) measured near field tire noise levels on a comparative basis over various surfaces with the following results:

PAVEMENT DESCRIPTION	RELATIVE LEVEL (dBA)
Grating with concrete fill	+7
Grating, open	+1
Rutted PC concrete	0
Worn and grooved PC concrete	−1
Spray grip	−3
Smooth PC concrete	−6
Epoxy-asphalt	−7.5

Automobile Tire Noise Modeling

Passenger car tires were grouped by tread-pavement sets in the same manner as for truck tires. With the data available, variations between pavements are evident. The base values selected as being representative of passenger car tire noise are presented in Table 13. Various paving types have been grouped together, mainly by surface texture. The 6-dB relative value between new and pitted PCC is consistent with Foss' data (*56*).

The 50-ft dBA levels are estimated to be

$$L_{PA} = B_{ATN} + 40 \log \frac{V}{40} + \delta_{wet}\, 10 \quad (72)$$

where V is the vehicle velocity in mph, and δ_{wet} equals 1 if pavement is wet and 0 otherwise.

TABLE 12

PASSENGER CAR TIRE NOISE [a]

			NOISE (dBA) AT 50 FT						
			ASPHALTIC CONCRETE				PORTLAND CEMENT CONCRETE		
REFERENCE	TIRE TREAD	DATA TYPE	DENSE-GRADED, MEDIUM-COARSE FINISH	OPEN-GRADED	SMOOTH	ROUGH	NEW, SMOOTH, BRUSH FINISH	COARSE BROOM OR BURLAP-DRAG FINISH	OLD PITTED OR ROUGH
Colorado (*42*)	Straight rib	Test	70	65	—	—	—	65.5	71
Hillquist (*40*)	Straight rib	Typ.	68.5	64	64–66	70.5	61.5	62.5	—
Tetlow (*41*)	Straight rib	Typ.	66	63	—	68.5–71	—	—	—
Vargovick (*57*)	Straight rib	Test	—	—	—	—	62.4	—	—
General Mtrs. (*58*)	Straight rib	Test	—	—	65	—	—	—	—
Tetlow (*41*)	Straight rib	Typ.	—	62.5–64.5	—	—	—	—	—
Colorado (*42*)	Snow tread	Test	71.4	68	—	—	—	73.5	75.2
Tetlow (*41*)	Snow tread	Typ.	—	67.5	67.5	—	—	—	—
Tetlow (*41*)	Smooth	Typ.	—	60.5	—	—	—	—	—
Hillquist (*40*)	Smooth	Typ.	67	62.5	65	69	—	—	—

[a] 40 Mph; Speed dependence correction = 40 log V/40.

TABLE 13

AUTOMOBILE TIRE NOISE BASE VALUES, B_{ATN}

TIRE TREAD	NOISE BASE VALUE (dBA)[a] OPEN-GRADED AND SMOOTH AC AND NEW PCC	DENSE-GRADED, MEDIUM-COURSE AC	OLD PITTED PCC AND ROUGH AC
Straight rib	64(66.5)[b]	68(70.5)	70(72.5)
Snow tread	67.5(72)	71(75.5)	75(79.5)
Smooth	63	67	69

[a] At 50 ft, 40 mph.
[b] New (worn) tire tread.

TABLE 14

COMPARISON OF AUTOMOBILE AND TRUCK TIRE NOISE[a]

TIRE TREAD	NOISE BASE VALUE (dBA) AUTOMOBILE	TRUCK	AVE. DIFF.
Straight rib	64/68 (66.5/70.5)	70.5(73)[b]	4.5
Cross bar/snow tire	67.5/71 (72/75.5)	75(79.5)	5.8

[a] From Tables 10 and 13.
[b] New (worn) tire tread.

Comparison of Truck and Passenger Car Tire Noise Models

Comparison of truck and passenger car tire noise models should tend to indicate whether or not they are similar in nature, and whether or not load alone accounts for observed differences. Table 14 compares automobile and truck tire noise base values. No automobile tire noise values for rough, pitted portland cement concrete surfaces are given because corresponding values are not available for truck tires.

The expected difference, based on the ratio of the single-axle truck load to the total passenger car weight is 10 log (18,400/4,000) = 6.5 dB. However, the inner tire of truck duals is effectively shielded by 6 dB when measuring peak coast-by levels. Thus, the truck tire noise measurement is reduced by 2 dB from that which would be measured if only single tires were mounted. The expected difference between measured passenger car and truck rib tire noise is therefore 4.5 dB.

A similar comparison can be made between automobile snow tires and truck cross lug tires. The expected differences due to weight and dual tires apply. In addition, snow tires, which are noisier than straight rib tires, are mounted only on the drive wheels. With the noise of straight rib tires on the front, the resulting automobile tire noise is 1.5 dB less than if snow tires were mounted on all four wheels. The net expected difference is 4.5 + 1.5 = 6 dB, which compares favorably with the model average difference of 5.8 dB.

Automobile Tire Noise Parametric Variations

Unlike truck tires, automobile tires are not subject to wide ranges of loading. In addition, the noise production of straight rib tread patterns does not seem to change with load. Truck rib tires show an average noise degradation of 2.5 dB with wear. Hillquist and Carpenter (*40*) found similar results for straight rib and discrete block passenger car tires. No data are available on worn snow tires. The 4.5-dB increase with wear for truck cross lug tires is taken as an unbiased estimate of the wear factor for snow treads.

Wet pavement appears to have an adverse effect on passenger car tire noise. Rathe (*59*) measured a 14-dB average increase on wet asphaltic concrete and a 9-dB average increase on wet portland cement concrete. A value of 10 dB is used in the noise model for wet pavements.

Other parameters found to have negligible effect on coast-by noise are: (1) inflation pressure, (2) tire size, and (3) carcass construction (bias or radial).

Automobile Rotary Engines

Data for rotary engine noise are totally lacking. It is not believed that rotary engines should be inherently quieter than piston engines, although some spectrum differences should exist and the rotary engines would generally have lower power ratings.

Motorcycles

Information concerning motorcycle component noise is rather sketchy (*5*). Exhaust and intake noise are obviously dominant and engine noise is quite significant. Noise generation mechanisms are essentially the same as for other internal combustion engines. Discussion of the individual sources (except for tire noise) is deferred until motorcycle noise abatement potential is considered (in a later section).

Tire Noise

Insufficient published motorcycle tire noise data were found for forming a tire noise model. However, because agreement was found between automobile and truck tire noise models on the basis of 10 log (weight ratio), motorcycle tire noise can, in turn, be estimated from passenger car tire noise with some confidence. The expected difference between passenger car and motorcycle tire noise is on the basis of the weight ratio:

$$10 \log \frac{600}{4,000} = -8 \text{ dB} \qquad (73)$$

Inasmuch as the motorcycle travels on two tires, an additional correction is needed. Car tires nearest an observer are principally responsible for the measured noise, with possibly 1 dB being added by the farside tires. If all the weight were placed on the nearside tires, the level would decrease by 1 dB for removal of the farside tire noise and increase by 3 dB for doubling of weight, for a net change of +2 dB. Therefore, a two-wheeled vehicle is 2 dB noisier than a 4-wheeled vehicle of equal weight. With the weight correction, motorcycle tires are estimated to produce 6 dB less noise than passenger car tires. The estimates are given in Table 15.

Description of Motorcycle Noise

Figures 20 and 21 show, respectively, spectra of two 125-cc, 2-stroke motorcycles and two 350-cc, 4-stroke motorcycles as measured during SAE-J331 acceleration tests (*60*). The over-all levels for the two motorcycles of Figure 20 are 83 and 88 dBA, and for those of Figure 21, 84 and 91 dBA. Figures 22 and 23 show the maximum noise levels produced during SAE acceleration tests and in 40-mph drive-by for both 2- and 4-stroke engines. Larger-displacement engines had higher noise levels in the acceleration test but the opposite was true during drive-by. However, Serendipity data (*4*) do not show this reverse behavior.

Motorcycle Noise Models

Table 16 gives two candidate noise models for 2- and 4-stroke motorcycles at steady speeds and when accelerating from 30 mph. The Serendipity model (*4*) data were used to estimate velocity dependence for the AMA (*60*) models.

Figure 24 shows a comparison of these models as a function of engine displacement (speed variation is assumed the same). The small data base for the Serendipity data (*61*), makes use of Eqs. 75, 77, and 79 (Table 16) preferred.

Finally, the tire noise is considered:

$$L_{PA} = B_{MTN} + 40 \log \frac{V}{40} \qquad (80)$$

The worst case from Table 15 for a 600-lb (loaded) cycle (estimated $v_{cc} = 500$ cc) is a B_{MTN} of 69 dBA for new knobby tires at 40 mph and 76 dBA at 60 mph. Eq. 75 would give, equivalently, 71 and 78 dBA at the two speeds.

This indicates that Eqs. 75 and 77 are sufficiently accurate estimators to include tire noise at speeds above 40 mph and therefore Eq. 80 is redundant.

AGGREGATE NOISE MODELS AND APPLICATION

Application of the noise prediction equations of the previous three sections is relatively straightforward, given sufficient supporting information. From the vehicle operation standpoint, either the cruise or the acceleration condition can be considered.

Tire noise has been shown to depend entirely on vehicle speed, given a vehicle tire-road surface combination. However, the other noise sources have noise generation properties dependent on engine speed and power. Given transmission and rear end ratios and tire size, road speed and engine speed can be related. Fan speed can be related to engine speed through the pulley ratio. Table 17 gives typical values for some of these parameters for distinguishable classes of vehicles.

Truck Noise

Figure 25 shows the speed and power ranges of a typical 300-hp, 4-stroke turbocharged diesel engine as a function of road speed, based on the nominal rear-end ratio and tire size from Table 17 (typical 10-speed transmission). The

TABLE 15

MOTORCYCLE TIRE NOISE BASE VALUES, B_{MTN}

	NOISE BASE VALUE (dBA)[a]		
TIRE TREAD	OPEN-GRADED AND SMOOTH AC AND NEW PCC	DENSE-GRADED MEDIUM-COARSE AC	OLD PITTED PCC AND ROUGH AC
Straight rib	58(60.5)[b]	62(64.5)	64(66.5)
Knobby	61.5(66)	65(69.5)	69(73.5)

[a] At 50 ft, 40 mph, for 600-lb (loaded) vehicle.
[b] New (worn) tire tread.

TABLE 16

MOTORCYCLE NOISE MODELS (dBA at 50 feet)

SOURCE	MODEL	EQ. NO.	REMARKS
Serendipity (*4*)	$L_{PA}=66+30 \log \frac{V}{40} + 10 \log \frac{v_{cc}}{100}$	(74)	4-stroke, steady speed
AMA (*60*)	$L_{PA}=74+30 \log \frac{V}{40} - 4.24 \frac{v_{cc}}{100}$	(75)	4-stroke, steady speed
Serendipity (*4*)	$L_{PA}=65+20 \log \frac{V}{40} + 6 \log \frac{v_{cc}}{100}$	(76)	2-stroke, steady speed
AMA (*60*)	$L_{PA}=74+20 \log \frac{V}{40} - 4.24 \log \frac{v_{cc}}{100}$	(77)	2-stroke, steady speed
Serendipity (*4*)	$L_{PA}=77+8 \log \frac{v_{cc}}{100}$	(78)	2- or 4-stroke, accel. from 30 mph
AMA (*60*)	$L_{PA}=83+8.95 \log \frac{v_{cc}}{100}$	(79)	2- or 4-stroke, accel. from 30 mph

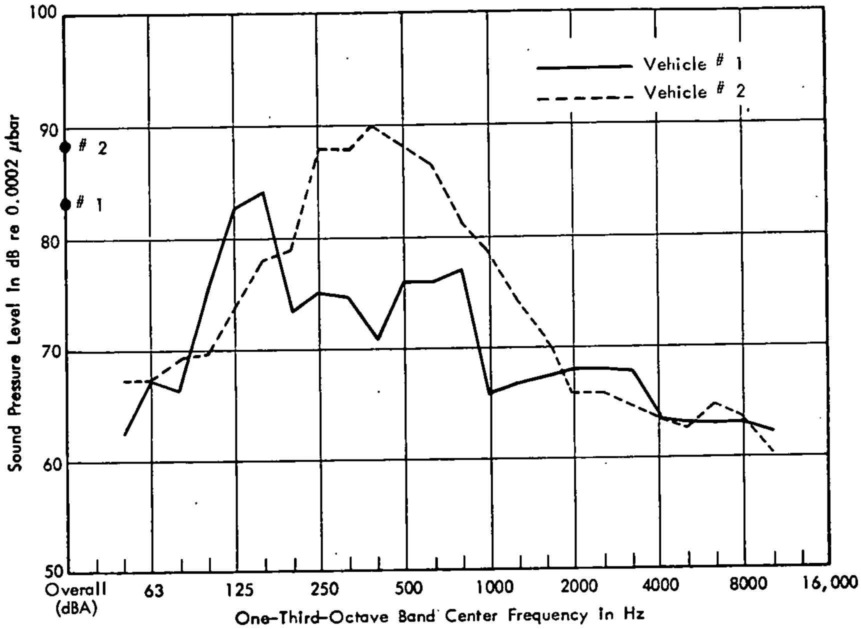


Figure 20. Comparison of spectrum levels for two 125-cc, 2-stroke motorcycles in SAE acceleration test (60).

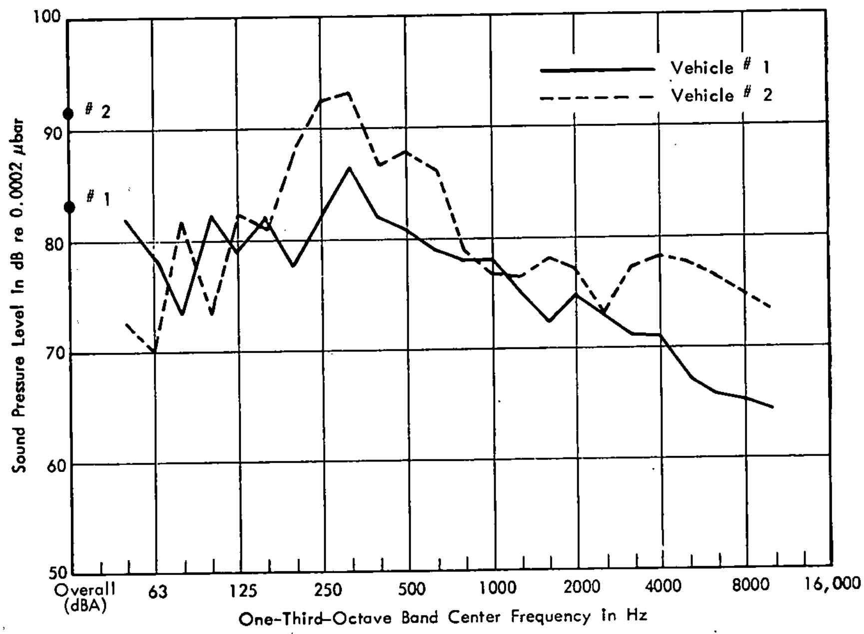


Figure 21. Comparison of spectrum levels for two 350-cc, 4-stroke motorcycles in SAE acceleration test (60).

truck driver has a choice of two gears at each road speed. In general, he will tend to operate the vehicle at the maximum speed possible, limited only by power when on a grade and by traffic and speed limits when on the level. Curves similar to Figure 25 for particular engines, transmissions, rear-end ratios, GVW, and tire size are necessary (and sufficient with other information provided in this report) to utilize the diesel truck noise model of Figure 26.

Figures 27 and 28 give estimates for engine, exhaust, and fan noise for a nominal diesel truck as calculated with the model. Figure 28 shows that the exterior noise of a diesel truck can be expected to vary approximately 10 dB over the speed range from 20 to 65 mph. In the highway speed range from 45 to 65 mph, the average variation is 5 dB, which is different from the constant-noise assumption in the preceding study (*2*).

Table 18 presents a summary of published data for individual heavy diesel trucks during acceleration testing. The table also gives levels for mixtures of gasoline- and diesel-powered heavy trucks during cruise.

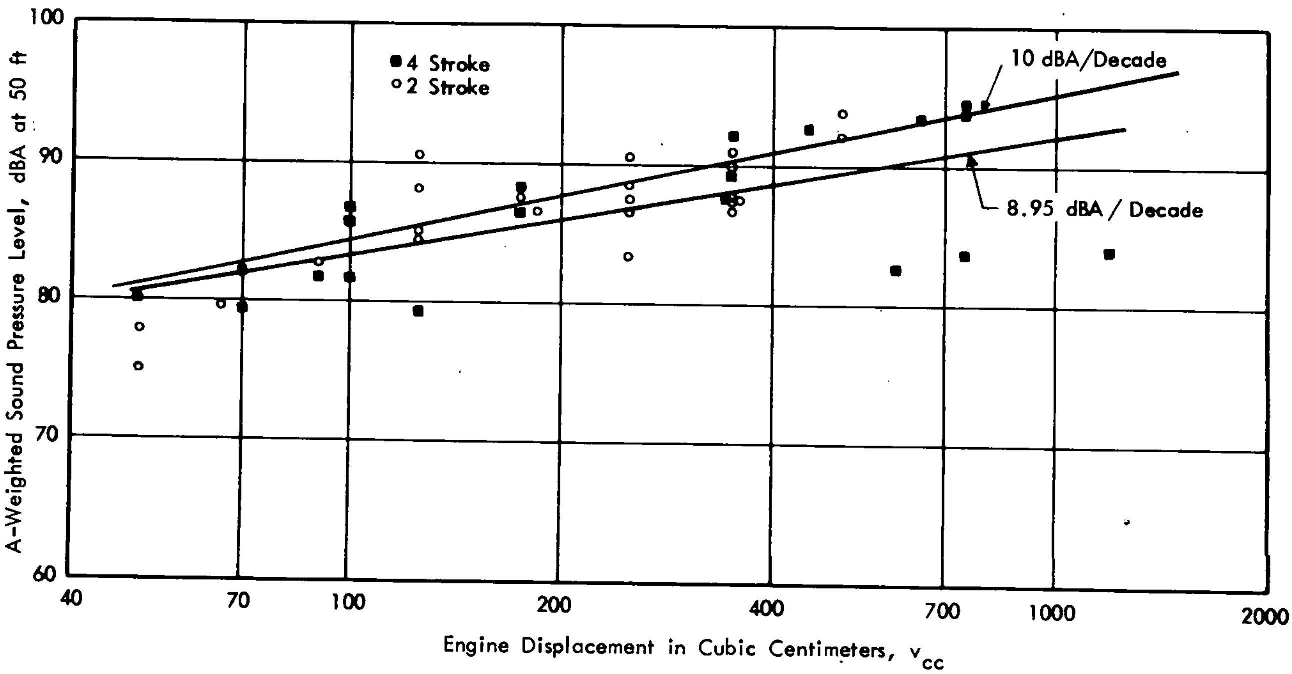


Figure 22. Maximum noise levels produced during SAE motorcycle acceleration tests (60).

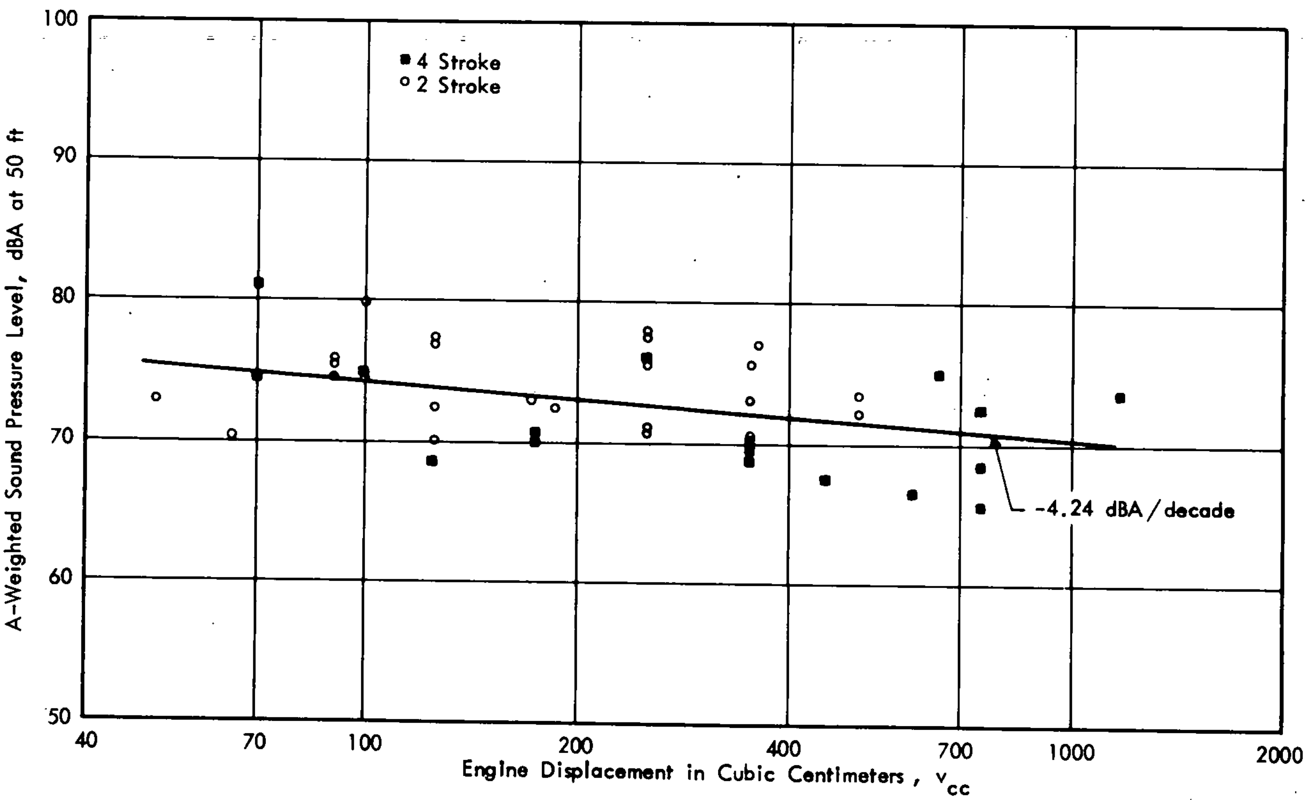


Figure 23. Maximum noise levels produced during 40-mph motorcycle driveby at 50-ft distance (60).

Automobile Noise

Figure 29 shows a typical large passenger car engine speed and power range as a function of road speed, based on the nominal rear-end ratio and tire size of Table 17 (typical 3-speed transmission). Curves similar to those of Figure 29 are necessary to utilize the automobile noise model of Figure 30. Table 19 gives measured values for passenger cars for comparison with calculations. For reference,

Table 20 gives data regarding power trains for a few models of passenger cars.

Motorcycle Noise

The models given in Table 16 are dependent only on engine displacement and speed. Table 21 gives measured values for both accelerating and cruise conditions. The principal sources furnished the data base for the modeling, so good agreement is expected.

REDUCTION POTENTIAL

In this section, estimates of total vehicle noise reduction potential are generated from estimates of component noise reduction potential. Component noise abatement potential is based on technical feasibility and economic practicality.

TABLE 17

CHARACTERISTICS OF TYPICAL VEHICLES

VEHICLE TYPE	PROPULSION TYPE	ENGINE SPEED RANGE (RPM)	PEAK TORQUE ENGINE SPEED (RPM)	NOMINAL REAR-END RATIO	TIRES (REV/MI)	ENGINE SPEED AT 60 MPH (RPM)	FAN RATIO, F_r	FAN DIAM., d_f (IN.)	FAN TIP SPEED (FT/SEC)[a]
Heavy truck	Diesel, ≥ 600 in.^{3}	1200–2100	1500	4.1	490	2000	1.2	28	290
Medium truck	Diesel, ≤ 600 in.^{3}	1800–3300	1800	5	520	2600	1.0	24	260
Medium truck	Gasoline	800–3600	2000	6.5	540	3500	1.0	20	305
Large passenger car and light truck	Gasoline	1000–4600	2400	2.9	770	2230	1.1	17.5	187
Small passenger car	Gasoline	1500–5500	3600	3.9	815	3200	1.1	15	220
Motorcycle	Four-stroke	2000–9000	7000	7.7	775	6000	—	—	—
Motorcycle	Two-stroke	1000–9000	7000	5.8	775	4500	—	—	—

[a] At 60 mph.

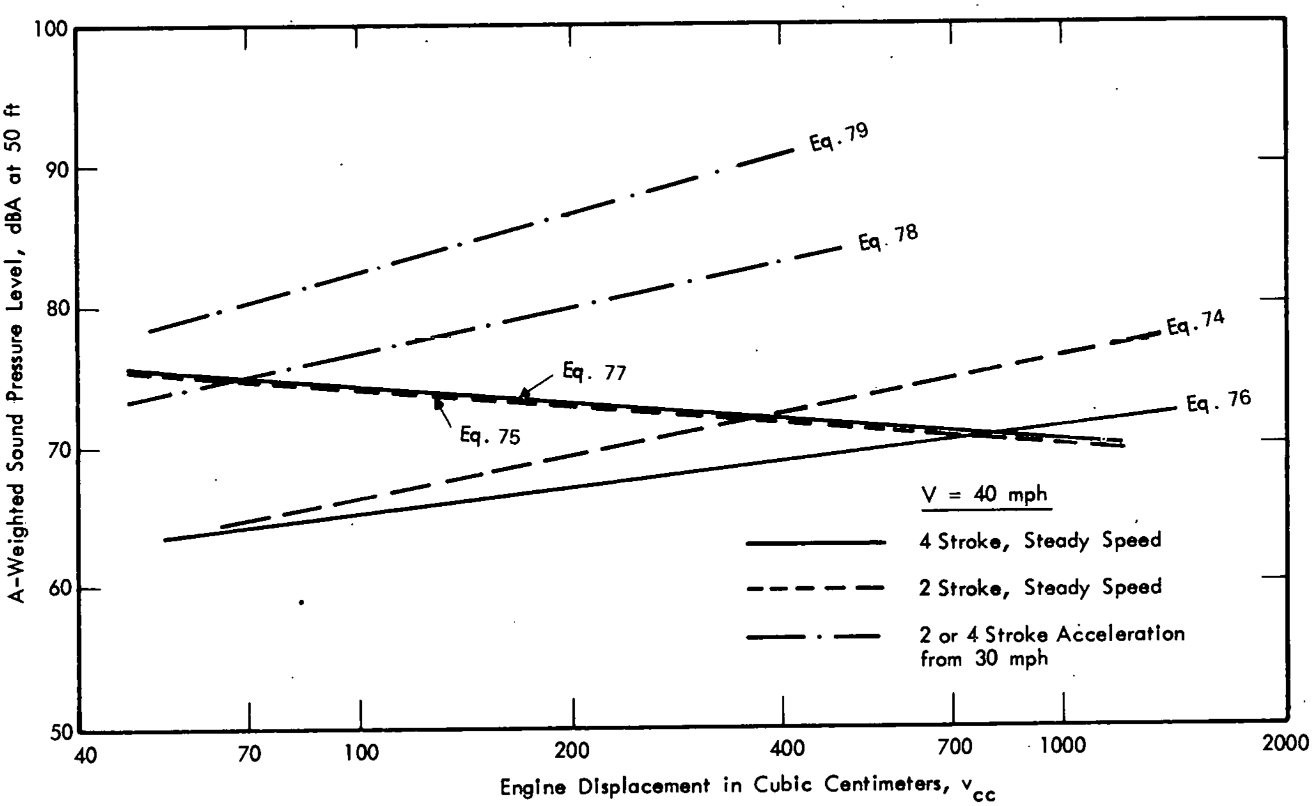


Figure 24. Comparison of motorcycle noise models (4, 60).

Diesel Trucks

Engine Noise Reduction

Noise reduction involves either modification of the engine or use of enclosures (covers or partial enclosures). Law (*62*) relates the following changes made to a Detroit Diesel 8V-71 engine to effect noise reduction:

1. Piston and liner clearance reduction.
2. Reduced piston, piston pin, and upper connecting rod joint clearances and lubrication at higher pressures.
3. Spur gear-type oil pump replaced by a screw-type pump.
4. Pump idler gear changed to nylon.
5. Rear gear train replaced by a belt.
6. Hydraulic valve lifters installed.
7. Pilot injectors installed (these start fuel burning in a precombustion chamber to reduce combustion noise).
8. Separation of the main bearing webs from the lower section of the cylinder block.

The net reduction effected was 4 dBA. However, Law states that other studies were less successful, with reductions of from 1 to 3 dB. Cummins Engine Company (*77*) has estimated a maximum of 3 dB reduction through engine modification.

The most promising methods for engine noise reduction are close-fitting covers (shields) and engine enclosures. Laminated steel covers closely fitted over valve covers, oil pan, blower covers, and cylinder block side panels gave 3- to 5-dB reductions. Total engine enclosures have been shown to provide from 8- to 15-dBA (*62*) and from 12- to 23-dBA (*78*) reductions. To be effective the enclosures have been vibration-isolated from the engine, completely sealed, and covered internally with acoustical insulation. Enclosures of steel, aluminum, and fiberglass have been used (*62, 77, 78*). Partial enclosures or acoustic ducts achieve noise reduction values between those attributed to close-fitting covers and total enclosures (*77*).

Close-fitting engine covers are essentially an integral part of the engine, which minimizes their impact on vehicle maintenance. In additon, because they are presently available for only the cooled portions of the engine (not the exhaust manifold), they do not create any cooling problem. Engine enclosures, on the other hand, are afflicted with both maintenance and cooling problems. Maintenance requires at least partial removal of the enclosures. The heat

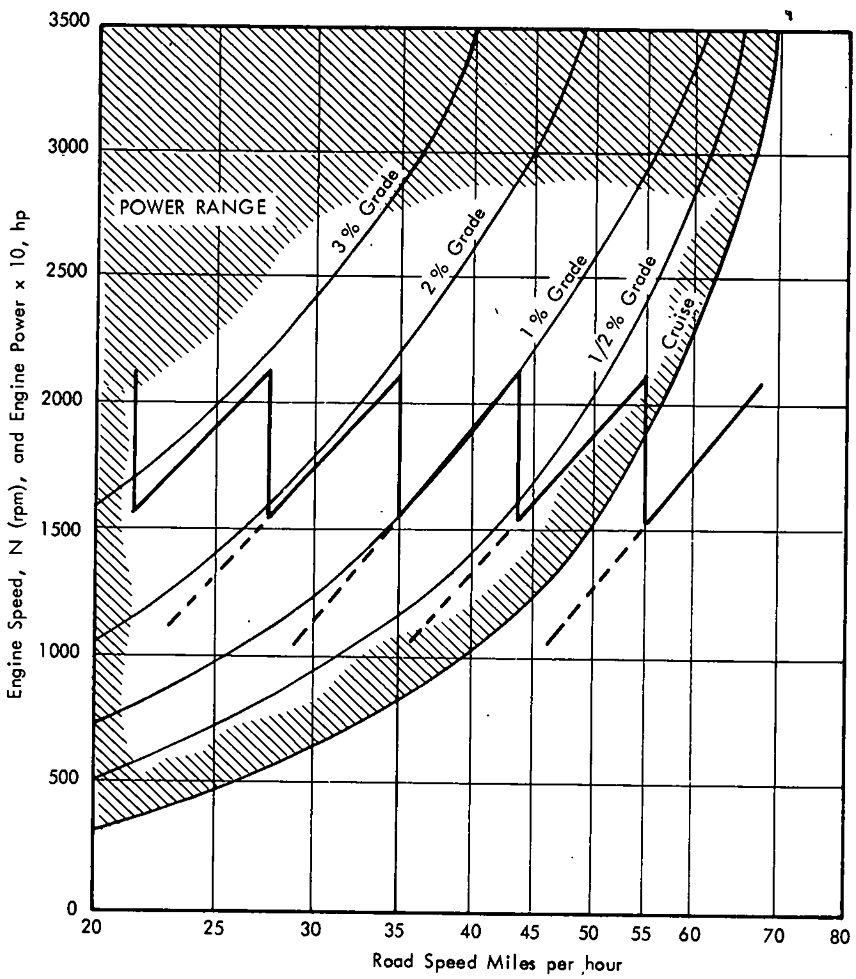


Figure 25. Diesel engine speed and power, typical 10-speed transmission, GVW=73,000 lb..

rejection of the exhaust manifold is sufficient to raise the temperature of an insulated, airtight enclosure to a point where the fire hazard is a serious consideration.

In the DOT Quiet Truck Program (*77*), total enclosure of the engine was rejected in favor of close-fitting covers (Cummins NTC-350 engine). Approximately 3 dB reduction was expected to be obtained from the covers. To achieve additional engine noise reduction, a belly pan was added to the truck chassis and the underside of the cab sitting over the engine became the top of the flow-through engine enclosure, which was sealed against the belly pan. The fan was moved forward and air was ducted through the enclosure. Acoustical insulation (glass fiber covered with high-temperature plastic film) covered the interior of the enclosure. Whereas complete enclosures and covers attenuate noise by acting as barriers, the quiet truck enclosure absorbed sound and (almost) removed line-of-sight exposure.

Although total noise reduction for the enclosure system was not measured, the quiet truck achieved 72 dBA. Engine noise is estimated to be 69 or 70 dBA. When compared to the 80 dBA of the engine with covers, this gives an estimated ducted enclosure effectiveness of 10 or 11 dB.

Other engine noise reduction studies are included in Refs. *70, 79, 80, 81, 82*. Table 22 summarizes potential engine noise reductions.

Exhaust Noise Reduction

Noise reduction involves improved muffling through use of (a) manifold mufflers, (b) optimum muffler selection (high insertion loss), (c) dual exhaust mufflers, (d) wrapping of exhaust mufflers, (e) vibration isolation between exhaust manifold and exhaust piping.

Manifold mufflers have been shown to be effective and useful devices. Table 23 gives the performance of a manifold muffler (*22*) as a function of engine speed and power for different exhaust system configurations, including a "T" branch, dual exhaust mufflers, and a glass fiber-lined secondary (stack) muffler in place of a tail pipe (Cummins NTC-350 engine). Manifold muffler performance is relatively independent of exhaust system configuration, offering a 3- to 5-dB reduction.

In general, the reduction afforded by exhaust mufflers is dependent on both the muffler type and the engine for which it is to be used. Achievement of insertion losses of up to 30 dB is possible without increasing engine back pressure significantly (Fig. 31). Ideally, one would choose a muffler with the maximum insertion loss. However, cost considerations (especially the dependence of fuel consumption on exhaust system back pressure) can become the deciding factor in muffler selection.

Dual exhaust mufflers afford reduced engine back pressure. The introduction of splitter "T" cans lined internally with sound absorbing material can yield an additional 2- to 6-dBA reducton.

Wrapping of exhaust mufflers with outer covers of asbestos and sheet metal will reduce sound being radiated from the muffler shell. A muffler shell vibrating at levels of from 1 to 3 g (*32*) might alone yield 50-ft levels of 60 to 70 dBA, which could be important if total truck noise were reduced near these levels. Furthermore, it is important to vibration-isolate the exhaust pipe from the engine manifold.

Fan Noise Reduction

Candidate techniques for reducing fan noise include: (a) stopping the fan when it is not needed with a water temperature controlled clutch (*33, 5, 83*); (b) slowing the fan when it is not needed with an air temperature controlled viscous clutch (*37, 5, 83*); (c) replacing the fan with a larger, slower turning unit (*37, 5, 62*); (d) replacing the fan with a higher performance unit (more blades, wider blades) and reducing the fan speed (*84*); (e) decreasing the fan tip clearance (to improve performance) and reducing fan speed (*62, 84*); (f) optimizing the cooling system to minimize the product of $QP^2{}_S$ (provide a larger radiator) (*83*); and (g) decreasing inlet turbulence to the fan (*83*).

The noise reduction derived from a thermatic clutch depends on the fan demand or duty cycle. Figure 32 shows four cooling system-related curves—engine power versus road speed, engine heat rejection versus engine power, radiator heat transfer versus fan flow performance, and ram air versus vehicle speed. These curves are oriented in such a manner that their common axes are parallel. Consider for example a truck speed of 50 mph on a 2 percent grade. Three hundred fifty horsepower are required and the heat rejection is close to 10,000 Btu/min. A 6-ft^2 radiator (four row, ten fins/in.) would require an air flow of more than 10,000 cfm to transfer this much heat. A 10-ft^2 radiator of the same construction could do it with a flow of slightly less than 8,000 cfm. According to Fig. 32(d), ram air will provide a little more than 5,000 cfm through the 6-ft^2 radiator and more than 8,000 cfm through the 10-ft^2 radiator. The fan would have to be running if the 6-ft^2 radiator was being used. However, the ram air is sufficient for the 10-ft^2 radiator and the fan could be turned off.

Figure 32 shows performance characteristics that are reasonably well defined. Functional relations of truck speed versus power and engine heat rejection have only small differences from model to model. Radiator thermal performance does vary, but only over a range of a factor of two for commercially popular cores. The curve presented as Figure 32(d) is based on thermal measurements taken on the Freightliner quiet truck (*85*).

Figure 32 has been used to calculate the region of the engine-power-versus-speed curve where there is a deficiency of ram air. This information, presented in Figure 33, shows that fan demand is inversely proportional to the size of the radiator. Moreover, the portion of a truck's operation time where the fan is off increases dramatically with increased radiator size inasmuch as the proportion of highways decreases with grade. In order to qualify as a legitimate noise reduction measure, a criterion should be established. This criterion could be based on an air-to-boil temperature measurement with the fan off. This should be done at a fixed power because high-powered engines would be penalized (they go up hills faster, creating more ram air). An air-to-boil temperature difference of 115 F at 25 mph while delivering 250 hp is easily achievable and would limit fan demand to grades above 3 percent on hot days.

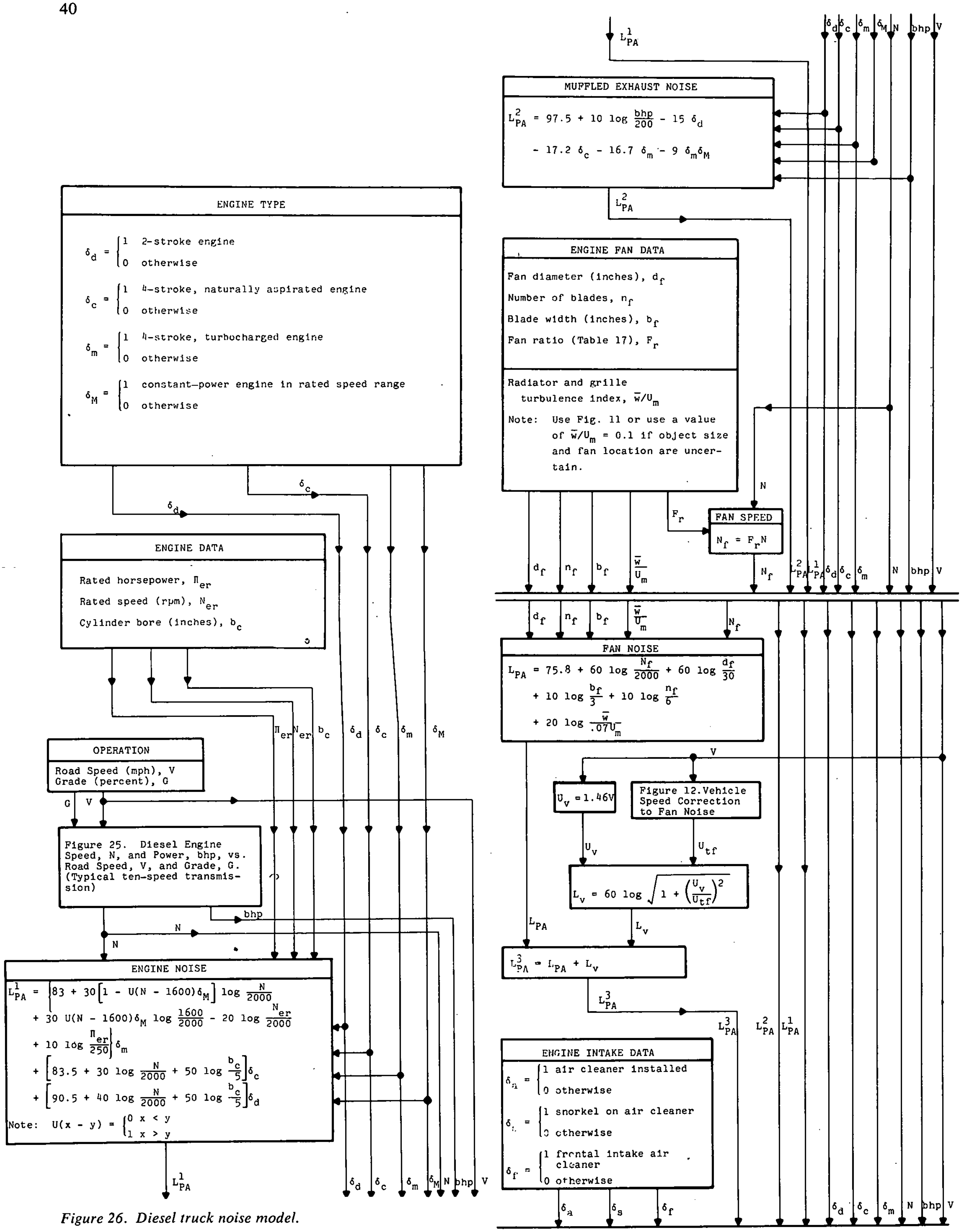
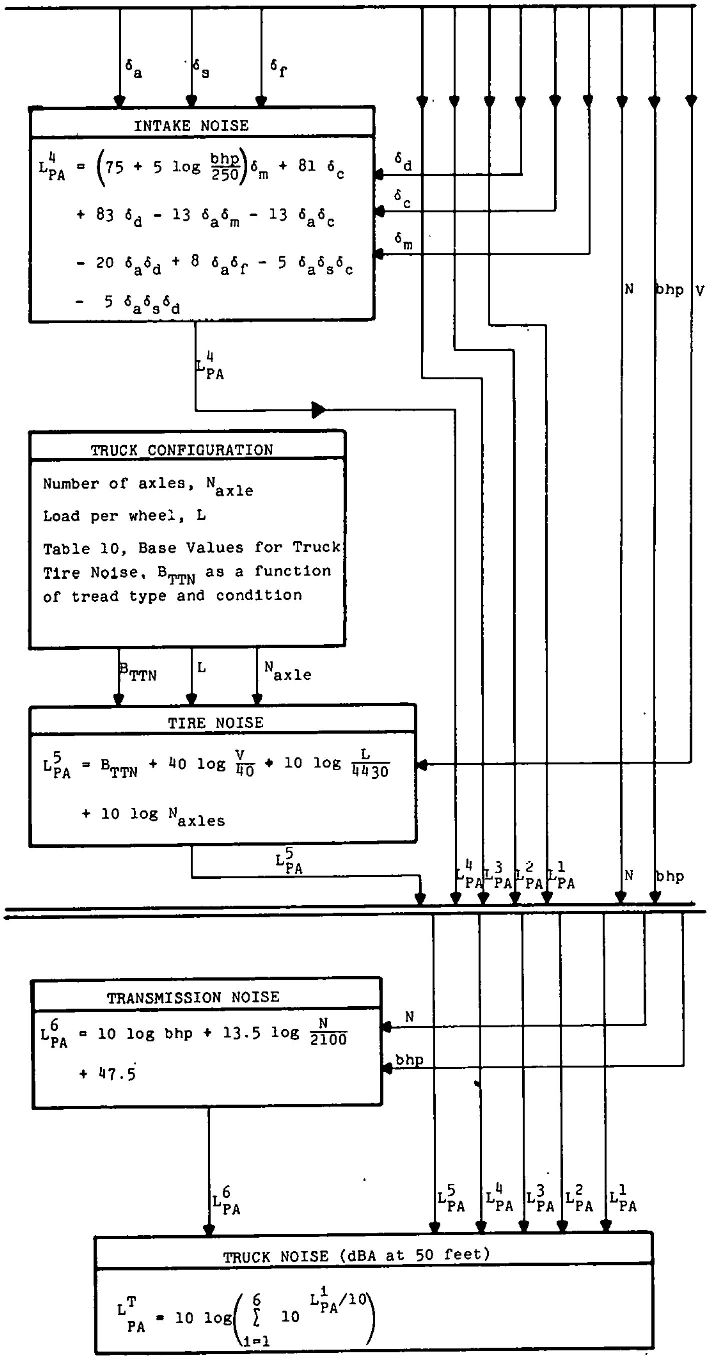


Figure 26. Diesel truck noise model.

Viscous fan clutches respond to impinging air flow temperature, and go from almost totally engaged to almost totally disengaged (Fig. 34). When disengaged, the fan turns at slightly more than four-tenths speed, generating approximately 21 dB less noise than at engaged speed. The same discussion about fan demand and noise control effectiveness of thermatic clutches applies to viscous clutches. The fuel savings realized by not running the fan are offset by the disengaged drag and the engaged slippage.

Designing the cooling system with a large, slow turning fan has been suggested. However, no substantiating evidence bears out noise reduction. Fan laws (*86*) do not indicate a decrease in noise with size when flow and static pressure are held constant. Comparison of fan curves shows that tip speed remains virtually constant for the same flow performance. Nevertheless, some noise reduction may be



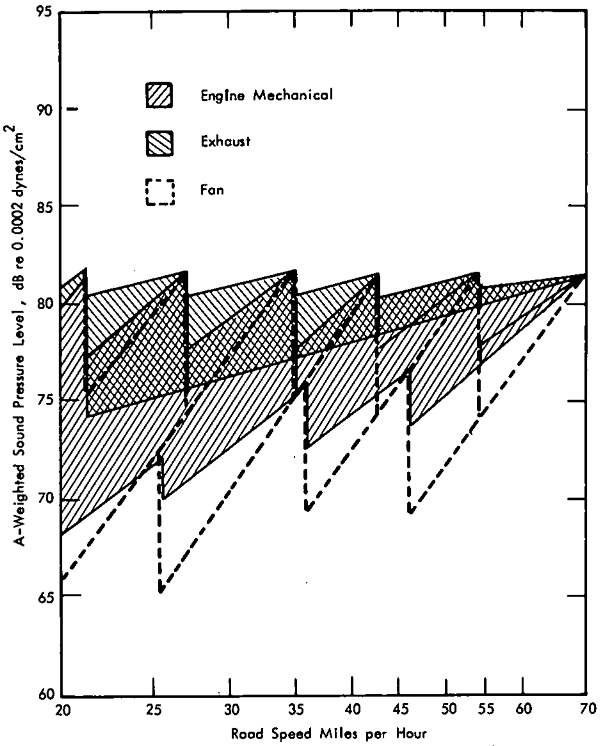


Figure 27. Component contributions to nominal truck noise measured at 50 ft.

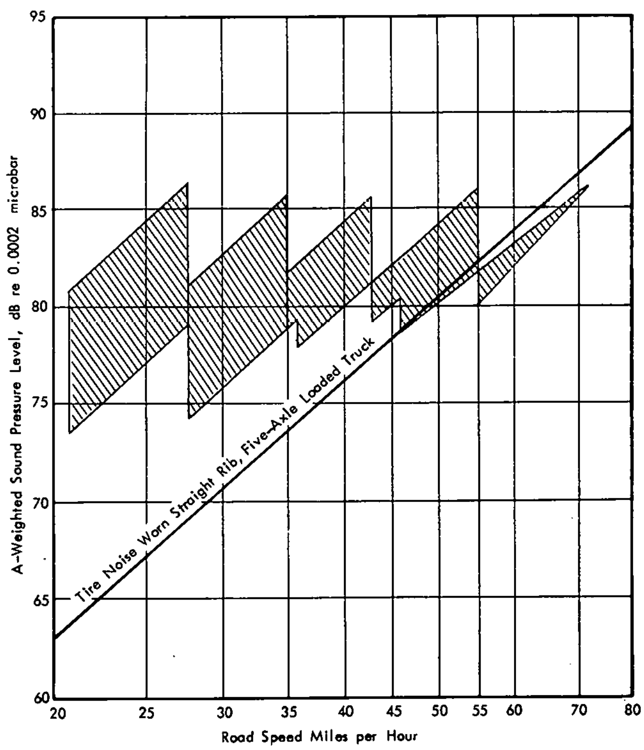


Figure 28. Sum of diesel engine, exhaust, and fan noise (Fig. 27) measured at 50 ft.

achieved due to the second-order effects: (a) reducing the blade passage frequency lowers the "A"-weighted noise level; (b) the ratio of tip clearance to diameter may be decreased, tending to improve flow performance; (c) a fan that sweeps the width of the radiator should have better inlet flow characteristics; (d) a fan that discharges air around the engine instead of into the engine obstruction may have better flow characteristics.

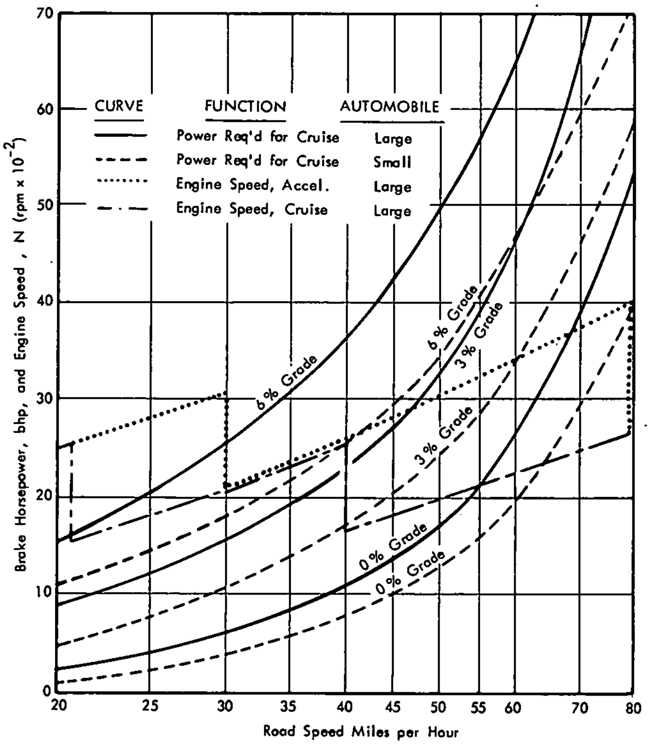


Figure 29. Power and engine speed of passenger cars vs road speed (132).

Fan noise reduction can definitely be achieved by improving the cooling system performance with high-performance fans, radiator core selection, radiator size selection, and cooling air recirculation control. The gross difference in ideal and realized fan performance should be motivation for continued work in this area.

No great promise is held for the development of inherently quiet fans, because inlet turbulence and discharge obstructions seem to be more significant from the noise generation standpoint than is perfection of the blade shape. On the other hand, many things can be done that will ensure large noise production, such as operating the fan in an aerodynamically stalled condition.

Intake Noise Reduction

Present-day air cleaners provide sufficient reduction of intake noise such that 50-ft levels are below 70 dBA (62 to 68 dBA on the average (*23*), 72 to 76 dBA maximum (*35*). With snorkels and inlet silencers, the levels can be reduced sufficiently at present to allow achievement of projected truck noise reduction far into the future. Intake noise on the Freightliner quiet truck was 62 dBA.

Tire Noise Reduction

Tire noise reduction is essentially tire tread-roadway surface selection. Barring some unanticipated technical breakthrough in tire noise, noise reduction for existing highways is a matter of tread selection. The data presented in Table 10 show that use of the neutral rib and rib tire treads effect noise reductions of from 4.5 to 6 dBA over the cross lug tread and from 15.5 to 17 dBA over the pocket retread. Noise reduction by tire selection (or exclusion) is being required by regulation for the first time by the EPA. Noise emission standards for interstate motor carriers (*87*) pro-

TABLE 18

HEAVY TRUCK OVER-ALL INDIVIDUAL VEHICLE NOISE AT SAE STANDARD ACCELERATING AND CRUISE CONDITIONS

SAE ACCELERATION, DIESEL ONLY				CRUISE, 35 MPH				CRUISE, 55–65 MPH			
NOISE (dBA)				NOISE (dBA)				NOISE (dBA)			
AVE.	STD. DEV.	NO. VEH.	REF.	AVE.	STD. DEV.	NO. VEH.	REF.	AVE.	STD. DEV.	NO. VEH.	REF.
87.6	1.3	11	Wyle (*5*)	77	2.8	105	CHP (*65*)	87.5	4	5838	CHP-1965
87.2	2.9	11	Law (*62*)	78.4	4	58	Olson (*72*)	87.8	2.8	172	CHP (*65*)
87	1.8	14	DOT (*63*)	80.9	4	32	Olson (*72*)	88	3	531	Foss (*73*)
88.1	0.9	14	Freightliner (*22*)	77	N/A	Typ	Hillquist (*53*)	88.3	4	515	BBN (*74*)
85.8	1.3	9	Johnston (*64*)					87.9	3	122	Olson (*72*)
85.6	2.5	4	CHP (*65*)	79.5	3.5	Typ	(Best est.)	85.3	3.2	6	CHP (*65*)
84.5	1.3	3	WHI (*66*)					85.6	3.4	6	WHI (*66*)
85.5	N/A	Typ	Hillquist (*53*)					85	N/A	Typ	Hillquist (*53*)
88	N/A	1	Cummins (*67*)								
87.6	N/A	1	Scott (*68*)					87.5	3.5	Typ	(Best est.)
88	N/A	1	Freightliner (*32*)								
88	N/A	1	IHC (*69*)								
87	N/A	Typ	Jenkins J5 (*70*)								
88	N/A	Typ	Ringham R2 (*71*)								
87	1.5	Typ	(Best est.)								

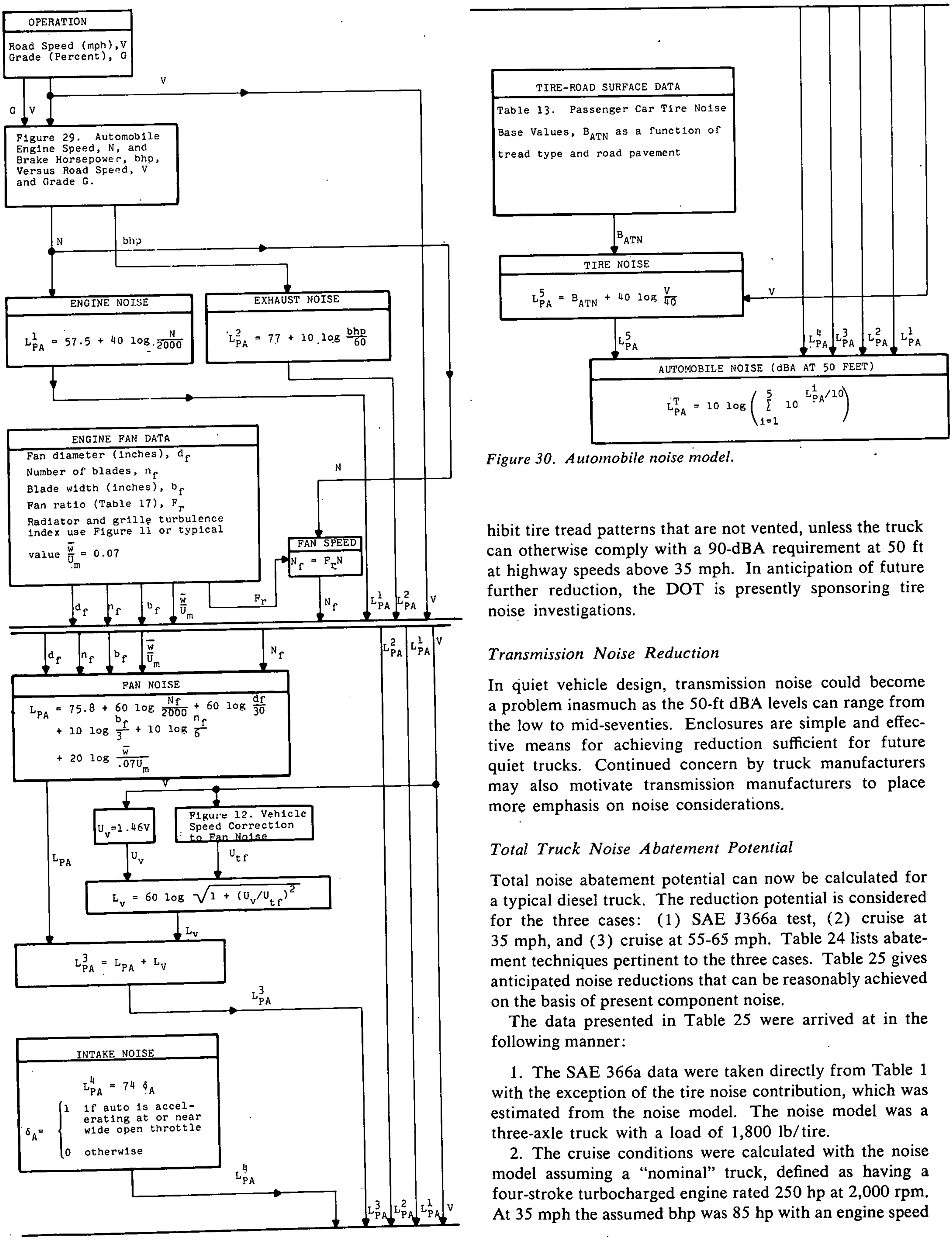


Figure 30. Automobile noise model.

hibit tire tread patterns that are not vented, unless the truck can otherwise comply with a 90-dBA requirement at 50 ft at highway speeds above 35 mph. In anticipation of future further reduction, the DOT is presently sponsoring tire noise investigations.

Transmission Noise Reduction

In quiet vehicle design, transmission noise could become a problem inasmuch as the 50-ft dBA levels can range from the low to mid-seventies. Enclosures are simple and effective means for achieving reduction sufficient for future quiet trucks. Continued concern by truck manufacturers may also motivate transmission manufacturers to place more emphasis on noise considerations.

Total Truck Noise Abatement Potential

Total noise abatement potential can now be calculated for a typical diesel truck. The reduction potential is considered for the three cases: (1) SAE J366a test, (2) cruise at 35 mph, and (3) cruise at 55-65 mph. Table 24 lists abatement techniques pertinent to the three cases. Table 25 gives anticipated noise reductions that can be reasonably achieved on the basis of present component noise.

The data presented in Table 25 were arrived at in the following manner:

1. The SAE 366a data were taken directly from Table 1 with the exception of the tire noise contribution, which was estimated from the noise model. The noise model was a three-axle truck with a load of 1,800 lb/tire.

2. The cruise conditions were calculated with the noise model assuming a "nominal" truck, defined as having a four-stroke turbocharged engine rated 250 hp at 2,000 rpm. At 35 mph the assumed bhp was 85 hp with an engine speed

TABLE 19

PASSENGER CAR OVER-ALL INDIVIDUAL VEHICLE NOISE AT SAE STANDARD ACCELERATING AND CRUISE CONDITIONS

SAE ACCELERATION NOISE (dBA)				CRUISE, 35 MPH NOISE (dBA)				CRUISE, 55–65 MPH NOISE (dBA)			
AVE.	STD. DEV.	NO. CARS	REF.	AVE.	STD. DEV.	NO. CARS	REF.	AVE.	STD. DEV.	NO. CARS	REF.
79.7	4	8	G.M. (*58*)	68	3	9395	CHP (*76*)	74.2	3.1	2865	CHP (*76*)
80	3.4	4	Vargovick (*57*)	68	3.1	762	CHP (*65*)	78.9	2.6	476	CHP (*65*)
76.5	4	13	BBN (*75*)	64.4	3	215	Olson (*72*)	78.6	2	337	Foss (*73*)
77.3	2	3	Hillquist (*53*)	61.4	1.4	8	GM (*58*)	73	2.5	283	Olson (*72*)
80	3	Typ	(Best est.)	62	1.5	4	Vargovick (*57*)	71.5	2.1	4	Vargovick (*57*)
				64.2	3	13	BBN (*75*)	72.8	2.3	8	GM (*58*)
				69	N/A	Typ	Hillquist (*53*)	76.5	N/A	Typ	Hillquist (*53*)
				65	N/A	Typ	Hillquist (*53*)	73	N/A	Typ	Hillquist (*53*)
				66	3	Typ	(Best est.)	77.5	3.	Typ	(Best est.)

TABLE 20

PASSENGER CAR POWER TRAINS

CAR MAKE	CAR MODEL	ENGINE TYPE	ENGINE (%)[a]	REAR-END RATIO	TIRES SIZE	TIRES (REV/MILE)	ENGINE REV/MILE	FAN DIA. (IN.)	FAN TIP SPEED (FT/SEC)[b]	TRANS. TYPE	TRANS. (%)[a]
Chevrolet	Full size	$V8^{327}$	95	3.08	8.25×14	753	2320	—	—	2-spd. auto.	96
Ford	Mustang	$V8^{351}$	81	2.75	E78×14	797	2270	17.5	173	3-spd. auto.	70
VW	Bug	4^{1300cc}	100	4.375	5.60×15	780	3400	—	—	4-spd. man.	
Ford	Full size	$V8^{302}$	98	2.80	8.25×15	755	2110	18.3	167	3-spd. auto.	98
Chevrolet	Chevelle	$V8^{307}$	89	2.73	7.35×14	791	2160	—	—	2-spd. auto.	78
Ford	Fairlane	$V8^{351}$	86	2.79	7.75×14	766	2110	17.5	161	3-spd. auto.	85
Pontiac	Tempest	$V8^{350}$	83.9	3.23	7.35×14	801	2590	—	—	3-spd. auto.	88
Ford	Falcon	6^{170}	80	3.08	6.95×14	817	2510	15.5	170	3-spd. man.	22
Ford	Falcon	6^{170}	80	2.83	6.95×14	817	2320	17	185	3-spd. auto.	78
Plymouth	Sport Fury	$V8^{318}$	—	3.23	7.75×14	765	2470	—	—	3-spd. auto.	

[a] Percentage of vehicles of the given type that use the given engine or transmission.
[b] At 60 mph.

TABLE 21

MOTORCYCLE OVER-ALL INDIVIDUAL VEHICLE NOISE AT SAE STANDARD ACCELERATING AND CRUISE CONDITIONS

SAE ACCELERATION NOISE (dBA)				CRUISE, 35 MPH NOISE (dBA)				CRUISE, 55–65 MPH NOISE (dBA)			
AVE.	STD. DEV.	NO. VEH.	REF.	AVE.	STD. DEV.	NO. VEH.	REF.	AVE.	STD. DEV.	NO. VEH.	REF.
89.7	4.7	11	AMA (*60*)	72.7	4.4	11	AMA (*60*)	81.8	3.3	26	CHP (*65*)
88	—	—	Wyle (*5*)	65.3	.3	7	Serendip. (*4*)	77.5	N/A	Typ	Hillquist (*53*)
88	N/A	Typ	Hillquist (*53*)	69.5	N/A	4 stk[a]	Serendip. (*4*)	75	2.7	7	Serendip. (*4*)
90.4	N/A	Typ	Serendip. (*4*)	66.6	N/A	2 stk[a]	Serendip. (*4*)	76.5	N/A	4 stk[a]	Serendip. (*4*)
81	5.3	7	Serendip. (*4*)					71.3	N/A	2 stk[a]	Serendip. (*4*)
88	5	Typ	(Best est.)	73	4		(Best est.)	81	3		(Best est.)

[a] Typical, 350-cc displacement.

TABLE 22

POTENTIAL ENGINE NOISE REDUCTION

NOISE REDUCTION TECHNIQUE	REDUCTION EXPECTED (dBA)	ADVANTAGES [a]	DISADVANTAGES [a]
Engine modification (62) (77)	1–3 1–3	Considered most desirable from standpoint of maintenance and cooling requirements.	Low noise reduction.
Close-fitting covers (62) (78) (77)	3–5 6 1–3	Moderate noise reduction.	No attenuation of noise from hot manifolds.
Total sealed enclosures (62) (78)	8–15 12–23	High noise reduction.	Maintenance and cooling.
Ducted enclosure systems (77)	10–12	High noise reduction.	Requires cab and chasis modifications.

[a] Cost considerations excluded.

TABLE 23

MANIFOLD MUFFLER PERFORMANCE (NOISE REDUCTION)

EXHAUST CONFIGURATION			NOISE REDUCTION (dBA) FOR ENGINE SPEED AND POWER		
"T"	MUFFLER DIA. (IN.)	STACK MUFFLER	2300 RPM 10 HP	2000 RPM 290 HP	1550 RPM 270 HP
—	—	—	4	7	8
—	9	—	3	3	5.5
Can	10½	—	1.2	3.5	5.3
Can	10½	X	0.5	4	5.5
Can	—	—	6	4.5	7

Source: Ref. *22*, Tests a-g, j-l.

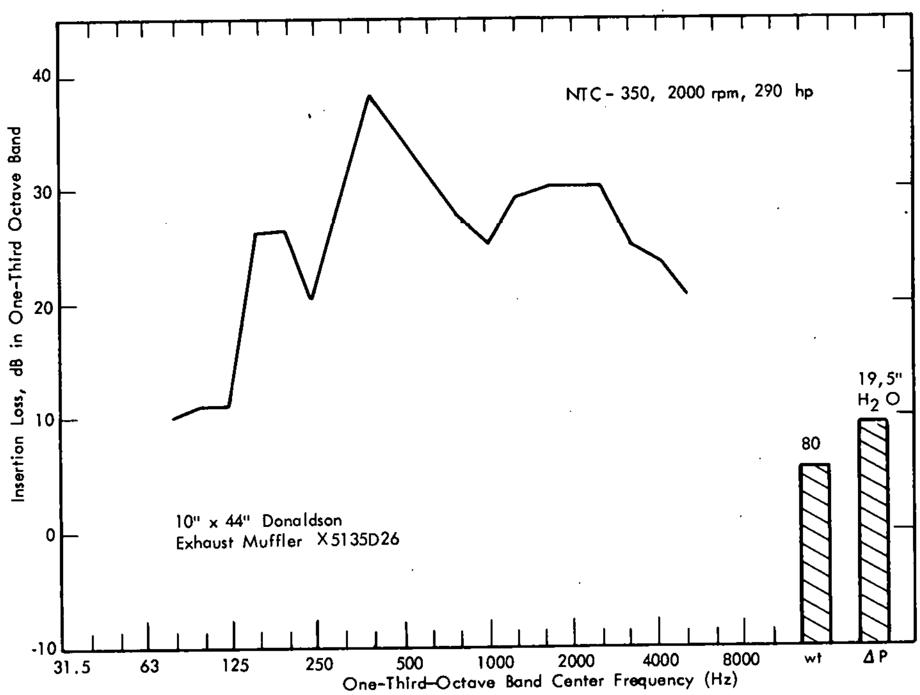


Figure 31. Experimental muffler with high insertion loss (22).

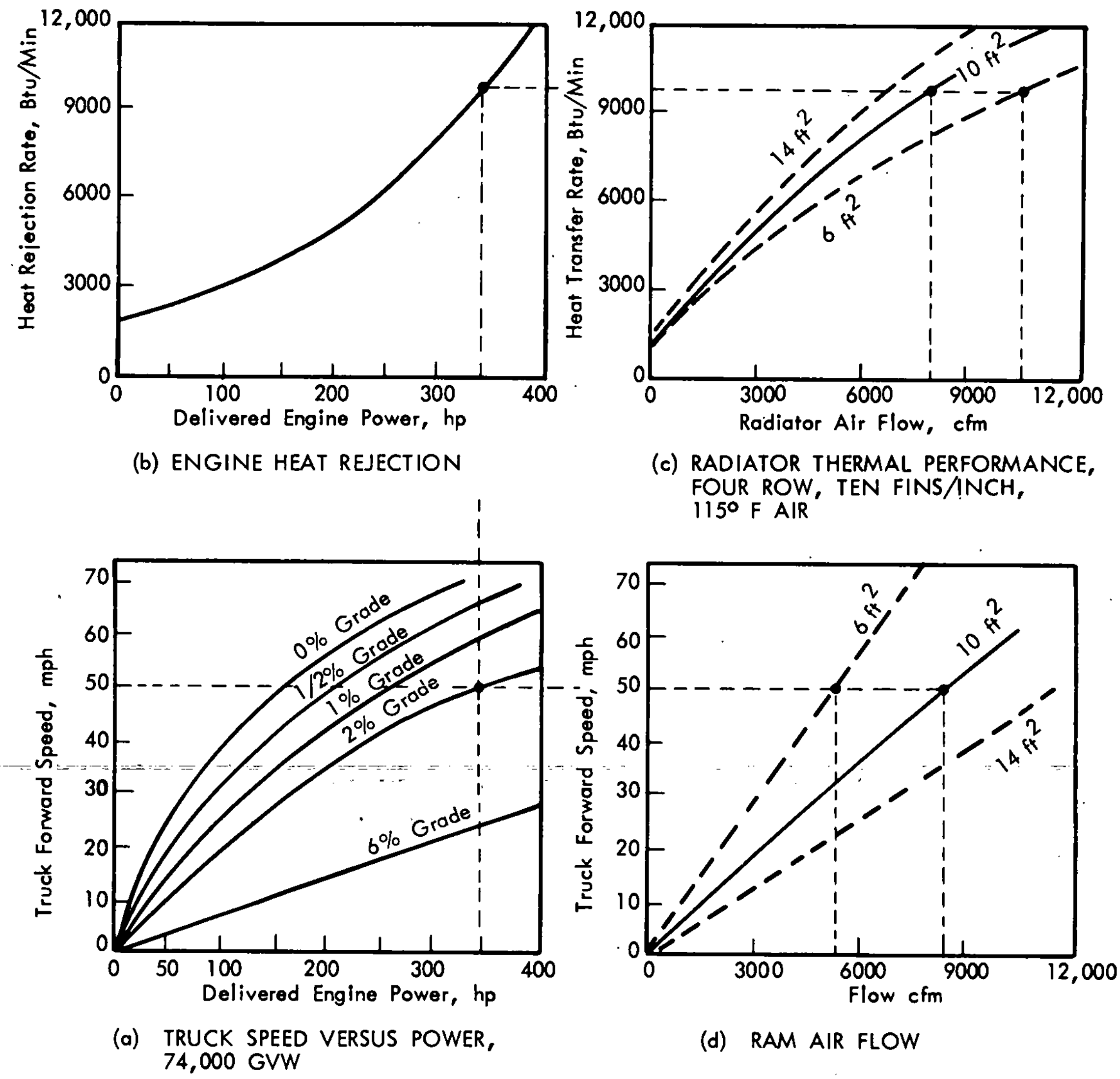


Figure 32. Truck cooling system performance related to vehicle speed and required engine power.

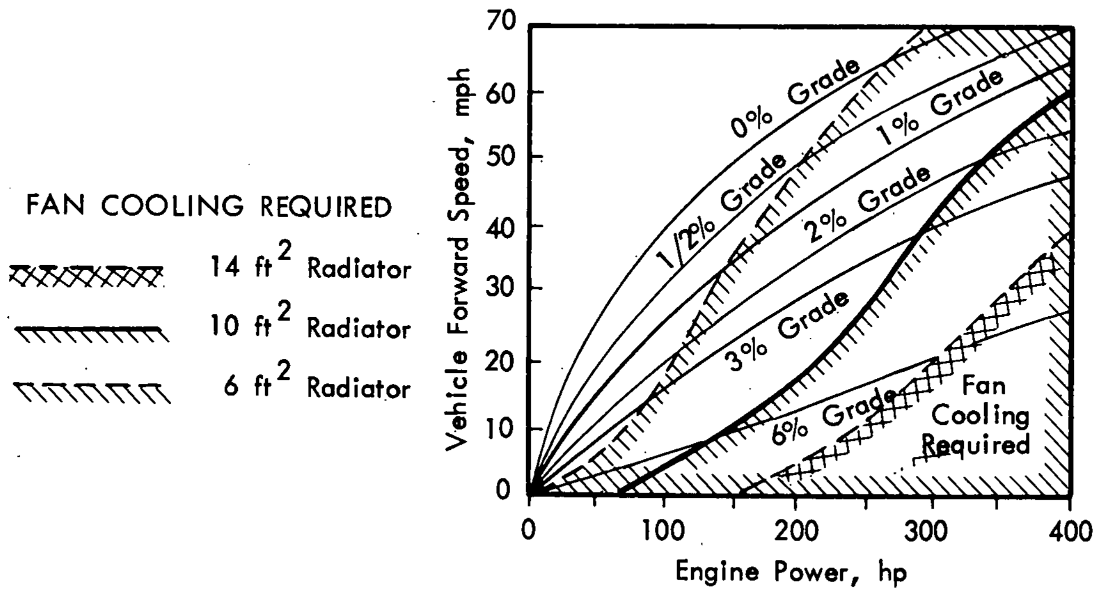


Figure 33. Fan cooling speed as a function of forward speed and engine power. Based on Figure 32 (74,000-lb GVW truck).

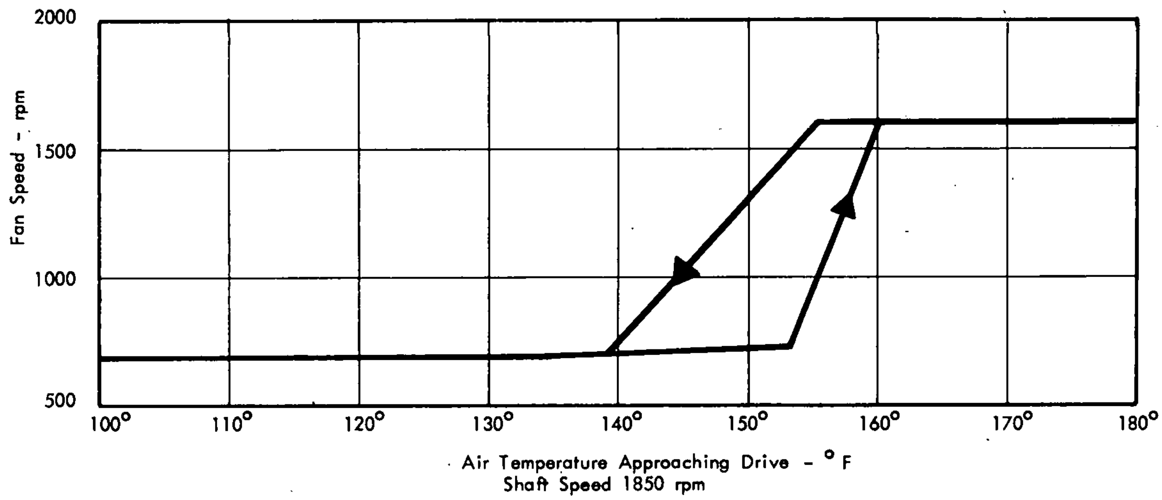


Figure 34. Performance characteristics of a typical truck fan viscous-drive clutch.

of 1,850 rpm. At 55-65 mph assumed bhp was 220 hp with an engine speed of 2,000 rpm. The engine fan diameter was assumed to be 28 in. with a fan tip speed of 290 ft/sec at 60 mph. The fan was assumed to have six 3-in. blades. The assumed radiator and grille turbulence index, $\overline{w}/U_m$, was set equal to 0.10. The fan ratio was taken equal to 1.2.

The truck was assumed to be a three-axle, 10-tire unit with a load of 4,430 lb/tire on drive axles. All tires were assumed in new condition. The nominal levels were calculated using cross rib tires and the reduced levels assumed a straight rib tire configuration.

It should be noted that the SAE tests presented in Table 25 represent an average calculated from field measurements whereas the cruise conditions are truck noise model predictions. Although the "nominal" truck is meant to represent the typical situation, comparison between SAE and cruise conditions should be carefully interpreted.

Automobiles

Engine Noise Reduction

Data regarding engine noise reduction through modifications of the automobile engine are unavailable. Based on results of diesel engine studies, a reduction of from 1 to 3 dB might be achieved through reduction of engine clearances and certain structural modifications. The most promising technique is the use of close fitting covers, with reductions of from 3 to 8 dB anticipated. Stewart (*88*) relates General Motors use of barriers over the front wheel well areas of an experimental quiet automobile.

Exhaust Noise Reduction

Beter exhaust noise reduction can be obtained with larger mufflers. Several automobile mufflers have been designed that have insertion losses of from 30 to 40 dB (5 to 15 dB above present-generation mufflers (*4*)), and they are postulated to have lower back pressures than existing mufflers. In addition, larger pipe sizes, dual mufflers, and splitter cans are reasonable, with anticipated reductions of from 3 to 5 dB. The use of manifold mufflers has not been investigated (they do not seem to be economically viable).

Fan Noise Reduction

All of the techniques for reducing truck fan noise are applicable. Radiator enlargement and the introduction of either thermatic or viscous fan clutches are within reason. Radiator enlargement would allow fan slowing at low-speed cruise conditions. However, to reduce noise with the fan engaged, larger radiators and slower fans would be necessary. Reduction of fan speed to 60 percent of the present top speed would yield about a 13-dB decrease.

Intake Noise Reduction

Auxiliary intake mufflers or acoustically treated ducts to the passenger compartment (the latter being the most desirable from the standpoint of reducing the noise level without degrading engine performance) can yield up to 6-dB reduction (*88*). During cruise no reduction is necessary with present air cleaners.

Tire Noise Reduction

Again, as for trucks, selection of rib tires is necessary.

Other Noise Reduction Measures

Two General Motors vehicles (*88*) were outfitted with large mufflers and auxiliary intake mufflers, and the fan was removed. SAE J986a acceleration tests were run before and after. The vehicles achieved 73- and 75-dBA levels (from 84 and 78 dBA). The following changes were then made to the first treated vehicle:

1. Intake auxiliary muffler replaced with a lined duct to the passenger compartment.

TABLE 24

DIESEL TRUCK COMPONENT NOISE ABATEMENT POTENTIAL

NOISE SOURCE AND POTENTIAL ABATEMENT	MINIMUM ANTICIPATED ADDITIONAL NOISE REDUCTION (dBA) SAE J366A	CRUISE, 35 MPH	CRUISE, 55–65 MPH
Engine casing:			
Close-fitting covers	3	3	3
Ducted enclosure	11	11	11
Engine mounts	—	—	—
Net reduction	14	14	14
Exhaust system:			
Manifold muffler	4	4	4
Splitter cans	2	2	2
High insertion loss muffler	13	13	13
Dual mufflers	—	—	—
Vibration isolation	—	—	—
Wrapped mufflers	—	—	—
Net reduction	19	19	19
Fan:			
Thermatic control (larger radiator)	0	Fan noise level	Fan noise level
Viscous clutch (larger radiator)	3	21	21
High-performance, slow fan (0.6*N*)	13	—	—
Fan inlet improvement	—	—	—
Net reduction	13 [a]	21 [b]	21 [b]
Intake:			
Properly chosen present-day air cleaners and snorkels are adequate noise reduction measures	12	12	12
Tires: [c]			
Present neutral rib and rib tires	4.5	4.5	4.5
Transmission and differential:			
Shields	20	20	20

[a] Assumes fan engaged.
[b] Minimum.
[c] Assumes present truck has cross-lug tires.

TABLE 25

DIESEL TRUCK NOISE ABATEMENT POTENTIAL

	NOISE ABATEMENT POTENTIAL (dBA AT 50 FT)								
	NOMINAL LEVEL			NET REDUCTION [a]			POTENTIAL REDUCED LEVEL		
NOISE SOURCE	SAE J366A	CRUISE, 35 MPH	CRUISE, 55–65 MPH	SAE J366A	CRUISE, 35 MPH	CRUISE, 55–65 MPH	SAE J366A	CRUISE, 35 MPH	CRUISE, 55–65 MPH
Engine casing	81.5	82.0	83.0	14	14	14	67.5	68.0	69.0
Exhaust system	81.7	77.1	81.2	19	19	19	62.7	58.1	62.2
Fan	81.1	80.1	82.5	13 [b]	21 [c]	21 [c]	68.1	59.1	61.5
Intake	74.0	74.0	74.0	12	12	12	62.0	62.0	62.0
Tires, new on good quality pavement	71.5	75.5	85.0	4.5	4.5	4.5	67.0	71.0	80.5
Transmission	75.0	75.0	75.0	20	20	20	55.0	55.0	55.0
Over-all levels	86.9	86.1	89.5	—	—	—	73.2	73.5	81.0

[a] From Table 24.
[b] High-performance slow fan (0.6 engine speed).
[c] Viscous clutch fan.

2. Exhaust system wrapped with acoustically absorptive material.
3. Rear axle, drive shaft, and transmission wrapped.
4. Belly pan installed from the front cross member to the rear axle.
5. Barriers placed over valve covers, air cleaner, and front wheel wells.
6. Power steering and alternator belts removed.

All of the changes (which were, incidentally, considered by Stewart (*88*) to be impractical) resulted in an additional 2-dBA reduction. The second vehicle had the following changes made:

1. Larger intake muffler installed.
2. Exhaust system (dual) wrapped.
3. Rear axle and transmission wrapped.
4. Engine compartment lined with sound-absorbing material.
5. Power steering and alternator belts removed.

The net reduction was again 2 dBA (*88*).

Total Automobile Noise Abatement Potential

Total noise reduction potential is calculated for a typical automobile in Tables 26 and 27 (light gasoline-powered trucks are considered to be in this category).

Motorcycles

Motorcycle Engine Noise Reduction

No data are available that show demonstrated noise reduction for motorcycle engines. Indeed, engine noise for the lightweight, air-cooled, commercially popular machine is the noise source of most concern (*5*). Without drastically changing the configuration of the motorcycle (say by the addition of a shroud), only 1- to 3-dB reduction is considered achievable. Further noise reduction could be achieved by de-rating the engine and limiting the top engine speed (an additional 3-dB reduction could be achieved in this manner without compromising highway performance).

Motorcycle Exhaust Noise Reduction

Because the quality of motorcycle muffling has historically been judged by the rap and not the sideline noise, the potential for exhaust muffling appears great. Indeed, recent production units have had to satisfy California and Chicago ordinances, with subsequent attention to exhaust noise reduction. Additional reduction of 6 dB is considered possible by doubling both the muffler volume and the back pressure. De-rating of the engine could produce another 1- to 3-dB reduction.

TABLE 26

AUTOMOBILE COMPONENT NOISE ABATEMENT POTENTIAL

	MINIMUM ANTICIPATED ADDITIONAL NOISE REDUCTION (dBA)		
NOISE SOURCE AND POTENTIAL ABATEMENT	SAE J396A	CRUISE, 35 MPH	CRUISE, 55–65 MPH
Engine casing:			
Close-fitting covers and wheel well barriers	5	5	5
Exhaust system:			
High insertion loss muffler	15	15	15
Dual mufflers and splitter cans	3	3	3
Wrapped exhaust vibration isolation	—	—	—
Net reduction	18	18	18
Fan:			
Thermatic control (larger radiator)	0	Fan noise level	Fan noise level
Viscous clutch (larger radiator)	3–6	21	21
High-performance, slow fan	13	—	—
Fan inlet improvement	—	—	—
Net reduction	13 [a]	21	21
Intake:			
Auxiliary intake muffler	6	6 [b]	6 [b]
Tires [c]	0	0	0
Other sources	6	6	6

[a] Assumes fan engaged.
[b] Reduction in other than wide-open throttle is not necessary.
[c] Assumes present automobile has rib tires.

TABLE 27

AUTOMOBILE NOISE ABATEMENT POTENTIAL

	NOISE ABATEMENT POTENTIAL (dBA AT 50 FT)								
	NOMINAL LEVEL			POTENTIAL ABATEMENT [a]			POTENTIAL REDUCED LEVEL		
NOISE SOURCE	SAE J986A	CRUISE, 35 MPH	CRUISE, 55–65 MPH	SAE J986A	CRUISE, 35 MPH	CRUISE, 55–65 MPH	SAE J986A	CRUISE, 35 MPH	CRUISE, 55–65 MPH
Engine casing	73	60	60	5	5	5	68	55	55
Exhaust	81	68	72	18	18	18	63	50	54
Fan	76	66	66	13	21	21	63 [b]	45 [c]	45 [b]
Intake	74	—	—	6	6	6	68	—	—
Tires	60	64	72.5	0	0	0	60	64	72.5
Other sources	72	72	72	6	6	6	66	66	66
Potential automobile reduced levels							73	68	73.5

[a] From Table 26.
[b] High-performance slow fan (0.6 engine speed).
[c] Viscous clutch fan.

Motorcycle Intake Noise Reduction

Untreated intake noise would be the dominant source if a high degree of muffling were employed. No published data are available on the performance of intake silencers. Six dB is considered the unsubstantiated maximum that current-technology intake muffling could achieve.

Motorcycle Tire Noise Reduction

Motorcycle tire noise should not be a significant contributor to over-all vehicle noise unless knobby tires are used on particularly rough pavement. Nevertheless, the potential for noise reduction lies in limiting motorcycles to straight rib tires for highway use.

Aggregate Motorcycle Noise Abatement

The reduced noise estimates for motorcycles are presented in Table 28. The component contributions for nominal levels are the experimentally determined values. (Table 3). The total noise for the SAE acceleration test (88 dBA) agrees with the AMA model value (Table 16). The nominal values for cruise were also determined from the AMA model. The total reduced noise values for the cruise condition were estimated by taking the same differences as exist between the nominal SAE and cruise conditions. Tire noise at 71 dBA appeared as a major contributor, raising the total level from 70 to 73 dBA.

ABATEMENT COST ESTIMATES

Two approaches are available in the estimation of costs of highway vehicle noise reduction. The first entails summarizing and evaluating industry-supplied information on the typical per-vehicle cost to achieve prescribed noise limits. The second approach is to synthesize quieted vehicles and "cost out" the noise control features.

The first approach is presently being employed by the EPA in the course of formulating rules for vehicle noise control (*6, 83, 89*). Because this is both an on-going and an extensive effort, no attempt is made to duplicate the findings. Some published over-all vehicle noise reduction costs are examined in Chapter Six. The second approach is used herein.

TABLE 28

MOTORCYCLE[a] COMPONENT NOISE ABATEMENT POTENTIAL

	NOISE ABATEMENT POTENTIAL (dBA AT 50 FT)								
	NOMINAL LEVEL			POTENTIAL ABATEMENT			POTENTIAL REDUCED LEVEL		
NOISE SOURCE	SAE J331	CRUISE, 35 MPH	CRUISE, 55–65 MPH	SAE J331	CRUISE, 35 MPH	CRUISE, 55–65 MPH	SAE J331	CRUISE, 35 MPH	CRUISE, 55–65 MPH
Engine casing	78			4–6	4–6	4–6	73		
Exhaust	86			7–9	7–9	7–9	78		
Intake	82			6	6	6	76		
Tires	64	64	71	—	—	—	64	64	71
Total	88	73.7	76.7	—	—	—	81	67	73

[a] 350 cc, 4-stroke.

Diesel Trucks

Estimates of Initial Costs to Customer

Table 29 gives estimated costs for the various noise control measures applicable to diesel trucks (those listed in Tables 24 and 25) (*90*). A 72.5-dBA truck (SAE J366a test) is estimated to cost the customer about $1,400 more than the present cost.

Operation and Maintenance Costs

Operation and maintenance costs will vary from truck to truck depending on their operation. For example, when cargo weight is less than the legal maximum, decreased fuel economy arises from having to haul around the additional weight of the noise control features and from degradation of engine performance owing to those features; but when the weight of the cargo is such that the legal weight limit is attained, allowed cargo weight is lower than before owing to the weight of the noise control measures. Engine performance degradation also penalizes the operation.

Fax (*77, 90*) has estimated these costs for the Freightliner quiet truck based on the following assumptions:

1. The average truck runs 125,000 miles/year, of which 25,000 miles are speed limited and 100,000 miles are power limited. The average cost (in dollars/year) for operation below legal weight limit owing to decreased fuel economy from hauling the additional weight, W_{NR}, is

$$\Delta\$ = (1.085 \times 10^{-6}) \times (\text{miles/year}) \times (\text{fuel cost, \$/gal}) \times (W_{NR}, \text{lb}_m) \qquad (81)$$

2. The average truck is weight limited during 5 percent of its operations. Assuming an $0.08/ton-mile cargo rate, lost revenues owing to W_{NR}, in dollars per year, amount to

$$\Delta\$ = 2.5 \times 10^{-2}\, W_{NR} \qquad (82)$$

(Every pound of noise control is assumed equivalent to a pound of lost cargo.)

3. The added cost owing to engine performance degradation can be directly related in increased engine back pressure, which for engines in the 250- to 350-hp range is (*77*):

For Power-Limited Operation

$$\Delta\$ = \left(1.08 \times 10^{-4} \frac{\text{gal}}{\text{mile}} \Big/ \text{in. } H_2O\right) \times (\text{fuel cost, \$/gal}) \times (\text{miles/year}) \times (\Delta p, \text{in. } H_2O) \qquad (83)$$

TABLE 29

ESTIMATED INITIAL COSTS OF DIESEL TRUCK NOISE ABATEMENT [a]

NOISE CONTROL MEASURE		STANDARD PRODUCT REPLACED		ADDITIONAL COST ($)		
DESCRIPTION	COST($)	DESCRIPTION	COST($)	ITEM [b]	ASSEMBLY [b, c]	NET
Close-fitting engine covers	143	None	0	143	0	143
Ducted (flow-through) engine enclosure	350	None	0	350	100	450
Manifold muffler	150	Exh. man.	38	112	9	121
Splitter "T" can muffler	15	None	0	15	4	19
Dual mufflers	120	Single exh. muffler	45	75	9	83
Wrap exhaust pipes	120	None	0	120	54	174
Engine mounts	72	None	0	72	9	81
Thermatic control clutch [d]	195	Fan hub	90	105	45	150
Viscous fan clutch [d]	(90)	None	0	(90)	(10)	(100)
High-performance fan	18	Std. fan	12	6	0	6
Increased fan-rad. spacing	50	None	0	50	0	50
Best air cleaner and snorkel	180	Std. air cleaner	120	60	0	60
Transmission shield	97	None	0	97	23	120
Total estimated initial cost to achieve SAE J366a noise levels of Table 25						1457 (1407)

[a] Cost differential of cross-lug and rib tires excluded.
[b] Passed on to customer by manufacturer (1.5 markup assumed).
[c] Labor rate assumed to be $12.00/hr.
[d] Choice to be made.
Source: Fax (*90*).

For Speed-Limited Operation

$$\Delta\$ = \left(1.22 \times 10^{-4} \frac{\text{gal}}{\text{mile}} \Big/ \text{in. } H_2O\right)$$
$$\times(\text{fuel cost, \$/gal}) \times (\text{miles/year})$$
$$\times(\Delta p, \text{in. } H_2O) \qquad (84)$$

In addition to cost penalties, use of a thermatic control fan could yield a power savings, estimated to be $16 per horsepower-year (the power to turn the fan ranges between 5 and 15 hp).

Additional operation costs arising from increased engine wear were not estimated. Estimates for those costs should be available after a one-year field test of the Freightliner design (*77*).

Additional maintenance cost can be estimated on the basis of a $12/hr labor rate. Table 30 summarizes operational and maintenance information.

Additional operation costs, in dollars per year, from replacement of noise control equipment must be based on operational life. Assuming operational life is the same for similar equipment able to perform the same functions with and without noise control features, replacement cost additions can be based on purchase price difference. This is assumed in Table 30. Operational scenarios are not attempted in this study.

Automobiles

Calculation of total automobile noise reduction costs from data regarding component noise reduction costs is not possible; data simply are unavailable. In the broader sense, a cost increase of 100 percent for highly damped sandwich construction covers (valve covers, oil pan, etc.) is probable (*44*). Costs of an additional exhaust muffler and an intake muffler should be anticipated. Engine shields are estimated to cost 1 to 2 percent of total engine costs (*44*). Increases in specific fuel consumption of 0.1 percent per in. of Hg back pressure increase are reasonable (*91*). A 1 percent decrease in horsepower output per in. of Hg increase in engine back pressure can be expected (*91*).

Maintenance cost increases would essentially be attributable to additional muffler replacement (assumed 2-year life).

Motorcycles

The cost of extra muffling for motorcycles is estimated by increasing the present muffler cost by a factor of 1.5. For an average of three mufflers per motorcycle at an average cost of $10 per unit, the additional cost is $15 for 4-stroke machines. Two-stroke motorcycles have resonating chambers, so muffling is less of a problem (*5*). The expected cost is less than that for 4-stroke machines.

No data are available for intake muffling or for engine component noise improvement.

TABLE 30

DIESEL TRUCK NOISE ABATEMENT; ESTIMATED OPERATIONAL AND MAINTENANCE DATA

NOISE CONTROL MEASURE	OPERATIONAL LIFE	ADDL. MAINT. (HR/YR)	ADDL. WEIGHT, W_{NR} (lb_m)	BACKPRESSURE INCREASE, Δp (in. H_2O)	POWER SAVINGS (hp)
Close-fitting engine covers	Engine life	1	25	0	0
Ducted engine enclosure	Truck life	6	250	0	0
Manifold muffler	5 yr	0	100	0	0
Spliter "T" can muffler	2 yr	0.5	40	21.5	—
Dual mufflers	2 yr	0.2	50	0	0
Wrap exhaust pipe	2 yr	1	50	0	0
Engine mounts	2 yr	0	10	0	0
Thermatic fan clutch	Engine life	0	10	0	15
Viscous fan clutch	Engine life	0	5	0	13½
High-performance fan	Engine life	0	2	0	0
Increased fan-rad. space	Engine life	0	10	0	0
Best air cleaner and snorkel	Engine life	0.5	5	0	0
Transmission shield	Engine life	1	88	0	0

Source: Fax (*90*).

CHAPTER THREE

FINDINGS—PROPAGATION AND CONTROL OF HIGHWAY NOISE

This chapter presents the findings from five studies: free-field propagation, highway measures for noise reduction, vehicle noise directivity patterns, truck drive-by noise levels by type and location, and surveys of noise prediction procedure users.

FREE-FIELD PROPAGATION

The free-field traffic noise data, collected and reduced as outlined in Chapter One, are given in Tables B-1 through B-9, which also include the traffic conditions observed during each measurement run. The atmospheric conditions (wind, temperature, humidity) during the various measurement runs are given in Table B-10.

General Data Evaluation

General studies of the free-field propagation of traffic noise were pursued using a traffic noise model of the form

$$L_{100\alpha} = \xi + \beta \log S + \gamma \log V + \delta M - \epsilon \log D \qquad (85)$$

where

$L_{100\alpha}$ = 100α percentage level of the traffic noise distribution, in dBA, as defined in Appendix A;
S = traffic speed, in mph;
V = traffic volume, in vph;
M = truck mix (truck/total traffic ratio), in percent;
D = "equivalent distance" * from roadway, in ft; and
$\xi,\beta,\gamma,\delta,\epsilon$ = regression coefficients.

Eq. 85 is similar to the model for automobile traffic noise suggested in *NCHRP Report 117* (*2*) as well as by other investigators (*92, 93*). The model assumes that the traffic noise (in dBA) falls off linearly with the logarithm of distance, independent of traffic conditions; i.e., the propagation loss is a constant that is not dependent on either distance from the roadway or any of the traffic variables. Even in the absence of ground effects, where the loss is due solely to divergence, these assumptions are not rigorously correct, as discussed in Chapter One. Nevertheless, Eq. 85 should provide an acceptable approximation for study.

Multiple regression analyses were performed by conventional procedures (*94*, pp. 419-462) on the data collected during the free field noise surveys using the model of Eq. 85. The data for each microphone height and percentage level at each site were analyzed separately. The analyses at the 10- and 15-ft heights did not include data for locations at 50 and 1,600 ft from the roadside because the measurements at these locations were always made at a height of 5 ft. Furthermore, because the average traffic speed was about the same during all measurements at all sites, the second term in Eq. 85 was simply lumped into the intercept coefficient, ξ. The estimates of the coefficient ϵ at various microphone heights, percentage levels, and sites are summarized in Table 31. This coefficient, which includes the effects of both the divergence loss and ground effects, is hereafter referred to as the "propagation loss factor."

Visual inspection of Table 31 suggests a significant difference between the results for Site 1 and those obtained at Sites 2 and 3. However, the significance of the variations with microphone height and percentage level at each site is not so obvious. Hence, the homogeneity of the estimated propagation loss factors was evaluated by conventional two-way analysis of variance procedures (*94*, pp. 467-478, 482). The results (Table 32) show that the propagation loss factor does vary significantly (at the 1.0 percent level of significance) with variations in both height above the ground and percentage level at Sites 1 and 3, but not at Site 2. These results warrant discussion.

Variations with Percentage Level

Table 32 indicates a strong dependence of the propagation loss factor, ϵ, on the percentage level, $L_{100\alpha}$, at Site 1, but not at Site 2. A weak but statistically significant dependence (at the 1 percent level of significance) is revealed at Site 3. In all cases, the propagation loss factor increases with decreasing percentage level, suggesting that the variance of the measured traffic noise collapses with increasing distance from the roadway. This is consistent with the

TABLE 31

SUMMARY OF ESTIMATED PROPAGATION LOSS FACTORS FOR FREE-FIELD TRAFFIC NOISE

SITE NO.	HEIGHT ABOVE GROUND (FT)	ESTIMATED PROPAGATION LOSS FACTOR, ϵ, AT PERCENTAGE LEVEL				
		L_{01}	L_{10}	L_{50}	L_{90}	L_{eq}
1	5 [a]	11.6	9.8	9.2	8.4	9.6
	10	12.9	11.9	11.1	10.2	11.3
	15	13.8	11.3	10.6	10.4	11.1
2	5 [a]	14.4	15.5	14.7	13.8	14.8
	10	19.0	17.0	15.8	14.9	16.4
	15	15.0	17.5	16.2	15.3	16.5
3	5 [a]	16.5	17.1	15.4	13.3	14.8
	10	19.4	19.1	16.0	13.7	17.2
	15	17.3	15.4	11.7	10.3	13.8

[a] Includes data at locations 50 and 1,600 ft from roadside.

* See Appendix B for definition of "equivalent distance" used for these studies.

results of both theoretical (*95*) and experimental studies (*92, 93*) by previous investigators.

It appears that the dependence of the propagation loss factor on percentage level is revealed more clearly at Site 1 than at Sites 2 and 3 because of the relatively low traffic volumes (as low as 250 vph) associated with the data at Site 1. As noted in Chapter One, the divergence loss assessed in terms of the various percentage levels will be different for low traffic volumes, but must ultimately collapse to a common value as traffic volume increases. It appears that the traffic volumes associated with the measurements at Sites 2 and 3 (generally over 4,000 vph) are sufficient to approximate the latter situation.

To demonstrate in more quantitative terms the influence of traffic volume on traffic noise variance, consider the complete regression equation for traffic noise determined from the data at Site 1 using the regression model of Eq. 85. For the microphone height of 5 ft, the equations for the four percentage points plus the L_{eq} level were found to be as follows:

TABLE 32

RESULTS OF HOMOGENEITY TESTS OF PROPAGATION LOSS FACTORS FOR VARIOUS PERCENTAGE LEVELS AND MEASUREMENT HEIGHTS

	VARIATION OF ϵ WITH PERCENTAGE LEVEL			VARIATION OF ϵ WITH HEIGHT ABOVE GROUND		
SITE NO.	VALUE OF F	CRITICAL VALUE OF F [a]	STATIS. SIGNIF.	VALUE OF F	CRITICAL VALUE OF F [a]	STATIS. SIGNIF.
1	41.54	7.01	Yes	51.51	8.65	Yes
2	1.58	7.01	No	5.04	8.65	No
3	9.91	7.01	Yes	13.86	8.65	Yes

[a] At 1 percent level of significance.

$$L_{01} = 91.7 + 2.49 \log V + 0.13\,M - 11.60 \log D \quad \text{(6a)}$$
$$L_{10} = 75.6 + 4.57 \log V + 0.19\,M - 9.75 \log D \quad \text{(6b)}$$
$$L_{50} = 61.2 + 7.27 \log V + 0.17\,M - 9.24 \log D \quad \text{(6c)}$$
$$L_{90} = 47.8 + 9.78 \log V + 0.17\,M - 8.40 \log D \quad \text{(6d)}$$
$$L_{eq} = 68.9 + 5.64 \log V + 0.19\,M - 9.56 \log D \quad \text{(6e)}$$

Figure 35 shows plots of these percentage levels versus traffic volume, with truck mix and distance fixed at $M =$ 5 percent and $D = 100$ ft, respectively. It is clear that the dispersion of the noise does indeed collapse with increasing traffic volume. Furthermore, the dispersion for any given traffic volume, as measured by the difference between the L_{10} and the L_{50} level, is in reasonably good agreement with past data and the recommendations presented in *NCHRP Report 117* (*2*).

Similar plots of percentage levels versus distance, with traffic volume and truck mix fixed at $V = 1{,}000$ vph and $M = 5$ percent, respectively, are shown in Figure 36. A collapse of traffic noise dispersion with distance is apparent in these plots, but is not as pronounced as might be expected.

In summary, at relatively low traffic volumes (<5,000 vph) and at distances within 1,600 ft of the roadway, the propagation loss factor varies significantly with the percentage level used to describe the noise. Specifically, the smaller percentage levels are associated with a higher propagation loss factor, as would be expected from theoretical considerations (*95*). At higher volumes (>5,000 vph), it appears that a common propagation loss factor could be applied to all percentage levels.

Variations with Measurement Height

Table 32 indicates a dependence of the propagation loss factor, ϵ, on measurement height at Sites 1 and 3, but not at Site 2. The data of Table 31 reveal at all sites a common trend that appears to be responsible for the indicated dependence. Specifically, the value of ϵ appears to be

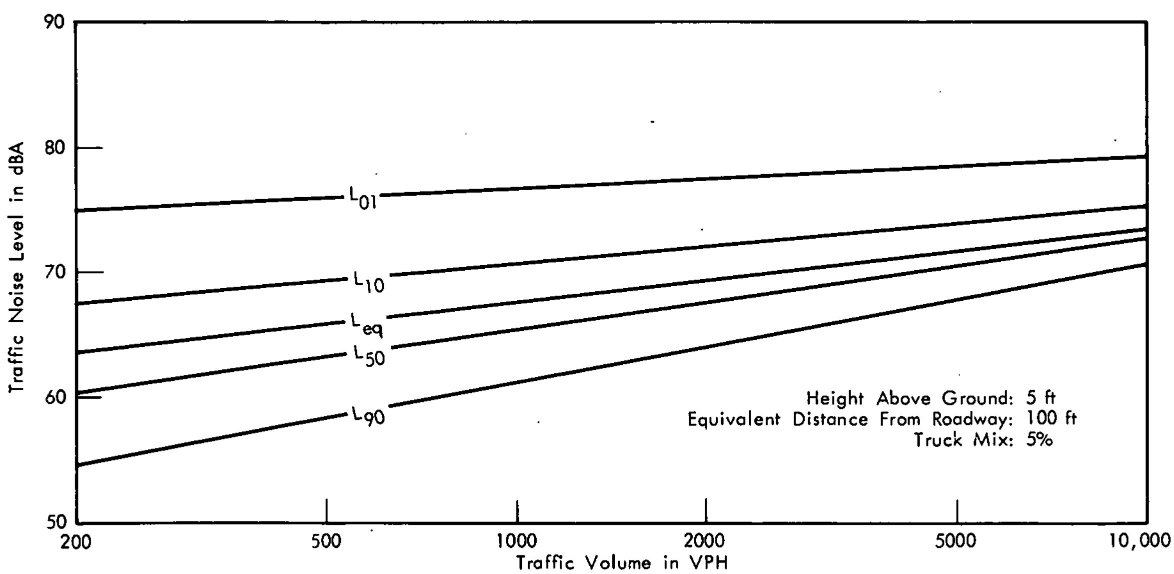


Figure 35. Free-field traffic noise vs traffic volume, Site 1.

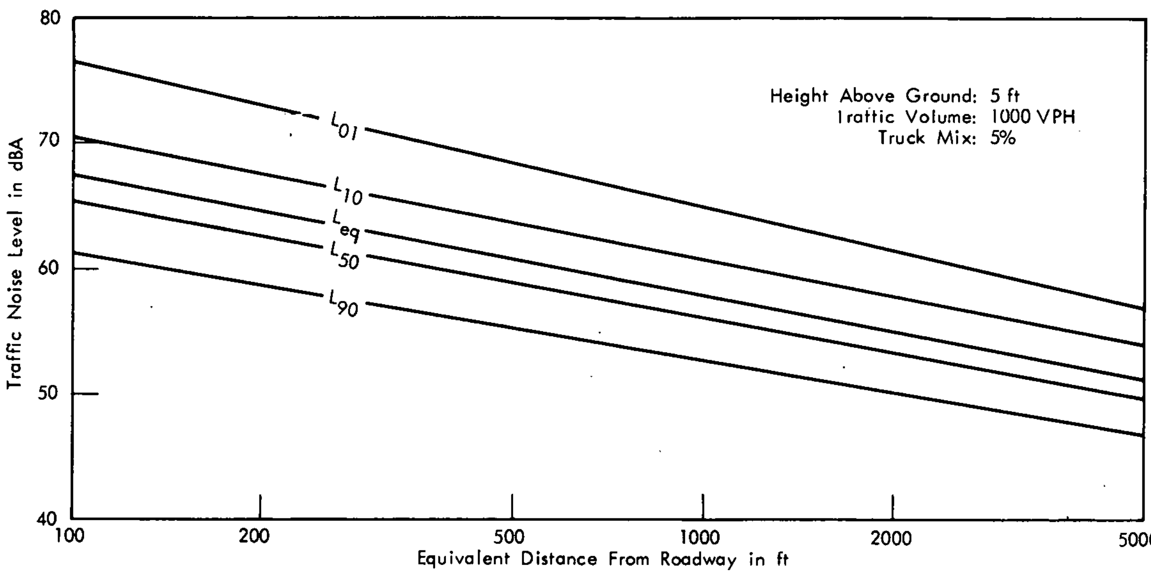


Figure 36. Free-field traffic noise vs distance from roadway, Site 1.

smaller at the 5-ft measurement height than at the 10-ft height. This contradicts the intuitive expectation that, due to ground cover absorption, the propagation loss at the 5-ft height should be greater, not less, than the loss at the 10-ft height. Hence, this result was investigated more thoroughly, as discussed in the next section.

Detailed Data Evaluation

The influence of measurement height and percentage level on free field traffic noise propagation was investigated in a general way in the previous section. It is now desirable to consider the possible influences of distance from the roadway and traffic conditions on the propagation characteristics. Further studies of the measurement height and percentage point dependence are also warranted. To this end, the data were divided into sets, each set consisting of up to six measurements obtained simultaneously at up to six different distances from the roadway (each set constitutes a "measurement run" as defined in Chapter One). This permitted calculation of a collection of individual propagation loss factors for the various measurement heights and sites, each associated with a specific set of traffic and environmental conditions.

Variations with Distance from Roadway

One method of evaluating possible variations in the propagation loss factor, ϵ, with distance, D, from the roadway is in terms of the correlation coefficient between the dBA noise levels at various distances and the logarithm of the distance. Table 33 gives estimates of this correlation coefficient, r, with the estimated propagation loss factor for each data set (measurement run) at all three sites. Results are presented only for the 5-ft height because the measurement runs at 5 ft included all six distances from the roadway, as opposed to only four distances for the 10- and 15-ft measurement heights.

As noted previously, the propagation loss factor for the small and large percentage values of the traffic noise must vary with distance due simply to the characteristics of the divergence loss. Beyond this, there is the problem of a possible distance dependence associated with the ground cover effects. The fundamental question of interest, however, is: Are these factors significant; i.e., must they be considered in the formulation of a traffic noise model. Table 33 suggests that they are not, at least for distances out to 1,600 ft from the roadway. Specifically, noting that the correlation coefficient between two variables is a measure of linear dependence ($r = 1$ indicates a perfect linear relationship), the generally strong correlation coefficients in Table 33 heavily support the conclusion that the propagation loss factor is not significantly influenced by distance from the roadway. The lack of a significant nonlinear distance dependence is further supported by visual inspection of plots of the noise level versus the logarithm of distance, as presented for selected L_{50} levels at Site 1 in Figure 37. The cases illustrated, representing a low, a medium, and a high traffic volume, show no apparent significant nonlinear trend. Similar results are generally found for all percentage levels at all sites.

In summary, it appears reasonable to assume that the propagation loss factor for traffic noise is a constant, independent of distance, at least for distances from 50 to 1,600 ft from the roadway and for reasonably high traffic volumes (over a few thousand vph). However, although not detected in the measurements, there is reason to believe that the assumption would fail for locations within a few hundred feet of low-volume traffic, particularly if the propagation loss is assessed in terms of a very small or very large percentage level (e.g., L_{10} or L_{90}).

Variations with Traffic Conditions

As for the distance studies just discussed, there is theoretical reason to believe that the propagation loss factor must be a function of traffic volume, at least when measured in

TABLE 33

SUMMARY OF PROPAGATION LOSS FACTORS MEASURED 5 FT ABOVE THE GROUND FOR VARIOUS MEASUREMENT RUNS

SITE NO.	RUN NO.	ESTIMATED REGRESSION COEFFICIENT, ϵ, AND CORRELATION COEFFICIENT, r, FOR PROPAGATION LOSS FACTOR AT VARIOUS PERCENTAGE LEVELS									
		L_{01} LEVEL		L_{10} LEVEL		L_{50} LEVEL		L_{90} LEVEL		L_{eq} LEVEL	
		ϵ	r	ϵ	r	ϵ	r	ϵ	r	ϵ	r
1	3	11.54	0.97	9.33	0.98	7.76	0.98	7.33	0.98	8.35	0.96
	4	10.82	0.98	7.42	0.96	6.43	0.90	5.88	0.90	7.38	0.94
	8	12.26	0.99	9.58	0.99	9.61	0.99	7.72	0.97	9.23	0.98
	9	12.99	0.94	7.77	0.72	9.22	0.96	7.74	0.83	9.79	0.96
	12	11.71	0.98	6.60	0.99	4.58	0.99	3.84	0.97	7.54	0.97
	13	13.00	0.97	13.31	1.00	12.69	1.00	11.82	1.00	12.83	1.00
	16	9.15	0.97	9.92	0.97	12.24	0.99	12.33	0.99	10.16	0.98
2	1	16.09	0.95	16.91	0.99	15.80	0.99	14.20	0.99	16.20	0.99
	4	14.36	0.94	15.35	0.95	16.22	0.99	15.62	0.99	15.42	0.98
	5	13.13	0.93	15.65	0.98	15.93	0.99	15.17	0.99	15.30	0.99
	9	19.54	0.98	16.26	0.97	13.15	0.92	12.69	0.96	15.06	0.97
	12	9.49	0.92	13.72	0.99	12.98	0.98	11.48	0.99	11.95	0.97
3	1	18.30	0.98	18.22	1.00	17.35	0.99	16.13	1.00	17.56	0.99
	4	22.67	0.99	18.90	1.00	16.87	0.99	15.78	0.99	18.04	0.99
	5	10.16	0.86	12.78	0.97	14.42	0.98	10.31	0.98	10.37	0.94
	9	18.27	0.96	20.32	0.97	17.77	0.97	14.74	0.95	18.16	0.97
	15	13.86	0.89	15.52	0.92	15.57	0.95	13.81	0.95	11.60	0.84

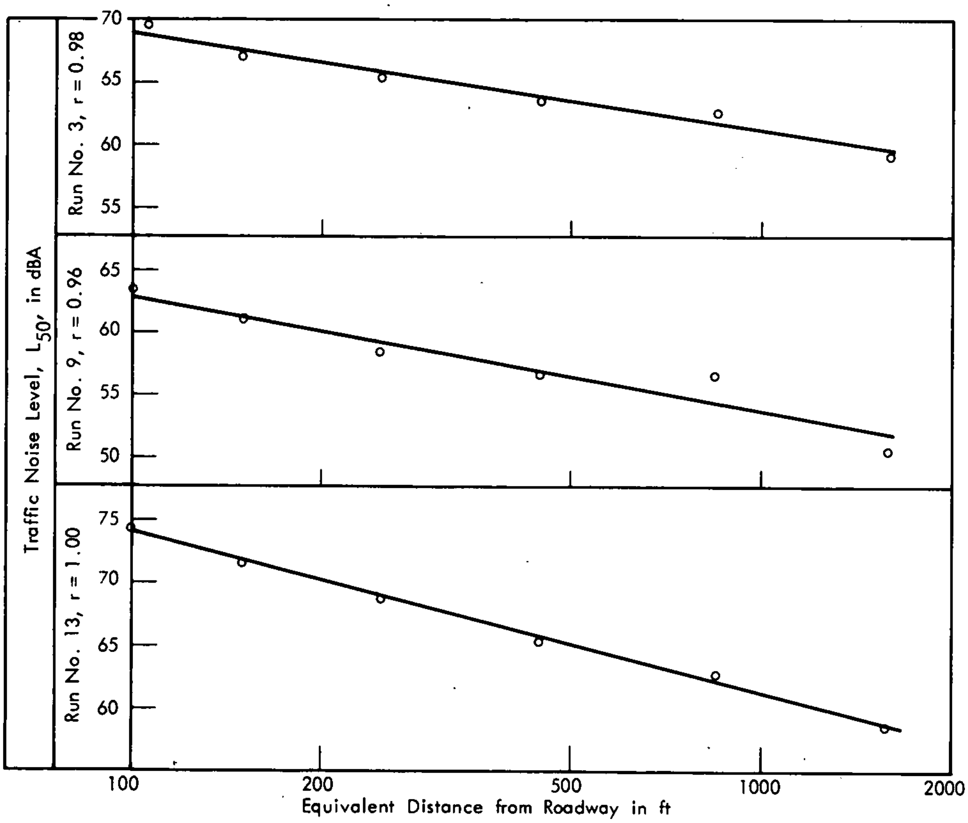


Figure 37. Traffic noise L_{50} levels vs distance, Site 1.

terms of the large and small percentage levels. Again, however, the pertinent issue is whether these effects are sufficiently significant to warrant attention in practical situations. The data for Site 1 were selected to study this issue inasmuch as experiments at Site 1 provided the widest range of traffic volume and truck mix. The estimated propagation loss factors at Site 1 are presented, with the associated traffic conditions, in Table 34. Visual inspection suggests a significant variation in the propagation loss factors among some of the measurement runs representing different traffic conditions. To check this, the loss factors at each height were tested for homogeneity by conventional two-way analysis of variance procedures (*94*, pp. 467-478, 482), with the results presented in Table 35. These results reveal a weak but statistically significant variation in the loss factors for different measurement runs as well as the different percentage levels. Hence, the issue was pursued further by conventional correlation and regression analysis procedures (*94*, pp. 419-462). Specifically, a regression model for propagation loss as a function of traffic volume, V, and truck mix, M, was assumed, as follows:

$$\epsilon = \xi + \gamma \log V + \delta M \tag{87}$$

The propagation loss factors for the various percentage points in Table 34 were then fit to the model of Eq. 87, first for each height separately, and then for all heights together. For the L_{01}, L_{10}, and L_{eq} levels, the multiple correlation coefficients for the fit, as well as the estimates of the coefficients γ and δ, were not significantly different from zero, indicating no detectable dependence of ϵ on

TABLE 34

SUMMARY OF ESTIMATED PROPAGATION LOSS FACTORS UNDER VARIOUS TRAFFIC CONDITIONS, SITE 1

RUN NO.	MICRO-PHONE HT. (FT)	TRAFFIC VOLUME (VPH)	TRUCK MIX (%)	ESTIMATED REGRESSION COEFFICIENT, ϵ, FOR PROPAGATION LOSS FACTOR: L_{01} LEVEL	L_{10} LEVEL	L_{50} LEVEL	L_{90} LEVEL	L_{eq} LEVEL
3	5	2820	5.0	11.54	9.33	7.76	7.33	8.35
4		1940	8.3	10.82	7.42	6.43	5.88	7.38
8		678	5.3	12.26	9.58	9.61	7.72	9.23
9		487	8.3	12.99	7.77	9.22	7.74	9.79
12		252	23.8	11.71	6.60	4.58	3.84	7.54
13		8030	4.3	13.00	13.00	12.69	11.82	12.83
16		5400	2.2	9.15	9.92	12.24	12.33	10.16
2	10	3240	5.6	10.35	9.78	9.67	8.74	9.93
5		1152	4.0	12.33	9.23	8.55	6.45	9.07
7		842	7.1	13.36	11.60	12.30	11.08	11.79
10		360	20.0	12.87	11.82	10.61	10.60	11.28
14		7480	5.6	13.46	13.57	11.43	10.86	11.96
17		3510	5.5	9.05	12.73	11.22	10.30	11.34
20		2020	3.9	18.57	14.65	14.13	13.04	13.73
1	15	4120	6.8	10.73	7.46	8.35	10.74	8.57
6		1100	8.8	13.49	9.66	10.17	11.23	10.86
11		366	24.6	15.03	13.60	9.67	6.77	12.08
15		7150	3.9	14.72	13.40	12.17	11.98	12.52
18		2520	4.3	12.28	9.92	10.24	10.38	10.30
19		1728	4.9	16.51	13.49	13.22	11.61	12.15

TABLE 35

RESULTS OF HOMOGENEITY TESTS OF PROPAGATION LOSS FACTORS FOR VARIOUS MEASUREMENT RUNS, SITE 1

HEIGHT ABOVE GROUND (FT)	VARIATION OF ϵ WITH PERCENTAGE LEVEL: VALUE OF F	CRITICAL VALUE OF F [a]	STATIS. SIGNIF.	VARIATION OF ϵ WITH MEASUREMENT RUN: VALUE OF F	CRITICAL VALUE OF F [a]	STATIS. SIGNIF.
5	5.48	3.67	Yes	8.77	4.22	Yes
10	5.58	3.67	Yes	14.06	4.22	Yes
15	5.54	4.10	Yes	6.09	4.43	Yes

[a] At 1 percent level of significance.

either log V or M. For the L_{50}, and particularly the L_{90} levels, a marginal dependence of ϵ on log V was revealed. However, this was probably due to distortions of the L_{50} and L_{90} levels by the background ambient noise, which would be most pronounced for the low traffic volume cases; i.e., those cases when the traffic noise is lowest. To confirm this, the propagation loss factors in Table 34 were reevaluated by analysis of variance procedures with all data for traffic volumes of less than $V = 2{,}000$ vph excluded. The evaluation now revealed no significant variations in the propagation loss factors among the remaining high-volume measurement runs at any of the three measurement heights.

In summary, it appears reasonable to assume that the propagation loss factor is not significantly dependent on traffic conditions for traffic volumes of over 2,000 vph. The loss factor might be significantly influenced by volumes lower than 2,000 vph, but the data do not permit a resolution of this issue due to ambient noise influences on the low traffic volume measurements.

Restudy of Variations with Measurement Height and Percentage Level

Evaluations summarized in Table 32 suggested that the propagation loss factor is, in some cases, dependent on measurement height. Specifically, there was an indication that the loss factor increased with measurement height (from 5 to 10 ft), contrary to intuitive expectations. Noting that this result was most pronounced at Site 1 where traffic volumes were often low, it appears this anomaly might be due to the influence of ambient noise. To check this possibility, the detailed propagation loss factor data for Site 1, as presented in Table 34, were tested for homogeneity among measurement heights, after excluding all measurement runs involving traffic volumes of less than $V = 2{,}500$ vph. The homogeneity test was performed by conventional two-way analysis of variance procedures. It is clear from the results (Table 36) that the data for measurement runs at low traffic volumes were indeed responsible for the indicated dependence on measurement height in Table 32, at least for the case of Site 1. The results in Table 36 also confirm that there is no significant difference in the propagation loss factor at various percentage levels for the case where the traffic volume is relatively high (over 2,500 vph).

In summary, it appears reasonable to assume that the propagation loss factor is not significantly dependent on measurement height for heights of up to 15 ft above the ground. Ultimately, of course, the propagation loss would be expected to fall as the height increased above 15 ft over a lush ground cover (*96*).

TABLE 36

RESULTS OF HOMOGENEITY TESTS OF SELECTED PROPAGATION LOSS FACTORS FOR VARIOUS MEASUREMENT HEIGHTS, SITE 1

FACTOR TESTED	VALUE OF F	CRITICAL VALUE OF F [a]	STATIS. SIGNIF.
Interaction between percentage level and height	0.37	3.17	No
Variation of ϵ with percentage level	0.41	4.02	No
Variation of ϵ with height above ground	0.014	5.39	No

[a] At 1 percent level of significance.

REDUCTION MEASURES

The traffic noise data for the roadside barrier, elevated roadway, and depressed roadway sites were converted to excess noise reductions and compared to predicted noise reductions based on the incoherent line source model shown in Figure 38. The comparisons were made using measured noise reductions based on both L_{50} and L_{10} levels, as follows.

Data Comparison Techniques

The agreement between the measured and predicted noise reductions at the various locations for each site was assessed in terms of three statistical parameters, as follows:

1. The average discrepancy between the measured and predicted results, defining an over-all bias error in the predictions.
2. The standard deviation of the discrepancies between the measured and predicted results, defining an over-all random error in the predictions.

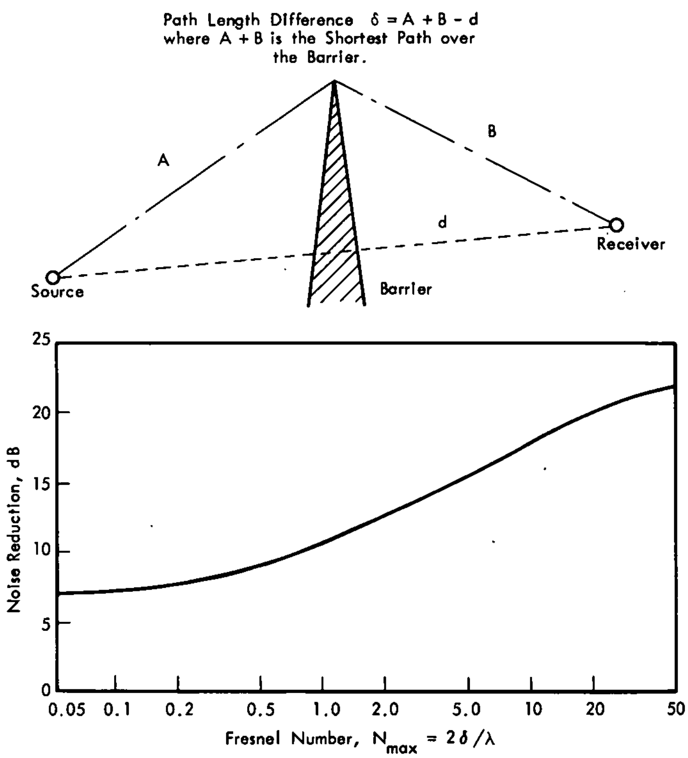


Figure 38. Noise reductions for an infinitely long barrier running parallel to an incoherent line source.

3. The least-squares line for the measurements versus the predictions, defining a bias error in the predictions as a function of noise reduction magnitude.

To be specific, let x_i and y_i be the predicted and measured noise reductions, respectively, at the ith location. The discrepancy at the ith location is then given by

$$\Delta_i = y_i - x_i \tag{88}$$

The average discrepancy, indicative of a bias error, is defined as

$$\overline{\Delta} = \frac{1}{n} \sum_{i=1}^{n} \Delta_i \tag{89}$$

where n is the number of locations. The standard deviation, indicative of a random error, is defined as

$$s_\Delta = \left[\frac{1}{n-1} \sum_{i=1}^{n} (\Delta_i - \overline{\Delta})^2 \right]^{\frac{1}{2}} \tag{90}$$

The least-squares line is given by

$$y = a + b\,x \tag{91}$$

where

$$a = \overline{y} - b\overline{x} \tag{92}$$

$$b = \sum_{i=1}^{n} y_i(x_i - x) \Big/ \sum_{i=1}^{n} (x_i - \overline{x})^2 \tag{93}$$

For the case of perfect agreement between the measurements and predictions, it is clear that $y = x$, meaning $a = 0$ and $b = 1$.

The quantities defined in Eqs. 89, 90, and 91 were calculated for the measured and predicted noise reductions at each of the three sites. For the case of an unbiased agreement between the measurements and predictions, it follows that $\overline{\Delta} = 0$, $a = 0$, and $b = 1$. Hence, the values for these three parameters were tested for statistically significant differences from their ideal values by conventional statistical procedures (*97*, pp. 99-113). For the case of the random error, as indicated by s_Δ, a statistically significant difference from zero would always be expected, due to measurement errors if nothing else.

Comparisons Based on L_{50} Levels

The measured and predicted noise reductions for the various locations at all three sites are presented in Tables C-1, C-2, and C-3. The measured noise reductions are based on raw data for both L_{50} and L_{10} levels, detailed in Appendix A of *NCHRP Report 144* (*3*).* The predictions are based on the incoherent line source model summarized in Figure 38. The results of the various assessments of the agreement between measured and predicted noise reductions at each site, based on L_{50} levels, are summarized in Table 37.

In Table 37, there are no significant differences, on the average, between the measured and predicted noise reductions for any of the three configurations. Hence, it appears that the incoherent line source prediction procedure of Figure 38 yields unbiased estimates for the L_{50} noise reductions provided by roadside barriers, elevated roadway configurations, and depressed roadway configurations. Using the standard deviation of the discrepancies as a measure of random error, the random error in the agreement is about 1.5 dBA for all three configurations. The magnitude of this error is qualitatively illustrated by the scatter plot in Figure 39. Remembering the various assumptions involved in the application of the prediction procedure, this is not considered an unreasonable degree of random error.

Comparisons Based on L_{10} Levels

Results of the various assessments of the agreement between measured and predicted noise reductions at each site, based

* L_{10} levels for the roadside barrier configuration are excluded because these data appear to be unreliable.

TABLE 37

AGREEMENT BETWEEN PREDICTED AND MEASURED NOISE REDUCTIONS BASED ON L_{50} LEVELS

SITE AND SAMPLE SIZE	ASSESSMENT PARAMETER	COMPUTED RESULT	IDEAL RESULT	DIFF.[a] STATIST. SIGNIF.
Roadside	Ave. discrep., $\overline{\Delta}$	0.03 dBA	0	No
barrier	Std. dev., s_Δ	1.64 dBA	0	—
(Fig. C-1)	Intercept, a	−2.01 dBA	0	No
$n=50$	Slope, b	1.19	1.0	No
Elevated	Ave. discrep., $\overline{\Delta}$	0.38 dBA	0	No
roadway	Std. dev., s_Δ	1.39 dBA	0	—
(Fig. C-2)	Intercept, a	−2.64 dBA	0	No
$n=24$	Slope, b	1.29	1.0	No
Depressed	Ave. discrep., $\overline{\Delta}$	−0.10 dBA	0	No
roadway	Std. dev., s_Δ	1.60 dBA	0	—
(Fig. C-3)	Intercept, a	0.65 dBA	0	No
$n=24$	Slope, b	0.91	1.0	No

[a] Tested at the 1 percent level of significance.

TABLE 38

AGREEMENT BETWEEN PREDICTED AND MEASURED NOISE REDUCTIONS BASED ON L_{10} LEVELS

SITE AND SAMPLE SIZE	ASSESSMENT PARAMETER	COMPUTED RESULT	IDEAL RESULT	DIFF.[a] STATIST. SIGNIF.
Elevated roadway (Fig. C-2) $n=24$	Ave. discrep., $\bar{\Delta}$	0.26 dBA	0	No
	Std. dev., s_Δ	1.50 dBA	0	—
	Intercept, a	−1.46 dBA	0	No
	Slope, b	1.16	1.0	No
Depressed roadway (Fig. C-3) $n=24$	Ave. discrep., $\bar{\Delta}$	1.02 dBA	0	Yes
	Std. dev., s_Δ	1.55 dBA	0	—
	Intercept, a	2.07 dBA	0	No
	Slope, b	0.88	1.0	No

[a] Tested at the 1 percent level of significance.

on L_{10} levels, are summarized in Table 38. No comparisons are made for the roadside barrier because the validity of the basic L_{10} data for this case is in question, as noted earlier. In Table 38, the agreement for the elevated roadway configuration obtained using L_{10} levels is equally as good as the agreement provided by the L_{50} levels. For the depressed roadway configuration there is a small but statistically significant discrepancy between the measured and predicted results. On balance, however, the agreement is still good.

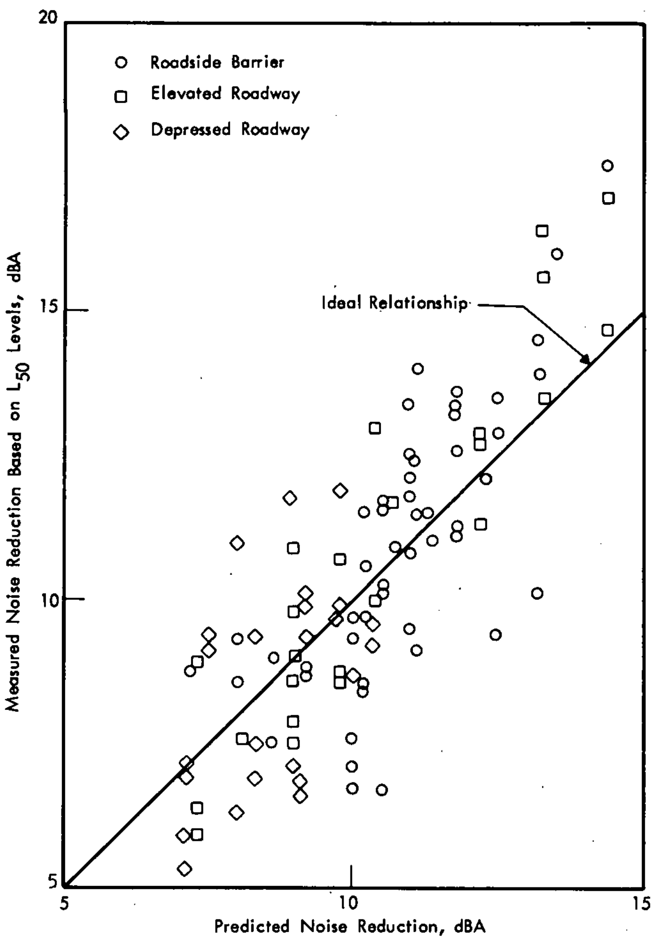


Figure 39. Measured vs predicted noise reductions for various highway noise shielding configurations.

Construction Cost Data

The five states that responded to a solicitation of information provided varying amounts of cost data for 18 hypothetical and actual sites as follows:

Site 1—8-lane, at-grade highway in California (hypothetical).
Site 2—8-lane, depressed (20 ft) highway in California (hypothetical).
Site 3—8-lane, fill-elevated (20 ft) highway in California (hypothetical).
Site 4—8-lane, elevated (24 ft) structure in California (hypothetical).
Site 5—10-lane, depressed (35 ft) freeway in California (Century Freeway, Route 105 in Los Angeles).
Site 6—10-lane, fill-elevated (25 ft) freeway in California (Century Freeway, Route 105 in Los Angeles)
Site 7—10-lane, elevated (30 ft) structure in California (Century Freeway, Route 105 in Los Angeles).
Site 8—6-lane, at-grade highway in Colorado (hypothetical).
Site 9—6-lane, depressed (20 ft) highway in Colorado (hypothetical).
Site 10—6-lane, fill-elevated (20 ft) highway in Colorado (hypothetical).
Site 11—6-lane, elevated (20 ft) structure in Colorado (hypothetical).
Site 12—6-lane, at-grade highway in Connecticut (Newington-Wethersfield-Rocky Hill).
Site 13—6-lane, depressed (20 ft) highway in Connecticut (Newington-Wethersfield-Rocky Hill).
Site 14—6-lane, fill-elevated (20 ft) highway in Connecticut (not available).
Site 15—2-lane, elevated (16 ft) structure in Connecticut (Newington-Wethersfield-Rocky Hill).

Site 16—4-lane, at-grade highway in Illinois (Route I-74 in Moline).

Site 17—4-lane, elevated (30 ft) structure in Illinois (Route I-74 in Moline).

Site 18—At-grade highway in Michigan with no roadway description provided (hypothetical).

Complete descriptions of the highway sites are presented in Table C-4.

The cost data were provided in four categories as follows:

1. Right-of-way acquisition costs.
2. Capital costs for at-grade, depressed, fill-elevated, and structure-elevated highways.
3. Capital costs for barriers and berms.
4. Operating and maintenance costs for highways.

Right-of-Way Acquisition Costs

The data on right-of-way acquisition costs are detailed in Table C-5 and summarized in Table 39. The latter includes all acquisition costs, as follows:

1. Land prices.
2. Price of existing structures.
3. Liquidated damages.
4. Legal expenses.
5. Compensation for moving and relocation.
6. Utility relocations and adjustments.
7. Miscellaneous expenses.

In summary, the right-of-way acquisition costs vary widely depending on the location and type of roadway. The issue of primary interest here, however, is the percent change in cost for depressed, fill-elevated, and structure-elevated roadways relative to an at-grade roadway. The results indicate that the costs for depressed and fill-elevated roadways are higher, all other things equal, due to the wider right-of-way required. However, the costs are the same or less for elevated structures, because they involve no slopes and are often used with a reduced right-of-way buffer zone.

Highway Construction Costs

The data acquired on highway construction costs are detailed in Table C-6 and summarized in Table 40. The latter, under "basic construction costs," includes the following:

1. Roadway clearing and excavation.
2. Installation of drainage.
3. Pavement.
4. Shoulders.
5. Roadway appurtenances.
6. Landscaping.
7. Lighting.
8. Signing.
9. Miscellaneous expenses.

The costs of street crossings and ramps are listed separately. Total construction costs are presented in the last column for those cases where sufficient data were supplied.

Berm and Barrier Construction Costs

The data acquired on berm and barrier construction costs are detailed in Table 41. They include the following cost factors:

TABLE 39

SUMMARY OF RIGHT-OF-WAY ACQUISITION COSTS

STATE AND SITE	NO. LANES AND TYPE OF ROAD [a]	GENERAL COMPOSITION OF LAND ACQUIRED	RIGHT-OF-WAY WIDTH (FT)	RIGHT-OF-WAY COST ($1000) PER ACRE [b]	RIGHT-OF-WAY COST ($1000) PER MILE
CA, 1	8–G	Typical California urban area	229	246	6828
CA, 2	8–D	Typical California urban area	229	296	8216
CA, 3	8–E	Typical California urban area	229	302	8383
CA, 4	8–S	Typical California urban area	229	178	4941
CA, 5	10–D	90% resid., 5% comm., 5% public	174	320	6800
CA, 6	10–E	90% resid., 10% comm.	278	320	10800
CA, 7	10–S	25% resid., 75% indus.	409	236	11700
CO, 8	6–G	20% resid., 10% comm., 70% indus.	47	150	855
CO, 9	6–D	20% resid., 10% comm., 70% indus.	47	300	1709
CO, 10	6–E	20% resid., 10% comm., 70% indus.	47	300	1709
CO, 11	6–S	20% resid., 10% comm., 70% indus.	47	100	570
CT, 12	6–G	Typical Connecticut urban area	173	362	7591
CT, 13	6–D	Typical Connecticut urban area	173	362	7591
CT, 14	6–E	Typical Connecticut urban area	173	362	7591
CT, 15	2–S	Typical Connecticut urban area	173	—	—
IL, 16	4–G	39% resid., 2% comm., 59% farm [c]	4	500	242
IL, 17	4–S	39% resid., 2% comm., 59% farm [c]	4	250	121

[a] G = at grade, D = depressed, E = fill elevated, S = elevated structure.
[b] As right-of-way.
[c] Estimated from other data provided.
Note: No right-of-way acquisition cost data were provided for site 18.

1. Excavation.
2. Foundation construction.
3. Materials.
4. Labor for installation.

Also, they apply to barriers along both sides of the roadway. The cost for a one-sided berm or barrier would be one-half the cost figure given in the table.

In summary, the cost data provided by the various states again show considerable scatter. For example, the cost for a 20-ft-high reinforced concrete barrier quoted by Illinois is twice as high (more than $4 million per mile greater) than the cost estimated by Connecticut. Of course, this difference might be explained in part by the fact that the Illinois cost was in terms of 1970 dollars whereas the Connecticut cost was quoted in terms of 1968 dollars. On balance, it appears that brick or concrete block barriers are the best buy.

Maintenance and Operating Costs

The maintenance and operating costs associated with conventional highways, as reported by various states, are summarized in Table 42 and include the maintenance items of:

1. Landscaping upkeep.
2. Highway clearing.
3. Structures upkeep.
4. Right-of-way maintenance.
5. Repairs of guardrails and fences.

and the operating items of:

1. Upkeep of traffic signs and lighting.
2. Power.
3. Snow and water removal.

The data provided by the various states suggest that there is no difference in the maintenance and operating costs associated with at-grade, depressed, fill-elevated, and structure-elevated roadways. Although this is a questionable suggestion, it may well be reasonable to assume that the cost differences among the various types of roadways are sufficiently small to be ignored.

VEHICLE NOISE DIRECTIVITY

The directivity noise data, collected and reduced as outlined in Chapter One, are detailed in Tables D-1 and D-2. The atmospheric conditions (wind, temperature, humidity) during the various measurement runs are recorded in Table D-3. The evaluation of these data is summarized in the following.

Data Evaluation Techniques

For each measurement run involving peak noise measurements at four angles ($P_{6°}$, $P_{19°}$, $P_{32°}$, $P_{45°}$), two descriptors were defined, as follows:

$$\Delta = \frac{P_{45°} + P_{32°}}{2} - \frac{P_{19°} + P_{6°}}{2} \quad (94)$$

$$\overline{P} = \frac{P_{45°} + P_{32°} + P_{19°} + P_{6°}}{4} \quad (95)$$

The first descriptor, Δ, referred to herein as the "distortion factor," constitutes a measure of the directivity of the radiated noise ($\Delta = 0$ for omnidirectional noise). The second descriptor, $\overline{P}$, is simply a measure of the average noise radiated by the source.

Evaluation of the data, in terms of both distortion factors

TABLE 40

SUMMARY OF CONSTRUCTION COSTS

STATE AND SITE	NO. LANES AND TYPE OF ROAD [a]	BASIC CONSTR. COST ($1000/MI)	STREET CROSSINGS NUMBER URBAN	STREET CROSSINGS NUMBER SUBURBAN	STREET CROSSINGS COST EACH ($1000)	ON-OFF RAMPS NUMBER URBAN	ON-OFF RAMPS NUMBER SUBURBAN	ON-OFF RAMPS COST EACH ($1000)	TOTAL [b] CONSTR. COST ($1000/mi)
CA, 1	8–G	2100	4	2	450	2	1	1450	4450
CA, 2	8–D	2400	4	2	510	2	1	1450	4870
CA, 3	8–E	1750	4	2	400	2	1	1450	4000
CA, 4	8–S	14800	4	2	400	2	1	1984	17580
CA, 5	10–D	5700	4	2	— [c]	2	1	2579	8280
CA, 6	10–E	2430	4	2	— [c]	2	1	1984	4410
CA, 7	10–S	16400	4	2	— [c]	2	1	803	17200
CO, 8	6–G	766	6	4	100	8	8	— [c]	1166
CO, 9	6–D	1528	6	4	—	8	8	25	—
CO, 10	6–E	1528	6	4	—	8	8	25	—
CO, 11	6–S	—	6	4	—	8	8	—	—
CT, 12–15	6–M	5600	3	—	87	1	—	62	—
IL, 16	4–G	2192	1	½	687	6	2	— [c]	2530
IL, 17	4–S	—	—	—	—	—	—	—	—
MI, 18	—	1500	6	3	—	8	4	45	—

[a] G = at grade, D = depressed, E = fill elevated, S = elevated structure, M = mixed.
[b] Suburban crossings and ramps.
[c] Included in basic construction cost.

TABLE 41

SUMMARY OF BERM AND BARRIER COSTS

DESCRIPTION OF BERMS OR BARRIERS	STATE AND YEAR	HEIGHT (FT)	COST [a] ($1000/MI)
Precast concrete panels, architecturally finished, secured to steel or concrete framework	CA–73	8	253
	CT–68	10	686
	CT–68	20	1373
	CT–68	30	2059
Reinforced concrete walls	CA–73	6	760
	CT–63	20	4224
	IL–70	10	3292
	IL–70	20	8466
	IL–70	30	15641
	IL–70	34	17187
Brick walls	CT–72	10	528
	CT–72	20	1056
Concrete block wall, 8 in. thick	CA–73	6	158
	CA–73	13	338
	CA–73	20	500
Corrugated steel barriers	CA–73	6	148
	CT–71	10	1056
	CT–71	20	2112
	CT–71	30	3168
Wood wall, 4 in. thick	CT–73	4	475
Earth berms, 3 to 1 slopes, 5 ft wide at top	CT–73	10–17	803 [b]

[a] For a berm or barrier on both sides of the roadway.
[b] Does not include cost of additional right-of-way that would be required.

TABLE 42

SUMMARY OF MAINTENANCE AND OPERATING COSTS

STATE AND SITE	NO. LANES AND TYPE OF ROAD	COST PER MILE [a] ($) MAINT.	OPER.
CA, 1	8–G	15000	1500
CA, 2	8–D	15000	1500
CA, 3	8–E	15000	1500
CA, 4	8–S	15000	1500
CO, 8–11	6–G, D, E, S	5000	3000
CT, 12–15	6–G, D, E; 2–S	←20000→	
IL, 16	4–G	2630	2000
MI, 18	—	5000	4000

[a] IL in 1971 dollars; CA, CO, and MI in 1972 dollars; CT in 1974 dollars.

and average values, was pursued using multiple regression models of the form

$$\Delta = \xi + \beta \log S + \gamma \log N + \delta E \qquad (96)$$

$$\overline{P} = \xi' + \beta' \log S + \gamma' \log N + \delta' E \qquad (97)$$

where

S = the vehicle speed, in mph;
N = the number of wheels;
E = the exhaust type; and
$\xi, \beta, \gamma, \delta, \xi', \beta', \gamma', \delta'$ = regression coefficients

The five classes of exhausts were ordered in terms of the noise one might assume they would generate, as follows:

1. Exhaust under chassis.
2. Single stack, left side.
3. Single stack, middle.
3. Two stacks, each side.
5. Single stack, right side.

Directivity Patterns and Distortion

Typical directivity patterns for the various types of vehicles passing at Site A are shown in Figure 40. The circular shape of the directivity patterns in these figures tends to confirm the results obtained on passenger cars by Rathé (*98*).

By use of Eq. 94, the average distortion, Δ, for the 66 trucks studied at Site B was found to be +0.87 dBA, with a standard deviation of 0.85 dBA. This supports the conclusion that trucks are almost omnidirectional sources. The fact that the distortion factor, Δ, is in general positive indicates that highway noise sources radiate slightly less horizontally than they do at a slant angle.

Keeping in mind that the distortion is small, a regression study was performed using the model given in Eq. 96. The initial results indicated that a better understanding of the problem could be reached by separating the samples into two classes: "fast trucks" with speeds above 62 mph and

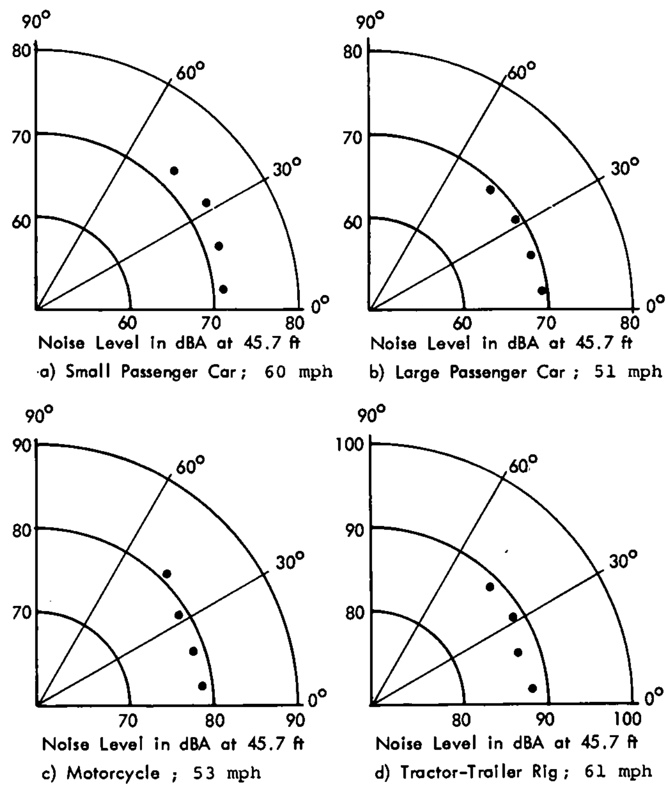


Figure 40. Noise directivity patterns for vehicles.

"slow trucks" with speeds below 62 mph. For slow trucks, the average distortion was computed to be 1.03 dBA ($\sigma = 0.93$). For the fast trucks, the distortion was slightly less, 0.68 dBA ($\sigma = 0.73$). For slow trucks, however, there is no significant dependence of the distortion on speed, number of wheels, or type of stack. For fast trucks, there is some evidence of a dependence on the number of wheels. A simple regression analysis of the distortion, Δ, as a function of N led to the statistically significant equation

$$\Delta = -2.5 + 2.7 \log N \quad \text{with } 6 \leqq N \leqq 18 \tag{98}$$

which indicates that the distortion, though small, increases with the number of wheels.

Spectra

One-third-octave band spectra of the noise at the four angles were analyzed for selected cases. Typical examples are shown in Figures 41 through 44. These analyses do not reveal a significant variation in the spectra from one angle to another. Although some variation appears to exist at the lower frequencies, there is no distinct trend in the variation. It is believed that these apparent variations at the low frequencies are the result of statistical uncertainties common to short-time, averaged, narrow-bandwidth, random data (*97*, pp. 184-193).

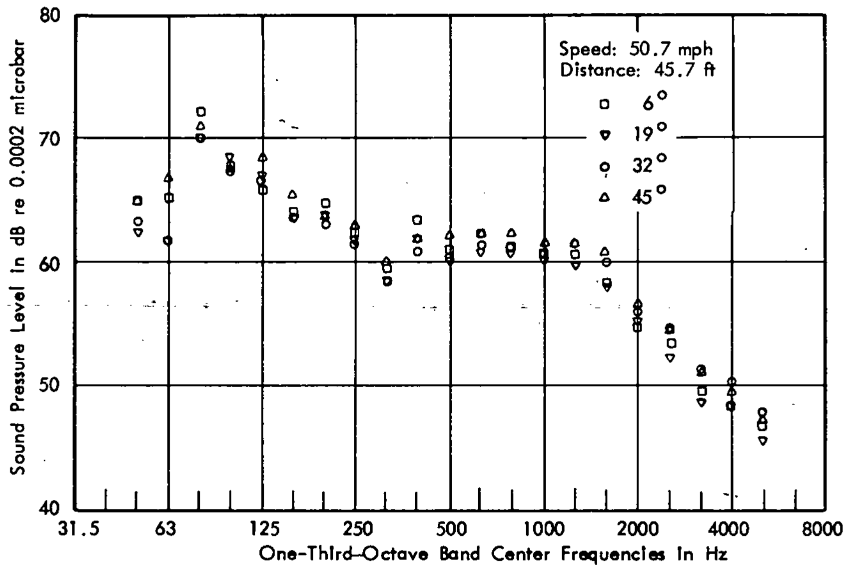


Figure 41. One-third-octave band spectrum of noise from a passing automobile.

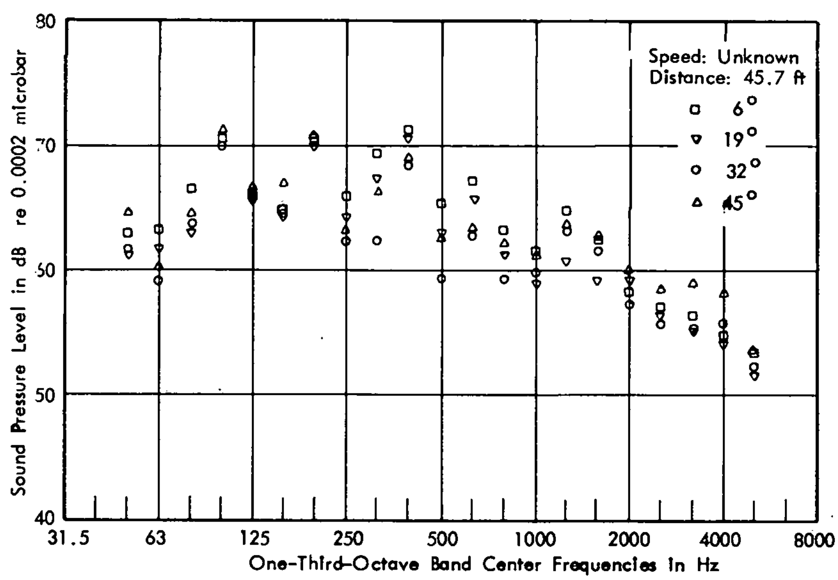


Figure 42. One-third-octave band spectrum of noise from a passing motorcycle.

TRUCK NOISE LEVELS

A summary of the peak drive-by sound levels for the various types of trucks at all seven sites is presented in Tables E-1 through E-7. The atmospheric conditions (wind, temperatures, humidity) during the surveys at the various sites are recorded in Table E-8. Evaluations of these data are summarized in the following.

Data Evaluation Procedures

As a first step in evaluation of the peak drive-by noise levels measured at 50 ft off the axis of motion (referred to hereafter as "peak noise levels"), the means and standard deviations were computed for vehicles in various categories, as summarized in Table 43. It is clear from these results that the truck peak noise levels increase with the

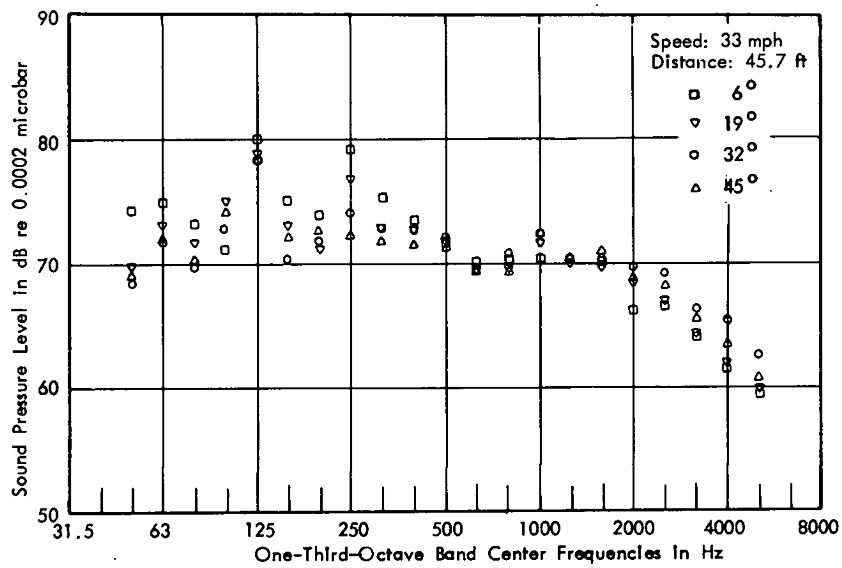


Figure 43. One-third-octave band spectrum of noise from a passing truck (low stack).

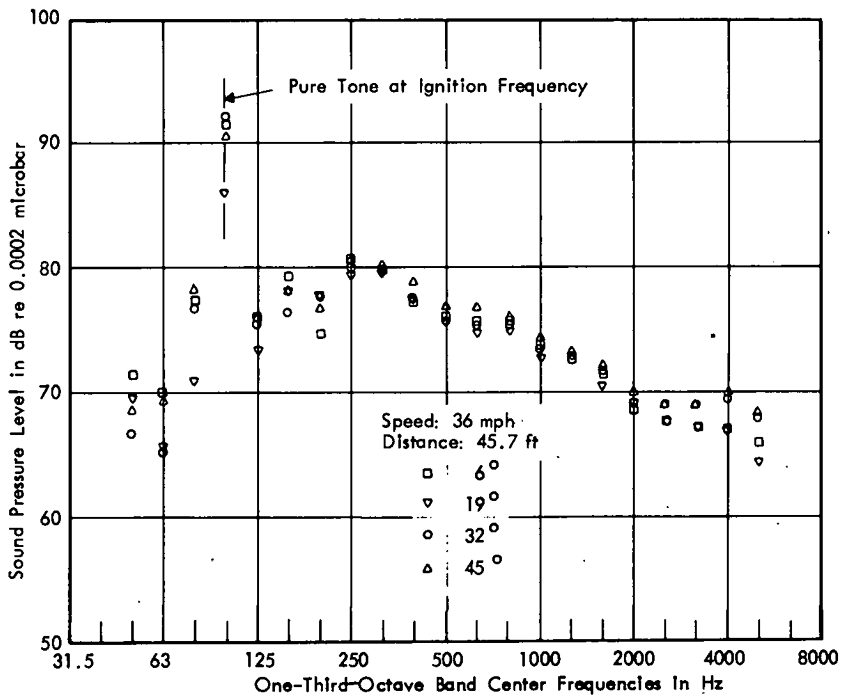


Figure 44. One-third-octave band spectrum of noise from a passing truck (high stack).

number of axles, the largest increase occurring in the step from two to three axles. Note that the average peak noise levels for motorhomes and buses correspond reasonably well to the levels for trucks with a similar number of axles. The same is true of the peak noise levels for low- and high-exhaust trucks. However, there is a significant difference in the peak noise levels for trucks traveling at speeds under 50 mph and over 50 mph which cannot be accounted for by a difference in the number of axles. In summary, it appears that the number of axles and speed are the primary factors defining the peak noise levels.

Based on these preliminary results, evaluation of the peak noise level data was pursued using a model of the form

$$\mathrm{PNL} = \alpha + \beta \log N + \gamma \log S \qquad (99)$$

where

PNL = peak drive-by noise level at 50 ft, in dBA;
N = number of axles;
S = truck speed, in mph; and
α, β, γ = regression coefficients.

Eq. 99 describes the peak noise level of trucks as a function of the number of axles and the truck speed only. All other parameters influencing the noise emission are absorbed in the intercept coefficient, α, or as random error.

Comparisons Among Sites

By use of the model of Eq. 99, the peak noise levels at each site were analyzed by conventional multiple regression analysis procedures (*94*). The estimated correlation coefficients, r, and regression coefficients (α, β, γ) are summarized in Table 44. By substituting the estimated regression coefficients into Eq. 99, the average peak levels measured at the various sites may be directly compared for any desired number of axles and vehicle speed. For example, assuming four axles and speeds of: (a) 35 mph and (b) 50 mph, the average peak noise levels of the trucks at the various sites are as summarized in the last two columns of Table 44. The four-axle case was selected for the comparisons because it represents the approximate average number of axles for the trucks at the various sites, and not because it represents a typical truck. Five-axle trucks are actually more common in practice.

In Table 44, the correlation coefficients vary from $r = 0.50$ to $r = 0.78$. In broad terms, this means that the peak noise level of an individual truck is about 25 to 50 percent dependent on the two parameters, number of axles and speed. For the specific case of four-axle trucks traveling at 35 and 50 mph, the regression lines for the seven sites predict average peak noise levels that are within 2 dBA of the over-all average in most cases. Although the differences in the peak levels among the sites are statistically significant in some cases, the differences are not considered sufficiently large in physical terms to warrant separate treatment of the data for different sites. Hence, the data for all sites are pooled for further study.

Variations with Other Parameters

Again using the model of Eq. 99, the peak noise levels were analyzed to permit comparisons among various categories of vehicles, including:

1. Trucks with different numbers of axles.
2. Trucks at speeds of less than 50 mph versus trucks at speeds of greater than 50 mph.
3. Trucks versus motorhomes and buses.
4. Trucks with low exhausts versus trucks with high exhausts.

The estimated correlation and regression coefficients for these cases are summarized in Table 45, which also gives the predicted peak noise levels for speeds of 35 and 50 mph, and the indicated number of axles, computed by substituting the appropriate regression coefficients into Eq. 99.

TABLE 43

SUMMARY OF AVERAGE VEHICLE PEAK NOISE LEVELS

VEHICLE CATEGORY	SAMPLE SIZE	MEAN NUMBER OF AXLES	VEHICLE SPEED (MPH) MEAN	STD. DEV.	PEAK NOISE LEVEL (dBA) MEAN	STD. DEV.
All vehicles	3534	3.81	56.9	6.7	85.7	5.1
All motorhomes	51	2.03	57.2	6.1	78.5	3.2
All buses	73	2.21	55.4	8.1	82.2	3.3
All trucks	3410	3.88	56.9	6.7	85.9	5.0
2-Axle trucks	675	2.0	55.5	7.1	80.6	4.1
3-Axle trucks	320	3.0	53.6	6.9	83.9	3.8
4-Axle trucks	368	4.0	56.2	6.9	85.4	4.0
5-Axle trucks	2022	5.0	58.0	6.1	88.0	4.1
≥6-Axle trucks	25	6.0	54.5	8.4	88.4	3.2
≥3-Axle trucks	2735	4.63	57.2	6.5	87.2	4.3
Low-exhaust trucks	1137	2.66	55.0	7.1	82.2	4.5
High-exhaust trucks	2273	4.70	57.8	6.3	87.7	4.1
Trucks below 50 mph	440	3.39	44.6	6.1	81.4	4.8
Trucks above 50 mph	2970	3.97	58.5	4.9	86.5	4.8

Variations with Number of Axles

Referring to the speed corrected data in the last two columns of Table 45, it is clear that the peak noise levels progressively increase with the number of axles, as previously suggested in Table 43. The greatest increase—4 to 5 dBA—occurs in the step from two to three axles. This is greater than the total increase from three to six axles.

These results are further demonstrated in Figure 45(a), which presents the regression lines for the peak noise levels of trucks with various numbers of axles. The peak levels for trucks with three axles or more clearly cluster around a level well above that for two-axle trucks at all speeds. In summary, it appears reasonable for the purposes of a simplified model to group all trucks with three axles or more into a single category—"heavy trucks." Two-axle trucks (vehicles with six wheels) are referred to as "medium trucks."

Variations with Speed

The peak noise level model of Eq. 99 assumes that the noise level varies linearly with the logarithm of speed. To check this assumption, the truck noise data were divided into two

TABLE 44

CORRELATION AND REGRESSION COEFFICIENTS FOR PEAK NOISE LEVELS OF TRUCKS VERSUS NUMBER OF AXLES AND SPEED AT DIFFERENT SITES

MEASUREMENT SITE				VEHICLE SPEED (MPH)		PEAK NOISE LEVEL (dBA)		CORRELATION AND REGRESSION COEFFICIENTS				AVERAGE PEAK NOISE LEVEL FOR 4 AXLES (dBA)	
NO.	STATE	SAMPLE SIZE	MEAN NUMBER OF AXLES	MEAN	STD. DEV.	MEAN	STD. DEV.	r	α	β	γ	35 MPH	50 MPH
1	Cal.	388	3.61	51.3	5.7	83.3	3.7	0.60	43.2	12.6	19.4	80.7	83.7
2	Col.[a]	306	3.55	51.6	7.1	84.6	4.4	0.66	46.3	15.1	17.5	82.4	85.1
3	Ill.	948	4.42	57.2	4.7	87.9	4.8	0.50	18.8	16.0	33.5	80.2	85.3
4	Kent.	606	4.06	61.3	5.4	87.7	4.2	0.75	10.9	15.7	37.7	78.6	84.4
5	N.Y.	426	3.48	59.8	5.9	87.7	3.8	0.78	24.4	13.8	31.5	81.3	86.2
6	Tex.	379	3.38	56.1	7.3	82.6	5.5	0.78	30.5	20.7	23.6	79.4	83.1
7	Tex.	357	3.97	56.5	6.2	83.3	4.1	0.61	56.0	15.6	10.3	81.3	82.9
All sites		3410	3.88	56.9	6.7	85.9	5.0	0.68	17.4	16.6	33.5	79.1	84.3

[a] Data corrected for altitude.

TABLE 45

CORRELATION AND REGRESSION COEFFICIENTS FOR PEAK NOISE LEVELS OF TRUCKS IN VARIOUS CATEGORIES

VEHICLE CATEGORY	SAMPLE SIZE	MEAN NUMBER OF AXLES	VEHICLE SPEED (MPH)		PEAK NOISE LEVEL (dBA)		CORREL. AND REGRESSION COEFF.				PEAK NOISE LEVEL (dBA)		
			MEAN	STD. DEV.	MEAN	STD. DEV.	r	α	β	γ	35 MPH	50 MPH	NO. AXLES
2-Axle trucks	675	2.	55.5	7.1	80.6	4.1	0.48	20.8	—	34.3	73.8	79.1	2
3-Axle trucks	320	3.	53.6	6.9	83.9	3.8	0.43	35.2	—	28.2	78.7	83.1	3
4-Axle trucks	368	4.	56.2	6.9	85.4	4.0	0.55	18.0	—	38.6	77.6	83.6	4
5-Axle trucks	2022	5.	58.0	6.1	88.0	4.1	0.40	28.6	—	33.7	80.6	85.8	5
≥6-Axle trucks	25	6.18	54.5	8.4	88.4	3.2	0.71	44.8	—	25.1	83.6	87.4	6
≥3-Axle trucks	2735	4.63	57.2	6.5	87.2	5.0	0.47	12.0	21.0	34.8	80.4	85.8	5
All trucks	3410	3.88	56.9	6.7	85.9	5.0	0.68	17.4	16.6	33.5	79.1	84.3	—
Motorhomes	51	2.03	57.2	6.1	78.5	3.2	0.31	38.0	−2.6	23.5	73.5	77.1	2
Buses	73	2.21	55.4	8.1	82.2	3.3	0.38	50.7	1.5	18.8	80.2	83.1	2
Low-exhaust trucks	1137	2.66	55.0	7.1	82.2	4.5	0.61	22.1	13.6	31.2	78.5	83.3	4
High-exhaust trucks	2273	4.70	57.8	6.3	87.7	4.1	0.47	20.2	12.2	33.7	79.6	84.8	4
Trucks below 50 mph	440	3.39	44.6	6.1	81.4	4.8	0.63	64.3	17.9	4.6	—	—	—
Trucks above 50 mph	2970	3.97	58.5	4.9	86.5	4.8	0.64	6.26		40.0	—	—	—
All vehicles	3534	3.81	56.9	6.7	85.7	5.1	0.69	19.1	16.8	32.4	79.2	84.3	

categories: (a) trucks traveling at speeds of less than 50 mph and (b) trucks traveling at speeds of more than 50 mph. The regression coefficients for these two cases are presented in Table 45, and the regression lines are plotted in Figure 45(b). Superimposed on these plots is the regression line for the peak noise of trucks at all speeds. All of the regression lines have been calculated assuming four axles to eliminate the number of axles as a variable in the comparisons.

Figure 45(b) strongly suggests that the speed dependence is not linear, as assumed in Eq. 99. Specifically, at speeds below 50 mph, the peak noise level is not as strongly dependent on speed as it is above 50 mph. Below 50 mph, the truck noise is probably dominated by power-train sources, which are relatively independent of speed. Above 50 mph, tire noise takes over. The coefficient of 40 on the log *S* term in this case is consistent with past studies that suggest tire noise increases with the fourth power of speed (*99*). It should be noted, however, that the over-all regression line is within 2 dBA of the individual regression lines for all speeds from 40 to 80 mph.

Trucks Versus Motorhomes and Buses

Again referring to Table 45, it appears that motorhomes are slightly quieter than trucks with a similar number of axles, whereas buses appear to be somewhat noisier. However, the sample sizes for motorhomes and buses are not

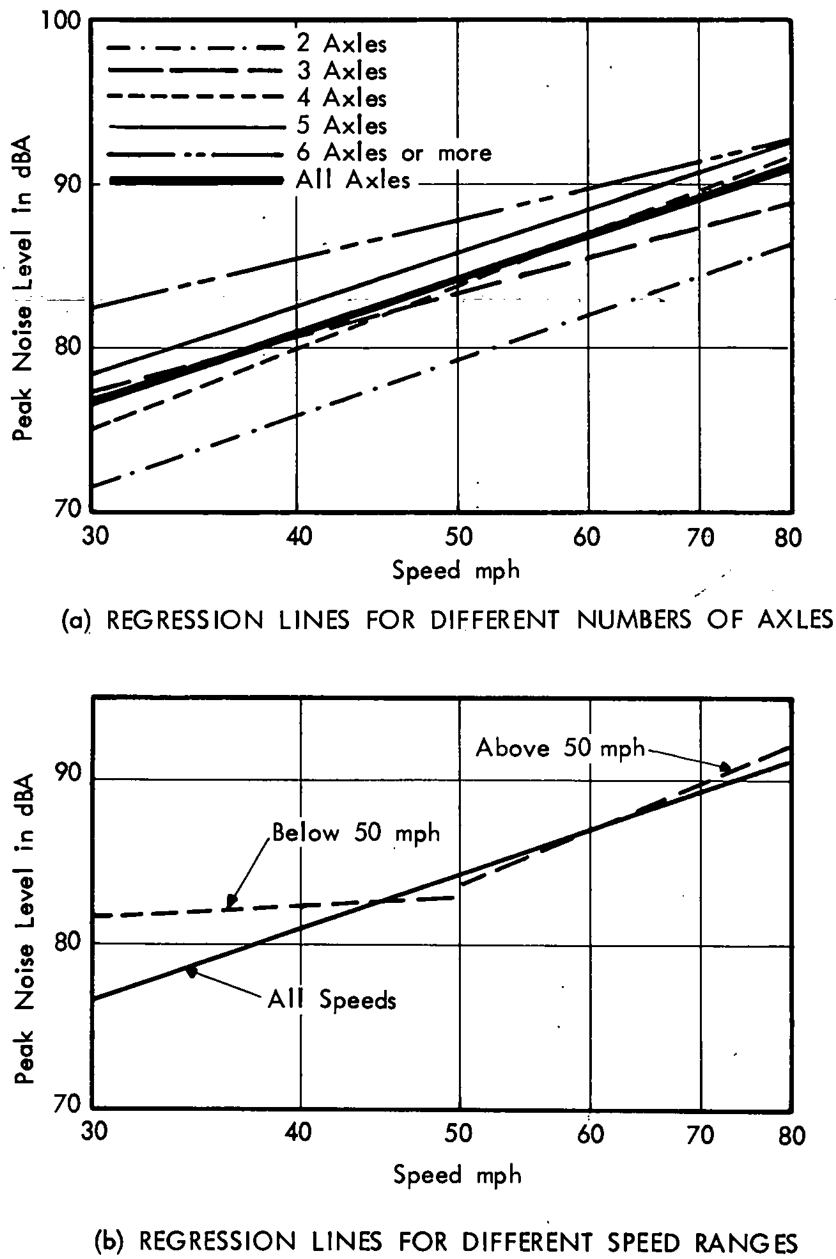


Figure 45. Peak noise levels of trucks vs speed for various numbers of axles and speed ranges.

adequate to draw firm conclusions. Because motorhomes and buses constitute a very small portion of the total vehicle population, there should be little error in considering them as trucks with the appropriate number of axles.

Low Versus High Exhausts

It is seen from Table 45 that the average noise level, without corrections, for low-exhaust trucks is more than 5 dBA less than for high-exhaust trucks. However, after correcting the data to a common speed and number of axles, the difference between the two cases is only 0.5 dBA at 50 mph. It follows that low-exhaust trucks tend to be quieter primarily because they have fewer axles. Hence, no distinction need be made between trucks wtih low and high exhausts, at least in terms of the peak noise level. It should be mentioned that there is a difference in the effective noise source location for the two cases. The equivalent noise source for the high exhaust case is obviously higher than for the low exhaust case.

Peak Noise Level Distributions

A final issue of concern is the distribution characteristic of the peak noise levels for trucks. The distributions of peak levels for heavy trucks only (3 axles or more) are illustrated for each of the seven sites in Figure 46. The distributions are presented with peak levels plotted against a normally scaled ordinate; i.e., normally distributed data would plot as a straight line. Also, the apparent differences among the seven sites are due in large part to the differences in average speed and number of axles for the trucks at the different sites, as demonstrated in the previous section.

Two important characteristics of the plots in Figure 46 should be emphasized. First, the plots are nearly linear at all sites, meaning the distribution of the peak noise levels closely approximates a normal distribution. Second, the plots all have a similar slope, meaning the standard deviations of the peak noise levels are similar at all sites (about 4 dBA).

In summary, it appears reasonable to assume that the peak noise levels for trucks are normally distributed, with a standard deviation that is independent of the highway location. Referring again to Table 44, it is also reasonable to assume that the average peak noise level will vary by no more than about ±2 dBA among various locations for trucks with the same number of axles and traveling at the same speed.

Now consider the peak noise levels for heavy trucks (3 axles or more) versus medium trucks (2 axles and 6 wheels) with the data for all seven sites pooled. The peak noise level distributions for these two cases are shown in Figure 47, which includes the composite distribution of the peak noise levels for all trucks. The data have been corrected to a common speed of 50 mph to eliminate the influence of speed differences on the comparisons. The speed correction was made by assuming that the peak noise level varies with the third power of speed. It is clear from Figure 47 that medium trucks are quieter than heavy trucks by about 8 dBA. However, the distributions in both cases are approximately normal and have a similar standard deviation of about 4 and 5 dBA, respectively.

Noise Emission Levels

From the viewpoint of developing a traffic noise prediction model, a parameter of considerable interest is the noise emission level, EL, defined as the rms value of the peak drive-by noise levels. For the case of normally distributed peak levels, the noise emission level is given by

$$\mathrm{EL} = \mu + 0.115\sigma^2 \qquad (100)$$

where μ is the mean value of the peak levels (equal to the L_{50} level for normally distributed data) and σ is the standard deviation of the peak levels. The noise emission levels for the medium and heavy trucks at each of the seven sites, together with appropriate 95% confidence interval limits, are summarized in Table 46. These emission levels are not normalized for either vehicle speed or number of axles. Hence, the variations from state to state are due in part to differences in the average speeds and numbers of axles for the trucks in these states, as opposed to differences in the actual emission levels of similar trucks. For example, referring to Table 44, the average truck speeds in California were substantially lower than in most other states, which explains in large part the low noise emission levels indicated for California.

REVIEW OF PREDICTION METHODS

Review of the various methods used both in the United States and abroad for the prediction of highway noise indicates that there are three broad categories of procedures (*92*) based, respectively, on use of (a) nomographs (*1, 2, 93, 98, 100-112*), (b) computer programs (*1, 2, 102, 111-113*), and (c) scale models (*102, 114-117*). The common feature of the procedures is that they treat separately the noise emission level of the sources and the propagation characteristics. The first two types are the most common, and further are closely related in that the computer methods are generally sophisticated extrapolations of the nomograph techniques. The scale model methods, however, permit interesting experimental studies, in particular in the case of complex configuration.

Nomograph Methods and Computer Methods

Use of graphic procedures has in recent years become quite common in many countries, as summarized in Table 47. Their use is generally quite simple, permitting results to be obtained in a very short time for a large number of observer locations. They also offer the advantage of letting the user test quickly the effects of changes in selected variables (such as traffic volume, distance, or barrier height) on the noise levels. However, construction of a nomograph requires a number of hypotheses that limit the range of predictions. To compensate for their shortcomings, nomographs must be accompanied by a number of correction tables, or be used only as preliminary prediction or design tools. In the latter case, the nomograph is inseparable from

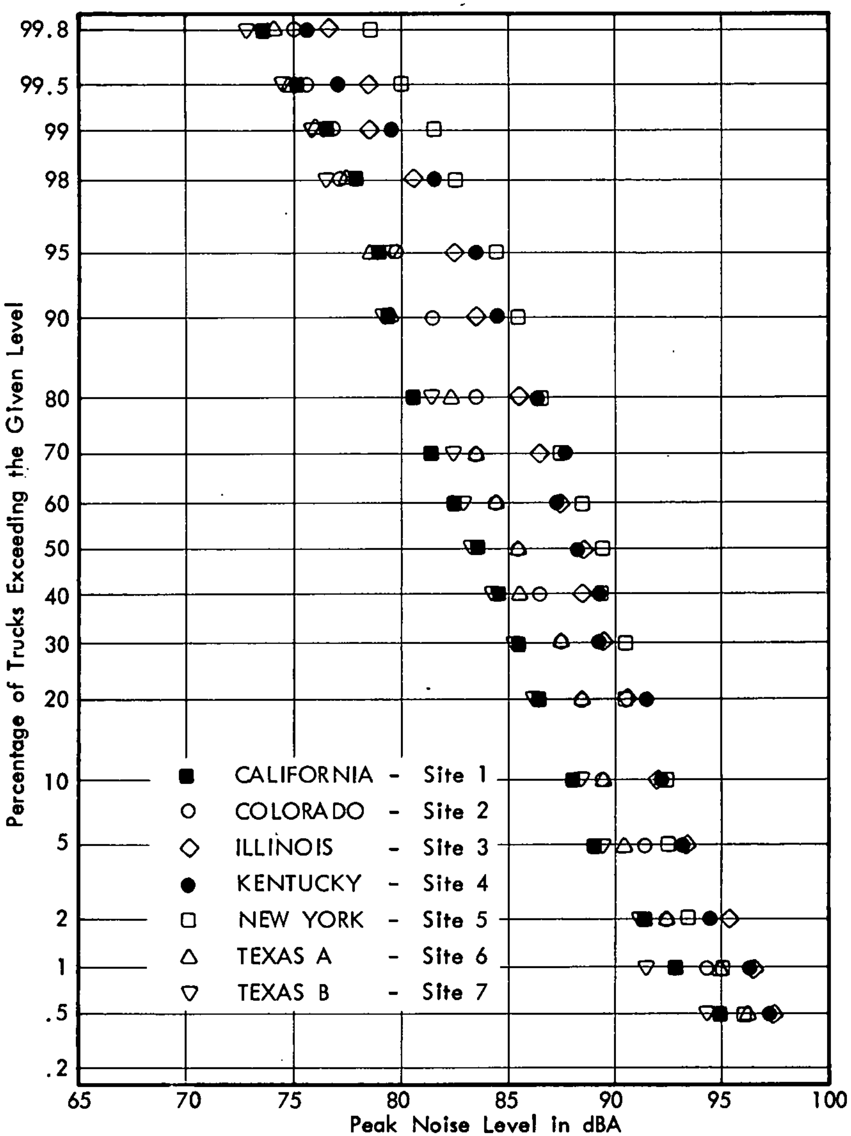


Figure 46. Distribution of peak noise levels for heavy trucks at seven sites.

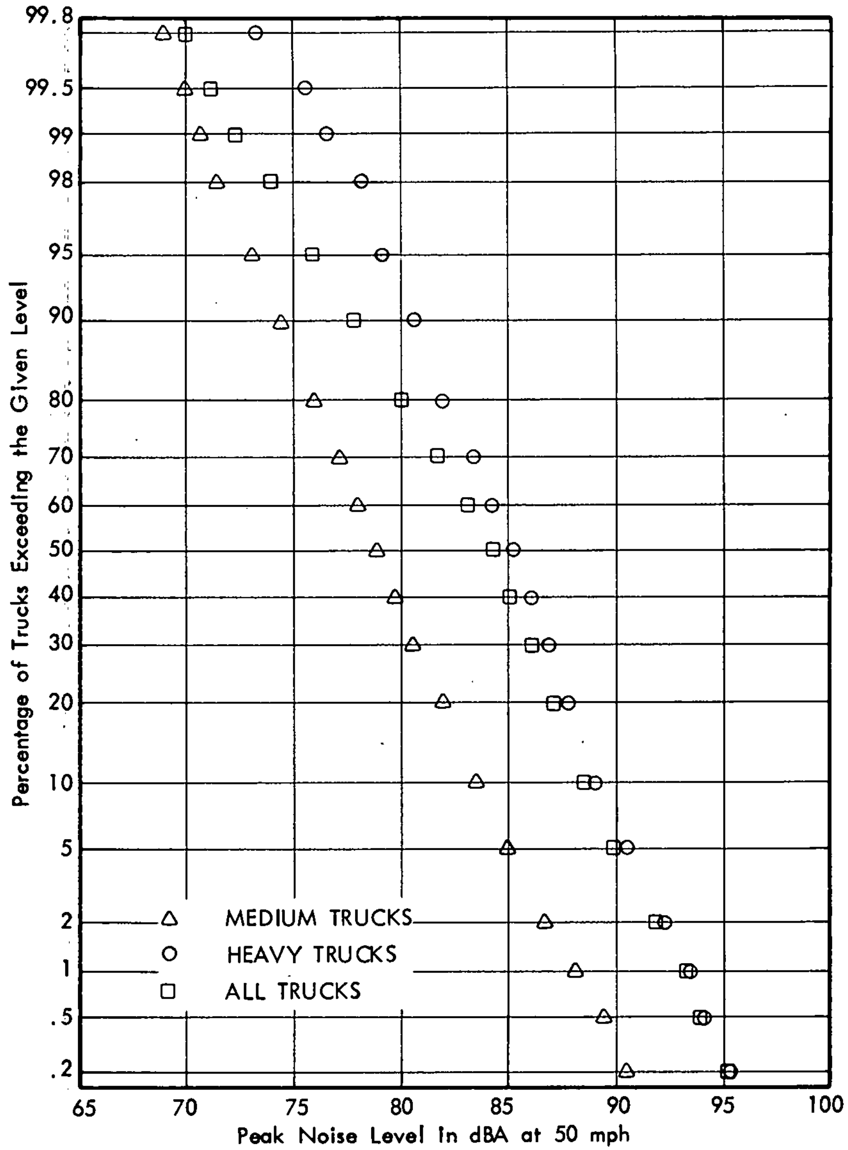


Figure 47. Distribution of peak noise levels for medium and heavy trucks at 50 mph.

TABLE 46

NOISE EMISSION LEVELS FOR MEDIUM[a] AND HEAVY[b] TRUCKS IN VARIOUS STATES

SITE		MEDIUM TRUCKS					HEAVY TRUCKS				
		PEAK NOISE LEVEL (dBA)					PEAK NOISE LEVEL (dBA)				
NO.	STATE	MEAN	STD. DEV.	SAMPLE SIZE	EMISSION LEVEL (dBA)	95% CONFID. LIMITS	MEAN	STD. DEV.	SAMPLE SIZE	EMISSION LEVEL (dBA)	95% CONFID. LIMITS
1	Cal.	80.6	2.6	83	81.4	±0.48	84.0	3.9	305	85.8	±0.34
2	Col.	80.5	4.4	84	82.7	±0.80	86.1	4.4	222	88.3	±0.38
3	Ill.	82.1	3.0	74	83.1	±0.58	88.4	4.9	874	91.2	±0.26
4	Kent.	81.9	3.1	106	83.0	±0.50	89.0	4.4	500	91.2	±0.24
5	N.Y.	84.0	3.2	127	85.2	±0.47	89.3	4.0	299	91.1	±0.27
6	Tex.	77.4	3.9	135	79.1	±0.55	85.5	6.1	244	89.8	±0.40
7	Tex.	78.6	3.7	66	80.2	±0.76	84.4	4.2	291	86.4	±0.32
All sites		80.6	4.1	675	82.5	±0.27	87.2	5.0	2735	90.1	±0.14

[a] 2 axles and 6 wheels. [b] 3 or more axles.

TABLE 47

SUMMARY OF TRAFFIC NOISE PREDICTION METHODS USED IN THE UNITED STATES AND ABROAD

AUTHOR	REF.	METHOD	DATE	DESCRIPTOR	COUNTRY
Anderson (BBN)	100	Graphs	1973	L_{10}	U.S.A.
Blitz (TRRL)	101	Graphs	1973	L_{10}	Great Britain
Delany (NRL)	1, 102	Graphs, models, computation	1972	L_{10}, L_{50}, L_{90}	Great Britain
Gordon (TRB/BBN)	2	Computation, graphs	1971	L_{50}, L_{10}	U.S.A.
"Guide du Bruit" (SETRA)	103	Graphs	1972	L_{50}	France
Ingemansson	104	Graphs	1970	L_{eq}/24h	Sweden
Johnson and Saunders (NPL)	93	Graphs	1967	L_{50}	Great Britain
Jonasson (LUND)	105	Graphs	1973	L_{eq}	Sweden
Lamure and Auzou (CSTB)	106	Graphs	1966	L_{50}	France
Rathé	98	Graphs	1966	L_1, L_{50}	Switzerland
Reinhold	107	Graphs	1971	L_{eq}, L_5, L_{95}	Germany
Scholes and Sargent (BRS)	108	Graphs	1971	L_{10}	Great Britain
Schultz (HUD/BBN)	109	Graphs	1971	L_{50}	U.S.A.
Van Noort and Oosting	110	Graphs	1973	L_{eq}	Netherlands
Wesler (DOT/BBN)	111	Graphs, computation	1972	L_{10}	U.S.A.
Anderson (DOT/BBN)	112	Graphs	—	L_{10}	U.S.A.
Kurze et al. (DOT/BBN)	113	Graphs	—	L_{10}	U.S.A.

a computer program design to treat complex situations with the desired degree of accuracy.

Even computer prediction methods suffer from two intrinsic limitations. First, the precision is limited by the complex nature of the problem. Particularly troublesome factors are the variability of noise emission levels of individual vehicles and the large number of variables necessary to accurately describe features of the terrain and obstacles. Second, computer programs must generally perform calculations under the basic assumption that the traffic noise levels are normally distributed. This hypothesis is a gross approximation in some cases, but is necessary to economically compute statistical descriptors.

The types of descriptors used for the various prediction methods used in the United States and abroad are summarized in Table 47. This table indicates that a consensus is building for use of the equivalent level, L_{eq} (*104, 105, 107, 110*), which is representative of the actual amount of acoustical energy radiated and propagated. It is believed that use of L_{eq}, whenever it is permitted by law, would result in greater prediction accuracy, particularly for the case of low traffic volumes.

Scale Models

For complex situations involving a great variety of roadways, obstacles, sources, and receivers, the prediction of traffic noise levels by use of a computer program can become impractical. Even the most elaborate program simply cannot allow for all the details that might occur. In such cases, use of scale models becomes an attractive alternative (*102, 114-117*); they permit prediction of noise levels, as well as study of complex noise control procedures, without the need for extensive calculations. General use of models by highway engineers, treating a large number of projects, is clearly impractical because of the cost and the time involved in conception of a model. However, scale models can provide a valuable research tool for large projects because of their flexibility and accuracy. A number of studies have demonstrated that once the major problems of choosing the dimensions, the proper materials, and the source characteristics for a traffic noise situation have been solved, the scale model can provide remarkably accurate results for problems such as zoning studies over large areas.

Several scale models have been built and studied either as research tools or as actual noise control evaluation tools. Most have been air models (*102, 114-116*), although water models have also been used (*117*). Simulation of traffic noise has been achieved through use of a variety of techniques, ranging from single omnidirectional sources (*102, 117*) to arrays of loudspeakers (*115*) or bells (*116*).

In summary, comparison of the various methods for predicting traffic noise demonstrates the need for a practical scheme consisting of a set of nomographs to be used in conjunction with a computer program that would provide sufficient accuracy, as well as the ability to study a large number of locations and rather complex configurations. Use of combined graphical and computational tools should also suppress the cost of highway noise predictions.

CHAPTER FOUR

FINDINGS—COMMUNITY MEASURES TO REDUCE NOISE IMPACT

This chapter presents the results of studies into community measures to reduce noise impact, including: land-use control, building construction, and noise barriers.

LAND-USE CONTROL

Three general suggestions for suppressing the impact of highway noise on neighboring communities through proper use are:

1. Clear the land area bordering on the right-of-way of all occupied structures to form an open buffer zone.
2. Restrict use of the land area bordering on the right-of-way to those commercial activities that are least sensitive to intruding noise (such as storage facilities and warehouses) or that normally would have a relatively high noise environment (such as shopping centers and manufacturing facilities).
3. Restrict use of the land area bordering on the right-of-way to closely spaced and properly sound-treated high-rise office and apartment buildings, which would then serve as a partial noise shield for the remainder of the community.

All three of these suggested land-use strategies could be applied to an existing community only at great expense, due to the need to remove existing structures along the right-of-way. Application of the suggestions to future planned communities would generally involve more acceptable costs.

Clear Bordering Land for Open Buffer Zone

This approach is analogous to extending the width of the highway right-of-way. Assuming that the resulting buffer zone is fully open except for normal vegetation, the noise reduction potential of this strategy is only that due to the traffic noise propagation loss associated with the increased distance between the highway and adjacent community structures. From Chapter Three, the propagation loss factor for highway traffic noise varies from the theoretical line source spreading loss value of 3 dBA per doubling of distance to an upper limit of about 4.5 dBA per doubling of distance for land with a relatively lush ground cover. Hence, from the viewpoint of those structures which are closest to the highway, the buffer zone would reduce the noise levels at the first row of structures by a maximum of $15 \log (F/R)$ dBA, where F is the equivalent distance from the effective traffic line source to the outer edge of the free zone, and R is the equivalent distance from the effective traffic line source to the edge of the right-of-way. However, it should be carefully notcd that, from the viewpoint of structures at a fixed distance from the right-of-way beyond the buffer zone, the presence of the buffer zone will actually result in increased noise levels due to the absence of the shielding that otherwise would have been provided by structures in that area.

To clarify this point, consider a specific case where the area bordering on the right-of-way is cleared for 300 ft beyond the edge of the right-of-way. Further assume the edge of the right-of-way to be about 100 ft from the effective line source representing the traffic flow on the highway. Using the upper limit of 4.5 dBA per doubling of distance for the propagation loss factor, it follows that the noise level at the outer edge of the buffer zone will be at most 15 log (400/100) = 9 dBA lower than the noise level at the edge of the right-of-way. However, if the buffer zone were not present, a structure located 300 ft from the edge of the right-of-way would still enjoy the 9-dBA reduction due to propagation loss, as well as additional noise reduction due to the shielding of structures located in the first 300 ft bordering on the right-of-way. This additional noise reduction might amount to about 6 dBA for the case of two rows of single-story houses, to perhaps 10 dB for closely spaced multistory structures (*3*). In summary, use of a buffer zone obviously will eliminate noise problems for structures that would otherwise border on the right-of-way, but will generally increase the noise problems for structures deeper in the community, assuming similar locations relative to the highway.

A logical technique for increasing the noise reduction across a buffer zone bordering on a right-of-way is to place noise obstructions in the zone. Conventional masonry barriers or earth berms provide an obvious solution. However, barriers are most effective when used within the right-of-way along the roadside, as discussed in Chapter Three. This study is concerned only with measures beyond the right-of-way. Another type of obstruction suitable for a buffer zone would be a dense growth of tall trees. Although the noise reduction potential available from trees is often exaggerated, one might expect up to 5 dBA of reduction per 100 ft of depth, to a maximum of 10 dBA total, assuming the trees are sufficiently dense to totally block the line of sight between the community and the highway.

Use Border Land For Noise-Insensitive Structures

The approach here is to restrict the use of land bordering on the right-of-way to structures of two types: (a) structures that are not normally occupied, such as storage facilities and warehouses, and (b) structures that house activities producing a relatively high ambient noise level, such as shopping centers and manufacturing facilities. The former type of structure is preferred, but the normal community would probably not require a sufficient number of normally unoccupied structures to border the entire length of the right-of-way. Hence, structures in the latter category would also have to be used in most cases.

The principle in this approach is straightforward. For the case of normally unoccupied structures, traffic noise can have no adverse impact on individuals if there are no individuals present to hear it. For the case of structures housing activities producing considerable self noise, the impact of intruding traffic noise is of less significance. In either case, this approach protects the remainder of the community by increasing its distance from the highway while still providing some additional noise reduction due to intervening structural shielding.

Use Border Land For High-Rise Structures

The principle in this approach is to provide noise reduction for the community at large, through both increased distance from the highway and structural shielding, by restricting the land use bordering on the right-of-way to closely spaced high-rise structures. Of course, the high-rise structures would require extensive sound treatment. Furthermore, the structures should be for functions that generally do not involve outside activities. Commercial office buildings are desirable from this viewpoint, although apartment houses for adult tenants might also be considered.

As discussed earlier, structures of two stories or more that are closely spaced along a highway might be expected to provide up to 10 dBA of noise reduction beyond that due to propagation loss. Of course, single-story houses or commercial buildings would provide perhaps 4 to 6 dBA of reduction if they were located in place of the high-rise structures. Hence, the net additional noise reduction provided to the community at large might be about 5 dBA over the noise reduction due to the increased distance from the highway. Within the high-rise structures, up to 15 dBA of additional noise reduction could be provided by proper sound treatment, as detailed in a later section.

Capital Costs of Land-Use Strategies

For the case of a highway passing through an existing community, the cost of acquiring land for a clear buffer zone would be similar to the cost of acquiring a right-of-way. Typical right-of-way acquisition costs for several urban areas, as reported by four state highway departments, are summarized in Table 48. It is clear from these data that the land acquisition costs vary widely with the location and composition of the community area involved. However, the cost is substantial in all cases. For example, even for the lowest costs reported by Colorado, the cost of acquiring and clearing a 300-ft-wide buffer zone on each side of a highway through a developed urban area would be about $3½ million per mile of highway. The corresponding figure for a large California urban area (central Los Angeles) would be more than $20 million per mile. It seems unlikely that such a cost could be justified solely on the grounds of noise reduction.

For the case of a future community planned for development along a highway, the cost of acquiring land for a buffer zone would, of course, be much less. Nevertheless, one must anticipate that the buffer zone land would ultimately increase in value, perhaps to the figures stated for land prices in Table 1, as the community became fully developed. Hence, the ultimate cost of the buffer zone would still be quite substantial.

The idea of limiting construction along the right-of-way to only those structures associated with activities that are relatively insensitive to noise is attractive for the case of future communities, inasmuch as it involves no direct costs. However, application of this strategy to an existing community might involve extensive land acquisition expenses, as summarized in Table 48. Hence, it seems unlikely that it could be justified in this case.

The cost associated with restricting land use along the right-of-way to high-rise structures is exactly the same as

TABLE 48

TYPICAL LAND ACQUISITION COSTS IN URBAN AREAS

		LAND CLASS. (%)			LAND ACQUISITION COSTS ($/ACRE)						
STATE	YEAR	RES.	COMM.	INDUS.	LAND	STRUCTURES	LIQ. DAM.	LEGAL EXP.	MOVING AND RELOC.	OTHER	TOTAL
Calif.	1972	90	10	—	82,400	118,100	4,200	32,200	28,200	12,700	277,800
Colo.	1973	20	10	70	33,400	11,300	2,200	200	100	300	47,500
Conn.	1969				100,300	63,300	—	900	1,100	2,000	172,600
Ill.	1969–70	—	100	—	124,500	106,600	2,600	1,400	25,700	9,500	270,300

discussed in the preceding section, except now the cost of sound treatment for the structures must be added. These sound treatment costs are detailed in the next section. The strategy poses no aesthetic problems, and might provide a few dBA of additional noise reduction to the remainder of the community due to the shielding effects of the structures. On balance, it constitutes a relatively attractive strategy for applications to newly developing communities where expensive land acquisition problems can be avoided.

BUILDING CONSTRUCTION

There is obviously a wide variety of materials and constructions for any type of building within a given geographical zone. However, to make the problem at hand tractable, it is necessary to define "typical" exterior building constructions for each zone defined in Figure 48, as well as "typical" exterior construction components and materials. Having defined these "typical" constructions and components, it is then possible to detail the modifications and changes necessary to achieve a desired degree of noise reduction. Even with these simplifications, the details of the required modifications and changes are voluminous. Hence, to preserve continuity in the text, all construction details are presented in a series of appendices.

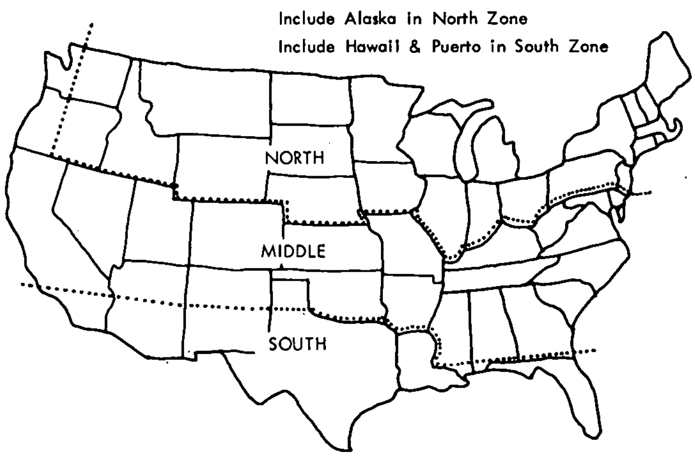


Figure 48. Geographic zone boundaries for different types of building construction.

Typical Building Constructions

A summary of typical exterior building constructions is presented in Appendix G. Simple descriptions of the structural frame, exterior wall, windows, exterior doors, roof/ceiling, and underfloor construction are summarized for each of the 12 building types of interest. The indoor environmental control system is also described for each structure. Under each construction component, differences in construction type and material among the three geographical zones are noted. Finally, typical constructions are included for both existing and planned structures.

Typical Construction Components and Materials

A summary of typical exterior construction components and materials for typical building structures is presented in Appendix H. This appendix provides a tabulation of simple descriptions and definitions of construction terms that are referred to in later summary tables. Included are descriptions of typical constructions and materials for structural frames, exterior walls, windows, exterior doors, roof/ceiling and underfloor members, and environmental control systems. These definitions, combined with the descriptions in Appendix G, permit a simple description of the construction of the 12 types of buildings in each of the three regional zones.

Required Constructions for Noise Reduction

The recommended minimum modifications of existing structures required to achieve various degrees of noise reductions are summarized for each of the 12 building types in Appendix I. The recommended constructions required for planned structures are detailed in Appendix J. In both appendices, the recommended modifications and constructions are listed for each significant exterior component and the indoor environmental control system separately. However, the indicated noise reduction is a composite number to be expected from all applicable modifications or constructions taken together. The recommended modifications and constructions are listed first for structures in the south zone, followed by the middle zone, and finally the north zone. The modifications and constructions listed in Appendices I and J are presented in a coding system detailed for the recommended modifications to existing structures in Appendix K, and for the recommended constructions for planned structures in Appendix L. General descriptions and definitions of acoustical materials and treatments used in sound reduction constructions are summarized in Appendix M, which is a reference for the descriptions included in Appendices K and L.

The coding system used in Appendices K and L includes two letters defining the construction component (for example, DC denotes door construction) and a number defining the specific type of modification. It should be emphasized that the numerical order of the code does not necessarily correspond to the degree of improvement provided by the modification or construction. For example, the acoustical performance of RM-5 (resiliently mounted drywall) is better than RM-4 (rigidly mounted drywall), but RM-4 is not necessarily better than RM-3 (resiliently furred drywall). As a further example, the acoustical performance of EC-11 (insulated metal panel) is better than EC-10, a similar construction, but not better than EC-9 (heavy masonry wall).

More than one type of modification or construction is listed for certain exterior components in Appendices I and J. In some cases, one of two or even three modifications or constructions may be selected for an exterior component (such as exterior wall EC-1, -3, or -5 for 5-dB improvement to single-family residences in the South). In other cases, modifications or constructions are given for more than one construction type under a single exterior component (such as exterior wall modification EM-3 if curtain wall, or EM-4 if other wall for 15-dB improvement to hospitals in the South). More than one modification or construction is given for certain components (such as modification CM-2 and -3 to environmental control system for a 10-dB improvement to schools).

The required modifications and constructions are based on past experience and current calculations. Actual field measurements of modified structures and new sound-isolating constructions form the basis for noise-reduction estimates. Calculations of composite noise reductions are based on known or estimated sound transmission loss values of exterior components, and the assumed surface areas of the components.

Transmission of exterior sound through windows and doors generally dominates the indoor sound levels and, hence, tends to be the limiting factor on noise reduction. In general, conventional window constructions have the lowest sound transmission loss of the exterior components because of the low mass and single-thickness construction of the glass. Also, exterior noise transmits through air gaps around the operable sash, and radiates directly into the building interior. The same is generally true of door construction. For this reason, windows and doors must be weatherstripped or gasketed to reduce sound leakage around window sash and door panels. In the required constructions windows and doors are weatherstripped or gasketed, as well as of double construction, for the highest improvement in noise reduction.

Capital Costs of Building Noise-Reduction Measures

The total capital costs for both modifications to existing structures and new constructions of planned structures were estimated by the following procedures:

1. The unit (or base) costs for each of the modification and construction types summarized in Appendices K and L were estimated using current construction cost data.
2. Appropriate assumptions were made for each of the major building types. For example, the typical size of indoor spaces and exterior dimensions, and the number of windows and doors, were assumed. Also, the descriptions of the building types, as summarized in Appendices G and H, were considered.
3. The unit costs for the modification and construction types were then applied to assumed areas and/or numbers of exterior components to project the unit costs into a total cost of modifications or new constructions. The total cost includes the cost of the environmental control system.
4. Next an add-on factor was applied to the total modification or construction costs to generate a final cost. For modifications, 50 percent of the total cost was added to the total cost of public works structures, such as schools and hospitals, and 40 percent for other building types to cover overhead and profit, plan check, permits, clean-up, etc. For planned structures, 15 percent of the total construction cost was added to the total costs to cover overhead and profit.
5. The final costs then were projected into final unit costs per building type.

The estimated costs of the modifications required to obtain 5, 10, and 15 dBA of noise reduction in existing structures are summarized in Table 49. Similar cost data for the additional constructions required to obtain the stated noise reductions in future structures are summarized in Table 50.

The unit costs presented in Tables 49 and 50 are total costs for the recommended composite modifications. The units for the total cost in each building category are considered to be the most appropriate for that building type. For example, the unit of cost for single-family residences is a total cost per dwelling, because the average size of a house can be approximated. The unit of cost for a high-rise apartment building is a total cost per apartment, not cost per building, because the size of such a building cannot be accurately approximated.

The differences in cost among the three zones reflect the differences in required modifications or constructions, not the difference in base costs between the zones. The cost data in Tables 49 and 50 are all based on an estimated national average construction cost, using Los Angeles area data as a basis for the estimates. Of course, the actual construction costs within any zone vary from city to city, and from urban to rural areas. However, there appears to be no consistency in costs between zones or within zones. Los Angeles area costs were considered as good as any for the purposes of estimating a national average, inasmuch as costs in that city are approximately equal to the national average cost index. To be more specific, the actual cost index for the Los Angeles area is 4 percent below the average of 82 cities in the United States. The costs in Tables 49 and 50 include this consideration. Note that actual costs in any zone can vary by approximately ±10 percent from the national average, depending on the local factors.

TABLE 49

MODIFICATION COSTS FOR VARIOUS AMOUNTS OF BUILDING NOISE REDUCTION

TYPE OF STRUCTURE	COST UNIT	COST ($) FOR VARIOUS AMOUNTS OF NOISE REDUCTION								
		SOUTH ZONE [a]			MIDDLE ZONE [a]			NORTH ZONE [a]		
		5 dBA	10 dBA	15 dBA	5 dBA	10 dBA	15 dBA	5 dBA	10 dBA	15 dBA
Single-family dwelling	Dwelling	5,500	10,400	12,800	6,000	11,000	13,200	4,800	7,580	12,050
Multi-family dwelling	Apartment	2,730	4,150	5,500	3,320	4,460	5,800	1,150	2,080	3,870
High-rise apartment	Apartment	775	2,180	2,500	775	2,180	2,500	775	1,890	2,910
School	Classroom	3,300	8,000	10,400	3,310	6,850	10,300	2,175	3,810	7,380
Church	Person	—	—	—	—	—	—	—	—	—
Auditorium	Sq ft of floor area	4.34	4.36	4.58	4.34	4.36	4.58	4.34	4.36	4.58
Hospital	Patient room	300	725	1,180	300	725	1,180	300	725	1,180
Low-rise motel	Guest room	2,000	2,980	3,380	2,000	2,980	3,380	2,000	2,530	3,380
High-rise hotel	Guest room	380	750	935	379	748	935	380	750	935
High-rise commercial	Linear ft ext wall per story	54	83	93	54	83	93	54	83	93
Low-rise commercial	150 sq ft of office area	465	1,050	1,460	347	828	1,480	347	828	1,480
Industrial plant	Sq ft of floor area	0.33	1.85	3.69	0.33	1.85	3.69	0.33	1.85	3.69

[a] See Figure 48.

TABLE 50

CONSTRUCTION COSTS FOR VARIOUS AMOUNTS OF BUILDING NOISE REDUCTION

TYPE OF STRUCTURE	COST UNIT	COST ($) FOR VARIOUS AMOUNTS OF NOISE REDUCTION								
		SOUTH ZONE [a]			MIDDLE ZONE [a]			NORTH ZONE [a]		
		5 dBA	10 dBA	15 dBA	5 dBA	10 dBA	15 dBA	5 dBA	10 dBA	15 dBA
Single-family dwelling	Dwelling	3,990	5,460	6,920	3,990	5,460	6,920	4,200	6,060	6,320
Multi-family dwelling	Apartment	1,800	2,870	2,990	1,760	2,870	3,110	2,040	2,870	3,120
High-rise apartment	Apartment	570	1,370	1,520	570	1,370	1,520	570	1,370	1,520
School	Classroom	2,260	4,130	4,500	2,260	4,020	4,500	1,340	3,170	3,280
Church	Person	22	42	55	22	42	55	22	42	55
Auditorium	Sq ft of floor area	1.04	1.04	0.68	1.04	1.04	0.68	1.04	1.04	0.68
Hospital	Patient room	213	500	603	213	500	660	213	500	603
Low-rise motel	Guest room	1,665	1,790	2,140	1,665	1,790	2,140	1,665	1,790	2,140
High-rise hotel	Guest room	312	568	892	440	688	880	440	688	880
High-rise commercial	Linear ft ext wall per story	18.75	78	83	18.75	78	83	18.75	78	83
Low-rise commercial	150 sq ft of office area	371	768	1,060	371	768	1,060	371	768	1,060
Industrial plant	Sq ft of floor area	0.18	1.77	1.88	0.18	1.77	1.88	0.18	1.77	1.88

[a] See Figure 48.

NOISE BARRIERS

As discussed in the preceding section, sound treatment of individual community structures can provide up to 15 dBA of noise reduction, but only to individuals inside the structures. Hence, this approach cannot be fully effective for a structure that serves a function involving considerable outside activity (for example, a school). In such cases, an alternate approach that might be considered is the use of physical barriers (walls) constructed along the property line of some commonly occupied outside area. Such barriers might be used alone, or in conjunction with improved sound treatment of the building structure of interest.

When properly constructed, sound barriers can realistically provide up to 15 dBA of noise reduction. In broad terms, the principal requirements for an effective barrier are as follows:

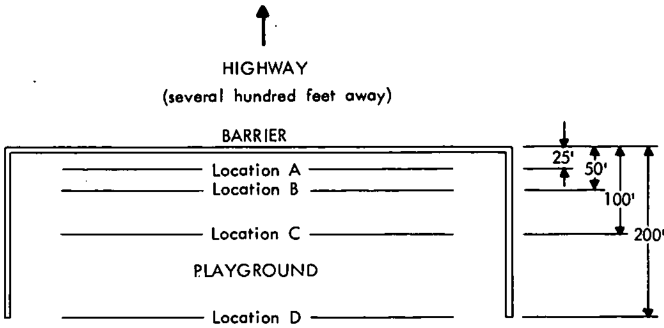
1. It should be sufficiently tall and wide to fully block the line of sight between the source and the observer.
2. It should be sufficiently massive to make the noise reaching the observer by direct transmission through the barrier very small compared to the noise reaching the observer by diffraction over or around the barrier. For a 15-dBA barrier this goal is generally achieved with a barrier surface weight density of 4 lb/ft^2, assuming the noise source is highway traffic.
3. It should be located as close as practicable to either the source or the observer.

The performance of barriers when used for traffic noise suppression within the highway right-of-way (roadside barriers) has been discussed in Chapter Three. The noise reduction prediction techniques and construction data provided there apply equally as well to community barriers.

Acoustical Performance

The noise reduction provided by a barrier is a detailed function of the barrier geometry, the noise source geometry, the observer location, and the noise frequency. However, the barrier reduction prediction problem can be greatly simplified if it is assumed that (a) the noise source is traffic noise modeled by an infinitely long line of incoherent point sources, (b) the barrier is infinitely wide, and (c) the noise is measured in terms of A-weighted sound levels (dBA). Under these assumptions, the noise reduction provided by a barrier may be estimated in terms of a single parameter, the path length difference denoted by δ, which is defined as the shortest distance between the source and observer formed by two straight lines passing over the barrier, minus the shortest distance between the source and observer formed by one straight line passing through the barrier. (See Chapter Three details.)

The assumption of an infinitely wide barrier clearly cannot be complied with in practice. However, for the case of barriers designed to protect a closed area, the assumption can be approximately satisfied by wrapping the barrier around the sides of the area. For example, consider a school playground that is 600 ft wide and 200 ft deep. An



Barrier Height (feet)	Approximate Noise Reduction in dBA at Various Play Ground Locations			
	A	B	C	D
10	9.2	8.0	7.2	6.8
15	12.5	10.7	9.2	7.9
20	14.9	12.9	11.1	9.5

Figure 49. Playground barrier noise reductions.

effective barrier for this case would wrap around the school yard, as shown in Figure 49. If it is assumed that the playground is at the same elevation as a highway located at least several hundred feet away from the barrier, the approximate noise reductions at an observer located within the school yard about 5 ft above the ground would be as summarized in Figure 49. Note that the noise reductions increase with increasing barrier height, and decrease with increasing observer distance from the barrier. Further note that barrier heights of less than 10 ft are not suggested because the acoustical performance of barriers falls off very rapidly below this height.

Construction

Various types of construction have been used for barriers in highway noise-reduction applications. Included are precast concrete panels secured to a steel or concrete framework, reinforced concrete walls, brick walls, concrete block walls, corrugated steel panels, and wood walls. From the viewpoint of acoustical performance, the type of construction is not important as long as the resulting barrier is totally solid (has no holes in it) and sufficiently massive (has a surface weight density of at least 4 lb/ft^2). Of course, from the economic viewpoint, some types of con-

TABLE 51

COMMUNITY SOUND BARRIER CONSTRUCTION COSTS

TYPE OF CONSTRUCTION	COST FOR VARIOUS BARRIER HEIGHTS ($/LIN FT)		
	10 FT	15 FT	20 FT
Precast concrete panels secured to steel or concrete framework	70	100	130
Brick walls	50	75	100
Concrete block walls	25	36	47

struction are more desirable than others. Based on the construction cost data for roadside barriers summarized in Chapter Three, concrete block generally provides the most inexpensive type of construction.

Capital Costs

The capital costs for sound barriers are surveyed in Chapter Three. The approximate costs per linear foot for three common types of barrier construction are summarized in Table 51. Note that concrete block generally provides the most inexpensive type of construction.

It is clear from Table 51 that the cost of barriers can be substantial if they are used to protect a relatively large area. For example, consider the school playground barrier shown in Figure 49. Even using concrete block construction and only a 10-ft height, this barrier would cost about $25,000. For a 20-ft height, the cost would almost double. Other types of construction could lead to costs of more than $100,000 for this illustration.

CHAPTER FIVE

FINDINGS—ECONOMIC EVALUATION OF NOISE-REDUCTION STRATEGIES

BASIC COSTS OF VEHICLE NOISE-REDUCTION MEASURES

Basic cost data for the quieting of automobiles, light trucks, and heavy trucks are detailed in Chapter Two. These data are summarized in this chapter and used to estimate the cost-effectiveness of the various vehicle noise-reduction strategies of interest.

Automobiles and Light Trucks

Capital Cost Changes

Based on the results presented in Chapter Two, the most definitive capital cost data available at this time for reduction of exterior noise from passenger cars and light trucks is that provided by General Motors (*118*), as summarized in Table 52.

The cost data apply to noise reduction measures on new vehicles only; the cost of retrofitting noise control measures on automobiles currently in service is not considered in this study. Further, the GM noise-reduction predictions were based on full-throttle acceleration per SAE Standard J986a. The noise reductions for cruise at 55 to 65 mph were computed using the typical automobile noise source values in Table 27, where tire noise is held constant (straight-rib tires are considered part of the baseline design).

TABLE 52

ESTIMATED CAPITAL COSTS FOR NOISE REDUCTION OF PASSENGER CARS AND LIGHT TRUCKS

NOISE REDUCTION (ΔdBA)		COST DIFF. PER VEHICLE (Δ$)		
		PASSENGER CARS		LIGHT TRUCKS, AVE.
SAE-J366A	CRUISE AT 55 TO 65 MPH	RANGE [a]	AVE.	
6	3	4–16	9	17
11	4	20–110	55	100

[a] For six categories of widely used passenger cars.

Operating Cost Changes

The primary change in the operating costs of a typical automobile or light truck due to noise-reduction measures is expected to result from the increased back pressure caused by the necessary muffler improvements. For an average automobile or light truck at highway speeds, this increased backpressure might be about 1.5 in. Hg for a good muffler (*27*). Assuming a 0.1 percent increase in specific fuel consumption per inch increase in Hg backpressure (*91*), an average specific fuel consumption of about 0.5 lb/bhp-hr (*91*), and an average of 50 bhp, the resulting increase in fuel consumption due to the noise control measures would be about 0.038 lb/hr. This is further equivalent to about 0.006 gal/hr or 0.00015 gal/mile. Finally, assuming fuel costs at $0.40/gal, and about 11,000 miles a year of operation for the typical automobile and 20,000 miles a year for the typical light truck, the change in operating cost due to noise reduction measures reduces to about $0.65 per year for automobiles and $1.20 per year for light trucks.

Maintenance Cost Changes

The primary change in the maintenance cost of a typical automobile or light truck due to noise reduction measures is expected to be the increased cost of muffler replacement. Assuming a $20 increase in the muffler costs and a two-year life, this amounts to about $10 per year increase in cost.

Heavy Trucks

Capital Cost Changes

Capital cost data for the reduction of exterior noise from heavy trucks are available from several sources, as summarized in Table 53. Most of these values were estimated for diesel-powered trucks, but estimates for gasoline-powered heavy trucks do not differ significantly. The noise reductions for cruise at 55 to 65 mph are estimates computed from stated SAE J366 noise reductions with the aid of the basic truck noise source data given in Table 25.

The most reliable data in Table 53 are believed to be BBN results from the Freightliner Quiet Truck Program (*77*), which are detailed in Table 54. However, all the available data are reasonably consistent, except perhaps for the GM data, which appear to suggest somewhat higher costs than other sources for the larger noise reductions.

The BBN retrofit data in Table 53 are arrived at by assuming all measures in Table 54 are added, except for the ducted engine-transmission enclosure and the increased fan-radiator spacing, which are not considered economically feasible modifications for existing trucks. All items are priced as shown in the left-hand column, under the assumption that all modifications are made during a major engine overhaul period when additional labor costs would be similar to those required for a factory installation.

As a final note on the capital costs of noise-reduction equipment for heavy trucks, the retrofit costs given in Table 53 do not include the cost of switching from cross-rib to straight-rib tires. It is assumed that the change of this item would be made during a normal tire replacement interval at no net increase in cost.

Operating Cost Changes

The most thorough information on the changes in operating costs due to the addition of noise-reduction equipment on

TABLE 53

CAPITAL COSTS FOR NOISE REDUCTION OF HEAVY TRUCKS

NOISE REDUCTION (ΔdBA)				
SAE-J366	CRUISE AT 55 TO 65 MPH [a]	NEW OR RETROFIT	COST DIFFERENCE PER VEHICLE (Δ$)	SOURCE OF DATA
14	8	New	Approx. 1400	BBN (Ch. 2, *77*)
11	7	New	400 to 1200	Wyle (*6*)
6	5	New	150 to 600	Wyle (*6*)
3	3	New	100 to 300	Wyle (*6*)
11	7	New	1900 to 2200	GM (*119*)
6	5	New	400 to 700	GM (*119*)
3	3	New	200	GM (*119*)
6	5	Retro.	Approx. 800	BBN (Ch. 2)
5	5	Retro.	580 to 845	EPA (*120*)

[a] Assumes a switch from cross-rib to straight-rib tires.

TABLE 54

ESTIMATED CAPITAL COSTS FOR NOISE REDUCTION OF A HEAVY DIESEL TRUCK

NOISE CONTROL ITEM		STD. ITEM REPLACED		ADDITIONAL COST (Δ$)		
DESCRIPTION	COST ($)	DESCRIPTION	COST ($)	ITEM	LABOR [a]	NET
Close-fitting engine covers	143	None	0	143	0	143
Ducted (flow-through) engine and transmission enclosure	447	None	0	447	123	570
Manifold muffler	150	Exh. manifold	38	112	9	121
Dual muffler	120	Single muffler	45	75	9	83
Wrap exhaust pipes	120	Single muffler	0	120	54	174
Engine mounts	72	None	0	72	9	81
Thermatic control clutch [b]	195 [b]	Fan hub	90	105 [b]	45 [b]	150 [b]
Viscous fan clutch [b]	180 [b]	Fan hub	90	90 [b]	0 [b]	90 [b]
High-performance fan	18	Std. fan	12	6	0	6
Increased fan-radiator spacing	50	None	0	50	0	50
Best air cleaner and snorkel	180	Std. air cleaner	120	60	0	60
Total estimated capital costs to achieve noise levels of Table 25						1378 to 1438

[a] Assumes equipment is installed at the factory or during a major engine overhaul.
[b] Choice to be made.

heavy trucks is that provided by the Quiet Truck Program, as summarized in Chapter Two. The changes in operating costs required to achieve 8 dBA of noise reduction at highway speeds result from three factors: (a) the additional weight of the noise control measures, (b) the changes in engine performance, and (c) the changes in engine power requirements.

Consider first the added weight. Assume a truck operates such that it is speed limited 20 percent of the time and power limited 80 percent of the time. Further assume that the truck is weight limited 5 percent of the time, meaning the cargo weight must be reduced by the amount of weight added by noise control measures to keep the total weight within legal limits. These percentages are believed to be representative of the average truck (*77*). Using these figures, the added operating cost in dollars per year required to carry the additional weight of noise control equipment, assuming a cargo rate of \$0.08 per ton-mile, is estimated by Averill and Patterson (*77*) to be

$$\Delta\$ = \left[\left(1.085 \times 10^{-6}\,\frac{\text{gal}}{\text{mile-lb}}\right)(\text{use in miles/year})\right.$$
$$\left.(\text{fuel cost in \$/gallon}) + \left(2.5 \times 10^{-2}\,\frac{\text{dollars}}{\text{year-lb}_{NR}}\right)\right]$$
$$(\text{NRW in lb}) \qquad (101)$$

where NRW denotes the weight of the required noise-reduction equipment. The first term in Eq. 101 is the cost due to the extra weight; the second term is the cost due to lost cargo. For the case of a new truck, the additional weight required to achieve 8 dBA of noise reduction at highway cruise speeds is about 600 lb, as detailed in Table 55. Assuming the average truck operates 125,000 miles per year and fuel costs \$0.25/gal, Eq. 101 reduces to $\Delta\$ \simeq \$35/$year for new trucks. For the case of an existing truck retrofitted for 5 dBA of noise reduction at highway cruise speeds, the additional weight is about 250 lb. Using the same fuel cost and mileage figures as before, Eq. 101 reduces to $\Delta\$ = \$15/$year.

Concerning the engine performance, the change in operating costs in dollars per year due to changes in engine performance are estimated by Averill and Patterson (*77*) to be as follows:

(a) For power-limited operations:

$$\Delta\$ = \left(1.08 \times 10^{-4}\,\frac{\text{gal}}{\text{mile-in. } H_2O}\right)$$
$$(\text{fuel cost in \$/gal})$$
$$\times\ (\text{use in miles/year})(\Delta p \text{ in in. } H_2O) \qquad (102a)$$

(b) For speed-limited operations:

$$\Delta\$ = \left(1.22 \times 10^{-4}\,\frac{\text{gal}}{\text{miles-in. } H_2O}\right)$$
$$(\text{fuel cost in \$/gal})$$
$$\times\ (\text{use in miles/year})(\Delta p \text{ in in. } H_2O) \qquad (102b)$$

The important parameter in Eq. 102 is the change in engine backpressure (Δp in inches of H_2O), which in turn is a function of the type of muffler used. Referring to Table 55, none of the noise reduction measures causes a significant increase in backpressure. To the contrary, muffler improvements might yield a backpressure reduction of perhaps 4 in. of H_2O. Using Eq. 102 with previous assumptions, this would produce a savings of about \$15/year.

Finally, concerning engine power requirements, it is seen from Table 55 that the use of either a thermatic or viscous fan clutch will provide a horsepower saving estimated to be from 5 to 15 bhp. Lack of a more definite number for this

TABLE 55

DIESEL TRUCK NOISE ABATEMENT, ESTIMATED OPERATIONAL AND MAINTENANCE DATA

NOISE CONTROL MEASURE	OPERATIONAL LIFE	ADDIT. MAINT. (HR/YR)	ADDIT. WT., W_{NR} (LB)	BACK-PRESSURE INCREASE, Δp (IN H_2O)	HORSE-POWER SAVINGS
Close fitting covers	Engine life	1	25	0	0
Ducted engine and transmission enclosure	Truck life	6	338	0	0
Manifold mufflers	5 years	0	100	0	0
Dual mufflers	2 years	0.2	45	−4	<1
Wrap exhaust pipe	2 years	1	50	0	0
Engine mounts	2 years	0	10	0	0
Thermatic fan clutch [a]	Engine life	0	10	0	5–15 [b]
Viscous fan clutch [a]	Engine life	0	0	0	5–15 [b]
High-performance fan	Engine life	0	2	0	0
Increased fan-radiator spacing	Engine life	0	10	0	0
Best air cleaner and snorkel	Engine life	0.5	5	0	0
Total		7.7	585 to 595	−4	5 to 15

[a] Choice to be made.
[b] Horsepower savings are a function of vehicle speed and engine rpm.

saving is due to uncertainties in the amount of horsepower required to operate a conventional fan at highway speeds. To be conservative, an average power saving of 5 bhp will be assumed. The reduced operating costs associated with this reduced horsepower requirement are given by

$$\left(\text{SFC, in } \frac{\text{lb}}{\text{bhp-hr}}\right)(\Delta\text{bhp})\,(\text{use in hr/year})$$
$$(\text{fuel cost in \$/gal})\,(\text{gal/lb}) \qquad (103)$$

Assuming a typical specific fuel consumption for trucks of 0.35 lb/bhp-hr, an average use of 3,000 hr/year, and a fuel cost of $0.25/gal, Eq. 103 yields average annual savings of about $200, a substantial amount. These savings apply to both new and retrofitted trucks.

Maintenance Cost Changes

The changes in maintenance costs for an 8-dBA noise reduction, as determined from the Quiet Truck program, are also outlined in Table 55. For the reasons discussed in Chapter One, the cost of replacing worn out equipment items for heavy trucks is being treated as a capital expense, not a maintenance expense. Hence, the only maintenance costs of concern are those due to additional labor, estimated to be 7.7 manhours per year in Table 55. Assuming a labor rate of $12.50/hr, this gives an additional maintenance cost of $96/year.

Summary

The changes in cost associated with the maximum noise reductions currently feasible for automobiles and trucks are summarized in Table 56. These data are adequate for calculating the cost of all vehicle noise-reduction strategies of interest, except for the strategy of diverting all heavy trucks to an alternate route. The cost associated with this last strategy is a function of the total operating cost per mile for a heavy truck, including the value of travel time. This cost is estimated from American Trucking Association data (*121*) to be about $1.25 for large intercity carriers (in 1972 dollars).

TABLE 56

SUMMARY OF SOURCE NOISE-REDUCTION COST DATA

TYPE OF VEHICLE	NEW OR RETRO-FIT	NOISE REDUC-TION [a] (ΔDBA)	INCREASED COSTS CAPI-TAL (Δ$)	OPER. (Δ$/YR)	MAINT. (Δ$/YR)
Automobile	New	4	55	0.45	10
Light truck	New	4	100	1.20	10
Heavy truck	New	8	1400	−180	96 [b]
Heavy truck	Retro.	5	800	−200	96 [b]

[a] Assuming cruise on level grade at 55 to 65 mph.
[b] Does not include wornout equipment replacement costs.

BASIC COSTS OF HIGHWAY NOISE-REDUCTION MEASURES

Basic cost data for various types of highway noise-reduction measures are available from Chapter Three, as well as a report covering comprehensive studies of the highway noise problem prepared for the Department of Transportation (DOT) by Serendipity, Inc. (*122*). Appropriate data from these two documents are summarized in the following.

Elevated and Depressed Highways

Capital Cost Changes

Of concern here is the change in capital costs required to elevate or depress a highway relative to a conventional at-grade highway of similar capability. For highways through urban areas, the major portion of the total costs of a highway is the right-of-way acquisition costs, which include (a) land cost, (b) cost of existing structures, (c) liquidation damages, (d) legal expenses, (e) compensation for moving and relocation, and (f) utility relocations and adjustments.

These right-of-way acquisition costs, of course, vary widely with location, as indicated by the brief summary in Table 57. In any case, the additional right-of-way requirement for depressed and fill-elevated (but not structure elevated) highways constitutes a major source of additional cost. Based on assumptions stated earlier, the increased right-of-way required for fill elevations and depressions is given by

$$\text{Additional width} = 2\,R\,Y \qquad (104)$$

where Y is the depth of the depression or height of the elevation, in feet, and R is the slope. Hence, for a 20-ft depressed or elevated roadway with a slope of 2:1, the additional right-of-way would be about 80 ft. From Table 57, this would add $2.22 million per mile to a highway through a typical California urban area.

Construction costs for various highway configurations also vary with location, but not as widely as right-of-way acquisition costs. Estimated construction costs for a highway through a typical California urban area (Chapter

TABLE 57

TYPICAL RIGHT-OF-WAY LAND ACQUISITION COSTS

YEAR AND REF.	DESCRIPTION OF ACQUIRED LAND	COST ($1000/ ACRE)
1973 (Ch. 3)	Typical California urban area	229
1972 (Ch. 3)	California urban; 90% resid., 5% comm., 5% public	174
1972 (Ch. 3)	California urban; 90% resid., 10% comm.	278
1972 (Ch. 3)	California urban; 25% resid., 75% indus.	409
1973 (Ch. 3)	Colorado urban; 20% resid., 10% comm., 70% indus.	47
1969 (Ch. 3)	Typical Connecticut urban area	173
1970 (Ch. 3)	Illinois urban; 100% comm.	270
1970 (*122*)	Maryland urban; 100% resid.	177

Three) and a Baltimore residential area (*122*) are given in Table 58. The total construction costs include (a) roadway clearing and excavation, (b) installation of drainage, (c) pavement, (d) shoulders, (e) street crossings and ramps, (f) roadway appurtenance, (g) landscaping, (h) lighting, (i) signing, and (j) miscellaneous expenses. Also given in Table 58 are the total highway costs (a) in dollars, and (b) as ratios to the cost of an at-grade highway. The California data are for an 8-lane highway, whereas the Baltimore figures apply to a 6-lane highway. Hence, the right-of-way for the California data is 24 ft wider to allow for the two additional lanes.

Operating and Maintenance Cost Changes

Typical highway operating and maintenance costs for various states are detailed in Chapter Three. Reported maintenance costs vary from $2,630 per mile for a typical 4-lane highway in Illinois to $15,000 per mile for a typical 8-lane highway in California. Reported operating costs fall between $1,500 and $4,000 per mile. However, the available data do not suggest a significant difference in the maintenance and operating costs for at-grade, depressed, and elevated configurations. Hence, it is assumed that the cost differences among the various highway configurations are sufficiently small to be ignored.

Roadside Barriers and Earth Berms

Capital Cost Changes

Basic capital cost data for barriers and berms from Chapter Three, as well as the DOT study (*122*), are summarized in Table 59. The figures from the two sources are in reasonable agreement except for the reinforced concrete walls, where the costs reported by three different state highway departments are substantially higher than the estimates from the DOT study. Also, the costs do not include the acquisition of increased right-of-way, which generally would be required for earth berms.

Construction of roadside barriers or berms constitutes a highway noise-control measure that can be applied either to existing highways or to future planned highways. Furthermore, the measure can be used with any highway configuration (at grade, depressed, or elevated). For the case of existing highways, the total cost of the measure would be as given in Table 59, assuming a sufficiently wide right-of-way is available. For planned highways, the cost of the measure might be less than suggested in Table 59 in certain cases. For example, the cost of building a depressed highway with an earth berm might be somewhat less, due to reduced earthmoving expenses, than the sum of the individual costs for a depressed highway and an earth berm, as given in Tables 58 and 59, respectively. However, because earthmoving costs are minor compared to basic construction and right-of-way acquisition costs, the savings would be relatively small.

Operating and Maintenance Cost Changes

Addition of roadside barriers or berms should not result in any significant change in the highway operating costs. However, roadside barriers could involve a significant increase in maintenance costs, depending on the details of their construction. The single largest maintenance cost factor is repair of damage caused by vehicle collisions with the barriers during run-off-road accidents. This problem is complicated by the fact that such collisions tend to increase the severity of run-off-road accidents, which in itself constitutes an additional cost that is difficult to quantify. Of course, the accidental collision problem can be reduced by

TABLE 58

TYPICAL COSTS OF VARIOUS HIGHWAY CONFIGURATIONS

DESCRIPTION, YEAR, REF.	HIGHWAY CONFIGURATION	RIGHT-OF-WAY WIDTH (FT)	COST ($1000/MI) RIGHT-OF-WAY	CONSTR.	TOTAL	COST RELATIVE TO AT-GRADE COSTS
8 Lanes in typical California urban area, 1973 (Ch. 3)	At grade	256	7110	4450	11560	1.00
	Depressed 20 ft with 2:1 slopes	336	9330	4870	14200	1.23
	Elevated 20 ft on fill with 2:1 slopes	336	9330	4000	13330	1.15
	Elevated 24 ft on structure	256	7110	18600	25700	2.22
6 Lanes in typical Baltimore residential area, 1970 (*122*)	At grade	232	4970	1860	6830	1.00
	Depressed 20 ft with 2:1 slopes	312	6700	2790	9490	1.39
	Elevated 20 ft on structure	232	4970	21000	26000	3.81

TABLE 59

SUMMARY OF BARRIER AND BERM COSTS [a]

DESCRIPTION OF BERMS OR BARRIERS	HT. (FT)	COSTS REPORTED BY STATE [b] STATE AND YEAR	COST PER MILE ($1000)	COST PER MILE ESTIMATED IN REF. 122 ($1000)
Precast concrete panels, architecturally finished, secured to steel or concrete framework	8	CA–73	253	592
	10	CT–68	686	728
	20	CT–68	1373	1416
	30	CT–68	2059	2102
Reinforced concrete walls	6	CA–73	760	—
	20	CT–63	4224	—
	10	IL–70	3292	422?
	20	IL–70	8466	1076?
	30	IL–70	15641	—
	34	IL–70	17187	—
Brick walls	10	CT–72	528	492
	20	CT–72	1056	940
Concrete block wall, 8 in. thick	6	CA–73	158	153
	13	CA–73	338	282
	20	CA–73	500	412
Corrugated steel barriers	6	CA–73	148	—
	10	CT–71	1056	—
	20	CT–71	2112	—
	30	CT–71	3168	—
Wood wall, 4 in. thick	4	CT–73	475	—
Earth berm, 65 to 105 ft at base	10–17	CT–73	803 [c]	—
Earth berm, 50 ft at base	15	—	—	248 [c]

[a] For a berm or barrier on both sides of the roadway.
[b] See Chapter 3.
[c] Does not include cost of additional right-of-way that would be required.

increasing the distance between the barrier and the highway shoulder, but this also reduces the acoustical efficiency of the barrier. Current highway design standards suggest that roadside barriers should be at least 15 ft from the edge of the highway shoulder. On the other hand, barrier attenuation prediction models indicate that barriers should be no more than 50 ft from the shoulder (excluding use with depressed roadways) for optimum noise-reduction potential. It appears that locating barriers about 25 ft from the highway shoulder constitutes a reasonable compromise between safety and acoustical efficiency.

Two other actions that can greatly reduce the maintenance costs due to accidental vehicle collisions without reducing the acoustical efficiency of a barrier are as follows:

1. Build a conventional guardrail between the highway shoulder and the barrier that will protect the barrier from damage due to all but the most severe run-off-road vehicle accidents.
2. Build the barrier on top of an earth berm, say 4 to 5 ft high, which would be less prone to physical damage requiring expensive repairs due to run-off-road vehicle accidents.

For the purposes of this study, it is assumed that one or both of these measures is taken in construction of roadside barriers. Even then, there will probably be some additional cost for maintenance of barriers due to accident damage and upkeep. For the case of concrete block barriers, this additional cost is broadly estimated to be about $5,000 per mile per year.

Costs for Surface Repavement

The cost of repaving an existing highway is heavily dependent on many factors, including the location of the highway, the width, the thickness of the new pavement, the job size, traffic diversion problems, etc. However, current construction cost data (*123*) indicate the cost for paving a concrete base with a 3-in. thickness of asphalt to be about $0.33/sq ft for large jobs. Using this figure, the cost of repaving an 8-lane highway with 3 in. of asphalt would be about $200,000/mile. Of course, there would probably be some additional costs beyond the laying of pavement, such as those associated with cleaning and preparing the old surface, diverting traffic, etc. However, as a first order of approximation, the $200,000/mile figure is used. It is assumed that repaving will not significantly alter the highway operation and maintenance costs.

Basic Costs of Community Noise-Reduction Measures

The costs associated with noise reductions at the community level by possible zoning actions affecting land use are too nebulous to be quantified. The changes in capital costs associated with interior noise reductions through structural sound insulation, however, can be and have been thoroughly quantified in Chapter Four. These costs vary somewhat with regional location. Typical figures for structures in the middle region of the United States are summarized in Table 60, which includes the change in capital costs for both future constructions and modifications to existing structures.

Although the measures required to reduce the interior noise of community structures might involve some minor changes in annual maintenance costs, the expected changes are sufficiently small relative to the capital cost changes to be ignored.

For the case of operating costs, materials that are effective for noise reduction also tend to be good heat insulators. Hence, it is reasonable to believe that the changes required to achieve interior noise reductions would also lead to reduced heating costs, particularly in northern areas. On the other hand, the noise reduction measures generally require some form of central forced ventilation and/or air conditioning, even in those areas where it might not normally be required. This will cause increased electrical use, particularly for single-family dwellings where air conditioning is not considered as part of the baseline construction. A cursory evaluation of these factors suggests that the decreased operating costs due to reduced heating requirements will, on the average, be of the same general magnitude as the increased operating costs due to the addition of air conditioning. Hence, it is assumed that the net change in operating costs due to sound treatment is negligible, at least for the case of single-family dwellings. It should be noted, however, that the required addition of central air conditioning provides qualitative benefits that are not being considered.

NORMALIZED COST OF VARIOUS NOISE-REDUCTION STRATEGIES

With the basic cost data summarized in the preceding sections and the cost evaluation procedures outlined in Chapter One, the cost-effectiveness of each noise reduction strategy being considered can now be defined in terms of the annual cost for 1 dBA of noise reduction along a single mile of highway. This measure of cost-effectiveness, referred to hereafter as the "normalized cost" of the noise reduction, is given by

$$\text{Normalized cost} = \frac{\text{EUAC per mile of highway}}{\text{Noise reduction, in dBA}} \qquad (105)$$

and has the units of dollars/mile-year/dBA. For example, if a noise reduction measure provides 5 dBA of noise reduction along a 10-mile stretch of highway at a normalized cost of $1,000/mile-year/dBA, the total cost of the measure over a period of five years would be $250,000.

For both the vehicle and highway noise-reduction measures, the noise-reduction potentials, as well as the costs, depend on the heavy truck traffic mix ratio; i.e., the percentage of the total traffic volume composed of heavy trucks. Hence, all normalized costs are computed for four representative truck mix ratios—0%, 5%, 10%, 20%. Calculations of the net noise reduction for mixed traffic are performed using the assumptions detailed in Chapter One.

TABLE 60

SUMMARY OF STRUCTURE NOISE-REDUCTION COSTS

		COST (1973 $) FOR SPECIFIED NOISE REDUCTION [a]					
		FUTURE CONSTRUCTIONS			MODIFICATIONS OF EXISTING STRUCTURES		
TYPE OF STRUCTURE	COST UNIT	5 dBA	10 dBA	15 dBA	5 dBA	10 dBA	15 dBA
Single-family house	Dwelling	3990	5460	6920	6000	11000	13200
Multi-family dwelling	Apartment	1760	2870	3110	3320	4460	5800
High-rise apartment	Apartment	570	1370	1520	775	2180	2500
School	Classroom	2260	4020	4500	3310	6850	10300
Church	Person	22	42	55	—[b]	—[b]	—[b]
Auditorium	Sq ft of floor area	1.04	1.04	0.68	4.34	4.36	4.58
Hospital	Patient room	213	500	660	300	725	1180
Low-rise motel	Guest room	1665	1790	2140	2000	2980	3380
High-rise hotel	Guest room	440	688	880	379	748	935
High-rise commercial	Linear ft ext wall per story	18.75	78	83	54	83	93
Low-rise commercial	150 sq ft of floor area	371	768	1060	347	828	1480
Industrial plant	Sq ft of floor area	0.18	1.77	1.88	0.33	1.85	3.69

[a] In the Middle Zone (see Fig. 48).
[b] The required modifications are considered economically impractical.

Vehicle Noise-Reduction Measures

In review, the vehicle noise-reduction strategies considered in this study include the following:

1. Design all new automobiles and trucks for the maximum noise reduction practical with current technology.
2. Design all new heavy trucks only for the maximum noise reduction practical with current technology.
3. Retrofit all existing heavy trucks only for the maximum noise reduction practical with current technology.
4. Divert all heavy trucks to an alternate route more remote from the highway where the noise reduction is desired.

Before calculating the normalized costs of these four strategies, it is necessary to determine the equivalent uniform annual and mileage costs (EUAC and EUMC) for the vehicle noise-reduction equipment.

For the case of automobiles and light trucks, where the noise reduction equipment (excluding mufflers) is assumed to be good for the life of the vehicle, the EUAC values are calculated directly from the cost data in Table 56. For the case of heavy trucks, where the various equipment items have different useful lives, the EUAC values are calculated item by item using the data in Tables 54 and 55, as detailed in Table 61. The final EUAC and EUMC values for the four vehicle noise-reduction strategies are summarized in Table 62, which indicates that the noise reduction and EUMC for automobiles and light trucks are about the same. Hence, light trucks can be considered as automobiles with no significant error for the desired economic evaluations. This is done in all further calculations. The equivalent uniform annual cost is defined by

$$\text{EUAC} = (I - T)(\text{CR}, r, n) + P + M + rT \qquad (106)$$

where

I = capital investment at time zero, in dollars;
T = estimated terminal value of I at the end of n years, in dollars;
CR = capital recovery factor;
r = money time discount factor, per year;
n = useful service life or analysis period, in years;
P = equivalent uniform expense per year for operation, in dollars; and
M = equivalent uniform expense per year for maintenance, in dollars.

The capital recovery factor, CR, combines return of capital (depreciation) with return on capital (investment return) at the discount rate of r for n years. This compound interest factor, given by

$$\text{CR} = \frac{r(1+r)^n}{(1+r)^n - 1} \qquad (107)$$

is based on the sinking fund concept that provides for an increasing yearly depreciation return and a decreasing yearly investment return, such that the sum of the two factors is constant over n years.

It should be noted that the cost terms in Eq. 106 represent the change in cost due to the noise-reduction measure, rather than an absolute cost. For example, the change in cost associated with quieting a heavy truck is the cost of the quiet truck minus the cost of a similar truck without noise-reduction equipment. It follows that some of the cost changes might be negative, reflecting a cost reduction due to the noise-reduction measure. For example, use of a thermatic or viscous fan clutch as a noise-reduction measure on a heavy truck will actually reduce the operating cost

TABLE 61

EUAC CALCULATIONS FOR HEAVY TRUCK NOISE-REDUCTION EQUIPMENT

NOISE-REDUCTION EQUIPMENT	NEW TRUCKS [a] ADD. COST ($)	NEW TRUCKS [a] USEFUL LIFE (YR)	NEW TRUCKS [a] EUAC ($)	EXISTING TRUCKS (RETROFITS) [a] ADD. COST ($)	EXISTING TRUCKS (RETROFITS) [a] USEFUL LIFE (YR)	EXISTING TRUCKS (RETROFITS) [a] EUAC ($)
Close-fitting engine covers	143	5	38	143	3	58
Ducted engine and transmission enclosure	570	8	107	—	—	—
Manifold muffler	121	5	32	121	3	49
Dual muffler	83	2	48	83	2	48
Wrap exhaust pipes	174	2	100	174	2	100
Engine mounts	81	2	47	81	2	81
Thermatic fan clutch	150	5	40	150	3	60
High-performance fan	6	5	2	6	3	2
Increased fan-rad. spacing	50	5	13	—	—	—
Best air cleaner and snorkel	60	5	16	60	3	24
Operating costs			−180			−200
Maintenance			96			96
Total EUAC			359			318

[a] Labor costs in all cost figures assume that the equipment replacement is accomplished during a normal major overhaul of the engine.

TABLE 62

EUAC AND EUMC FOR VEHICLE NOISE-REDUCTION MEASURES

TYPE OF VEHICLE	NEW OR RETROFIT	NOISE RED.[a] (ΔdBA)	EUAC PER VEHICLE ($/YR)	EUMC[b] PER VEHICLE ($/MI)
Automobiles	New	4	19	0.0017
Light trucks	New	4	30	0.0015
Heavy trucks	New	8	359	0.0029
Heavy trucks	Retro.	5	318	0.0025

[a] Assumes cruise on level grade at 55 to 65 mph.
[b] Assumes annual use of 11,000 miles for automobiles, 20,000 miles for light trucks, and 125,000 miles for heavy trucks.

for the truck, because it reduces the horsepower consumed by the fan.

Finally, because the costs of concern must be measured in terms of a change from an existing situation or baseline design, it is necessary to define the baseline designs to which noise-control measures are applied. The baseline designs assumed for the purposes of this study are as follows:

1. For motor vehicles, the baseline design is that generally prevailing in the 1973 models, including such specific designs that are for safety and emission controls. Straight-rib tires are considered within the baseline design for automobiles and light trucks, but cross-rib tires (NBS tread patterns D, E, F; see Fig. 16) are assumed in the baseline design for heavy trucks.
2. For highways, the baseline design is that design the highway department would construct with the grade line at ground level on the basis that no feature of the design would be specifically directed to reduction of noise.
3. For community structures along the highway route, the baseline design is that design being constructed in that locality without specific features to prevent the penetration of noise to the interior of the structures. Any insulation for space heating or space cooling now standard is considered within the baseline design, even though such insulation provides interior noise reduction. However, central air conditioning is not considered within the baseline design for residential dwellings.

For the motor vehicle noise-reduction measures considered in this study, the equivalent uniform annual cost is computed using the following assumptions:

1. The money time discount factor is $r = 0.10$.
2. The terminal value of the noise-reduction equipment on new automobiles is $T = 0$ after $n = 11$ years.
3. The terminal value of the noise reduction equipment on new light trucks is $T = 0$ after $n = 8$ years.
4. The terminal value of the noise-reduction equipment on either new or retrofitted heavy trucks is $T = 0$ after $n = 2$ to 8 years, depending on the specific equipment.

The first assumption is consistent with the discount factor currently used by the Department of Transportation. The second and third assumptions suggest that the noise-reduction equipment (excluding mufflers) for automobiles and light trucks is good for the useful life of the vehicle. The average useful life of automobiles is estimated from recent Department of Transportation data (*124*) to be about 120,000 miles at an average use of 11,000 miles per year for 11 years. The average useful life of light trucks is estimated to be about 160,000 miles at an average use of 20,000 miles per year for 8 years. Of course, the annual use of both automobiles and light trucks is heavily dependent on their age; the annual use is much higher, on the average, for new vehicles than for old vehicles. However, this does not influence the desired economic calculations, as long as it is assumed the noise-reduction equipment is good for the life of the vehicle.

Concerning the last assumption, discussions with representatives of both a heavy truck manufacturer and a trucking company lead to the following conclusions. The average heavy truck is operated about 125,000 miles per year for 4 to 6 years by its first owner. During this period, the engine is overhauled two or three times, which is generally the limit for continued reliable and efficient performance. Often, the truck is then sold to a second owner who may use the truck only for the remaining engine life, or replace the engine and use the truck for several additional years. It follows that a heavy truck might outlive much of its noise-reduction equipment. Hence, the equivalent uniform annual cost of the equipment should be computed item by item. The alternative would be to carry the equipment replacement costs as a maintenance expense. However, this approach would ignore the interest costs, which are substantial for some of the more expensive items.

For the case of new trucks, the useful lives of equipment items are assumed to be (a) 8 years for items good for the life of the truck, (b) 5 years for items good for the life of the engine, and (c) 2 years for all others, as detailed later. For the case of existing trucks that are retrofitted, it is at least one practical approach acceptable for the purposes of this study. Specifically, convert the EUAC in dollars/vehicle-year to an EUMC (equivalent uniform mileage cost) in dollars/vehicle-mile by dividing the EUAC by the average yearly use in vehicle miles. Now convert the EUMC in dollars/vehicle-mile back to an EUAC in dollars/highway mile by multiplying the EUMC by the traffic volume in vehicles/year. The result is an effective equivalent uniform annual cost ($EUAC_e$) in dollars per highway mile, which may be expressed as

$$EUAC_e = (EUMC)V = (EUAC)V/M \qquad (108)$$

where

V = traffic volume, in vehicles per year, over a given mile of highway;
M = average vehicle use, in miles per year;
EUAC = equivalent uniform annual cost, in dollars per vehicle-year, as given by Eq. 106;
EUMC = equivalent uniform mileage cost, in dollars per vehicle-mile (=EUAC/M); and
$EUAC_e$ = equivalent uniform annual cost, in dollars per highway mile-year.

Application of Eq. 108 poses one serious problem; specifically, the definition of an appropriate value for M (the average vehicle use). On the one hand, it might be argued that this value should reflect only the miles per year spent by the average vehicle on a highway passing through a community where traffic noise is a major problem. This approach, however, would totally ignore the benefits of vehicle noise reduction during operation on city streets or in rural areas. The logical alternative is to let M equal the total annual miles the vehicle is driven. Of course, this technique would bill the noise-reduction costs equally to all miles of operation, incuding those miles that might be driven on rural roads where the demand for noise reduction is not as great as in urban areas.

Although neither of the foregoing definitions for M is wholly satisfying, it is believed that the definition based on total annual use is the more desirable of the two. Hence, in this study vehicle noise-reduction costs are computed using Eq. 108, where M is the total average vehicle use in miles per year. It should be understood, however, that this approach effectively asserts that a dBA of vehicle noise reduction is as valuable on a mile of city street or country road, as on a mile of urban highway. This assertion is particularly critical for the case of heavy interstate trucks, where more than 90 percent of the total operating miles might be on highways through sparsely populated areas. If the total cost of heavy truck noise-reduction measures were billed against only those miles spent on urban highways, the resulting computed noise-reduction cost per mile would be increased by perhaps an order of magnitude. Hence, the assumption greatly influences the apparent cost-effectiveness of this noise-reduction strategy.

For those strategies involving use of vehicle noise-reduction equipment, there is no change in travel time, because the speed and route of the vehicle are not altered. However, this is not true for the strategy of diverting all heavy trucks to an alternate route. In this case, there is no change in capital costs resulting from the strategy. Furthermore, assuming the alternate route has curvatures, grades, and traffic interference similar to the normal route, there is no change in the operating and maintenance costs on a per-mile basis. On the other hand, there is a change (usually an increase) in the time and distance the truck must travel. It follows that an $EUAC_e$ for this noise reduction strategy may be estimated by

$$EUAC_e = C_o V (D_a - D_n)/D_n \qquad (109)$$

where

C_o = truck operating cost, in dollars per mile, including the value of travel time;
V = truck traffic volume on alternate route;
D_a = total length, in miles, of alternate route diverted to; and
D_n = total length, in miles, of normal route diverted from.

Eq. 109 assumes that the alternate and normal routes are equal in their effects on the operating cost of trucks. Furthermore, application of Eq. 109 requires the assumption that an alternate route is available through an area where no noise reduction is needed, and that there are no starting or termination points for the trucks along that section of the normal route being diverted.

With the data in Table 62, the effective equivalent uniform annual cost ($EUMC_e$), as defined in Eq. 108, and the associated net noise reduction for the four strategies can be computed for various truck mix ratios to obtain the normalized cost of the strategies from Eq. 105. The results are given in Table 63, in which the $EUAC_e$ values are computed assuming a typical traffic volume for a 6- to 8-lane urban highway of $V = 40{,}000$ veh/day (14.6 million veh/year) for convenience. The net noise-reduction figures are calculated using the nominal vehicle noise levels given in Tables 25 and 27. The costs of the last strategy (diverting all heavy trucks to an alternate route) are computed for a 1 percent increase in route distance using Eq. 109 (1 percent is believed to be as small a distance increase as might normally be expected for an acceptable alternate truck route). The heavy truck operating cost for this strategy is assumed to be $C_o = \$1.25$/mile (*121*), as discussed earlier.

Highway Noise-Reduction Measures

As discussed earlier, the costs associated with highway noise reduction measures are heavily dependent on the details of the highway, including location, number of lanes, right-of-way requirements, etc. Hence, an accurate equivalent uniform annual cost (EUAC) value for a given measure should be established for each individual case as it arises. To obtain quantitative data for comparative evaluations, however, two general cases are considered, as follows:

1. An 8-lane highway through a typical California urban area, as described in Chapter Three and represented by the basic cost data in Tables 57, 58, and 59.

TABLE 63

NORMALIZED COSTS FOR VEHICLE NOISE-REDUCTION STRATEGIES

STRATEGY	TRUCK MIX (%)	$EUAC_e$/MILE [a] ($1000/MI-YR)	NOISE REDUCTION [b] (ΔdBA)	NORMALIZED COST [a] ($\left(\frac{\$1000/\text{MI-YR}}{\text{dBA}}\right)$)
(a) Quiet all new autos and trucks	0	25	4.0	6.2
	5	26	5.4	4.8
	10	27	6.1	4.4
	20	28	6.8	4.1
(b) Quiet all new heavy trucks only	0	0	0	—
	5	2.1	2.1	1.0
	10	4.2	3.3	1.3
	20	8.5	4.8	1.8
(c) Retrofit all existing heavy trucks	0	0	0	—
	5	1.8	1.6	1.1
	10	3.6	2.5	1.4
	20	7.3	3.4	2.1
(d) Divert all heavy trucks to a 5% longer alternate route	0		0	—
	5	9.1	2.6	3.5
	10	18	4.3	4.2
	20	36	6.9	5.2

[a] Assumes a yearly volume of 14.6 million vehicles.
[b] Assumes cruise on level grade at 55 to 65 mph.

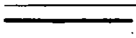
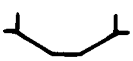
2. A 6-lane highway through a typical Baltimore residential area, as described and represented by the basic cost data given by Starley (*122*).

Based on the assumptions previously discussed, the EUAC of various noise-reduction measures for these two cases may be calculated directly from Eq. 106, with the results given in Table 64. The costs for constructions on the Baltimore 6-lane highway originally were estimated in terms of 1970 dollars; the data given in Table 64 are corrected for inflation to 1973 dollars by adding 15 percent to the 1970 prices. This factor is based on the DOT price index for highway construction costs (*125*).

From Table 64, the EUAC values computed from the two independent sources of data (Chapter Two and a previous DOT study (*122*)) are, with one exception, in good agreement for all configurations where direct comparisons can be made. For the case of elevated structures, the Balt-6 values from the DOT study far exceed not only the Calif-8 values given, but also all estimates for this type of construction as reported by several state highway depart-

TABLE 64

EUAC FOR HIGHWAY NOISE-REDUCTION MEASURES

TYPE OF CONSTRUCTION: SKETCH	TYPE OF CONSTRUCTION: DESCRIPTION	HEIGHT OR DEPTH (FT)	LOCATION AND NO. OF LANES	RIGHT-OF-WAY WIDTH (FT)	INCREASED CAPITAL COST [a] ($1000/MI)	EUAC ($1000/MI-YR)
	At grade	0	Calif.-8	256	0	0
	(reference)	0	Balt.-6	232	0	0
	Roadside barriers	10	Calif.-8	256	260	31.5 [b]
	riers (8-in.	10	Balt.-6	232	261	31.6 [b]
	thick concrete	15	Calif.-8	256	380	43.8 [b]
	block construc-	15	Balt.-6	232	367	42.4 [b]
	tion)	20	Calif.-8	256	500	56.0 [b]
		20	Balt.-6	232	474	53.3 [b]
	Earth berms	15	Calif.-8	356	3020	308
		15	Balt.-6	332	2790	285
	Depression with	20	Calif.-8	336	2640	269
	2:1 slopes	20	Balt.-6	312	3040	310
		30	Balt.-6	352	4750	485
	Depression with	20	Calif.-8	336	2900	301 [b]
	2:1 slopes and	20	Balt.-6	312	3270	338 [b]
	10-ft barriers	30	Balt.-6	352	4980	513 [b]
	Depression with 2:1 slopes and 15-ft earth berms	20	Calif.-8	436	6220	636
	Vertical depression	20	Balt.-6	232	2280	233
		30	Balt.-6	232	3390	346
	Vertical depres-	20	Balt.-6	232	2510	261 [b]
	sion with 10-ft barriers	30	Balt.-6	232	3610	373 [b]
	Fill elevation with 2:1 slopes	20	Calif.-8	336	1770	180
	Fill elevation with 2:1 slopes and 10-ft barriers	20	Calif.-8	336	2030	212 [b]
	Elevated structure	24	Calif.-8	256	14100	1440
		20	Balt.-6	232	22000	2240
		30	Balt.-6	232	22600	2300
	Elevated structure	24	Calif.-8	256	14400	1470 [b]
	with 10-ft barriers	20	Balt.-6	232	23600	2410 [b]
		30	Balt.-6	232	24100	2460 [b]
Pavement resurfacing with 3 in. of open-graded asphalt, 8 lanes				—	200	23.5

[a] California figures in 1973 dollars; Baltimore figures corrected from 1970 to 1973 dollars.
[b] Includes $5000/year for additional maintenance expenses.

ments in Chapter Two of this study. For all further calculations, the Calif-8 data are used.

With the cost data in Table 64 plus the noise-reduction data in Table 65, the normalized costs of various highway noise-reduction measures can be calculated for different heavy truck mix ratios using Eq. 105, with the results summarized in Table 66. It should be emphasized that these results assume the observer is 5 ft above grade and 100 ft from the edge of the highway right-of-way. As the observer height increases, the noise reduction provided by all strategies diminishes rapidly. Hence, the data in Table 66 would not apply for an observer on an upper floor of a multistory structure near the highway.

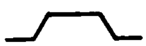
Finally, the consideration of roadside barriers has been limited to barriers heights between 10 and 20 ft. The acoustical efficiency of barriers with a height of less than 10 ft or more than 20 ft is considered questionable. As the height of a barrier falls below 10 ft, its ability to shield an observer from truck noise falls sharply. As the height of a barrier rises above 20 ft, the direct transmission of sound through the barrier starts to limit its noise-reduction potential, unless the barrier is constructed from a very thick and/or dense material.

For the highway noise-reduction measures considered in this study, the equivalent uniform annual cost is computed using the following assumptions:

1. The money time discount factor is $r = 0.10$.
2. The terminal value of a highway pavement is $T = 0$ after $n = 20$ years.
3. The terminal value of noise reduction constructions, excluding highway repavement, is $T = 0$ after $n = 40$ years.
4. The increase in right-of-way width required for the construction of elevated and depressed highway configurations, as well as roadside earth berms, is equal to the width of slopes required to construct the roadway fill, depression, or roadside berms.
5. No increase in right-of-way width is required for the construction of masonry or steel roadside barriers.

TABLE 65

NOISE REDUCTIONS FOR VARIOUS HIGHWAY CONFIGURATIONS

HIGHWAY CONFIGURATION [a] SKETCH	DESCRIPTION	HEIGHT OR DEPTH (FT)	TRUCK MIX (%)	NOISE REDUCTION [b] AT DIST. FROM ROW (dBA) 100 FT	500 FT
	Roadside barriers 25 ft from edge of shoulders; ROW width = 256 ft	10	0	9.9	9.5
			5	8.4	7.6
			10	7.9	7.0
			20	7.5	6.6
		15	0	12.0	11.6
			5	10.8	10.1
			10	10.4	9.6
			20	10.1	9.2
		20	0	13.9	13.3
			5	13.0	12.1
			10	12.6	11.7
			20	12.3	11.3
	Depressed roadway with 2:1 slopes; ROW width = 336 ft	20	0	9.9	11.4
			5	8.8	10.3
			10	8.4	9.8
			20	8.1	9.4
	Fill-elevated roadway with 2:1 slopes; ROW width = 336 ft	20	0	9.0	6.3
			5	7.6	2.7
			10	7.1	1.8
			20	6.7	1.1
	Elevated structure; ROW width = 256 ft	24	0	9.8	6.0
			5	9.6	2.4
			10	9.3	1.5
			20	8.8	0.8

[a] Assumes divided, 8 lanes, with 30-ft median.
[b] Based on an observer located 5 ft above grade.

The first assumption is consistent with the factor currently used by the Department of Transportation. The second assumption is consistent with general data for asphalt pavements (*8*). It follows that the capital recovery factor for repaving is CR = 0.117. The third assumption is considered a reasonable lower bound on the useful service life of the noise-reduction constructions of interest. It should be remembered that the constructions of concern here are only those required to add shielding to a normal ground-level highway; specifically, land excavations and fills, elevated structures, roadside barriers, and additional right-of-way, but not the pavement, signs, and other constructions that would be required for a ground-level highway. Many of these added constructions (additional right-of-way, for example) might have a useful service life far in excess of 40 years. Fortunately, for $r = 0.10$, the capital recovery factor is not very sensitive to the assumed service life beyond 40 years. For example, at $n = 40$, CR = 0.102; at $n = \infty$, CR $\doteq$ 0.100.

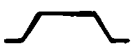
The last two assumptions concerning the right-of-way width are critical. Because right-of-way acquisition costs are often the largest single cost factor in the construction of highways through densely populated cities, the actual change in required right-of-way width caused by a noise-reduction measure could have a profound impact on the resulting cost of the strategy. Assumptions 4 and 5 are required to obtain quantitative results for evaluation. Furthermore, they are generally reasonable assumptions. However, it should be emphasized that highway designers often suppress the increased right-of-way requirements for fill elevations, depressions, and earth berms by reducing the median width and/or the distance between the edge of the construction (including slopes) and the right-of-way boundary. In such cases, the effective capital cost of the noise reduction construction might be significantly reduced.

With the foregoing assumptions and appropriate cost data for a given degree of noise reduction, an equivalent uniform annual cost (EUAC) for the various highway noise-reduction measures can be calculated from Eq. 106. The resulting figures directly provide a firm basis for cost comparisons with other traffic noise-reduction strategies.

For the community noise reduction measures involving

TABLE 66

NORMALIZED COSTS FOR HIGHWAY NOISE-REDUCTION STRATEGIES

EIGHT-LANE HIGHWAY CONFIGURATION		HEIGHT OR DEPTH	ROW WIDTH	EUAC[a]	NOISE REDUCTION[b] (ΔdBA) FOR TRUCK MIX OF				NORMALIZED COST ($1000/MI-YR/dBA) FOR TRUCK MIX OF			
SKETCH	DESCRIPTION	(FT)	(FT)	($1000/MI-YR)	0%	5%	10%	20%	0%	5%	10%	20%
	At grade (reference)	0	256	0	0	0	0	0	—	—	—	—
	Roadside barriers[c]	10	256	31.5	9.9	8.4	7.9	7.5	3.2	3.8	4.0	4.2
		15	256	43.8	12.0	10.8	10.4	10.1	3.6	4.0	4.2	4.3
		20	256	56.0	13.9	13.0	12.6	12.3	4.0	4.3	4.4	4.5
	Earth berms	15	356	308	12.3	11.3	10.9	10.6	25	27	28	29
	Depression with 2:1 slopes	20	336	269	9.9	8.8	8.4	8.1	27	31	32	33
	Depression with 2:1 slopes and 10-ft barriers	20	336	301	13.9	13.2	12.9	12.7	22	23	23	24
	Depression with 2:1 slopes and 15-ft earth berms	20	436	636	15.5	14.9	14.6	14.4	41	43	44	44
	Fill-elevation with 2:1 slopes	20	336	180	9.0	7.6	7.1	6.7	20	24	25	27
	Fill elevation with 2:1 slopes and 10-ft barriers	20	336	212	13.4	12.5	12.2	11.9	16	17	17	18
	Elevated structure	24	256	1440	9.8	9.6	9.3	8.8	150	150	150	160
	Elevated structure with 10-ft barriers	24	256	1470	13.6	12.4	12.0	11.7	110	120	120	130
Pavement resurfacing with 3 in. of open-graded asphalt, 8 lanes		—	256	23.5	1.5	1.5	1.5	1.5	16	16	16	16

[a] Cost data based on 8-lane highway through typical California urban area.
[b] Noise reduction based on free-flowing traffic (55 to 65 mph) for an observer 5 ft above grade and 100 ft from the right-of-way.
[c] Concrete block construction 25 ft from nearest lane.

the sound treatment of occupied structures, the equivalent uniform annual cost is computed using the following assumptions:

1. The money time discount factor is $r = 0.10$.
2. The terminal value of the noise-reduction construction is $T = 0$ after $n = 40$ years.

The justification for these two assumptions is exactly the same as presented for the highway noise-reduction constructions. They further lead to the same capital recovery factor; namely, CR = 0.102.

With these assumptions and appropriate cost data for a given degree of noise reduction, an equivalent uniform annual cost (EUAC) for the sound treatment of individual structures can be calculated from Eq. 106. Of course, there is still the problem of relating the EUAC for individual structures to an EUAC per highway-mile. This final step requires a specific configuration for the type of structures along the right-of-way, as well as some limit on the distance from the highway where noise control is considered necessary. However, for any given configuration and stated distance limit, an appropriate EUAC per highway-mile is readily calculated by summing the EUAC figures for the individual structures.

Housing Noise-Reduction Measures

As discussed in Chapter Four, of the various possible community noise-reduction measures, only two lend themselves to qualitative evaluation, as follows.

1. Add sound treatment to those structures bordering on the right-of-way.
2. Restrict the use of land bordering on the right-of-way to properly sound-treated, high-rise structures that would serve as a shield for the remainder of the community.

Even for these two strategies, a meaningful EUAC is difficult to establish in the absence of community details.

However, to provide a basis for quantitative evaluation, two typical situations are assumed, as follows.

1. The land bordering on each side of the right-of-way is occupied by parallel rows of single-unit family dwellings on 50-ft-wide lots (about 100 houses per row per mile).
2. The land bordering on each side of the right-of-way is occupied by a single row of high-rise commercial structures with an average height of five stories, an average floor plan of 60 × 120 ft laid lengthwise along the highway, and an average building separation distance of 50 ft (about 30 buildings per row mile).

For these two typical situations, four specific cases are considered, as follows.

Case 1. Obtain approximately 15 dBA of noise reduction by sound-treating the first three rows of houses on each side of the right-of-way, the first row for 15 dBA of reduction, the second row for 10 dBA of reduction, and the third row for 5 dBA of reduction.

Case 2. Obtain approximately 10 dBA of noise reduction by sound-treating the first two rows of houses on each side of the right-of-way, the first row for 10 dBA of noise reduction and the second row for 5 dBA of noise reduction.

Case 3: Obtain approximately 5 dBA of noise reduction by sound-treating the first row of houses on each side of the right-of-way for 5 dBA of noise reduction.

Case 4. Obtain approximately 10 dBA of noise reduction by treating the row of high-rise commercial buildings adjacent to the right-of-way for 10 dBA of noise reduction.

The formulation of these four cases is based on assumptions concerning estimated noise reductions due to shielding, as discussed in Chapter Four.

Based on assumptions detailed earlier and the basic cost data in Table 60, the EUAC values and normalized costs for each of the four cases of interest are calculated using Eq. 106, with the results given in Table 67. Note that these results apply to structures in the middle region (between the northern and southern regions) of the United States. Similar results can be generated for other regions of the United States using the basic data for sound treatment constructions detailed in Chapter Four. Of course, similar cost data may also be generated for any other special case of commercial structures or housing, as desired.

TABLE 67

NORMALIZED COSTS FOR HOUSING NOISE-REDUCTION STRATEGIES

TYPE OF MEASURE CASE	DESCRIPTION	NOISE REDUCTION (ΔDBA)	NEW OR EXISTING STRUCTURES	EUAC [a] (\$1000/MI-YR)	NORMALIZED COST [a] $\left(\frac{\$1000/\text{MI-YR}}{\text{dBA}}\right)$
1	Sound treat the first 3 rows of houses on each side of right-of-way	15	New	334	22
			Existing	616	41
2	Sound treat the first 2 rows of houses on each side of right-of-way	10	New	193	19
			Existing	347	35
3	Sound treat the first row of houses on each side of right-of-way	5	New	81.4	16
			Existing	122	24
4	Sound treat the first row of high-rise buildings on each side of right-of-way	10	New	172	17
			Existing	183	18

[a] Cost data apply to structures in the Middle region of the United States (see Fig. 48).

CHAPTER SIX

INTERPRETATIONS AND APPLICATIONS

LAWS, PROJECTIONS, AND PROPOSED NOISE REDUCTIONS

The significance of the estimates of technical feasibility of vehicle noise reduction should be judged in part by existing and proposed legislated noise limits. In the development of these limits, the technical aspects of noise control were considered, so good correlation between the limits and the noise-reduction estimates herein add credibility to both. On the other hand, the legislated limits were not developed explicitly with the idea of minimizing the national cost of highway noise control. Therefore, comparison of the estimated vehicle noise-reduction potential with present legislated limits may serve to identify less than optimal solutions.

Existing and Pending Legislated Noise Limits

Legislated noise limits are of two different types: (1) maximum noise levels permitted during operation of the vehicle and, (2) maximum new vehicle noise levels as measured under full-throttle, accelerating, and low-speed conditions. Both California and the City of Chicago, Ill., have legislated both types of limits. These have served as models for similar legislation by other cities and states. The noise regulations for new motor vehicles are summarized in Table 68. Operating limits are given in Table 69.

In addition to existing legislation, the States of Florida and Maryland are presently studying the advisability of imposing limits similar to those of California.

All of these state and local noise codes and ordinances may be superseded. The United States Environmental Protection Agency, charged with the responsibility of implementing the Noise Control Act of 1972, is presently conducting studies to arrive at levels "to promote an environment for all Americans free from noise that jeopardizes their health and welfare." The EPA Administrator has determined that noise standards are feasible for medium and heavy-duty trucks, considering best available technology and cost of compliance (*126*). The levels and the effective dates of application are indicated in Table 70. The proposal and adoption of similar regulations for automobiles and motorcycles is under study by the EPA.

The EPA has also announced its intent to impose operating noise limits on interstate carriers (*127, 87*). The proposed maximum levels are identical with those presently in force in the State of California.

Manufacturer-Furnished Total Vehicle Noise-Reduction Costs

The sources of total vehicle noise-reduction costs are limited to a presentation by General Motors Corporation (*58*) and

TABLE 68

SUMMARY OF NEW MOTOR VEHICLE NOISE LIMITS BY YEAR OF MANUFACTURE

JURISDICTION	CATEGORY [a]	NOISE LIMITS (dBA) [b] 1972	1973	1975	1978	1980	1988
California	GVW ≥6K	88	86	83	80		70
	MC	88	86	80	75		70
	AOMV	86	84	80	75		70
Chicago	GVW ≥8K	88	86	84		75	
	MC	88	86	84		75	
	PC, AOMV	86	84	80		75	
Boston [c]	GVW ≥10K	88	86	84		75	
	GVW ≤10K	86	84	80		75	
Nebraska	GVW ≥10K	88	86	84		75	
Colorado	GVW ≥6K	88	86				
	AOMV	86	84				
Nevada [c]	GVWR ≥6K	88	86				
	AOMV	86	84				
Minnesota	GVWR ≥6K	88		86			
	AOMV	86		84			
Pennsylvania	GVWR ≥7K		90				
	AOMV		84				
Connecticut	All			85			

[a] PC = passenger car; GVW = gross vehicle weight; GVWR = gross vehicle weight rating; MC = motorcycles; AOMV = any other motor vehicle.
[b] At 50 ft, accelerating passby.
[c] Regulation; all others law or ordinance.

TABLE 69

NOISE REGULATIONS FOR OPERATION OF MOTOR VEHICLES

			NOISE LIMIT [a]						
			UNDER 35 MPH				OVER 35 MPH		
VEHICLE TYPE	STATE OR CITY	WT. CLASS (LB)	LEVEL ROAD (dBA)	NOW (dBA)	CHANGE YEAR	THEN (dBA)	NOW (dBA)	CHANGE YEAR	THEN (dBA)
Trucks	California [b]	>6000	82	86	1975	83	90	—	—
	Colorado	>6000	82	86	1975	83	90	—	—
	Chicago	>8000	—	86	1975	84	90	—	—
	Colorado, Boulder	>10000	—	88	—	—	88	—	—
	Connecticut	>10000	82	86	1975	84	90	1975	88
	Indiana	>7000	—	92	—	—	92	—	—
	New York City	>8000	—	86	—	—	90	—	—
	Minnesota	>6000	—	88	1975	86	90	—	—
	Nebraska	>10000	—	88	1975	86	90	—	—
	Nevada	>6000	—	86	1975	83	90	—	—
	Pennsylvania	>7000	—	90	—	—	92	—	—
	Oahu, Hawaii	>6000	—	84	1977	75	88	1977	75
Cars	California [b]		74	76	—	—	82	—	—
	Colorado		74	82	—	—	82	—	—
	Chicago		—	76	1978	70	82	1978	79
	Colorado, Boulder		—	80	—	—	80	—	—
	Connecticut		74	76	—	—	82	—	—
	Indiana		—	76	—	—	82	—	—
	New York City		—	76	1978	70	82	1978	79
	Minnesota		—	82	—	—	86	—	—
	Nevada		—	76	—	—	82	—	—
	Pennsylvania		—	82	—	—	86	—	—
	Oahu, Hawaii		—	73	1977	65	79	1977	71
Motor-cycles	California [b]		77	82	—	—	86	—	—
	Chicago		—	82	1978	78	86	1978	82
	Connecticut		77	82	1975	80	86	1975	84
	New York City		—	82	1978	78	86	1978	82
	Indiana		—	82	—	—	86	—	—
	Pennsylvania		—	90	—	—	92	—	—
	Oahu, Hawaii		—	73	1977	65	79	1977	71

[a] dBA at 50 ft.
[b] No citation if tire noise predominates.

the estimates of retrofit costs for interstate carriers (*128*). These costs are presented in Figures 50 and 51. The truck noise data may be compared with results calculated using Tables 24, 25, and 29, by constructing trucks of various noise levels using selected noise control measures.

Automobile cost estimates cannot be compared in the same manner; however, total costs shown in Figure 51 may be interpreted in terms of required abatements from Table 26 and from the various combinations of noise control measures of Table 27.

TABLE 70

REDUCED VEHICLE NOISE LEVEL STEPS

VEHICLE TYPE	NOISE LEVEL (dBA) [a]		
	JAN. 1978	JAN. 1982	JAN. 1985
Heavy diesel trucks	83	80	Reserved
Heavy and medium gasoline trucks	83	80	Reserved

[a] Measured at 5 ft for SAE accelerating passby test (*6*).

Noise Abatement Estimates, Scheduled Legislated Limits, and Implications

Trucks

Reduction of truck noise below the 80 dBA scheduled by California in 1978 appears to be possible with an additional initial cost of from $400 to $700 (present dollars). Achievement of a 75-dBA truck to meet the scheduled Chicago 1980 level will increase the initial cost (in present dollars) into the $1,400 to $2,200 range (technical feasibility of achieving a 72-dBA truck has been demonstrated). Additional initial costs to the operator of a 70-dBA truck are unknown. However, Figure 50 clearly indicates that the California scheduled 1988 level limit of 70 dBA is going to be extremely expensive in terms of initial costs unless there is a major technical breakthrough. The costs of research to achieve and demonstrate such a breakthrough probably will have to be borne in part at the federal level.

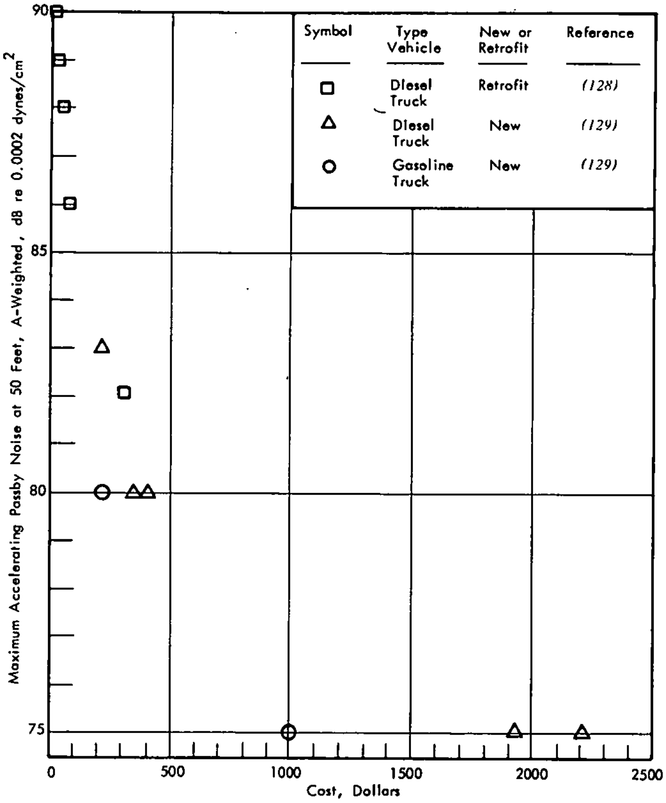


Figure 50. Average initial direct cost for truck noise reduction.

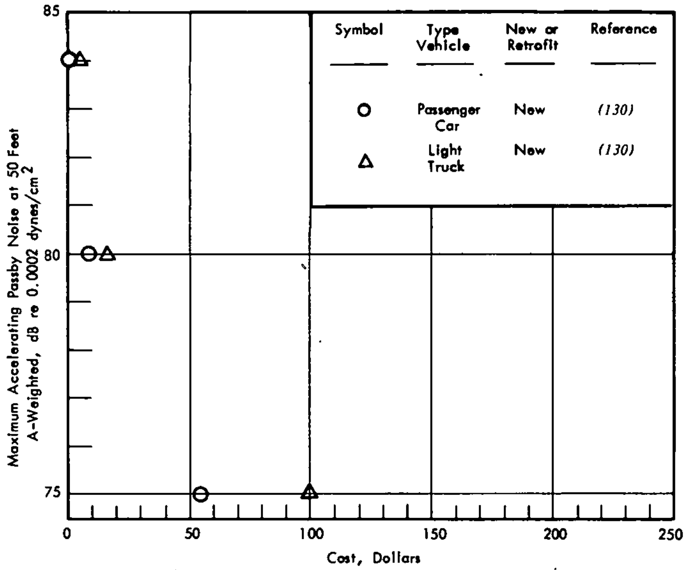


Figure 51. Average initial direct cost for passenger car and light truck noise reduction.

Automobiles

The 75-dBA level limits scheduled for California in 1978 and for Chicago in 1980 are achievable, with costs being moderate (Fig. 51). For the full-throttle test, costs increase significantly as vehicle levels approach 75 dBA; achievement of a level of 70 dBA is going to be very expensive (*88*). Again, the California 1988 limit appears to be attainable only with major configurational changes and perhaps will require significant engine performance degradation.

Motorcycles

Reduction of motorcycle noise levels (as measured in the SAE J331 test) to a level of 80 dBA (as scheduled by California for 1975) appears to require significant and undetermined modifications. An abated level of 81 dBA with improved mufflers is predicted. Figure 22 shows that even a small displacement engine (250 cc) would have trouble meeting the level.

Radically different designs, such as the Bavarian Motor Works (BMW) 450-cc machine are approximately 10 dB quieter than conventional high-performance models. Significant features of the BMW machine are (1) opposed cylinders, (2) drive shaft instead of a chain, (3) low horsepower-to-weight ratio. California's scheduled 1988 level of 70 dBA was conceived to be the ultimate desired vehicle noise limit without regard to technical feasibility.

HIGHWAY NOISE PROPAGATION AND TRAFFIC NOISE MODELS

The general interpretations of the findings from the various studies of Chapter Three are summarized from the viewpoint of applications to the development of a simple traffic noise model. Specific formulation of a model also is presented in this section.

Free-Field Noise Propagation

Consider first the case of relatively high traffic volumes, say greater than 2,500 vph, where the free-field propagation loss factor can be assumed a constant independent of percentage level, measurement height up to 15 ft, distance from the roadway up to 1,600 ft, and traffic conditions. The propagation loss factors for each of the three sites are presented in the form of 95 percent confidence intervals in Table 71.

From Table 71, the propagation loss factor for Site 1 is about $\epsilon = 10.9$, equivalent to a 3.3-dBA decrease per doubling of distance. This is only slightly greater than the free-field divergence loss of $\epsilon = 10$ (3 dBA) per doubling of distance for a theoretical line source. Inasmuch as very little ground attenuation would be anticipated from a freshly plowed field, this result is fully consistent with expectations.

For Site 2, the propagation loss factor is about $\epsilon = 15.8$, equivalent to a 4.8-dBA decrease per doubling of distance. Noting that a field of dense 3- to 4-ft-high asparagus represents as lush a ground cover as one would normally expect to find, it appears that $\epsilon \simeq 16$ might constitute a reasonable upper bound on the propagation loss factor in practice, at least for flat terrain where there is no blockage of the line-of-sight between the source and the observer.

For Site 3, the propagation loss factor is similar to that determined for Site 2. This is somewhat surprising because the parkland ground cover was not as dense or lush as the asparagus field. These results suggest that existence of a ground cover in the form of vegetation of any type will increase the propagation loss by above 50 percent over the divergence loss. This also suggests that the loss factor of $\epsilon = 15$ assumed in *NCHRP Report 117* (2) is a realistic figure for those cases where a thick ground cover exists.

Now consider the case of relatively low traffic volumes, say less than 2,500 vph, where the propagation loss factor varies significantly with the percentage level used to describe the noise. Data for this case were provided only by Site 1. Ignoring minor variations with traffic conditions and distance from the roadway, 95 percent confidence intervals for the propagation loss factor at various percentage levels are given in Table 72.

The results of Table 72 clearly demonstrate how the propagation loss factor increases at the lower percentage levels for the case of relatively low traffic volumes. It is interesting and important to note, however, that the propagation loss factor computed from the equivalent levels (L_{eq}) is statistically equivalent to the loss factor obtained under the more stable high-traffic volume conditions in Table 71.

In summary, a propagation loss of about 4.5 dBA per doubling of distance can be assumed for most reasonably level sites with a fully developed ground cover. If the noise is assessed in terms of L_{eq} levels, the loss factor may be considered a constant for all traffic volumes. However, if the noise is assessed in terms of L_{10} levels, the apparent loss factor will increase as the traffic volume falls.

TABLE 71

SUMMARY OF PROPAGATION LOSS FACTORS FOR HIGH TRAFFIC VOLUMES

SITE NO.	SITE DESCRIPTION	PROPAGATION LOSS FACTOR,[a] ϵ
1	Freshly plowed farmland	10.9 ± 0.5
2	Planted farmland (asparagus field)	15.8 ± 0.7
3	Parkland (grass and shrubs)	15.4 ± 1.4

[a] For traffic volumes greater than 2,500 vph.

TABLE 72

SUMMARY OF PROPAGATION LOSS FACTORS FOR LOW TRAFFIC VOLUMES, SITE 1

PROPAGATION LOSS FACTOR,[a] ϵ, FOR PERCENTAGE LEVELS OF				
L_{01}	L_{10}	L_{50}	L_{90}[b]	L_{eq}
13.9 ± 2.2	10.5 ± 1.8	10.2 ± 1.8	8.7 ± 1.9	10.4 ± 1.3

[a] Computed from data of Table 34.
[b] May be artificially low due to influence of ambient background noise on the measurements.

Highway Noise Reduction Measures

When noise reductions are computed from measured L_{50} levels, the results are in reasonable agreement, on the average, with the predictions obtained using the incoherent line source model outlined in Figure 38, where the traffic noise is assumed to be concentrated at 550 Hz ($\lambda = 2$). Furthermore, the agreement is equally good for all three shielding configurations considered; i.e., a roadside barrier, an elevated roadway, and a depressed roadway. When noise reductions are computed from measured L_{10} levels, the results still appear to be in good agreement with the incoherent line source predictions as long as the traffic volume is high. For the one site where traffic volumes were low during the measurements (less than 625 vph), the line source model appears to underpredict the noise reductions.

In summary, the noise reduction predictions, obtained using the procedure of Figure 38 with the noise source wavelength fixed at $\lambda = 2$ ft, are sufficiently accurate for most applications. The procedure appears to apply equally well to all types of noise reduction measures. It also appears to apply equally well to noise reductions assessed in terms of L_{10} and L_{50} levels.

Vehicle Noise Directivity

The findings of the vehicle noise directivity study tend to support the conclusion that most motor vehicles are at least quasi-omnidirectional noise sources in the vertical plane (normal to the direction of motion) at angles up to 45° above the horizontal. For the special case of trucks, there is limited evidence of a weak distortion in the directivity pattern of the radiated noise, which increases with the number of wheels at high speeds. Specifically, trucks with 10 or more wheels traveling at speeds of more than 60 mph appear to radiate more noise at angles of 30° to 45° than at angles of 0° to 15° above the horizontal. However, the difference is generally less than 1 dBA when measured at a distance of 45.7 ft from the longitudinal axis of the truck.

Truck Noise Levels

Based on the peak drive-by noise levels of individual trucks, as measured at a location 50 ft off the axis of motion, trucks may be broadly divided into two classes: (a) trucks with two axles and six wheels, called medium trucks, and (b) trucks with three or more axles, called heavy trucks. Trucks with two axles and four wheels, called light trucks, are considered to be automobiles in this study. The distributions of peak drive-by noise levels for medium and heavy trucks are approximately normal, with standard deviations of 4 and 5 dBA, respectively, and mean values given by

$$\text{Medium trucks: Mean dBA} = 20.8 + 34.3 \log S \tag{110}$$

$$\text{Heavy trucks: Mean dBA} = 12.0 + 21.0 \log N + 34.8 \log S \tag{111}$$

where S is the vehicle speed in mph and N is the number of axles.

The coefficient of the speed term in Eq. 111 is based on a regression analysis over a wide range of speeds up to about 75 mph. When the data for heavy trucks is limited to speeds of less than 50 mph, the appropriate regression equation is

$$\text{Heavy trucks } (S < 50)\text{: Mean dBA} = 64.3 + 17.9 \log N + 4.6 \log S \tag{112}$$

This result clearly demonstrates the rather weak dependence of heavy truck noise on speed in the range below 50 mph.

In terms of noise emission levels, the data indicate that the average noise emission level of trucks in six states from New York to California is about 82 dBA for medium trucks and 90 dBA for heavy trucks. The noise emission levels vary within a range of ±3 dBA among the various states, but much of this variation is due to differences in the average speed and number of axles for trucks operating in the various states.

Formulation of Traffic Noise Model

The following paragraphs outline a model for the prediction of traffic noise. This model is used in the design guide presented in *NCHRP Report 174*. The model is derived assuming traffic to be an infinite line of incoherent point sources, each being described by an emission level, EL. A complete derivation of the equations presented in the following is included in Appendix F.

The hourly equivalent level, L_h, of an infinite line source may be represented under ideal conditions by

$$L_h = L_{eq}\ (\text{hourly}) = 10 \log \frac{V}{S\,D} + \text{EL} + 2\ \text{dBA} \qquad (113)$$

where EL is the emission level of a single vehicle drive-by at a constant speed measured at 50 ft, in dBA; V is the vehicle volume by class (automobiles, medium trucks, or heavy trucks), in vehicles per hour; S is the average or group speed of the vehicle class, in mph; and D is the normal distance to the line source, in feet.

The emission level, EL, for each vehicle class of interest at a distance of 50 ft may be represented as follows:

Automobiles (vehicles with two axles and four wheels)

$$\text{EL}_1 = 22 + 30 \log S \text{ in dBA} \qquad (114)$$

Medium trucks (vehicles with two axles and six wheels)

$$\text{EL}_2 = 32 + 30 \log S \text{ in dBA} \qquad (115)$$

Heavy trucks (vehicles with three axles or more)

$$\text{EL}_3 = 90 \qquad (116)$$

These values are based on average experimental measurements of single-vehicle drive-bys. Since the line source model does not consider special propagation effects such as vehicle-to-vehicle shielding, the theoretically derived expression must be adjusted to be comparable with actual free-field highway noise measurements. Data presented in *NCHRP Report 144* (*3*) and acquired during the present program indicate that a single empirically derived constant can be introduced in the emission level equations to account for these differences. This permits the definition of a source level, SL, which is the effective noise level emitted by the source under actual traffic conditions, as follows:

$$\text{SL} = \text{EL} - 4\ \text{dBA} \qquad (117)$$

Hence, rather than using the theoretical model of Eq. 113, a more practical model for the hourly equivalent level is given by

$$L_h = 10 \log \frac{V}{S\,D} + \text{SL} + 2\ \text{dBA} \qquad (118)$$

where the source level, SL, is obtained from the emission level, EL. This empirical equation, which predicts hourly equivalent levels that are 4 dB less than those predicted by Eq. 113, shows good agreement with measured data.

It is important to note that the present model can be altered to reflect changes in the emission levels of vehicle classes. Such a need might result from the progressive introduction of quieter vehicles on the highways due to more stringent vehicle noise control standards. Chapter Two discusses in detail the problem of vehicle noise control.

The distance dependence in Eq. 118 includes the standard 3 dB/doubling of distance characteristic of an "ideal" line source. This condition holds true under very special circumstances, as explained in Chapter Three. However, in most practical applications, the "infinite line" source displays a 4.5 dB/doubling of distance. To account for this propagation, Eq. 118 is modified as follows:

$$L_h = 10 \log \frac{V}{D\,S} + \text{SL} + 2 - 5 \log \frac{D}{50} \qquad (119)$$

To accommodate such practical considerations as curves, gradient changes, roadway width, etc., a number of corrections must be developed to the basic traffic noise model in Eqs. 118 and 119. The first of these is the element correction that accounts for a finite noise source. In the case of Eq. 118 this correction is simply 10 log (θ/π), because the ideal condition assumes that equal subtended angles contribute equal amounts of energy. Thus, the corrected equation becomes

$$L_h = 10 \log \frac{V}{D\,S} + \text{SL} + 2 + 10 \log \frac{\theta}{\pi} \qquad (120)$$

for $\theta > 5°$ and where θ is the finite element subtended angle measured in radians.

In the case of Eq. 119, which includes the propagation factor of 4.5 dB/doubling of distance, the problem is further complicated because elements far away from the observer do not contribute equally to elements close to the observer for an equal subtended angle. Hence, an additional distance correction is required, leading to

$$L_h = 10 \log \frac{V}{D\,S} + \text{SL} + 2 + \left[\, 1.2 - 5 \log \frac{r_N}{50} \right] + 10 \log \frac{\theta}{\pi} \qquad (121)$$

for $\theta > 5°$ and where r_N is the distance (in feet) from the observer to the closest element point.

Both Eq. 120 and Eq. 121 hold true except for very small element subtended angles. For subtended angles of less than 5°, both Eq. 120 and Eq. 121 must be further modified as follows:

$$L_h(3.0\text{dB/dd}) = 10 \log \frac{V}{S} + \text{SL} + 10 \log \left(\frac{1}{r_N} - \frac{1}{r_F}\right) - 3 \qquad (122)$$

$$L_h(4.5\text{dB/dd}) = 10\log\frac{V}{S} + \text{SL} + 10\log\left(\frac{1}{r_N} - \frac{1}{r_F}\right) - 3 + \left(1.2 - 5\log\frac{r_N}{50}\right) \quad (123)$$

for $\theta \leq 5°$

where r_F is the distance (in feet) between the observer and the farthest element point.

Finally, because the end product must be described in terms of L_{10} levels (for use with PPM 90-2 noise guidelines), a conversion from the hourly equivalent level, L_h, to the 10th percentage level, L_{10}, must be described. This can be done if the statistical distribution of the equivalent levels is known. Appendix F presents the detailed derivation and assumptions considered. It is sufficient here to say that the relation between L_h and L_{10} can be established in terms of the quantity $V\,D/S$ as given in Table 73.

The conversions given in Table 73 are accurate to ±2 dB for values of $V\,D/S > 200$, because the time distribution of the highway noise can generally be considered normal in that region. However, for values of $VD/S < 200$, a normality assumption for the time distribution is generally invalid; i.e., the distribution of traffic noise levels in such cases may deviate widely from the normal distribution. This might result in a variability in the $L_h - L_{10}$ correction of up to 15 dBA. The cases (Classes V and VI) given in Table 73 assume that the vehicles are uniformly spaced along the roadway. This assumption represents the "worst" case or "noisiest" condition. Note that for $V\,D/S < 10$, no adjustment is provided because the relationship between $L_{10} - L_h$ can not be defined in this region.

A number of further adjustments are necessary to account for roadway width, gradient, pavement characteristics, traffic parameters, etc. These adjustments are presented in the form of rules in *NCHRP Report 174* (131). The rule justifications are discussed fully in Appendix F.

TABLE 73

RELATION BETWEEN L_{10} AND L_h

CLASS	PARAMETER A ($=V\,D/S$)	$L_{10}-L_h$
I	16,000 and above	1
II	3,000 to 16,000	2
III	200 to 3,000	3
IV	50 to 200	1
V	25 to 50	−2
VI	10 to 25	−5
VII	less than 10	—

COMMUNITY MEASURES TO REDUCE THE IMPACT OF HIGHWAY NOISE

Land-Use Applications

The desirability of a land-use strategy as a technique for suppressing the impact of highway noise on a neighboring community is dependent on various factors, including (a) cost, (b) aesthetic impact, and (c) generality of the noise reduction. The first factors, cost, is in turn heavily dependent on whether the strategy is applied to an existing community or a future planned community, as discussed in Chapter Four.

Consider first the use of a buffer zone. In most cases, capital costs associated with this strategy would be relatively high, whether applied to an existing or future community. On the other hand, use of a buffer zone introduces no aesthetic problems. To the contrary, if properly landscaped with tall shrubs or trees, it might be considered an attractive addition to the community. From the viewpoint of general community noise reduction, the buffer zone is not the best of alternatives. The only individuals protected by the buffer zone are those who would have occupied the structures in that area if the zone were not present. As discussed in Chapter Four, the presence of a buffer zone will actually increase the noise levels at locations along the zone border due to the lack of structural shielding from buildings that otherwise would stand on that area. Of course a dense growth of trees in the buffer zone would suppress this problem somewhat. On balance, use of an unoccupied buffer zone does not appear to be an attractive way to achieve highway noise reduction in the community.

Now consider the idea of limiting construction along the right-of-way to only those structures associated with activities that are relatively insensitive to noise. This approach is particularly attractive for applications to newly developing communities because it involves no direct capital costs. Furthermore, the strategy presents no major aesthetic problems. However, the noise control benefits of the strategy are limited to only that strip of land along the right-of-way where the land-use restrictions are imposed. There is no additional reduction in the general community noise level. Nevertheless, the strategy is considered to be the most attractive approach of those considered, at least for applications to newly developing communities.

Finally, consider the approach of limiting land use along the right-of-way to closely spaced high-rise structures that are properly sound treated. This strategy can be relatively expensive and provides no protection to individuals outside the structures. On the other hand, the strategy poses no aesthetic problems, and might provide a few dBA of additional noise reduction to the remainder of the community due to the shielding effects of the structures. On balance, it constitutes a moderately attractive strategy for applications to newly developing communities where expensive land acquisition problems can be avoided.

Building Noise Reduction Applications

Summarizing, from Tables 49 and 50 and the associated appendices, conventional building materials can be incorporated into the exterior construction of buildings to achieve effective control of highway noise. Commonly used materials (such as gypsum board, building insulation, thick glass, heavyweight doors, sealant, weather-stripping, gaskets) can be incorporated by conventional practices at reasonably standard costs. Material costs should be basically the same for modifications and new construction. Labor costs are generally the dominant factor in the high cost of acoustical treatments, especially in modifications.

Labor and administrative costs to install the required acoustical treatments are higher for modifications than for new construction because it is naturally more difficult to install such treatments in existing structures. The cost differences between modifications and new construction mainly reflect the difference in labor and administrative costs. Labor to remove existing walls, ceilings, and window sash; to modify existing window and door frames; and to install new double construction cause modification costs to be high. Modifying the existing environment control system or installing a new system in an existing structure is also costly. Overhead costs for building permits, city plan check, clean-up, etc., are added costs to modifications. Such overhead costs would already be included in the base price of new construction. The added costs for including required acoustical treatments in the construction of planned structures represent that cost for installing the treatments during the initial construction. Hence, installation practices and the costs of materials and labor for incorporating the treatments are considered standard for new construction.

Treatments appropriate for high sound insulation generally provide high thermal insulation as well. It follows that construction designed for interior noise reduction will usually influence the building operating expenses associated with heating and airconditioning costs by well over 50 percent. On the other hand, the sound treatment will usually require installation of a forced-air ventilation system, even when it otherwise might not be required. Hence, although winter heating costs should always be reduced, the required ventilation during the summer months, which otherwise might be achieved by opening windows, may increase the building operating expenses during warm weather.

Beyond cost, the only major objection to the strategy of adding sound treatment to individual community structures is that it provides no protection to individuals outside the structures. On the other hand, the strategy does have several attractive features, relative to other community noise control strategies, that should be noted. Specifically:

1. It can provide substantial amounts of interior noise reduction (up to 15 dBA).
2. It can be applied in varying degrees to different community structures, depending on their individual noise-reduction requirements.
3. It protects individuals within the structures from all intruding noise, not just highway noise.
4. It requires no zoning action or expensive land acquisition, even in existing communities.
5. It poses no aesthetic problems.

Hence, although the capital costs are relatively high, use of additional sound treatment in community structures is believed to be a viable technique for reducing the impact of traffic noise on either an existing or planned future community.

Community Sound Barrier Applications

The capital costs associated with construction of community sound barriers are relatively high, as summarized in Table 51. Beyond cost, community sound barriers have at least two other undesirable features. First, they provide rapidly diminishing protection to individuals above ground level; for example, on the upper floors of a multistory structure. Second, they are often considered unattractive by the community, and sometimes block scenic views. However, the strategy of using barriers does have a number of desirable features, including the following:

1. It can provide substantial amounts of exterior noise reduction (up to 15 dBA).
2. It can provide varying degrees of protection to different community areas, depending on their individual noise-reduction requirements.
3. It provides protection to individuals outside as well as inside structures.
4. It requires no zoning action or expensive land acquisition, even in existing communities.

In summary, community barriers do provide an effective method for obtaining substantial amounts of noise reduction in limited external areas that cannot be achieved by other community noise-reduction measures. Furthermore, the strategy can be readily applied to existing communities.

ECONOMIC EVALUATION OF HIGHWAY NOISE-REDUCTION STRATEGIES

Cost-Effectiveness of Vehicle Noise Reduction

The normalized costs of the four specific vehicle noise-reduction strategies evaluated in this study are plotted in Figure 52 as a function of the heavy truck mix ratio. Note that the normalized costs are a direct function of the traffic volume, as well as the heavy truck mix ratio. For convenience, all comparisons are made assuming an average daily traffic volume of 40,000 veh/day (14.6 million veh/year). Because the normalized costs of all four vehicle noise-reduction strategies are directly proportional to the traffic volume, the specific volume assumed does not alter the relative cost-effectiveness of the strategies.

The first two strategies apply only to new vehicles. It follows that they would not become fully effective until one complete turnover of the vehicle population has occurred. The other two strategies are applicable to existing vehicles; hence, the full benefits of the techniques could be achieved in a relatively short period of time.

Strategies Applicable to New Vehicles

The strategies applicable to new vehicles involve use of factory-installed noise reduction equipment to quiet (a) all trucks and automobiles, and (b) heavy trucks only. In both cases, the quieting is to the maximum extent practical with current technology. It is clear from Figure 52 that the strategy of quieting only the trucks is the most cost-effective approach by a wide margin for all reasonable truck mix ratios. The primary reason for this result is two-fold. First, current technology permits a far greater reduction in heavy truck noise than in automobile and light truck noise. Second, because heavy trucks are much noisier than automobiles and light trucks, reducing the noise of a heavy truck has a far greater impact on the total traffic noise level than reducing the noise of an automobile or light truck.

Another factor of considerable importance, however, is the total noise-reduction potential provided by the strategies. Referring to Figure 52, for any given truck mix ratio it is seen that the quieting of all vehicles provides a greater noise-reduction potential than the quieting of heavy trucks only. The difference in the noise reduction available from the two strategies collapses with increasing truck mix. This obviously must occur because the two strategies become identical for the limiting case of a 100 percent truck mix; i.e., when the traffic is composed solely of heavy trucks. At the lower truck mix ratios, however, the difference in noise reduction potential is substantial. For example, at a truck mix of $M = 5\%$, the quieting of all vehicles provides 5.4 dBA of noise reduction (at a normalized cost of $4,800/year-mile/dBA), whereas the quieting of heavy trucks alone provides only 2.1 dBA (at a normalized cost of $1,000/year-mile/dBA).

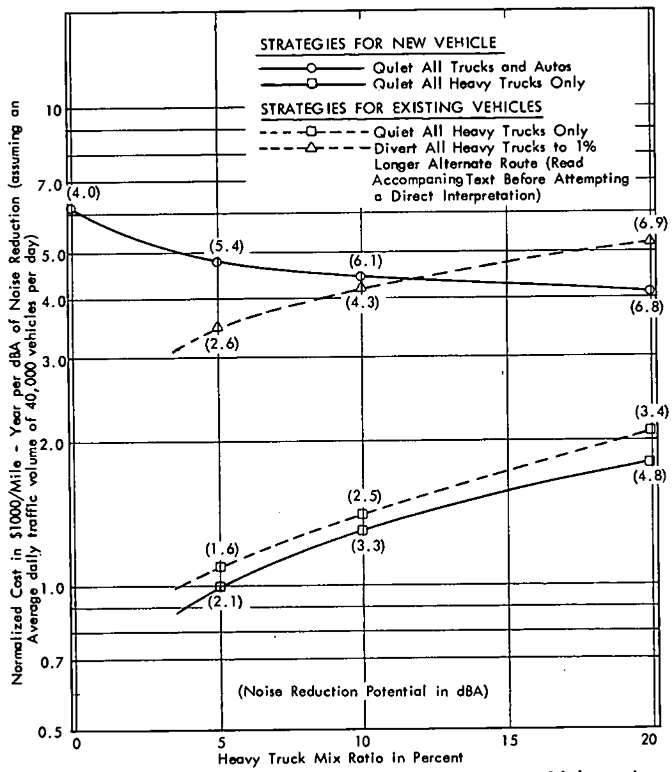


Figure 52. Normalized cost vs truck mix for vehicle noise-reduction strategies.

Strategies Applicable to Existing Vehicles

The two strategies applicable to existing vehicles include (a) retrofitting all existing heavy trucks with noise reduction equipment, and (b) diverting all heavy trucks to an alternate route more remote from the community. Caution must be exercised in making direct comparisons here for two reasons. First, the two strategies involve different scopes of application. Specifically, the diversion of heavy trucks to an alternate route is a strategy that can be effectively implemented at a local level on individual highways. However, this is not true of the truck quieting strategy. Because heavy trucks from anywhere in the country might travel any given highway, it follows that the quieting of heavy trucks must be implemented at a national level to be totally effective. Second, the method of computing costs is different for the two strategies, as detailed in an earlier chapter. In review, the truck quieting costs are billed uniformly against all miles traveled, whereas the truck diversion costs are billed against only those miles traveled on an alternate route. On this costing basis, it is clear from Figure 52 that the truck quieting strategy is the more cost-effective, even for the case where the truck diversion strategy increases the travel distance by only 1 percent. However, if one chooses to ignore the benefits of the noise reduction in sparsely populated areas provided by the truck quieting strategy, and to bill all truck quieting costs against only those miles where noise reduction is most demanded (where trucks might otherwise be diverted), a totally different conclusion is obtained. For example, if the average heavy truck spends more than 90 percent of its travel miles in sparsely populated areas where noise reduction is considered of no value, the cost of the truck quieting strategy might be interpreted as being more than ten times the amount shown in Figure 52. On this costing basis, the truck diversion strategy would be more cost-effective for increases of up to 5 percent in the alternate route travel distance.

Now consider the total noise reduction provided by the two strategies. Again from Figure 52, the diversion of heavy trucks provides greater noise-reduction potential than the quieting of trucks for all truck mix ratios. Of course, this must be true because the diversion of trucks constitutes a 100 percent quieting of trucks in the community area of interest. On the other hand, the amount of noise reduction provided by either strategy is not dramatic except at very high truck mix ratios.

Finally, two problems related to the truck diversion strategy should be mentioned. First, the strategy cannot apply to those trucks that must initiate and/or terminate their journey along the highway of interest. Second, the diversion of trucks to an alternate route does not eliminate noise, but only moves it to a less sensitive area. Normal development might ultimately require noise control measures for the alternate route as well.

Cost-Effectiveness of Highway Noise-Reduction Strategies

The normalized costs of the various highway noise-reduction constructions evaluated in this study are summarized in Figure 53. Note that the normalized costs are not a function of traffic volume, but are slightly dependent on the heavy truck mix. For clarity, because the dependence on truck mix is weak, normalized cost figures and the associated noise reductions are presented for the case of a 5 percent truck mix only. Further note that all of the constructions, excluding those involving roadside barriers and highway repavement, are applicable to future highways only. Roadside barriers can be used either for future or existing highways. Repavement is applicable only to existing highways in poor condition.

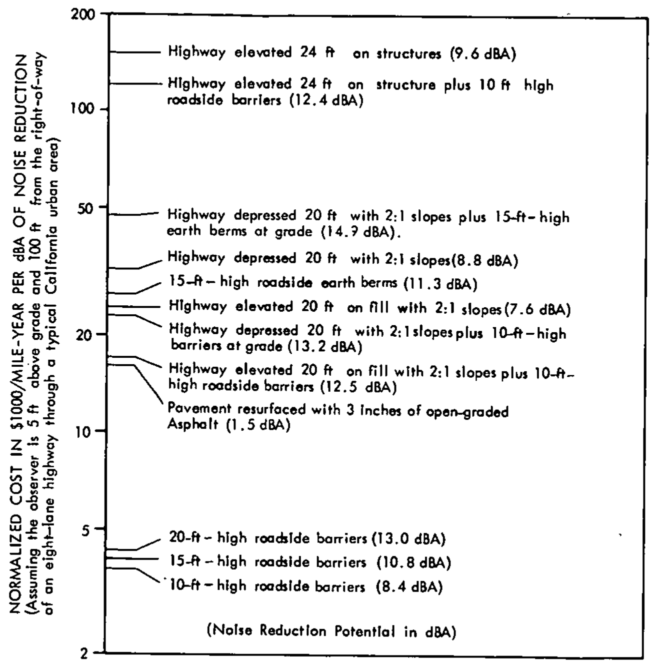


Figure 53. Normalized costs for highway noise-reduction strategies with a truck mix of 5 percent.

5. Barriers are often considered unattractive by the surrounding community.

The first two of these objections apply to all of the noise reduction measures summarized in Figure 53. The third and fourth objections also apply to depressed configurations and, to a lesser degree, elevated configurations with barriers. The last objection is unique to barrier configurations, but is not of major significance because proper landscaping can do much to suppress the aesthetic problem. In summary, none of the usually stated objections to roadside barriers would appear to justify the cost of an alternate highway noise-reduction measure, assuming noise control is the only criterion for the selection.

Following up on this last comment, the results in Figure 53 indeed suggest that construction of elevated and depressed highway configurations cannot be economically justified on the basis of noise reduction alone. However, it should be emphasized that other factors often warrant consideration of elevated or depressed configurations, independent of noise. For these cases, noise reduction becomes an added benefit that might influence the final design selection, but not control it. If so, it is important to note that the noise-reduction potential of elevated and depressed configurations can be greatly enhanced by the addition of barriers.

Strategies Applicable to New Highways

The results summarized in Figure 53 leave little doubt that the construction of roadside barriers is the most cost-effective method of achieving noise reduction in future highway designs. Roadside barriers 20 ft in height provide as much noise-reduction potential as any of the other constructions and at less than one-fifth the normalized cost. Note that the use of barriers with depressed and elevated configurations improves their cost-effectiveness significantly. Nevertheless, the same degree of noise reduction is available at a much lower cost from roadside barriers alone. These conclusions are fully consistent with the results of a previous study of the same subject (*122*).

As previously noted in Chapter Five, roadside barrier heights of less than 10 ft or greater than 20 ft are of questionable value. Within this range of heights, however, it appears that the choice of a barrier height can be based primarily on the desired degree of noise reduction; i.e., the normalized cost of noise reduction does not vary appreciably for heights between 10 and 20 ft.

Numerous objections are often raised to the use of roadside barriers as a noise-reduction measure, including the following:

1. Barriers lose much of their noise-reduction effectiveness when used in areas where the terrain is hilly.
2. Barriers provide little or no protection to individuals on the upper floors of multistory structures bordering on the highway right-of-way.
3. Barriers tend to aggravate the air pollution problem over the highway.
4. Barriers can increase the severity of run-off-road accidents if they are mounted too close to the shoulders.

Strategies Applicable to Existing Highways

The only highway noise-reduction measures applicable to existing highways are (a) the construction of roadside barriers and (b) repaving the highway with open-graded asphalt or some other "low noise" surface material. From Figure 53, it is seen that construction of roadside barriers is by far the more cost-effective of the two strategies and, further, provides the greater noise-reduction potential.

Repaving a highway to achieve traffic noise reduction does have some qualitative virtues worthy of mention. First, this strategy does not involve any of the numerous objectionable features associated with roadside barriers, as summarized in the previous section. Second, it is an action that often is warranted for other reasons; specifically, general highway upkeep. In such cases, where the cost is largely justified on other grounds, the resulting noise reduction is simply an added benefit obtained at a much lower cost than suggested in Figure 53. Third, the cost-benefits and noise reductions shown in Figure 53 were estimated assuming the vehicles using the repaved highway were not quieted. However, from Tables 25 and 27, the quieting of vehicles tends to accentuate the contribution of tire noise, which is the noise source reduced by repaving. Hence, it follows that repaving would yield much greater noise reduction (by a factor of perhaps 3 to 1) than indicated in Figure 53 if vehicle noise-control measures were also introduced.

Cost-Effectiveness of Community Noise-Reduction Strategies

The normalized costs of the four specific community noise-reduction measures evaluated in this study are summarized in Figure 54. The normalized costs are not dependent on either traffic volume or truck mix; further, the costs are presented for the noise-reduction measure applied to both new and existing structures.

Strategies Applicable to New Structures

From Figure 54(a), it is seen that the cost-effectiveness is similar for the four specific noise-reduction strategies considered, when applied to new constructions. Furthermore, there are no significant qualitative advantages to any one strategy over the others. However, there is at least one major qualitative objection to all of the strategies. Specifically, the strategies provide noise protection in areas bordering on the right-of-way only to those individuals inside structures. For the strategy involving the construction of high-rise buildings along the right-of-way, the shielding effects of the structures will provide some additional noise protection to individuals at locations more distant from the right-of-way, whether they are inside or outside structures. Nevertheless, none of the strategies benefit individuals outside structures bordering on the right-of-way.

Referring back to Chapter One, it should again be emphasized that the most cost-effective strategy for noise reduction at the community level is probably that which is based solely on proper land use; for example, zoning the community to restrict the use of land bordering on the right-of-way to those structures and activities that are least sensitive to outside noise intrusion (manufacturing facilities, warehouses, shopping centers, etc.). Although such a strategy does not lend itself to quantitative evaluation, it clearly provides an inexpensive way to reduce the noise exposure in the community areas most sensitive to noise, assuming such zoning policies can be and are pursued.

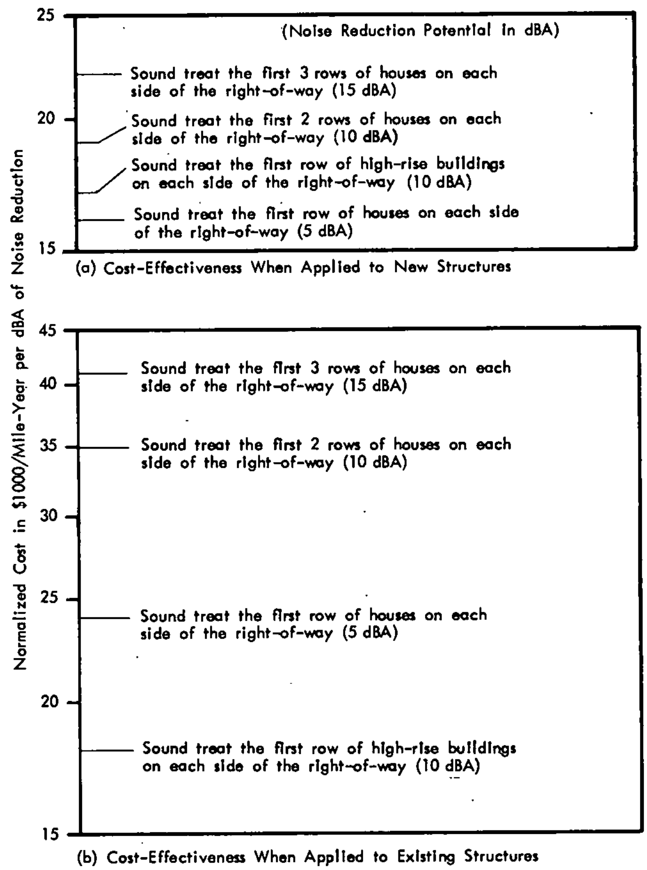


Figure 54. Normalized costs for community noise-reduction strategies.

Strategies Applicable to Existing Structures

Assuming the highway of interest passes through either an area of single-family dwellings or an area of high-rise structures, the normalized costs of the various strategies summarized in Figure 54(b) would apply. For this case the sound treatment of high-rise structures along the right-of-way becomes significantly more cost-effective than those strategies related to single-family dwellings. This is because it is relatively expensive to upgrade the sound insulation of an existing home. Beyond this, the conclusions here are the same as discussed for new structures in the preceding section.

Optimum Noise-Reduction Strategies Applicable to New Vehicles and Constructions

In the preceding sections, comparisons were made of the cost-effectiveness of various noise-control strategies within each of the three basic categories: (a) vehicle noise-reduction measures, (b) highway noise-reduction measures, and (c) community noise-reduction measures. Such comparisons could be made in a straightforward manner because both the scope of application and the method of computing costs are identical for the strategies within each category. However, the comparison of strategies among different categories is not so straightforward. The strategies related to highway and community noise-reduction measures pose no problem inasmuch as they involve a similar scope and pricing technique; i.e., the strategies in both categories apply to individual sections of highway and their total cost is charged against only those sections. The same is true of the vehicle noise-reduction measure involving diversion of all heavy trucks to an alternate route. The problem occurs when these strategies are compared to vehicle noise-reduction measures involving the quieting of vehicles.

As previously discussed, vehicles from any part of the country might sometimes use any given highway in the country. This is particularly true of heavy interstate trucks. Hence, the strategy of quieting vehicles (all vehicles or heavy trucks only) must be implemented at a national level to be fully effective. Furthermore, the vehicle noise reduction cannot be turned on for some sections of highway and turned off for others. The noise reduction is available for all miles traveled by the vehicle, or none of them. In this report, because vehicle quieting measures apply all the time, the normalized cost of the measures has been computed by billing their total cost uniformly against all miles traveled. As noted earlier, one might choose to ignore the noise-reduction benefits provided during those miles traveled through areas where noise reduction is most demanded; i.e., through those areas where roadside barriers and/or other such measures might be considered. This approach obviously would result in higher normalized costs than those shown in Figure 52, particularly for the case of interstate trucks where the vast majority of operational miles are generally through sparsely populated areas.

For the purposes of direct comparisons to the costs of highway and community noise-reduction measures, it appears reasonable to assume that the data in Figure 52 constitute lower bounds on the normalized costs of vehicle quieting measures. Cost comparisons in such a context are now made. It follows that if the normalized costs in Figure 52 for a given vehicle quieting measure exceed the normalized cost of a highway or community noise-reduction measure of interest, it can be concluded that the vehicle quieting strategy is more expensive. However, if the normalized cost in Figure 52 for the vehicle quieting measure is less than for a highway or community measure, other factors must be considered to determine which is the more cost-effective approach. For example, one might wish to recompute vehicle quieting costs based on the fractional portion of operational miles in high population density areas, or, better yet, based on some assessment of the value of noise reduction as a function of population density.

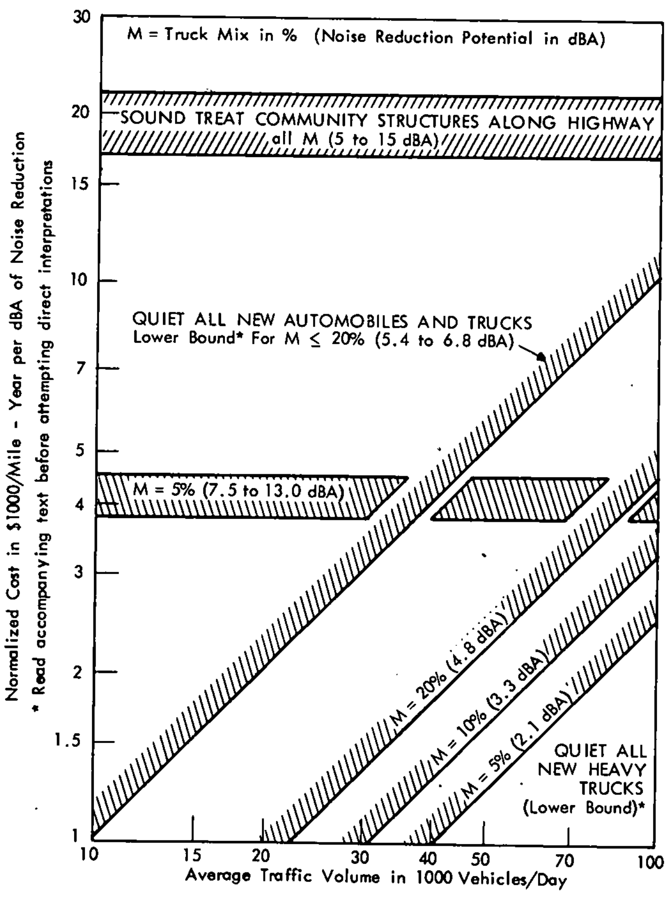


Figure 55. Normalized cost vs traffic volume for noise-reduction strategies applicable to new vehicles and constructions.

Direct Cost-Effectiveness Comparisons

Four noise-reduction strategies are of interest here. For the case of vehicle strategies, both the quieting of all new automobiles and trucks, and the quieting of new heavy trucks only warrant consideration. For the case of highway strategies, construction of roadside barriers is by far the most cost-effective approach. For the case of community strategies, sound treating community structures bordering on the right-of-way is the only noise-reduction technique that can be quantified for analysis.

The normalized costs of these four strategies are summarized in Figure 55. The normalized costs of the vehicle noise-reduction strategies are presented in terms of lower bounds only, for the reasons previously discussed. Also, these costs are a function of both traffic volume and truck mix. Data are presented for average traffic volumes of 10,000 to 100,000 veh/day. For the strategy of quieting all automobiles and trucks, the dependence on truck mix is sufficiently weak to permit a single bound to be used to define the costs for truck mix ratios of less than 20 percent. For the strategy of quieting heavy trucks only, separate bounds are presented for truck mix ratios of 5, 10, and 20 percent. The normalized costs of roadside barriers are not dependent on traffic volume, but are a weak function of truck mix. However, because the dependence is weak, the normalized costs for the truck mix ratios of interest (5 to 20 percent) are pooled into a single range of values. Similarly, because the normalized cost of barriers does not vary significantly with the barrier height (noise-reduction potential), the normalized costs for barrier heights of 10 to 20 ft are also pooled into a single range of values. The normalized costs of sound treating community structures along the highway, whether they be high-rise structures or single-family dwellings, are of the same order. Hence, these costs are also pooled into a single range of values.

Figure 55 may be broadly interpreted as follows. For traffic volumes of less than 100,000 veh/day, the quieting of all heavy trucks might be the most cost-effective method for achieving highway traffic noise reduction, depending on how the value of noise reduction in different areas is assessed. However, this approach will buy only about 2 to 5 dBA of noise reduction for truck mix ratios of 5 to 20 percent. For about twice the cost per dBA, about 5 to 7 dBA of noise reduction can be purchased by quieting all automobiles and light trucks, as well as heavy trucks, again assuming truck mix ratios of 5 to 20 percent. For traffic volumes of greater than 40,000 veh/day, roadside barriers are more cost-effective than the quieting of all automobiles and trucks, and further provide far greater noise-reduction potential (up to 13 dBA for a 20-ft barrier). For the specific example considered, the sound treatment of community structures is clearly the least cost-effective of all the strategies for all reasonable traffic volumes.

Two important points in Figure 55 are worthy of emphasis. First, the two vehicle noise-reduction strategies are not additive; i.e., one or the other must be used. However, the noise reduction provided by either vehicle strategy is directly additive to the noise reductions available from roadside barriers and/or the sound treatment of community structures. Hence, the three basic categories of strategies can be cascaded to obtain large amounts of total noise reduction, as demonstrated in later examples. Second, the cost-effectiveness of the heavy truck quieting strategy is so great that this approach would probably be the cheapest way to buy the first 2 to 5 dBA of noise reduction, even if one chose to charge the total cost of the strategy against only those miles traveled by heavy trucks on highways where noise reduction is most desired. For example, assume that only 25 percent of the mileage of the average heavy truck in an urban area is driven on highways where noise reduction is desired. Even if one ignores the benefits of the noise reduction provided during the other 75 percent of the truck's operational miles, and charges the entire cost of the noise reduction against the 25 percent of the miles on the highways of concern, it would still be cheaper to quiet all heavy trucks than to build roadside barriers if the average traffic volumes were less than about 30,000 veh/day.

Two final points of interest are the dependence of the data in Figure 55 on (a) the highway width and location and (b) the traffic flow conditions; i.e., free-flowing versus stop-and-go traffic. Concerning first the highway width and location, the width of the highway (number of lanes) will of course influence the expected traffic volume, but this is accounted for in Figure 55. The location of the highway will influence the cost of sound treating community structures, but not dramatically if attention is limited to densely populated urban areas. The data used in Figure 55 are for structures in the middle portion of the United States, and represent a reasonable average for the country. Assuming the construction of roadside barriers does not influence the selection of a right-of-way width, the cost of this strategy is also independent of the highway width and location. It follows that all of the normalized costs in Figure 55 are reasonably independent of the highway width and location. Hence, Figure 55 should be applicable to urban highways of any width constructed anywhere in the United States, within the limits of the various assumptions detailed earlier.

Concerning the traffic flow conditions, the noise reductions provided by highway and community measures are independent of the traffic flow conditions. The noise reductions available from quieted vehicles, however, are heavily dependent on the speed of the vehicles. The data in Figure 55 were calculated assuming free-flowing traffic at speeds of 55 to 65 mph. Referring to Tables 25 and 27, vehicle noise-reduction equipment provides greater noise abatement during acceleration at low speeds than during cruise at highway speeds. Hence, the data for vehicle quieting strategies in Figure 55 may be considered conservative for stop-and-go traffic conditions; that is, the noise reduction potential would be greater and the normalized cost would be lower than indicated.

Qualitative Considerations

The cost-effectiveness data in Figure 55 are based on numerous assumptions, as detailed in earlier sections. Because many of these assumptions may be violated in practice, it is wise to reconsider them as they relate to the desirability of the various strategies. These considerations, together with an assessment of other qualitative factors, are summarized in Table 74, which indicates that construction of roadside barriers involves the greatest total number of objectionable qualitative features, whereas the quieting of vehicles involves the fewest. In terms of major objectionable features, the sound treatment of community structures draws the poorest rating due to two serious deficiencies. First, if costs are to be kept within reason, this strategy can provide protection only for that portion of the community falling within a relatively narrow band around the right-of-way. Second, and perhaps more important, the strategy provides protection only to those individuals inside structures. The most serious objections to roadside barriers are

TABLE 74

SUMMARY OF ADVERSE QUALITATIVE FACTORS FOR NOISE-REDUCTION STRATEGIES APPLICABLE TO NEW VEHICLES AND STRUCTURES

UNDESIRABLE QUALITATIVE FACTOR	ADVERSE INFLUENCE OF FACTOR BY STRATEGY: QUIET ALL AUTOMOBILES AND TRUCKS	QUIET HEAVY TRUCKS ONLY	BUILD ROADSIDE BARRIERS	SOUND TREAT COMMUNITY STRUCTURES
Noise-reduction potential limited to area bordering on highway	None	None	Minor	Major
Noise-reduction potential limited to observers at ground level	None	None	Major	None
Noise-reduction potential limited to interior of community structures	None	None	None	Major
Noise-reduction potential adversely affected by hilly or rolling terrain	None	None	Mod.	None
Noise-reduction potential adversely affected by lack of maintenance	Minor	Minor	Minor	Minor
Noise-reduction strategy introduces safety hazards	None	None	Minor	None
Noise-reduction strategy aggravates air pollution problem over highway	None	None	Minor	None
Noise-reduction strategy is undesirable from the aesthetic viewpoint	None	None	Minor	None
Lengthy time required for noise-reduction strategy to become fully effective	Moderate	Minor	None	Minor
Noise-reduction strategy effective only at a national level	Major	Major	None	None
Noise-reduction strategy increases noise in vehicle passenger cab	None	None	Mod.	None

those related to the necessity of fully blocking the line of sight between the highway traffic and the observer. This clearly is not possible for individuals on the upper floors of high-rise buildings bordering on the right-of-way, and may be difficult even for individuals at ground level in those cases where the highway passes through hilly or rolling terrain. For the case of vehicle noise-reduction strategies, the most serious objection evolves from the fact that the strategies must be imposed on a national level to be effective; i.e., they cannot be implemented with full efficiency for individual highways because automobiles and trucks from any part of the country might travel the highway of concern.

There is another subjective consideration related to the selection of highway traffic noise-reduction strategies that is not listed in Table 74, but should nevertheless be mentioned. This consideration involves the immediate source of the funds to implement the strategy. The cost of vehicle noise-reduction measures generally would be paid by the vehicle owners through higher vehicle purchase and maintenance costs. The cost of roadside barriers would be paid by the cognizant highway department, probably through gasoline tax revenues. The cost of sound treating community structures might be paid either by the highway department, or directly by the purchaser of the structures. In any case, the individuals who use the highway and/or live near it will ultimately pay most if not all of the costs for any of the strategies. However, the desirability of different methods of payment may be interpreted in different ways. For example, assume a decision must be made between building roadside barriers or quieting trucks, where the ultimate costs, after weighting for qualitative factors, are equal. Due to the difference in the manner of payment for these two competitive measures, the owner of a trucking firm might be strongly inclined to favor the roadside barriers over the quieting of trucks, whereas the director of a state highway department might be equally inclined to take the opposite position. This subjective problem is recognized, but further consideration of its implications is not considered within the scope of this study.

In summary, from the viewpoint of the qualitative factors listed in Table 74, it appears that strategies related to the quieting of motor vehicles are the most desirable, and strategies related to the sound treating of community structures are the least desirable. The use of roadside barriers falls between these two extremes. This is a fortunate result, inasmuch as it corresponds in large degree with the ranking of the various strategies from a cost-effectiveness viewpoint, as summarized in Figure 55.

Illustrations

Application of Figure 55 to selection of optimum noise-reduction strategies for new vehicles and constructions is illustrated by considering specific cases. All illustrations are presented in the context of a general noise-reduction effect in a large metropolitan area with dense housing or commercial structures on both sides of all highways.

Case 1—Up to 5 dBA of Future Noise Reduction. From Figure 55 and Table 74, it appears that the most attractive way to buy the first 2 to 5 dBA of future highway noise reduction would be to have all new heavy trucks manufactured with equipment providing the maximum noise reduction permitted by current technology. Depending on how the value of noise reduction is assessed in various different areas, this strategy could be considered the most cost-effective of those evaluated in this study for traffic volumes of less than 100,000 veh/day. Specifically, for an extreme truck mix ratio of $M = 20$ percent and an average traffic volume of $V = 40{,}000$ veh/day, 4.8 dBA of noise reduction could be purchased for a minimum of (\$1,800/mile-year/dBA)(4.8 dBA) $\simeq$ \$9,000 per mile of traveled highway per year.

For the more common truck mix ratios of less than 20 percent, the minimum cost would be even lower. Of course, the noise-reduction potential would also be lower. However, it is for the higher truck mix ratios that noise reduction is most needed, because large truck mix ratios produce higher traffic noise levels.

Case 2—Up to 7 dBA of Future Noise Reduction. From an over-all viewpoint, the most attractive approach in this case appears to be a toss-up between the strategies of quieting all automobiles and trucks to the maximum extent consistent with current technology, and building 10-ft-high roadside barriers. Specifically, 10-ft-high barriers would provide about 7.5 dBA of noise reduction at a cost of (\$4,000/mile-year/dBA)(7.5 dBA) = \$30,000 per mile of highway per year. From Figure 55, this is about the same as the minimum cost associated with the quieting of all automobiles and trucks for an average traffic volume of approximately 40,000 veh/day. The total noise reduction provided by the vehicle quieting strategy is somewhat less; from 5.4 to 6.8 dBA, depending on the truck mix. However, from Table 74, qualitative factors favor the vehicle quieting approach.

Case 3—Up to 15 dBA of Future Noise Reduction. If more than 7 dBA or so of noise reduction is desired, roadside barriers provide the most cost-effective way to extend the reduction of traffic noise by another 7.5 to 13 dBA. For example, 20-ft-high barriers would provide an additional 13 dBA of noise reduction at a cost of (\$4,300/mile-year/dBA)(13 dBA) = \$56,000 per mile of barriers per year. Assuming all new heavy trucks have been quieted, the total resulting noise reduction would be about 15 dBA at a minimum cost of approximately \$58,000 per mile-year, assuming an average truck mix of 5 percent and a traffic volume of 40,00 veh/day.

Case 4—More Than 15 dBA of Future Noise Reduction. If a decision had been made to quiet all new automobiles and trucks, almost 20 dBA of noise reduction might be achieved by the addition of 20-ft roadside barriers. Assuming an average traffic volume of 40,000 veh/day, the minimum cost would be about \$80,000/mile-year. Any noise-reduction requirement beyond 20 dBA can be met only by adding community noise-reduction measures to the maximum potential of vehicle quieting and roadside barriers. The cost would be very high. For example, to reach 25 dBA of reduction, the first 20 dBA might be obtained as outlined above, and the last 5 dBA by sound treating the community structures along the highway. For the specific case being considered, this last 5 dBA would cost an additional \$80,000/year-mile at the minimum, bringing the total cost to more than \$160,000/year-mile assuming a traffic volume of 40,000 veh/day.

Optimum Noise-Reduction Strategies Applicable to Existing Vehicles and Constructions

Of concern now is the cost-effectiveness of those noise-reduction techniques applicable to existing vehicles and constructions. As in the preceding section, there is a problem in making direct comparisons between the vehicle noise-reduction measures and those strategies related to highway and community constructions.

In this case, however, only one vehicle measure poses a problem; specifically, the retrofitting of heavy trucks for noise reduction. The other vehicle measure of diverting all heavy trucks to an alternate route is applicable to individual highways and, hence, is directly comparable to the highway and community strategies.

Cost comparisons among the various strategies applicable to existing vehicles and constructions are now made in the same context as discussed in the preceding section. These comparisons are followed by a summary of qualitative considerations and illustrations.

Direct Cost-Effectiveness Comparisons

Again, four noise-reduction strategies are of interest. For the case of vehicle strategies, both the retrofitting of existing heavy trucks with noise-reduction equipment and the diversion of heavy trucks to an alternate route more remote from the community are of interest. For the case of highway strategies, construction of roadside barriers is the only economically feasible retrofit action for existing highways that provides substantial noise-reduction potential. For the case of community strategies, sound treating community structures bordering on the right-of-way is the only noise-reduction technique that can be quantified for analysis.

The normalized costs of these four strategies are compared in Figure 56. Again, the normalized costs of the heavy truck quieting strategy are presented in terms of lower bounds for average traffic volumes of 10,000 to 100,000 veh/day and truck mix ratios of 5, 10, and 20 percent, which cover the normal traffic conditions for most urban highways. For the heavy truck diversion strategy, the normalized costs are, of course, a function of the increased travel distance caused by the diversion. Hence, the costs are presented in terms of a lower bound based on a 1 percent increase in travel distance. As before, the normalized costs of roadside barriers for truck mix ratios of 5 to 20 percent and heights of 10 to 20 ft are pooled into a single range of values. The normalized costs of treating community structures are presented in terms of a lower bound, applicable to the case where the structures bordering on the right-of-way are high-rise commercial buildings. As in Figure 55, the data in Figure 56 are relatively independent of the highway width and location. Furthermore, the noise reductions provided by the two vehicle strategies are not additive, but either is directly

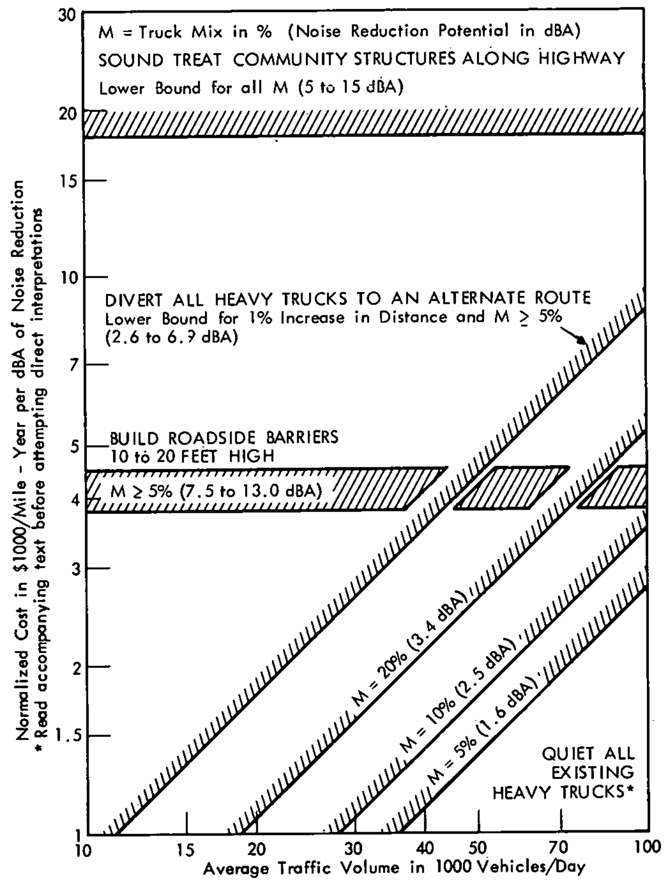


Figure 56. Normalized cost vs traffic volume for noise-reduction strategies applicable to existing vehicles and constructions.

additive to the noise reductions provided by the roadside barriers and/or the sound treating of community structures.

The interpretations of the results in Figure 56 are similar to the interpretations previously summarized for the results in Figure 55. Specifically, for all reasonable traffic volumes (less than 100,000 veh/day), the quieting of heavy trucks is probably the most cost-effective strategy, depending on how the value of noise reduction in different areas is assessed. However, the noise-reduction potential of this approach is limited to a maximum of about 3.5 dBA for truck mix ratios of 20 percent or less. Roadside barriers provide the next most cost-effective technique and sound treating community structures is the least cost-effective approach. Diversion of heavy trucks to an alternate route might, under proper circumstances, be more cost-effective than roadside barriers. For example, if an acceptable alternate route is available that increases the total travel distance by only 1 percent, and the average traffic volume is less than 40,000 veh/day with an extreme truck mix ratio of 20 percent, the diversion of trucks would be cheaper than building roadside barriers for the first 7 dBA of noise reduction. As for the results in Figure 55, it is important to note in Figure 56 that the cost-effectiveness of the truck quieting strategy becomes quite dramatic for the lower traffic volumes. Hence, even if one chose to compute costs by charging the retrofit expenses for heavy trucks against only those miles of highway where noise reduction is most desired, the truck quieting strategy might still be cheaper than roadside barriers in many cases.

Qualitative Considerations

Various qualitative considerations related to three of the four strategies of interest here have previously been summarized in Table 74. The strategy of diverting all heavy trucks to an alternate route, not included in Table 74, is not undesirable due to any of the factors listed in that table. However, this strategy does involve three major objections: (a) the strategy cannot apply to heavy trucks that initiate or terminate their travel along the highway; (b) an acceptable alternate route must be available for the highway of interest; and (c) the strategy does not eliminate traffic noise, but only moves it to supposedly less-sensitive areas. It is believed that these three factors make the strategy more objectionable, in qualitative terms, to the building of roadside barriers. The least objectionable of the strategies is still the quieting of heavy trucks, whereas the most objectionable remains the sound treatment of community structures. As before, the ranking of the strategies based on qualitative factors is similar to their ranking based on cost-effectiveness, as summarized in Figure 56.

Illustrations

Application of Figure 56 to the selection of optimum noise reduction strategies for existing vehicles and constructions is illustrated by considering specific cases. As before, all illustrations are presented in the context of a general noise-reduction effort in large metropolitan areas with dense housing or commercial structures on both sides of all highways.

Case 1—Up to 3 dBA of Noise Reduction. Considering both qualitative and quantitative factors, it appears that the most desirable way to buy the first few dBA of highway traffic noise reduction would be to retrofit all existing trucks with equipment to provide the maximum noise reduction practical with current technology. Depending on how the value of noise reduction is assessed in different areas, this strategy could be considered the most cost-effective of those considered for traffic volumes of less than 80,000 veh/day. For an extreme truck mix of 20 percent and an average traffic volume of 40,000 veh/day, 3.4 dBA of noise reduction could be purchased for a minimum of about $7,000 per mile of traveled highway per year. The cost per dBA goes down with truck mix ratio, but so does the noise reduction.

Case 2—Up to 7 dBA of Noise Reduction. If an acceptable alternate truck route were available that increased the total travel distance for heavy trucks by only a few percent, diversion of all heavy trucks to the alternate route might provide the most cost-effective strategy for this case, at least for relatively low traffic volumes and high truck mix ratios. Otherwise, 10-ft-high roadside barriers would satisfy the requirement at a cost of about $30,000/mile-year.

The cost of the heavy truck diversion strategy must be evaluated for each individual case using Figure 52 with the knowledge that the cost is directly proportional to both the traffic volume and the increased travel distance (the data in Figure 52 are for a volume of 40,000 veh/day and an increased travel distance of 1 percent). For example, assume an alternate route increases the travel distance by 4 percent over the normal highway route. Further assume extremely heavy truck traffic with a mix ratio of 20 percent is expected. From Figure 52, for a traffic volume of 20,000 veh/day, diversion of all heavy trucks to the alternate route would yield 6.9 dBA of noise reduction at a cost of ($5,200/year-mile/dBA) (6.9 dBA) (20,000 vpd/40,000 vpd) (4%/1%) = $72,000/year-mile. Hence, the cost of the strategy is more than double the cost of building roadside barriers. However, if the traffic volume were expected to be a relatively light 5,000 veh/day, the diversion of trucks would cost about $18,000/year-mile and, hence, be cheaper than building roadside barriers.

Case 3—Up to 15 dBA of Noise Reduction. Any noise-reduction requirement beyond about 7 dBA cannot be satisfied by vehicle noise-reduction strategies. The next most cost-effective strategy is to build roadside barriers that yield up to an additional 13 dBA or so of noise reduction. The considerations and costs associated with this approach are identical to those discussed for Case 3 in the previous section.

Case 4—More Than 15 dBA of Noise Reduction. Any noise-reduction requirement beyond 15 dBA can be met only by adding community noise-reduction measures to the maximum potential of heavy truck quieting and roadside barriers. The cost will be at least $18,000/mile-year for each additional dBA of noise reduction over 15.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

SOURCES AND CONTROL OF MOTOR VEHICLE NOISE

Conclusions

Certain primary conclusions can be stated regarding the results of the motor vehicle noise sources and control study, as follows:

1. The investigation of the individual noise-producing components of motor vehicles has led to a perspective view of their relative importance and to more complex and comprehensive models of motor vehicle noise.
2. Estimates of future abatement potential and of inherent increased costs obtained through vehicle component studies has allowed a better interpretation of the implications of proposed or scheduled noise limits, and the potential effectiveness of scheduled regulations or projected federal laws. The conclusion is that the EPA's 1983 75-dBA proposed noise limit is a far more viable and realistic projection than the scheduled 70-dBA California noise limit.

Suggested Future Work

Future studies for the highway engineer (in the realm of acoustical research and engineering) are suggested in the area of pavement surfaces, including investigation of:

1. The sound absorption properties of road surfaces.
2. The effect of macrotexture on tire noise.
3. The correlation between noise from tire-road surface interaction and pavement skid resistance.
4. The possibility of tire noise reduction through pavement grooving patterns.
5. The level of truck tire noise on open-graded asphaltic concrete and rough, pitted portland cement concrete.

Recommendations

This study has identified deficiencies in technical analyses and supportive data used to describe and control motor vehicle noise sources. The conduct of the research necessary to correct those deficiencies is, in general, beyond the range of interest of highway engineers. However, this should not preclude this report from making recommendations as to the nature of future studies, the results of which will be used to synthesize cost-effective highway noise control strategies. The existing deficiencies and recommendations for future study are presented in the following.

Engine casing noise modeling suffers from a lack of understanding of the contributions to the radiated noise from the combustion process and from mechanical sources. In addition, the noise-reduction potential of close-fitting covers, plus damping of sheet-metal panels, has not been evaluated in a comprehensive program.

An empirical study of existing truck and automobile engines based on presently available data and the underlying physical phenomena described herein would reduce the uncertainty in the application of the models presented.

Existing empirical models of fan noise suffice for accurate noise prediction for conventional, on-all-the-time, truck and automobile fans. However, with the advent of reduced noise cooling systems, the uncertainty of noise estimation will increase. Two areas of research should be devoted toward both reducing the uncertainty in understanding the noise production and reducing the noise itself, as follows:

1. The analysis of fan "on" time, based on ambient temperature, load, grade, and radiator frontal area, should be verified by an over-the-road measurements program.
2. The potential of fan quieting techniques, especially leading and trailing edge skewing, should be examined and demonstrated.

The understanding and data available relative to exhaust noise production and muffler effectiveness seem to be divided between design analysis relations and performance evaluation by model number. Design analysis is concerned with muffler internal properties such as the reactance and/or absorption of lined cavities, baffles, perforated plates and other internal components. At the other extreme of technical sophistication, specific mufflers are tested on various engines and the performance noted with no attempt to utilize the information parametrically. Between these endeavors is an area of empirical modeling that utilizes the principles of design analysis and the measured data from performance evaluation. Some effort was devoted toward this during the course of this study, but the procedure was not fully developed at the conclusion of the technical effort. Preliminary results showed that insertion loss of commercially available diesel engine mufflers could be estimated within a few dBA on the basis of expansion area ratio, length/acoustic wavelength, and back pressure/velocity pressure. This course of investigation should lead to muffler performance expressed in economically related parameters.

In the area of design analysis, a major source of error relates to a lack of understanding of the acoustic impedance of the exhaust pipe and manifold. Research in this area would benefit both modeling and noise reduction activities.

PROPAGATION AND CONTROL OF HIGHWAY NOISE

Specific Conclusions

The specific conclusions to be drawn from the studies in Chapter Three may be summarized as follows.

Traffic Noise Propagation

1. It is acceptable to assume that the free-field noise levels due to highway traffic are inversely proportional to the logarithm of equivalent distance from the roadway, at least for distances up to 1,600 ft.

2. The constant of proportionality in the relationship (the propagation loss factor) varies from about 10 (3-dBA decrease per doubling of distance) for the case of clear and level ground (such as a freshly plowed field) to about 16 (4.8-dBA decrease per doubling of distance) for a more lush ground cover (such as a field of 3-ft-high asparagus).

3. The propagation loss factor does not vary significantly with observer height above the ground, up to 15 ft.

4. For relatively high traffic volumes, say greater than 2,500 vph, the propagation loss factor does not vary significantly with the percentage level of the noise distribution.

5. For relatively low traffic volumes, say less than 2,500 vph, the propagation loss factor for small percentage levels (for example, L_{10}) is significantly higher than the loss factor for high percentage levels (for example, L_{90}).

6. When traffic noise is assessed in terms of the equivalent level, L_{eq}, the propagation loss factor for a given site appears to be constant for all traffic volumes.

Highway Noise-Reduction Measures

1. The noise reductions provided by barriers can be predicted with reasonable accuracy using conventional diffraction theory where the traffic noise source is assumed to be an infinitely long line of incoherent point sources with a wavelength of 2 ft. This assumes, of course, that the noise levels are measured in terms of A-weighted sound levels (dBA).

2. This same conclusion applies equally well to roadside barriers and the natural barriers inherent in elevated and depressed roadway configurations.

3. The previous two conclusions apply to noise levels assessed in terms of either the L_{10} or L_{50} levels.

Vehicle Noise Directivity

1. The noise radiated by various types of vehicles is almost omnidirectionally uniform for angles from 0° to 45° from the horizontal.

2. For the special case of trucks, there is limited evidence of a weak distortion in the directivity pattern of the radiated noise which increases with the number of wheels at high speed. However, the noise levels measured at 45.7 ft from the longitudinal axis of the truck vary by less than 1 dBA in most cases over the angular range from 0° to 45° from the horizontal.

3. It appears reasonable to assume for noise prediction purposes that the noise radiated from conventional vehicles, including trucks, is omnidirectional.

Truck Drive-by Noise

1. The peak drive-by noise levels of trucks correlate strongly with the number of axles, two-axle trucks being substantially quieter than trucks with three or more axles.

2. The peak noise levels also correlate with speed, although the dependence is weak at speeds below 50 mph.

3. The peak noise levels, given the same number of axles and speed, vary within a range of about ±2 dBA from one highway location to another.

4. The average noise emission level for trucks is about 82 dBA for medium trucks (two axles and four wheels), and about 90 dBA for heavy trucks (three or more axles).

General Conclusion and Recommendations

The results of the studies described in Chapter Three and other studies are sufficient to permit development of a traffic noise model that should be a significant improvement over the model used in *NCHRP Report 117*. There are, however, a number of remaining difficulties. The most important of these relate to the prediction of traffic noise levels for low traffic volumes and/or short observer distances in terms of L_{10} levels. Specifically, it is difficult to predict accurate L_{10} levels for values of $V\,D/S < 200$, where V is the traffic volume, in vph; D is the observer distance, in feet; and S is the traffic speed, in mph. The problem is that the L_{10} level under these conditions is heavily dependent on the exact distribution of the vehicles on the highway. Furthermore, the distribution cannot be accurately estimated. The Poisson assumption, which assumes a random distribution of vehicles along the highway, is commonly violated because of the tendency for vehicles to platoon, particularly on two-lane highways.

This problem would be largely eliminated if traffic noise levels were assessed in terms of the equivalent level, L_{eq}, as defined in Eq. 3, rather than in terms of a percentage point, such as L_{10}. The equivalent level is generally insensitive to the distribution of vehicles along the highway; hence, it provides a stable measure of the traffic noise even for very low values of $V\,D/S$. Other factors of importance to traffic noise prediction, such as propagation loss, also tend to be more stable when the noise is assessed in terms of L_{eq} levels.

The traffic noise prediction model developed in Chapter Three uses the L_{eq} level for all intermediate calculations. However, the final predictions must be converted to L_{10} levels due to the requirements of the FHWA noise guidelines. It is recommended that serious consideration be given to changing these guidelines to accept predictions in terms of L_{eq} levels. Of course, it is understood that this would involve derivation of entirely new noise criteria. However, it is not considered likely that major improvements can be made in the prediction of traffic noise levels for small $V\,D/S$ values in the absence of such a change.

COMMUNITY MEASURES TO REDUCE NOISE IMPACT

Land-Use Measures

The basic conclusions concerning land-use strategies as techniques for suppressing the impact of highway noise on a neighboring community may be summarized as follows:

1. The noise impact on the community areas along the highway right-of-way can be reduced by several land-use procedures including: (a) creation of a clear buffer zone; (b) restricting the land use to structures that are not normally occupied, such as storage facilities and warehouses;

(c) restricting the land use to structures that house activities with high self-generated noise levels, such as shopping centers and manufacturing facilities; and (d) restricting the land use to sound-treated high-rise structures that would provide some shielding for the remainder of the community.

2. No land-use strategy will provide significant amounts of noise reduction in the community beyond the limited area where the land-use restrictions are applied.

3. Application of land-use strategies to existing communities probably would not be economically practical in most cases due to the high costs associated with the acquisition of developed land.

4. Of the various land-use strategies considered, restricting the use of land bordering on the right-of-way to normally unoccupied structures appears to be the most attractive alternative, primarily because it can be implemented in future planned communities with no direct additional costs.

Building Noise-Reduction Measures

The basic conclusions concerning the reduction of interior noise in occupied structures by either modifications to existing structures or changes in the design of future structures may be summarized as follows:

1. In most cases, a 5-dB reduction in the interior noise levels of various types of structures can be achieved by sealing or efficiently weatherstripping window sash and door panels, adding insulation to attic spaces, and adding ceilings below an exposed roof deck, where applicable. The installation of such treatments is standard, and the costs are considered to be reasonably standard.

2. To realize a 10- or 15-dB reduction in the interior noise levels, the following general constructions are required: (a) heavyweight construction or resiliently mounted drywall walls and ceilings on the inside of lightweight exterior construction, (b) insulation within exterior walls and above ceilings, and (c) double windows and exterior doors and acoustically treated vent openings and exhaust and intake ducts. Such treatments in most cases are considered nontypical, and their incorporation is relatively costly.

3. To realize effective interior noise control, windows and exterior doors must be closed. Hence, all structures in noise-impacted areas should contain a mechanical system that provides year-around air treatment of indoor spaces.

4. The cost for materials and installation of a year-around air treatment system comprises a large percentage of the total modification or new construction costs of structures without existing or planned air conditioning systems. The cost for air conditioning may be as high as 50 percent or more of the total modification or construction costs.

5. In most cases, modification costs are higher than new construction costs. On the average, the modification costs for the same reduction in noise levels in the same type of structure are 1.5 to 2.0 times more than new construction costs. In the extreme case, the modifications to an auditorium are approximately 4.0 times as costly as the equivalent new construction.

6. In most cases, total modification costs are greater for structures in the South and Middle regions of the United States than in the North. The difference in cost reflects the difference in required modifications. Less modification is required in the North because most existing structures are composed of heavier-weight constructions due to climatic conditions.

7. In most cases, the unit cost for a given amount of noise reduction in a new construction is approximately equal in all zones, because required new constructions are similar in each zone.

8. Of course, the costs for modifications and new constructions increase as the incremental improvement in noise reduction increases. On the average, modification and construction costs for a 10-dB improvement to the same structure in the same zone are approximately 1.5 to 2.0 times the costs for a 5-dB improvement. On the other hand, the cost difference between a 10- and a 15-dB improvement is less than 1.5 times on the average. In fact, in certain cases, the cost difference may be relatively small between a 10- and a 15-dB improvement. Therefore, it may be desirable to incorporate the modifications or constructions required for 15-dB improvement when only a 10-dB improvement is required, because the benefits of greater noise reduction can be provided at a small increase in cost.

9. Costs for modifications to churches have not been determined because the required modifications appear impractical to incorporate. Removal of or modification to elaborate window, wall, and ceiling constructions, as well as interior decorations, would be very expensive, as well as detrimental to the spiritual and aesthetic effect of a religious space.

10. To analyze the cost-effectiveness of incorporating the required modifications or new constructions to buildings located in noise-impacted areas, apply the unit costs given in Tables 49 and 50 to appropriate dimensions and/or numbers of affected structures. The cost estimates given in these tables are approximate, but should be within 10 percent of the actual costs in most cases. For more accurate cost data, unit costs for specific cities or local areas should be analyzed separately.

Community Sound Barrier Measures

The basic conclusions concerning the use of sound barriers within the community as a technique for suppressing the impact of noise on areas outside of structures may be summarized as follows:

1. Properly designed barriers can provide up to 15 dBA of noise reduction in limited outside areas within the community.

2. To achieve maximum potential, the barriers must be up to 20 ft tall and wrap around the sides of the area to be protected.

3. Concrete block generally provides the most inexpensive type of barrier construction.

4. Barriers are aesthetically unattractive, but otherwise provide a straightforward method for reducing exterior noise in limited areas within an existing community.

ECONOMIC EVALUATION OF NOISE-REDUCTION STRATEGIES

Vehicle Noise-Reduction Strategies

The general conclusions concerning the desirability of various vehicle noise-reduction strategies may be summarized as follows.

Strategies Applicable to New Vehicles

When measured in terms of dollars per dBA of traffic noise-reduction potential, the quieting of heavy trucks only is a more cost-effective noise-reduction strategy than the quieting of all automobiles and trucks by a factor of more than two to one, assuming truck mix ratios of less than 20 percent. On the other hand, the quieting of all automobiles and trucks obviously provides a greater noise-reduction potential. For truck mix ratios of 5 to 20 percent, the quieting of all new automobiles and trucks to the maximum extent practicable with current technology would provide about 5 to 7 dBA of over-all traffic noise reduction, whereas the quieting of heavy trucks only would yield about 2 to 5 dBA.

Strategies Applicable to Existing Vehicles

Retrofitting of all existing automobiles with additional noise-reduction equipment is not considered practical. However, retrofitting of heavy trucks only is practical and could yield 1.5 to 3.5 dBA of over-all traffic noise reduction for truck mix ratios of 5 to 20 percent. The only other logical strategy for existing vehicles is to divert all heavy trucks to an alternate route more remote from the community. This approach can provide up to 7 dBA of over-all traffic noise reduction, but the cost would be very high if the alternate route increased the total travel distance by more than 1 percent or so.

Highway Noise-Reduction Strategies

The general conclusions concerning the desirability of various highway noise reduction constructions may be summarized as follows.

Strategies Applicable to New Highways

All other things equal, from the viewpoint of noise reduction construction of roadside barriers is more cost-effective than construction of various elevated and depression roadway configurations. Of course, natural terrain features or other considerations may justify construction of elevated or depressed roadways. In such cases, the addition of barriers can greatly enhance the noise-reduction potential of the construction. However, roadside barriers alone can generally provide the same amount of traffic noise reduction, up to about 13 dBA, at less than one-fifth the cost, assuming concrete block construction.

Strategies Applicable to Existing Highways

The only reasonable method for adding significant amounts of noise reduction to an existing highway construction is to build roadside barriers. For the case of highways with badly pitted or rough pavements, a small amount of noise reduction 1.5 dBA or so) might be achieved at reasonable cost by repaving the highway surface.

Community Noise-Reduction Strategies

The general conclusions concerning the desirability of various community noise-reduction actions and constructions may be summarized as follows.

Strategies Applicable to New Constructions

The most cost-effective techniques for reducing the impact of traffic noise on the community are those associated with proper land use; for example, restricting the use of land bordering on the right-of-way to structures housing those activities which are least sensitive to intruding noise (storage facilities, warehouses, shopping centers, manufacturing facilities, etc.). Up to 15 dBA of noise reduction inside structures can be achieved by proper sound insulating constructions, but only at a relatively high cost.

Strategies Applicable to Existing Constructions

Because land-use strategies are difficult to implement in an already developed community, the only logical options available involve modification of existing structures for additional interior noise reduction. Up to 15 dBA of additional interior noise reduction can be achieved by appropriate modifications, but the costs would be relatively high in terms of dollars per dBA.

Comparisons Among Strategies

Due to fundamental differences in cost evaluation procedures, it is difficult to make firm quantitative comparisons of the cost-effectiveness of vehicle noise-reduction strategies versus highway and community strategies. However, certain broad conclusions do appear appropriate, as follows.

Strategies Applicable to New Vehicles and Constructions

1. An attractive way to buy the first 2 to 5 dBA of future highway traffic noise reduction is to quiet all new heavy trucks.

2. One way to increase the noise reduction to the range of 5 to 7 dBA is to further quiet all new automobiles and light trucks as well. However, for highways with average traffic volumes exceeding 40,000 veh/day, this requirement probably could be met in a more cost-effective way by building 10-ft-high roadside barriers instead of quieting vehicles.

3. To obtain more than 7 dBA of noise reduction, roadside barriers provide the most cost-effective technique. When used in conjunction with quieted vehicles, a total traffic noise reduction of nearly 20 dBA is feasible.

4. If more than 20 dBA of noise reduction were desired, the sound treatment of community structures might be employed. However, for both qualitative and quantitative

reasons, this strategy is relatively unattractive and, in most cases, should be pursued only after the full potential of vehicle quieting techniques and roadside barriers has been exhausted.

Strategies Applicable to Existing Vehicles and Constructions

1. An attractive way to buy the first 1.5 to 3.5 dBA of highway traffic noise reduction is to retrofit all existing heavy trucks with appropriate noise control equipment.
2. In certain situations, up to 7 dBA of noise reduction might be obtained in a cost-effective way by diverting all heavy trucks to an alternate route more remote from the community.
3. The most desirable way to achieve the next 7 to 13 dBA of additional noise reduction is to build roadside barriers.
4. If more than 15 dBA or so of noise reduction were desired, the modification of existing community structures for additional interior noise reduction could be pursued. Again, however, this strategy is relatively unattractive in terms of both qualitative and quantitative factors.

REFERENCES

1. GALLOWAY, W. J., CLARK, W. E., and KERRICK, J. S., "Highway Noise—Measurement, Simulation, and Mixed Reactions." *NCHRP Report 78* (1969) 78 pp.
2. GORDON, C. G., GALLOWAY, W. J., KUGLER, B. A., and NELSON, D. L., "Highway Noise—A Design Guide for Highway Engineers." *NCHRP Report 117* (1971) 79 pp.
3. KUGLER, B. A., and PIERSOL, A. G., "Highway Noise —A Field Evaluation of Traffic Noise Reduction Measures." *NCHRP Report 144* (1973) 80 pp.
4. SERENDIPITY, INC., "A Study of the Magnitude of Transportation Noise Generation and Potential Abatement." *Rep. No. OST-ONA-71-1,* for U.S. Dept. of Transportation (Nov. 1970).
5. WYLE LABORATORIES, "Transportation Noise and Noise from Equipment Powered by Internal Combustion Engines." *Rep. NTID 300.13,* U.S. Envir. Protection Agency (Dec. 31, 1971).
6. WYLE LABORATORIES. Report covering work under Environmental Protection Agency Contract 68-01-1537.
7. DELANY, M. E., COPELAND, W. C., and PAYNE, R. C., "Propagation of Traffic Noise in Typical Urban Situations." *NPL Acoustics Rep. Ac 54,* Nat. Physical Laboratory, England (Oct. 1971).
8. WINFREY, R., *Economic Analysis for Highways.* Internat. Textbook Co., Scranton, Pa. (1969).
9. MILLS, C. H. G., and ASPINALL, D. T., "Some Aspects of Commercial Vehicle Noise." *Appl. Acoustics,* Vol. 1, No. 1 (Jan. 1968), pp. 47-66.
10. UNGAR, E. E., and ROSS, D., "Vibrations and Noise Due to Piston-Slap in Reciprocating Machinery." *J. Sound and Vibration,* Vol. 2, No. 2, pp. 132-146 (1965).
11. PRIEDE, T., "Noise Due to Combustion in Reciprocating Internal Combustion Engines." *Advances in Automobile Engines,* Part III, G. H. Tidbury, Pergamon (1964).
12. MAIDANIK, G., "Response of Ribbed Panels to Reverberant Acoustic Fields." *J. Acoust. Soc. Am.,* Vol. 34, p. 809 (1962).
13. SOROKA, W. W., and CHIEN, C. F., "Automotive Piston-Engine Noise and Its Reduction—A Literature Survey." SAE Paper 690452, Mid-Year Meeting, Chicago, Ill. (May 19-23, 1969).
14. White Motors Corporation, Advanced Products Division. Oral presentation at Portland, Oregon, Quiet Truck Symposium (Feb. 1973).
15. White Motor Corporation, Advanced Products Division. Quiet Truck Program. (Oct. 1972).
16. PRIEDE, T., "Noise and Vibration Problems in Commercial Vehicles." *J. Sound and Vibration,* Vol. 5, No. 1, pp. 129-154 (1967).
17. Department of Transportation, *Manual for Highway Noise Prediction.* Rep. No. DOT-TSC-FHWA-72-1, Transportation Research Center (1972).
18. HEMPEL, W., "Statistical Investigation into Diesel Engine Noise." *Trans. Inst. Marine Eng.* (UK), Vol. 82, No. 12, pp. 431-438 (Dec. 1970).
19. PRIEDE, T., "Origins of Automotive Vehicle Noise." *J. Sound and Vibration,* Vol. 15, No. 1, pp. 67-73 (Mar. 1971).
20. WATERS, P. E., and PRIEDE, T., "Origins of Diesel Truck Noise and Its Control." SAE Paper 720636.
21. CORDIER, O., and REYL, G., "The Noise Problem of Air Cooled Diesel Engines—Measures Towards Its Reduction with General Observations and Specific Results." SAE Paper 680045 (1968).
22. Freightliner Corp., Portland, Ore., Quiet Truck Program, Muffler Evaluation. (Nov. 15, 1972).
23. HUNT, R. E., KIRKLAND, F. C., and REYLE, S. P., "Truck Noise—VI A, Diesel Exhaust and Air Intake Noise." Rep. No. DOT-TSC-OST-73-12, prepared

for Dept. of Transportation, Transportation Systems Center, Cambridge, Mass. (July 1973).
24. Bolt Beranek and Newman, unpublished data.
25. Wu, T., "Control of Diesel Engine Exhaust Noise." SAE Paper 700701 (Oct. 14, 1970).
26. Beranek, L. L., *Noise and Vibration Control.* McGraw-Hill (1971).
27. Wonnacott, E. J., "Lower Exhaust Noise from Better Silencer Design Techniques." Presented at Symposium on Noise from Prime Movers, Inst. of Sound and Vibration Research, British Acoustical Soc. (July 9-10, 1973).
28. Ingard, U., and Ising, H., "Acoustic Nonlinearity of an Orifice." *J. Acoust. Soc. Amer.*, Vol. 42, No. 1, pp. 6-17 (July 1967).
29. Daly, B. B., "Noise Level in Fans." *J. Inst. Heating and Vent. Eng.*, pp. 29-51 (May 1958).
30. Sharland, I. J., "Sources of Noise in Axial-Flow Fans." *J. Sound and Vibration,* Vol. 1, No. 3, pp. 302-322 (1964).
31. Hayden, R. E., "Noise from Interaction of Flow with Rigid Surfaces: A Review of Current Status of Prediction Techniques." *NASA CR-2126* (Apr. 1973).
32. Freightliner Corp., "Preliminary Noise Diagnosis." Rep. No. 1, prepared for Dept. of Transportation, Office of Noise Abatement, Washington, D.C., under Contract DOT-OS-20095 (Nov. 1972).
33. *1967 Guide and Data Book.* Amer. Soc. Heating and Refrig. Eng.
34. Daly, B. B., "Noise Level in Fans." *J. Inst. Heating and Vent. Eng.*, pp. 38-39 (May 1958).
35. Donaldson Company, "Intake and Exhaust System Noise Attenuation." Technical proposal prepared for potential prime contractor of DOT contract—Diesel Truck Noise Reduction, RFP No. DOT-OS-20095.
36. Bender, E. K., and Leasure, W. A., "Tire-Road Interaction Noise." Presented at CCEA.
37. Hayden, R. E., "Roadside Noise from the Interaction of a Rolling Tire with the Road Surface." Purdue Univ. Noise Control Conf. (July 14-16, 1971).
38. Richards, M. G., "Automotive Tire Noise: A Comprehensive Experimental Study." *Eng. Pub. A-2973,* GM Proving Ground. Presented at National Noise and Vibration Control Conf., Chicago, Ill. (Sept. 11, 1973).
39. National Bureau of Standards, "Truck Tire Noise—I: Peak A-Weighted Sound Levels Due to Truck Tires." *Rep. OST-ONA-71-9* (Sept. 1970).
40. Hillquist, R. C., and Carpenter, P. C., "A Basic Study of Automobile Tire Noise." GM Proving Ground, Milford, Mich. Presented at 85th Meeting, Acoustical Soc. of America, Boston, Mass. (Apr. 13, 1973).
41. Tetlow, D., "Passenger Car and Truck Tire Noise." *Proc., Conf. on Motor Vehicle Noise,* GM Desert Proving Ground (Apr. 3-4, 1973).
42. Steere, L. B., "Noise Levels Associated with Plant-Mix Seals." *Rep. No. CDOH-P&R-R%SS-73-3,* prepared for Federal Highway Admin., Office of Development, by Colorado Div. of Highways, Planning and Research Div. (May 1973).
43. Society of Automotive Engineers, "Truck Tire Noise." *SP-373,* SAE (Oct. 1972).
44. Environmental Protection Agency, "Technology and Economics of Noise Control: National Programs and their Relations with State and Local Programs." Public Hearings on Noise Abatement and Control, Washington, D.C. (Nov. 9-12, 1971), Vol. VIII, Pg. 515.
45. Clendenen, D. A., "Truck Tire Noise." Presentation charts, Firestone Tire and Rubber Co.
46. Tetlow, D., "Truck Tire Noise." *Sound and Vibration* (Aug. 1971) pp. 17-23.
47. National Bureau of Standards, "Truck Noise—I: Peak A-Weighted Sound Levels Due to Truck Tires." *Rep. No. OST/TST-72-1* (July 1972).
48. Nayak, P. R., "Helical and Spur Gear Dynamics." BBN internal research.
49. Smith, P. W., and Lyon, R. H., "Sound and Structural Vibration." *NASA CR-160* (Mar. 1965).
50. Ungar, E. E., "Statistical Energy Analysis of Vibrating Systems," *Trans. ASME* (Nov. 1967) pp. 626-632.
51. Daly, M. J., "Freightliner Quiet Truck Project." Eaton Corp., Transmission Div., Report on Project 2107 (Nov. 20, 1972).
52. Zumbroich, J., "Untersuchungen des Gerausehverhaltene Moderner Hochlastgetriebe." Ph.D. thesis, Technische Hochschule, Aachen (1964).
53. Hillquist, R. K., and Scott, N. W., "Motor Vehicle Noise Spectra, Their Characteristics and Dependence Upon Operating Parameters." Paper N-1, presented at 84th Meeting, Acoustical Soc. of America, Miami Beach (28 Nov.-1 Dec. 1972).
54. Ingard, I., "Attenuation and Regeneration of Sound in Ducts and Jet Diffusers." *J. Acoustical Soc. Am.*, Vol. 31, No. 9, 1202-1212 (Sept. 1959).
55. Miller, L., "Power Plant Acoustics: Noise Control for Diesel, Gas, and Gas Turbine Engine Installations," Department of the Army, Office of the Chief of Engineers, Washington, D.C. (Sept. 1967).
56. Foss, R. M., "Tire Noise Properties of Two Resurfacing Materials Used on Highway Bridges for Repair of Wear." Applied Physics Laboratory, Univ. of Washington (Nov. 14, 1972).
57. Vargovick, R. J., "Noise Source Definition: Exterior Passenger Vehicle Noise." SAE *Paper 720274,* presented at Detroit, Mich. (Jan. 10-14, 1972).
58. General Motors Corp., "Truck Noise, Passenger Car Noise, and Tire Noise Demonstration, Appendix A." *Proc., Conf. on Motor Vehicle Noise,* GM Desert Proving Ground (Apr. 3-4, 1973).
59. Rathe, E. J., "Traffic Noise: The Influence of Road Surface and Traffic Volume." Thirteenth World Congress of the Road, Tokyo (1967).
60. Automobile Manufacturers Assn., "Noise Measurements of Motorcycles and Trucks." Vehicle Noise Study Subcommittee, AMA (June 1971).
61. Tanner, R. B., "Modeling of Motorcycle Noise." BBN memo. (Aug. 25, 1970).

62. Law, R., "Diesel Engine and Highway Truck Noise Reduction." SAE Paper No. 730240, Internat. Automotive Engineering Cong., Detroit, Mich. (January 8-12, 1973).
63. Close, W. H., and Clarke, R. M., "Truck Noise: II. Interior and Exterior A-Weighted Sound Levels of Typical Highway Trucks." *Rep. OST/TST-72-2*, Dept. of Transportation, Washington, D.C. (July 1972).
64. Johnston, L. E., "Technical Capabilities Relative to Truck Noise Reduction." *Proc. Conf. on Motor Vehicle Noise*, GM Desert Proving Ground (Apr. 3-4, 1973).
65. California Highway Patrol, "Noise Survey of Vehicles Operating on California Highways." (July 1971).
66. Western Highway Institute, "The June 15th CHP-CTA Sacramento Noise Test." Freightliner Research and Development Report 05-71, Western Highway Inst., San Francisco, Calif.
67. Cummins Engine Company, "Test Method 113." Pilot Installation Center, Cummins Engine Co., Columbus, Indiana (Mar. 1972).
68. Scott, W. N., "Vehicle Noise." Sound and Vibration Lab., Eng. and Research Office, Chrysler Corp. Presented at AAAS Ann. Meeting, Philadelphia (Dec. 29, 1971).
69. International Harvester Co., "Contract Review, Diesel Truck Noise Reduction." Truck Division, Engineering, for Dept. of Transportation, DOT-OS-20222. Presented at Portland, Ore. (Feb. 21-22, 1973).
70. Jenkins, S. H., and Kuehner, H. K., "Lowering Diesel Noise Through Hardware Modifications." *Automotive Eng.*, Vol. 81, No. 6, pp. 41-47 (June 1973).
71. Ringham, R. F., "The Truck Noise Problem, and What Might Be Done About It." SAE Paper 720624.
72. Olson, N., "Survey of Motor Vehicle Noise." *J. Acoust. Soc. Am.*, Vol. 52, No. 5, pp. 1291-1306 (1973).
73. Foss, R. N., "Vehicle Noise Study—Final Report." Univ. of Washington, Applied Physics Lab.; prepared for Washington State Department of Highways (1972).
74. Bolt Beranek and Newman, "Passenger Car Passby-Noise Levels." (HRB Project), BBN Rep. 2553 (June 14, 1973).
75. Bolt Beranek and Newman, "Noise Test Scores Clean Air Car Race." BBN Rep. 2065. Prepared for Office of Noise Abatement, Dept. of Transportation, Washington, D.C.
76. California Highway Patrol, "Passenger Car Noise Survey. (Jan. 1970).
77. Averill, D. W., and Patterson, W. N., "The Design of a Cost Effective Quiet Diesel Truck." SAE Paper 730714, West Coast Meeting, Portland, Ore. (1973).
78. Thein, G. E., "The Use of Specially Designed Covers and Shields to Reduce Diesel Engine Noise." SAE Paper 730244, Internat. Automotive Eng. Congress, Detroit, Mich. (Jan. 8-12, 1973).
79. Ronnhult, J., "Reducing Noise from Heavy Diesel Trucks by Engine Compartment Shielding." SAE Paper 730682, presented at Combined Commercial Vehicle Engineering Operations and Powerplant Meetings, Chicago, Ill. (June 18-22, 1973).
80. Jenkins, S. H., and Kuehner, H. K., "Diesel Engine Noise Reduction Hardware for Vehicle Noise Control." SAE Paper 730681, presented at Combined Commercial Vehicle Engineering Operations and Powerplant Meetings, Chicago, Ill. (June 18-22, 1973).
81. Staadt, R. L., "Less Noise from Diesel Trucks." SAE Paper 730712, West Coast Meeting, Portland, Ore. (1973).
82. Grover, E. C., and Lalor, N., "A Review of Low Noise Diesel Engine Design at ISVR." *J. Sound and Vibration*, Vol. 28, No. 3, pp. 403-431 (June 1973).
83. Environmental Protection Agency, "Interstate Motor Carrier Noise Control Regulation." Briefing document, draft 5 (May 15, 1972).
84. Page, W. H., and Beck, H. D., "Summary of Fan Noise and Performance Data." *Memo. Rep. E-120*, International Harvester Co. (Sept. 3, 1971).
85. Kaye, M. C., "ATB Tests with Quieted Truck." Freightliner Corp. internal report (Apr. 24, 1973).
86. Buffalo Forge Company, *Fan Engineering.* Sixth Ed., Buffalo, N.Y., p. 220.
87. Environmental Protection Agency, "Noise Emission Standards, Motor Carriers Engaged in Interstate Commerce." *Fed. Register*, Vol. 39, No. 209, pp. 38208-38216 (Oct. 29, 1974).
88. Stewart, E. E., "Technical Capabilities Relating to Passenger Car and Light Truck Noise Reduction." *Proc. of Conf. on Motor Vehicle Noise*, GM Desert Proving Ground (Apr. 3-4, 1973).
89. Environmental Protection Agency, Office of Noise Abatement and Control, "Environmental Protection Agency (40 CFR-202) Subchapter G—Noise Abatement, Motor Vehicle Noise Emission Standards, Notice of Proposed Rule Marking." Draft 5 (May 13, 1973).
90. Fax, G., "The Cost of Quieting Heavy Cab-Over-Engine Diesel Tractors." *BBN Rep. 2563* (not publ.)
91. Donaldson Company, "Effect of Exhaust System on Engine Performance." *Acoustics Tech. Bull. No. 9* (Mar. 1968).
92. Delany, M. E., "Prediction of Traffic Noise Levels." *NPL Acoustics Rep. Ac 56*, Nat. Physical Laboratory, England (Apr. 1972).
93. Johnson, D. R., and Saunders, E. G., "The Evaluation of Noise from Freely Flowing Road Traffic." *J. Sound and Vibration*, Vol. 7, No. 2, pp. 287-309 (1968).
94. Brownlee, K. A., *Statistical Theory and Methodology in Science and Engineering* (2nd. ed.), Wiley (1965).
95. Kurze, U. J., "Statistics of Road Traffic Noise." *J. Sound and Vibration*, Vol. 18, No. 2, pp. 171-195 (1971).
96. Delany, M. E., "A Practical Scheme for Predicting

Noise Levels (L_{10}) Arising from Road Traffic." *NPL Acoustic Rep. Ac 57,* Nat. Physical Laboratory, England (July 1972).

97. BENDAT, J. S., and PIERSOL, A. G., *Random Data: Analysis and Measurement Procedures.* Wiley-Interscience (1971).
98. RATHÉ, E. J., "Über den Larm des Strassenverkehrs." *Acustica,* Vol. 17, pp. 268-277 (1966).
99. FAVRE, B., "Moyens d'Estimation des Niveaux de Bruit de Circulation: Revue des Methodes Existantes." Institut de Recherche des Transports, Bron, France (1973).
100. ANDERSON, G. S., MILLER, R. L., and SCHWARTZ, R. M., "1972 Noise Levels and Noise Model for Median Truck Traffic." *BBN Rep. 2519A* (1973).
101. BLITZ, J., "Prediction of L_{10} on Urban Main Roads." *Acoustica,* Vol. 29, pp. 210-218 (1973).
102. DELANY, M. E., RENNIE, A. J., and COLLINS, K. M., "Scale Model Investigations of Traffic Noise Propagation." *NPL Acoustic Rep. Ac 58,* Nat. Physical Laboratory, England (Sept. 1972).
103. "Le Guide du Bruit des Routes Urbaines et de ses Implications Techniques," Ministère A.T.E.L.T., D.R.C.R., S.E.T.R.A. (Dec. 1972)
104. INGEMANSSON, ——, and LJUNGGREN, ——, "Bullerproblem vid trafikleder, Byggforskningen." R 20 (1970).
105. JONASSON, H. G., "A Theory of Traffic Noise Propagation with Applications to L_{eq}." *J. Sound and Vibration,* Vol. 30, No. 3, pp. 289-304 (1973).
106. LAMURE, C., and AUZOU, S., "Les Niveaux de Bruit au Voisinage des Autoroutes Dégagées." Cahiers du Centre Scientifique et Technique du Bâtiment, No. 599, Paris (Dec. 1964).
107. REINHOLD, G., "Bau- und verkehrstechnische Massnahmen zum Schutz gegen Strassenverkehrslärm." *Strassenbau und Strassenverkehrstechnik,* Heft 119 (1971).
108. SCHOLES, W. E., and SARGENT, J. W., "Designing Against Noise from Road Traffic." *Appl. Acoustics,* Vol. 4, pp. 203-234 (1971).
109. SCHULTZ, T. J., and MCMAHON, N. M., "HUD Noise Assessment Guidelines." *BBN Rep. No. 2176* (1971).
110. VAN NOORT, R. B. J. C., and OOSTING, W. A., "Verkeerslawaai en Wegontwerp." Directie Wegen, 'S—Gravenhage, 11 (Feb. 1973).
111. WESLER, J. E., "Manual for Highway Noise Prediction." USDOT, TSC, FHWA, 72—1 (Mar. 1972).
112. ANDERSON, G. S., MILLER, L. N., SHADLEY, J. R., "Fundamentals and Abatement of Highway Traffic Noise." FHWA/DOT NTIS PB 222 703 (1973).
113. KURZE, U. J., LEVISON, W. H., and SERBEN, S., "User's Manual for the Computer Program for the Prediction of Road Traffic Noise." *BBN Rep. No. 2359* (Contract No. DOT-STC-315) (May 1972).
114. Centre National de la Recherche Scientifique, Laboratoire de Mécanique et d'Acoustique. Private communication, Marseille (1974).
115. PINFOLD, ——, "Traffic Noise in Miniature." *New Scientist* (Dec. 1967).
116. RAPIN, J. M., "Etude des Modes de Protection Phonique aux Abords des Voies Rapides Urbaines." Centre Scientifique et Technique du Bâtiment, Paris (July 1969).
117. BIESELLE, ——, "Omnium Technique de l'Habitat." Laboratoire d'Hydraulique, Charenton, France.
118. STEWART, E. E., "Economic Impact of Noise Control for Passenger Cars and Light Trucks." *Proc., Conference on Motor Vehicle Noise,* pp. 35-37, General Motors Corp., Mesa, Ariz. (June 1, 1973).
119. JOHNSTON, L. E., "Economic Impact of Noise Control for Trucks." *Proc., Conference on Motor Vehicle Noise,* pp. 23-26, General Motors Corp., Mesa, Ariz. (June 1, 1973).
120. "Background Document to Proposed Interstate Motor Carrier Regulations." *Fed. Reg.,* Vol. 38, No. 144, Part 1, U.S. Environmental Protection Agency, Document 550/9-73-005, Washington, D.C. (Nov. 1973).
121. "American Trucking Trends, 1973." American Trucking Assns. (1973).
122. STARLEY, S. E., "An Analysis of Alternative Solutions to the Urban Highway Noise Problem." Report prepared for Dept. of Transportation under Contract No. FH-11-7507 by Serendipity, Inc., Arlington, Va. (Sept. 1971).
123. MOSELLE, G., ROBERTS, J. P., and SAXTON, A. S., *National Construction Estimator,* 21st ed. Craftsman Book Co., Los Angeles, Calif. (1973).
124. "National Personal Transportation Study," Rep. No. 2, "Annual Miles of Automobile Travel." U.S. Dept. of Transportation, Federal Highway Admin. (Apr. 1972).
125. "Price Trends for Federal-Aid Highway Construction," Third Quarter 1973. U.S. Dept. of Transportation (1973).
126. Environmental Protection Agency, "Transportation Equipment Noise Emission Controls—Medium and Heavy Trucks." *Fed. Reg.,* Vol. 41, No. 72 (Apr. 13, 1976), pp. 15538-15558.
127. "Notice of Proposed Rule Making." *Fed. Reg.,* Vol. 38, Sec. 202.15, P. 20103 (July 27, 1973).
128. MILLER, D. C., "Estimated Retrofit Costs Required to Meet Proposed Motor Carrier Noise Emission Standards." BBN memo. to W. E. Roper, EPA Office of Noise Abatement and Control, Regulations and Standards Staff (May 23, 1973).
129. JOHNSTON, L. E., "The Economic Impact of Truck Noise Reduction." *Proc. Conf. on Motor Vehicle Noise,* GM Desert Proving Ground (Apr. 3-4, 1973).
130. STEWART, E. E., "The Economic Impact of Passenger Car and Light Truck Noise Reduction." *Proc. Conf. on Motor Vehicle Noise,* GM Desert Proving Ground (Apr. 3-4, 1973).
131. KUGLER, B. A., COMMINS, D. E., and GALLOWAY, W. J., "Highway Noise—A Design Guide for Prediction and Control." *NCHRP Report 174* (1976).

132. TABOREK, C., "Mechanisms of Vehicles." Machine Design Spec. Publs. (1957).
133. FISK, D. J., "Statistical Sampling in Community Noise Measurement." *Jour. Sound and Vibration*, Vol. 36, No. 2, pp. 221-236 (1974).
134. GUTTMAN, I., WILKES, S. S., and HUNTER, J. S., *Introductory Engineering Statistics* (2nd Ed.), pp. 213-214. Wiley (1971).
135. "Highway Capacity Manual, 1965." *HRB Spec. Rep. 87* (1965) 411 pp.
136. KURZE, V., and ANDERSON, G. S., "Sound Attenuation by Barriers." *Appl. Acoustics*, Vol. 4, No. 1, pp. 35-53 (1971).
137. BRINTON, J. H., "Effects of Highway Landscape Development on Nearby Property." Franklin Inst. Res. Lab. (1969).
138. WIENER, F. M., and KEAST, D. H., "Experimental Study of the Propagation of Sound over Ground." *Jour. Acoust. Soc. Amer.*, Vol. 31, pp. 724-733 (1959).
139. HARRIS, C. M. (ed.), *Handbook of Noise*. McGraw-Hill (1957).

APPENDIX A

STATISTICAL ACCURACY OF PERCENTAGE POINT ESTIMATES

Consider a random variable, x, that can be described by a probability density function $f(x)$. The 100α percentage point * of $f(x)$, commonly denoted by x_α, is defined as that value of x which will be exceeded with probability α; that is,

$$\text{Prob}\,[x \geqq x_\alpha] = \int_{x_\alpha}^{\infty} f(x)\,dx = \alpha \qquad \text{(A-1)}$$

Now assume the variable, x, is sampled to obtain n representative values. Let the n sample values be ranked in order of increasing magnitude; i.e., $x_1, x_2, x_3, \ldots, x_k, \ldots, x_n$. An estimate of the 100α percentage point of $f(x)$ is clearly given by the value of the x_k sample, where $k = (1-\alpha)n$. In acoustical engineering, where x is an A-weighted noise measurement in dBA, such an estimate for the 100α percentage point of the distribution of dBA values is usually denoted by $L_{100\alpha}$. For example, the median value of the dBA data given by the 50 percentage point ($\alpha = 0.5$) is called the L_{50} level.

The problem of interest here is the statistical accuracy of percentage point estimates. To address this problem, let the following assumptions apply (the validity of these assumptions in the context of the traffic noise problem is dissussed later):

1. The random variable, x, is stationary over the time interval during which the sample values are collected.
2. The sample values, x_i; $i = 1, 2, 3, \ldots, k, \ldots, n$, are uncorrelated.
3. The random variable, x, can be described by a probability distribution function $F(x) = \text{Prob}\,[x' \leqq x]$, or the corresponding density function $f(x) = dF(x)/dx$.

* Percentage point is an engineering term. Most nonengineering statistical references prefer to define x_α as that value of x which will not be exceeded with probability α. With this definition, x_α is usually referred to as the 100α "percentile" of $f(x)$.

Under these assumptions, the probability density function for the value, w, of the 100α percentage point can be defined by (*97*, pp. 10-14)

$$g(w) = \frac{n!}{(k-1)!(n-k)!} F_x^{k-1}(w)[1 - F_x(w)]^{n-k} f_x(w) \qquad \text{(A-2)}$$

where $k = n(1-\alpha)$ and $F_x(w)$ is the probability distribution of x evaluated at w; i.e.,

$$F_x(w) = \int_{-\infty}^{W} f(x)dx \qquad \text{(A-3)}$$

Eq. A-2 is rigorous, but complicated. If attention is restricted to those cases where $n(1-\alpha)$ and $n\alpha$ are both greater than, say 10, Eq. A-2 can be greatly simplified. Specifically, it can then be assumed that w is normally distributed, with a mean and standard deviation of (*133*)

$$\mu_w = \mu_x + \sigma_x z_\alpha \qquad \text{(A-4a)}$$

$$\sigma_w = [\alpha(1-\alpha)/n]^{\frac{1}{2}} \sigma_x / p(z_\alpha) \qquad \text{(A-4b)}$$

where z_α is the 100α percentage point of the standardized normal distribution and $p(z_\alpha)$ is the ordinate value of the standardized normal density function at z_α. For example, if the mean and standard deviation of a traffic noise record are measured to be $\mu = 70$ dBA and $\sigma = 5$ dBA, respectively, and the L_{10} level ($\alpha = 0.10$) is determined using $n = 1{,}200$ independent sample values, $\mu_w = 70 + 1.282(5) = 76.4$ dBA and $\sigma_w = 8.66 \times 10^{-3}(5)/0.176 = 0.246$ dBA.

For the studies in this report, the sample size for the various traffic noise surveys was usually $n = 1{,}200$, and the percentage points of interest are generally those associated with $\alpha = 0.01$, 0.10, 0.50, and 0.90 (the L_{01}, L_{10}, L_{50}, and L_{90} levels). From Eq. A-4, a 95 percent confidence interval for the true percentage level based on an estimated percentage level for these cases becomes

$$\begin{aligned}
&\text{(a) General:} && L_{100\alpha} \pm 1.96\sigma_w \\
&\text{(b) } L_{01} \text{ Level:} && L_{01} \pm 0.21\sigma \\
&\text{(c) } L_{10} \text{ Level:} && L_{10} \pm 0.097\sigma \\
&\text{(d) } L_{50} \text{ Level:} && L_{50} \pm 0.071\sigma \\
&\text{(e) } L_{90} \text{ Level:} && L_{90} \pm 0.097\sigma
\end{aligned} \tag{A-5}$$

where σ is the standard deviation of the dBA data.

Now consider the assumptions used to arrive at the results in Eq. A-5. The assumption of stationarity should be acceptable as long as all parameters that control the traffic noise remain constant. These include traffic volume, traffic mix, traffic speed, atmospheric conditions, and roadway surface conditions. These parameters should be reasonably invariant over the 10-min interval required to collect a sample. Note that some investigators have tended to confuse stationarity with traffic continuity. Intermittent traffic conditions do not necessarily mean that the traffic noise is nonstationary. If the traditional notion of stationarity in random process theory is accepted (*134*), the traffic noise will represent a stationary random process, no matter how small the traffic volume may be, as long as the volume is constant based on sufficiently long averages.

The second assumption, statistical independence (no correlation) between sample values, is more critical. There are two factors that cause correlation between the samples obtained from a continuous dBA noise record. The first is due to the fact that the dBA detector circuit smooths the data with an exponentially weighted (RC type) averaging circuit that theoretically uses all past data to arrive at an instantaneous dBA value. If, however, the time interval between dBA readings is at least $5K$, where K is the time constant of the dBA detector, the correlation from this source is negligible. For the surveys in this report, $K = 0.1$ sec and the readings were taken 0.5 sec apart, so the correlation due to the dBA detector smoothing can be ignored.

The second source of correlation between sample values is related to the correlation inherent within the noise source. Specifically, if only one vehicle passes the measurement site during a 10-min run, 50 or so dBA values above ambient might be reduced from the resulting record. However, all of these values relate to the same vehicle, hence are clearly correlated. As a rule of thumb, the number of vehicles passing the measurement site during a run should be at least as great as the number of sample values collected, if an independence assumption is to be justified. For a sampling interval of 0.5 sec, this means the traffic volume should be at least 7,200 vph to justify an assumption of no correlation between sample values. For smaller volumes, Eq. A-4 should be solved with n equal to the number of vehicles that passed during the run, no matter how many sample values were collected.

APPENDIX B

SUPPLEMENTAL DATA FOR TRAFFIC NOISE PROPAGATION SURVEYS

The basic data acquired during the free-field traffic noise propagation studies are presented in Tables B-1 through B-10. The values of the various percentage levels of the traffic noise measured at the three sites are detailed in Tables B-1 through B-9, as are the traffic conditions observed during the measurements. The environmental conditions observed during the measurements are given in Table B-10.

The method of determining equivalent distance for the free-field noise propagation studies is also given in this appendix.

DETERMINATION OF EQUIVALENT DISTANCE FOR FREE-FIELD NOISE PROPAGATION STUDIES

The highway noise measurements for the free field propagation studies were made at six points on a normal to the roadway at distances of 50, 100, 200, 400, 800, and 1,600 ft from the edge of the near lane, denoted as d in Figure B-1. To accurately analyze the propagation characteristics, it was necessary to take into account the fact that the noise source was spread over a large area. Following a concept similar to that used in *NCHRP Report 117* (*2*), an equivalent distance between the theoretical position of the noise source and the observer was defined as follows:

$$D = \sqrt{d\,(d+a)} + \frac{V_2}{V_1 + V_2}\left[\sqrt{(d+a+b)(d+2a+b)} - \sqrt{d\,(d+a)}\right] \tag{B-1}$$

where

d = distance from the observer to the roadside, in ft;
a = width of all traffic lanes in one direction, in ft;
b = width of the median between the traffic lanes in the two directions, in ft;
V_1 = traffic volume for all lanes in one direction (closest to the observer), in vph;
V_2 = traffic volume for all lanes in opposite direction (farthest from the observer), in vph.

In the limit where $V_2 = 0$, Eq. B-1 reduces to

$$D\ (V_2 = 0) = \sqrt{d\ (d + a)} \qquad \text{(B-2)}$$

and where $V_1 = 0$,

$$D\ (V_1 = 0) = \sqrt{(d + a + b)(d + 2a + b)} \qquad \text{(B-3)}$$

The geometry of the measurement sites for the free-field noise propagation studies may be summarized as follows:

SITE NO.	a (FT)	b (FT)	NO. OF LANES
1	47	11	8
2	47	11	8
3	48	22	8

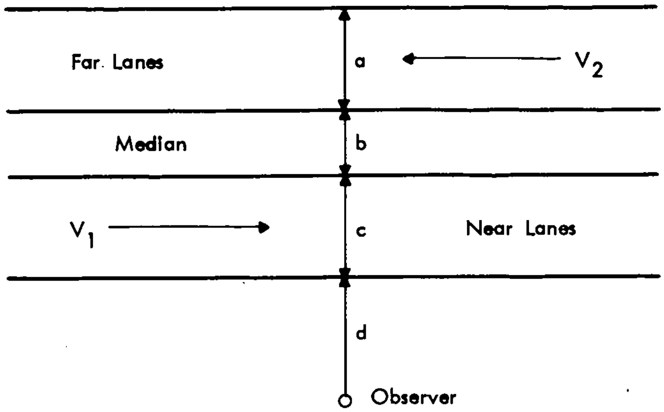


Figure B-1. Roadway parameters for free-field noise propagation studies.

TABLE B-1

FREE-FIELD TRAFFIC NOISE LEVELS 5 FEET ABOVE GROUND AT SITE 1

RUN NO.	DISTANCE (FT) FROM ROAD-SIDE	DISTANCE (FT) EQUIV-ALENT	TRAFFIC VOLUME (VPH)	TRUCK MIX (%)	TRAFFIC NOISE (dBA) FOR VARIOUS % POINTS L_{eq}	L_1	L_{10}	L_{50}	L_{00}
3	50	101.2	2820	5.0	71.5	79.6	74.1	69.8	66.3
4	50	85.5	1940	8.3	71.0	79.4	73.3	69.1	65.7
8	50	100.0	678	5.3	67.0	77.0	69.6	64.7	59.7
9	50	100.0	487	8.3	68.4	78.9	72.3	63.5	54.7
12	50	100.0	252	23.8	67.5	78.6	70.2	62.0	56.0
13	50	100.0	8030	4.3	75.2	81.0	77.4	74.4	72.3
16	50	89.5	5400	2.2	73.2	78.9	75.4	72.5	69.7
3	100	150.0	2820	5.0	68.2	74.6	70.7	67.1	64.4
4	100	135.0	1940	8.3	68.0	76.7	70.4	66.1	63.4
8	100	150.0	678	5.3	62.9	74.3	66.5	62.8	59.3
9	100	150.0	487	8.3	64.3	73.0	68.2	61.0	56.8
12	100	150.0	252	23.8	65.0	75.1	68.7	61.3	56.2
13	100	150.0	8030	4.3	72.0	76.4	74.0	71.6	69.7
16	100	140.0	5400	2.2	68.1	73.9	70.3	67.2	65.4
3	200	250.0	2820	5.0	65.3	71.6	69.0	65.5	63.0
4	200	235.0	1940	8.3	65.5	73.4	68.3	63.6	61.3
8	200	250.0	678	5.3	62.4	71.2	64.3	61.1	58.0
9	200	250.0	487	2.3	61.7	70.0	66.3	58.5	53.0
12	200	250.0	252	23.8	62.6	72.1	66.8	59.9	54.5
13	200	250.0	8030	4.3	69.3	74.0	70.8	68.7	67.2
16	200	240.0	5400	2.2	67.2	73.5	69.4	66.2	64.5
3	400	450.0	2820	5.0	64.4	69.1	66.8	63.8	61.0
4	400	435.0	1940	8.3	62.6	69.1	65.7	61.0	58.5
8	400	450.0	678	5.3	60.6	67.1	62.8	59.6	56.7
9	400	450.0	487	8.3	60.4	70.2	63.7	56.7	51.6
12	400	450.0	252	23.8	61.8	69.3	66.0	59.2	53.7
13	400	450.0	8030	4.3	65.9	68.9	67.6	65.5	64.0
16	400	440.0	5400	2.2	63.8	71.5	65.9	62.5	60.4
3	800	850.0	2820	5.0	63.5	67.8	65.9	62.8	60.6
4	800	835.0	1940	8.3	61.8	68.7	64.0	60.5	57.8
8	800	850.0	678	5.3	58.1	65.6	60.0	56.0	54.2
9	800	850.0	487	8.3	59.8	68.0	64.0	56.6	51.5
12	800	850.0	252	23.8	60.1	67.6	63.8	57.7	52.8
13	800	850.0	8030	4.3	63.0	66.0	64.7	62.7	61.5
16	800	840.0	5400	2.2	61.1	69.2	64.1	59.0	56.9
3	1600	1650.0	2320	5.0	59.9	64.0	61.3	59.3	56.4
4	1600	1635.0	1940	8.3	61.7	65.3	64.0	61.0	58.7
8	1600	1650.0	678	5.3	54.3	61.8	57.2	52.2	50.0
9	1600	1650.0	487	8.3	54.3	59.4	56.7	50.6	45.8
13	1600	1650.0	8030	4.3	59.1	65.5	60.6	58.5	57.2
16	1600	1640.0	5400	2.2	58.4	65.7	61.9	56.2	53.6

TABLE B–2

FREE-FIELD TRAFFIC NOISE LEVELS 10 FEET ABOVE GROUND AT SITE 1

RUN NO.	DISTANCE (FT) FROM ROAD-SIDE	DISTANCE (FT) EQUIV-ALENT	TRAFFIC VOLUME (VPH)	TRUCK MIX (%)	TRAFFIC NOISE (dBA) FOR VARIOUS % POINTS L_{eq}	L_1	L_{10}	L_{50}	L_{90}
2	100	145.3	3240	5.6	71.7	79.7	73.8	70.5	67.3
5	100	151.4	1152	4.0	68.5	77.5	70.8	67.0	62.8
7	100	146.6	842	7.1	67.9	78.7	69.9	65.0	60.0
10	100	146.0	360	20.0	67.7	77.4	72.0	64.1	57.7
14	100	148.2	7480	5.6	71.7	76.8	73.9	71.0	69.0
17	100	145.7	3510	5.5	72.2	78.0	74.6	71.4	69.0
20	100	146.6	2020	3.9	68.7	76.1	71.8	67.7	64.5
2	200	245.0	3240	5.6	69.8	77.2	71.9	68.7	66.1
5	200	251.0	1152	4.0	66.2	74.5	68.5	64.6	61.7
7	200	247.0	842	7.1	64.8	74.3	68.7	62.2	58.2
10	200	247.0	360	20.0	64.8	73.3	69.2	61.3	55.3
14	200	248.0	7480	5.6	71.0	75.1	73.0	70.1	68.4
17	200	245.0	3510	5.5	69.3	74.0	71.5	68.5	66.5
20	200	247.0	2020	3.9	65.3	71.6	68.0	64.2	61.1
2	400	445.0	3240	5.6	67.0	74.1	69.2	66.0	64.1
5	400	451.0	1152	4.0	63.8	70.8	66.0	62.6	60.0
7	400	447.0	842	7.1	61.8	69.7	65.3	59.2	56.8
10	400	447.0	360	20.0	61.9	69.8	66.2	58.6	50.0
14	400	448.0	7480	5.6	66.9	70.7	68.8	66.4	65.0
17	400	445.0	3510	5.5	66.8	72.2	68.8	66.0	64.3
20	400	447.0	2020	3.9	62.6	66.7	64.0	60.7	59.3
2	800	845.0	3240	5.6	64.2	71.9	66.4	63.2	60.6
5	800	851.0	1152	4.0	61.7	68.4	63.9	60.5	58.0
7	800	847.0	842	7.1	58.9	68.8	61.3	55.6	51.2
10	800	847.0	360	20.0	59.1	67.6	63.0	56.0	50.4
14	800	848.0	7480	5.6	63.1	67.0	64.0	62.7	61.1
17	800	845.0	3510	5.5	63.4	70.8	64.7	62.7	61.0
20	800	847.0	2020	3.9	58.0	62.0	60.7	56.9	54.1

TABLE B–3

FREE-FIELD TRAFFIC NOISE LEVELS 15 FEET ABOVE GROUND AT SITE 1

RUN NO.	DISTANCE (FT) FROM ROAD-SIDE	DISTANCE (FT) EQUIV-ALENT	TRAFFIC VOLUME (VPH)	TRUCK MIX (%)	TRAFFIC NOISE (dBA) FOR VARIOUS % POINTS L_{eq}	L_1	L_{10}	L_{50}	L_{90}
1	100	146.6	4120	6.8	72.7	79.2	74.9	71.8	69.3
6	100	146.6	1100	8.8	70.4	79.6	74.0	67.5	62.8
11	100	146.6	366	24.6	68.9	78.3	73.4	65.2	58.5
15	100	150.9	7150	3.9	71.6	76.7	73.8	71.0	69.1
18	100	149.5	2520	4.3	73.3	81.2	76.0	71.8	68.2
19	100	146.6	172	4.9	69.6	77.4	73.6	69.3	65.6
1	200	246.6	4120	6.8	70.1	75.7	72.3	69.1	67.0
6	200	246.6	1100	8.8	67.9	76.0	71.7	65.1	61.1
11	200	246.6	366	24.6	66.8	75.3	71.2	63.0	56.4
15	200	250.9	7150	3.9	70.8	75.1	72.9	70.3	68.5
18	200	249.5	2520	4.3	70.4	77.8	73.2	69.0	65.5
19	200	246.6	1728	4.9	67.3	73.2	70.2	66.1	62.5
1	400	446.6	4120	6.8	67.3	73.1	69.2	66.2	63.3
6	400	446.6	1100	8.8	65.5	72.8	70.0	63.3	58.2
11	400	446.0	366	24.6	63.8	71.0	68.0	60.6	55.0
15	400	450.9	7150	3.9	66.8	70.0	68.5	66.6	65.0
18	400	449.5	2520	4.3	68.1	75.0	70.6	66.2	63.0
19	400	446.6	1728	4.9	64.4	68.9	67.4	63.4	60.6
1	800	846.6	4120	6.8	66.3	70.9	69.5	65.6	61.4
6	800	846.6	1100	6.8	62.0	69.2	66.4	59.5	54.3
11	800	846.6	366	24.6	59.7	67.0	63.0	57.8	53.2
15	800	850.9	7150	3.9	62.6	66.2	64.2	62.2	60.4
18	800	849.5	2520	4.3	65.4	71.8	68.5	64.1	60.3
19	800	846.6	1728	4.9	60.3	64.8	63.1	59.0	56.4

TABLE B–4

FREE-FIELD TRAFFIC NOISE LEVELS 5 FEET ABOVE GROUND AT SITE 2

RUN NO.	DISTANCE (FT) FROM ROAD-SIDE	DISTANCE (FT) EQUIV-ALENT	TRAFFIC VOLUME (VPH)	TRUCK MIX (%)	TRAFFIC NOISE (dBA) FOR VARIOUS % POINTS L_{eq}	L_1	L_{10}	L_{50}	L_{90}
1	50	93.2	4310	8.1	76.4	84.1	79.8	74.1	70.1
4	50	94.8	4680	7.9	77.6	85.5	80.4	75.7	72.3
5	50	95.1	7700	3.6	77.9	85.7	79.8	76.3	73.9
9	50	103.1	4500	4.5	76.6	84.7	79.4	74.5	71.5
12	50	102.7	2630	6.8	75.3	83.4	78.3	73.3	69.3
1	100	143.2	4310	8.1	73.2	80.5	76.0	71.7	68.4
5	100	145.1	7700	3.6	72.5	77.2	74.5	72.0	70.0
9	100	153.1	4500	4.5	69.7	76.7	72.4	68.3	66.0
2	100	152.7	2630	6.8	69.8	77.8	72.7	67.9	65.0
1	200	243.2	4310	8.1	69.4	74.8	72.0	68.4	65.5
4	200	244.8	4680	7.9	70.4	77.1	73.2	69.1	65.8
5	200	245.1	7700	3.6	69.0	74.3	71.0	68.6	66.4
9	200	253.1	4500	4.5	70.6	76.0	73.2	69.7	67.1
2	200	252.7	2630	6.8	68.4	76.3	70.9	66.7	64.1
1	400	443.2	4310	8.1	63.0	68.0	65.4	62.2	59.9
4	400	444.8	4680	7.9	65.1	75.4	66.6	62.9	60.0
5	400	445.1	7700	3.6	64.4	75.0	65.1	62.6	61.2
9	400	453.1	4500	4.5	65.3	71.7	67.7	69.4	61.8
2	400	452.7	2630	6.8	66.0	75.0	68.5	63.9	61.3
1	800	843.2	4310	8.1	59.8	65.7	62.0	59.0	56.8
4	800	844.8	4680	7.9	60.2	67.1	62.1	59.3	56.6
5	800	853.1	4500	4.5	60.0	63.8	61.8	59.8	57.2
2	800	852.7	2630	6.8	64.0	75.2	64.4	60.7	58.5
1	1600	1643.2	4310	8.1	57.0	65.5	59.5	55.1	53.2
4	1600	1644.8	4680	7.9	59.6	69.1	63.0	56.2	53.4
5	1600	1645.1	7700	3.6	58.2	66.3	59.6	56.7	55.2
9	1600	1653.1	4500	4.5	57.7	60.0	59.2	57.5	56.1
2	1600	1652.7	2630	6.8	58.8	68.9	60.3	56.6	54.2

TABLE B–5

FREE-FIELD TRAFFIC NOISE LEVELS 10 FEET ABOVE GROUND AT SITE 2

RUN NO.	DISTANCE (FT) FROM ROAD-SIDE	DISTANCE (FT) EQUIV-ALENT	TRAFFIC VOLUME (VPH)	TRUCK MIX (%)	TRAFFIC NOISE (dBA) FOR VARIOUS % POINTS L_{eq}	L_1	L_{10}	L_{50}	L_{90}
2	100	143.1	4370	6.8	74.4	80.7	77.3	73.1	70.0
6	100	153.4	7320	4.2	74.0	78.8	76.0	73.4	71.1
8	100	152.4	6080	2.0	74.9	80.9	77.0	74.0	71.6
11	100	151.4	3050	2.8	71.4	78.7	74.0	69.8	67.1
2	200	243.1	4370	6.8	70.4	75.5	73.1	69.6	66.5
6	200	253.4	7320	4.2	69.1	73.8	71.0	68.5	66.1
8	200	252.4	6080	2.0	71.6	77.4	73.8	70.8	68.7
11	200	251.4	3050	2.8	69.6	75.8	72.4	68.4	65.7
2	400	443.1	4370	6.8	65.9	70.9	68.3	65.0	62.3
6	400	453.1	7320	4.2	63.8	67.8	65.6	63.5	61.2
8	400	252.4	6080	2.0	65.9	69.8	67.8	65.7	63.3
11	400	251.4	3050	2.8	66.4	72.0	68.8	65.7	63.0
2	800	843.1	4370	6.8	60.5	64.5	62.5	60.3	57.5
6	800	853.1	7320	4.2	60.0	63.0	61.5	59.8	58.2
8	800	852.4	6080	2.0	60.5	63.9	62.4	60.2	58.3
11	800	851.4	3050	2.8	63.6	69.0	66.0	62.7	60.3

TABLE B–6

FREE-FIELD TRAFFIC NOISE LEVELS 15 FEET ABOVE GROUND AT SITE 2

RUN NO.	DISTANCE (FT) FROM ROAD-SIDE	DISTANCE (FT) EQUIV-ALENT	TRAFFIC VOLUME (VPH)	TRUCK MIX (%)	TRAFFIC NOISE (dBA) FOR VARIOUS % POINTS L_{eq}	L_1	L_{10}	L_{50}	L_{90}
3	100	146.4	5170	8.7	75.5	82.8	78.4	74.0	70.7
7	100	153.8	6490	2.8	74.3	79.1	76.5	73.7	71.5
10	100	149.5	3890	3.7	71.1	78.5	74.2	69.3	66.6
3	200	246.4	5170	8.7	72.2	80.0	74.2	70.8	67.7
7	200	253.8	6490	2.8	70.5	74.9	72.5	69.9	68.1
10	200	249.5	3890	3.7	69.7	78.0	72.5	67.9	65.3
3	400	446.4	5170	8.7	69.2	79.0	70.8	67.4	64.5
7	400	453.8	6490	2.8	64.9	70.6	66.7	64.1	62.4
10	400	449.5	3890	3.7	65.7	74.7	68.1	64.2	61.8
3	800	846.4	5170	8.7	62.4	69.7	64.7	61.2	59.0
7	800	853.8	6490	2.8	60.0	67.7	61.0	59.1	57.3
10	800	849.5	3890	3.7	61.3	68.4	63.9	60.4	58.3

TABLE B–7

FREE-FIELD TRAFFIC NOISE LEVELS 5 FEET ABOVE GROUND AT SITE 3

RUN NO.	DISTANCE (FT) FROM ROAD-SIDE	DISTANCE (FT) EQUIV-ALENT	TRAFFIC VOLUME (VPH)	TRUCK MIX (%)	TRAFFIC NOISE (dBA) FOR VARIOUS % POINTS L_{eq}	L_1	L_{10}	L_{50}	L_{90}
1	50	117.6	10400	5.1	76.4	82.7	78.6	75.5	72.9
4	50	121.0	8840	4.7	76.2	84.3	79.5	75.6	72.1
1	100	167.6	10400	5.1	72.7	78.8	75.1	71.8	69.3
4	100	171.0	8840	4.7	72.7	79.8	75.2	71.5	68.4
5	100	181.1	6340	16.6	73.7	79.8	76.5	72.5	69.5
9	100	169.7	6130	18.8	72.8	79.3	76.2	71.3	67.2
12	100	171.0	5670	20.5	70.9	78.1	74.4	68.9	63.3
15	100	167.8	6580	15.9	70.7	76.9	73.9	69.3	65.7
1	200	267.6	10400	5.1	68.7	74.0	70.8	67.9	66.0
4	200	271.0	8840	4.7	68.7	74.4	71.2	67.8	65.2
5	200	281.1	6340	16.6	70.5	75.8	73.0	69.6	66.9
9	200	269.7	6130	18.8	67.4	74.4	70.8	65.5	61.1
12	200	271.0	5620	20.5	65.1	73.1	68.5	62.8	57.5
15	200	267.8	6580	15.9	66.3	72.8	69.4	64.9	61.0
1	400	467.6	10400	5.1	65.0	69.6	66.8	64.4	62.6
4	400	471.0	8840	4.7	64.9	69.4	67.2	64.2	62.0
5	400	481.1	6340	16.6	65.8	70.0	68.0	65.8	63.0
9	400	469.7	6130	18.8	60.2	66.3	62.9	59.2	56.2
12	400	471.0	5620	20.5	58.8	63.4	61.1	58.2	55.4
15	400	467.8	6580	15.9	58.6	64.2	60.8	57.7	55.3
4	800	871.0	8840	4.7	61.1	64.8	62.9	60.8	58.4
5	1600	1681.1	6340	16.6	69.5	69.5	63.5	61.3	59.4
9	1600	1669.1	6130	18.8	54.4	61.0	55.8	53.1	51.7
15	1600	1667.8	6580	15.9	58.8	63.0	58.3	53.6	51.5
1	800	867.6	10400	5.1	60.9	67.0	62.7	60.1	58.5

TABLE B–8

FREE-FIELD TRAFFIC NOISE LEVELS 10 FEET ABOVE GROUND AT SITE 3

	DISTANCE (FT)				TRAFFIC NOISE (dBA) FOR VARIOUS % POINTS				
RUN NO.	FROM ROAD-SIDE	EQUIV-ALENT	TRAFFIC VOLUME (VPH)	TRUCK MIX (%)	L_{eq}	L_1	L_{10}	L_{50}	L_{90}
2	100	163.8	9550	4.5	75.0	82.4	77.7	73.6	70.5
6	100	178.6	6820	15.3	73.8	79.0	76.4	73.1	70.1
8	100	172.4	6050	17.8	73.0	79.4	76.4	71.3	68.1
10	100	172.1	6480	16.7	72.0	78.6	75.2	70.4	65.9
13	100	165.2	6310	12.5	70.0	77.2	74.0	69.0	64.2
2	200	263.8	9550	4.5	70.7	76.0	73.1	69.8	67.3
6	200	278.5	6820	15.3	72.6	76.6	74.7	72.1	69.5
8	200	277.4	6050	17.8	71.8	76.9	74.6	70.7	67.5
10	200	272.1	6480	16.7	70.5	76.0	73.4	69.5	65.3
13	200	265.2	6310	12.5	68.8	74.6	71.9	67.5	63.1
2	400	463.8	9550	4.5	67.4	71.7	69.2	66.6	64.6
6	400	478.6	6820	15.3	68.6	72.0	70.5	68.3	66.2
8	400	472.4	6050	17.8	66.5	71.2	69.1	65.8	62.0
10	400	472.1	6480	16.7	63.3	68.1	66.0	62.5	59.4
13	400	465.2	6310	12.5	60.2	66.1	62.3	59.3	57.2
2	800	863.8	9500	4.5	62.9	69.4	64.3	62.1	60.3

TABLE B–9

FREE-FIELD TRAFFIC NOISE LEVELS 15 FEET ABOVE GROUND AT SITE 3

	DISTANCE (FT)				TRAFFIC NOISE (dBA) FOR VARIOUS % POINTS				
RUN NO.	FROM ROAD-SIDE	EQUIV-ALENT	TRAFFIC VOLUME (VPH)	TRUCK MIX (%)	L_{eq}	L_1	L_{10}	L_{50}	L_{90}
3	100	169.2	9030	4.1	75.6	82.0	78.9	73.9	71.3
7	100	180.9	5840	16.4	73.1	78.2	75.7	72.4	69.2
11	100	164.5	6100	16.9	71.5	77.0	74.7	70.2	66.1
14	100	165.8	5820	12.6	69.0	77.4	72.5	66.1	62.6
16	100	166.8	6540	15.5	70.9	77.8	74.1	69.1	64.5
3	200	269.2	9030	4.1	71.7	76.9	74.3	70.5	68.0
7	200	280.9	5840	16.4	73.1	77.2	75.2	72.7	70.2
11	200	264.5	6100	16.9	71.6	75.0	74.3	70.9	67.3
14	200	265.8	5820	12.6	68.9	75.7	72.3	66.7	63.2
16	200	266.8	6540	15.5	71.1	76.0	73.9	70.1	65.8
3	400	469.2	9080	4.1	68.0	72.8	70.6	67.1	64.7
7	400	480.9	5840	16.4	69.6	72.8	71.3	69.3	67.3
11	400	464.5	6100	16.9	65.5	69.7	67.8	65.0	62.4
14	400	465.8	5820	12.6	61.9	68.6	64.0	61.0	58.0
16	400	466.8	6540	15.5	65.6	70.9	68.6	64.8	60.1
3	800	869.2	9030	4.1	63.7	67.9	66.1	62.9	60.7

TABLE B-10

ENVIRONMENTAL DATA FOR FREE-FIELD TRAFFIC NOISE SURVEYS

SITE NO.	DATE	TIME	APPLIES TO RUNS	WIND SPEED (MPH)	WIND DIRECTION	TEMP. (°F)	REL. HUM. (%)	REMARKS
1	11-06-72	19:57	1, 2, 3	2	East	54	85	Clear
		21:40	4, 5	<2	—	52	75	Clear
		23:50	6, 7, 8, 9	<2	—	52	87	Clear
	11-07-72	2:18	10, 11, 12	3	South	57	69	Clear
		16:30	13	6–8	West	64	66	Clear
		17:35	14, 15, 16	5	West	61	78	Clear/gusty
		19:46	17, 18	0	—	56.5	76.5	Very light rain
		21:29	19, 20	0	—	58	74	Rain
2	11-08-72	13:40	1, 2	12	West	71.5	46.5	Gusty
		14:27	3	14	West	68.5	48.5	Gusty
		14:48	4	14	West	68	50	Gusty
		16:57	5, 6, 7, 8	4	West	61	61	Gusty
		18:32	9, 10	0	—	52	84	Clear
		19:11	11, 12	0	—	49.5	83	Clear
3	11-09-72	16:47	1, 2	2.5	Northeast	64.5	49	Clear
		18:15	3, 4	4	North	60	58	Clear
	11-10-72	9:12	5, 6, 7	0	—	55.5	68	Clear
		10:00	8, 9	0	—	58	61	Clear
		11:00	10, 11	0	—	61.5	63.5	Clear
		11:40	12, 13	8	Southwest	65	56	Gusty
		12:20	14, 15, 16	7	Southwest	68	50	Gusty

APPENDIX C

SUPPLEMENTAL DATA FOR EVALUATION OF HIGHWAY NOISE-REDUCTION MEASURES

Traffic noise data for three highway sites were used to evaluate the noise reduction provided by three types of highway constructions, as follows:

1. Roadside barrier configuration as shown in Figure C-1.
2. Elevated roadway configuration as shown in Figure C-2.
3. Depressed roadway configuration as shown in Figure C-3.

Further details on these sites are available from *NCHRP Report 144* (*3*).

The measured and predicted noise reductions for the three sites are detailed in Tables C-1 through C-3. The predicted noise reductions were computed using the procedure outlined in Figure 38, with the noise assumed to have a wavelength of $\lambda = 2$ ft. Basic cost data for right-of-way acquisition and highway construction are presented in Tables C-4 through C-7.

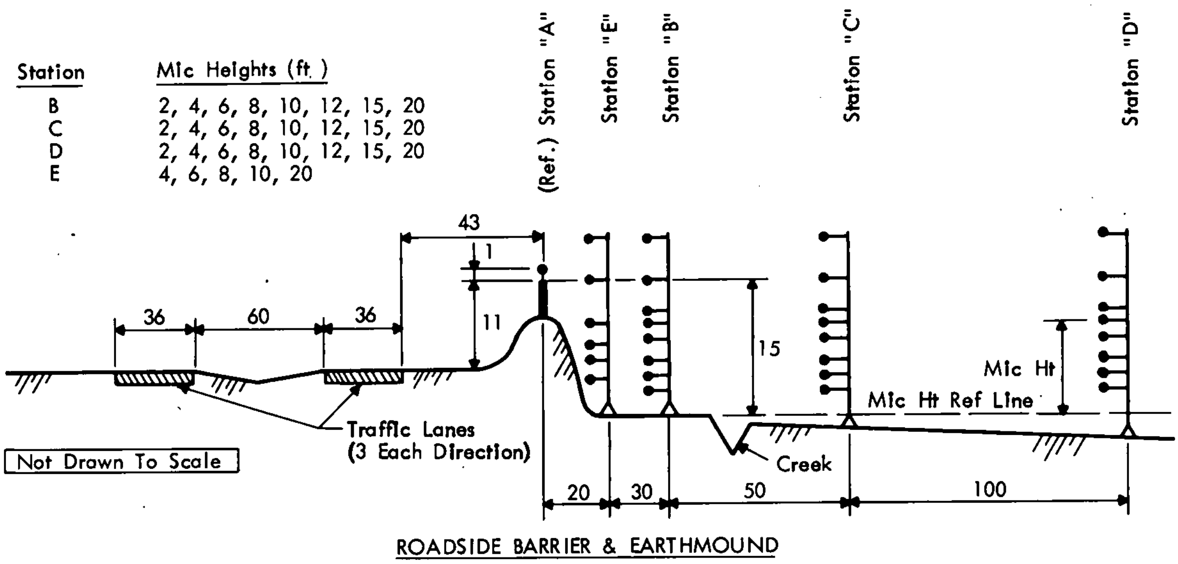


Figure C-1. Cross section and acoustic measurement stations at Site 1 (I-680, Milpitas, Calif.)

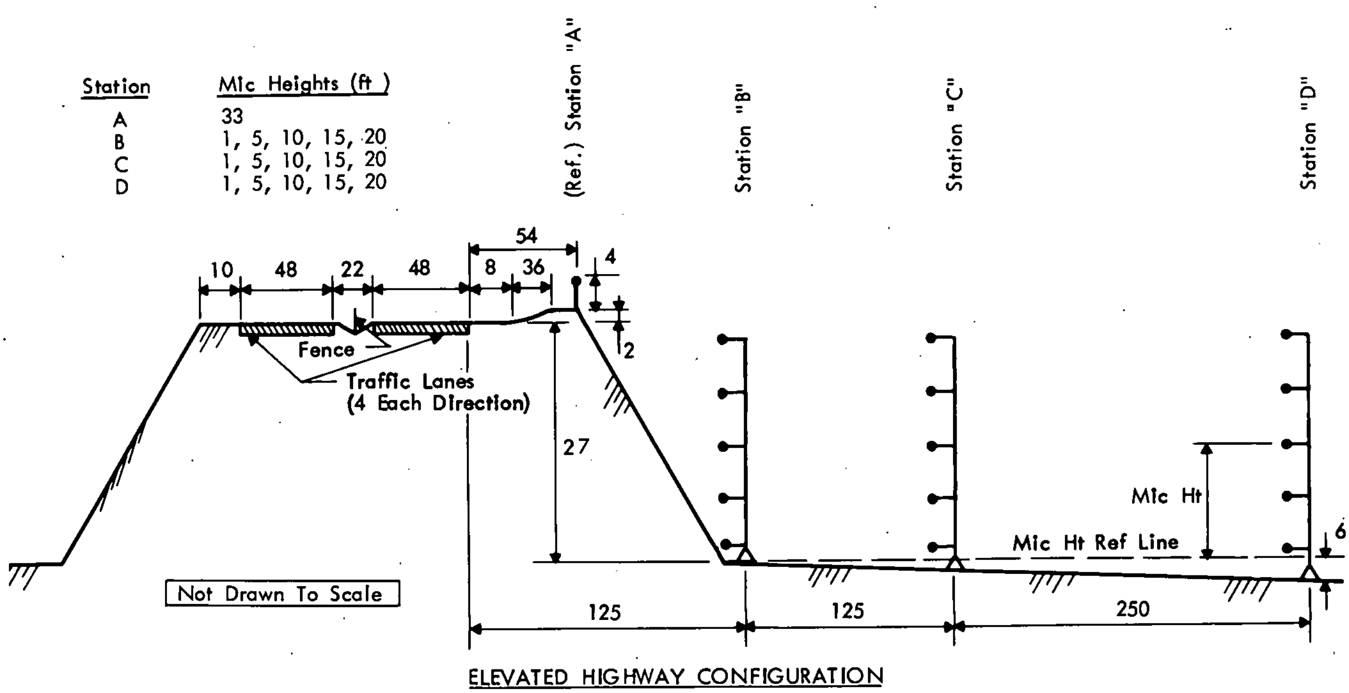


Figure C-2. Cross section and acoustic measurement stations at Site 2 (US 101, Encino, Calif.)

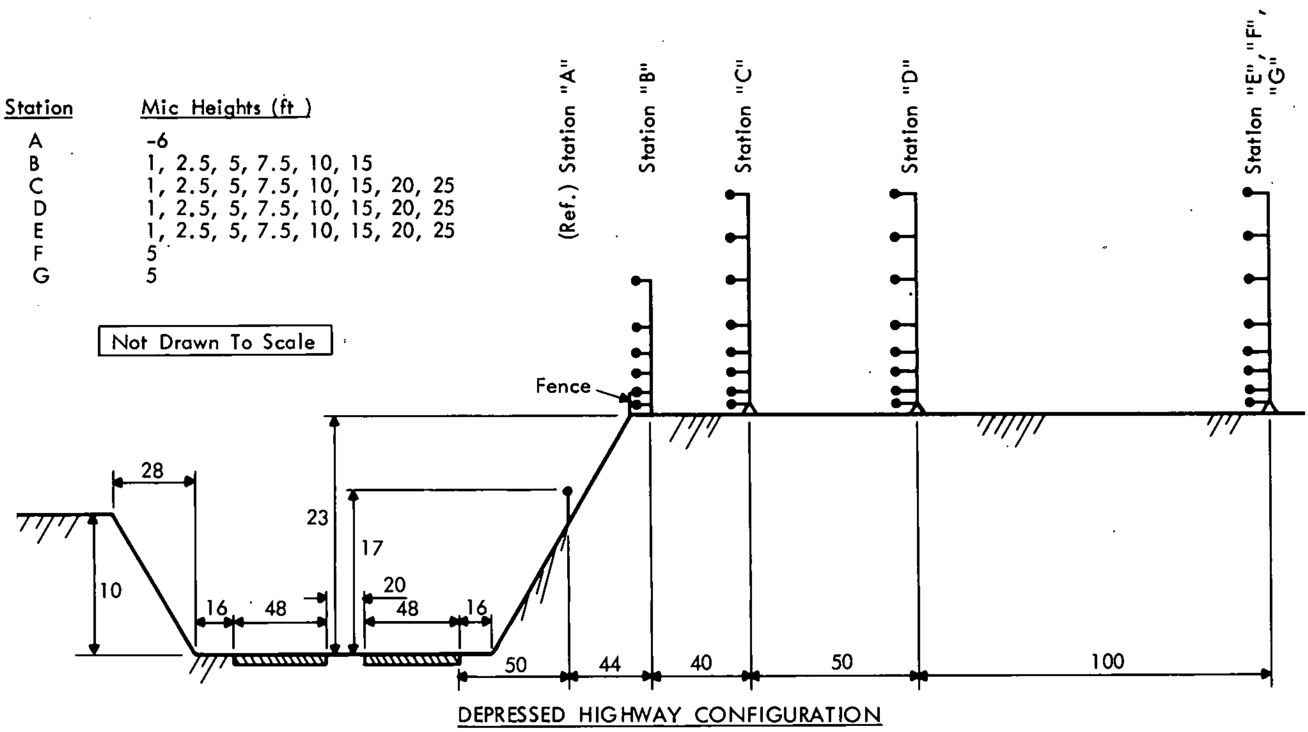


Figure C-3. Cross section and acoustic measurement stations at Site 3 (I-35W, Minneapolis, Minn.)

TABLE C–1

MEASURED AND PREDICTED NOISE REDUCTIONS FOR ROADSIDE BARRIER CONFIGURATION

RUN NO.[a]	TRAFFIC VOLUME (VPH)	MICROPHONE HT. (FT)	NOISE REDUCTION (dBA) AS MEASURED [b] AND PREDICTED AT VARIOUS DISTANCES FROM ROADSIDE: 63 FT [c] MEAS.[d]	63 FT [c] PRED.	93 FT [e] MEAS.[d]	93 FT [e] PRED.	143 FT [f] MEAS.[d]	143 FT [f] PRED.	243 FT [g] MEAS.[d]	243 FT [g] PRED.
1	324	2	—	—	14.5	13.2	13.3	11.8	11.8	11.0
4	432	2	—	—	10.1	13.2	11.1	11.8	9.5	11.0
14	564	2	—	—	13.9	13.2	13.6	11.8	13.4	11.0
13	588	4	—	—	9.4	12.5	11.0	11.4	10.9	10.7
15	496	4	—	—	12.9	12.5	—	—	—	—
20	486	4	—	—	13.5	12.5	—	—	—	—
21	456	4	17.5	14.4	—	—	—	—	—	—
2	348	6	—	—	11.3	11.8	10.8	11.0	—	—
5	492	6	—	—	12.6	11.8	12.1	11.0	10.2	10.5
12	618	6	—	—	13.2	11.8	12.5	11.0	11.6	10.5
22	522	6	16.0	13.5	—	—	—	—	—	—
3	—	8	—	—	11.5	11.1	6.7	10.5	—	—
6	534	8	—	—	12.4	11.1	11.7	10.5	10.6	10.2
17	372	8	—	—	11.5	11.1	10.1	10.5	8.5	10.2
23	522	8	12.1	12.3	—	—	—	—	—	—
7	624	10	—	—	9.7	10.2	9.7	10.0	9.3	10.0
10	456	10	—	—	8.4	10.2	7.6	10.0	7.1	10.0
15	496	10	—	—	—	—	6.7	10.0	—	—
20	486	10	—	—	11.5	10.2	—	—	—	—
21	456	10	14.0	11.1	—	—	—	—	—	—
22	522	10	9.1	11.1	—	—	—	—	—	—
8	492	15	—	—	9.3	8.0	9.0	8.6	8.7	9.2
19	402	15	—	—	8.6	8.0	7.5	8.6	8.7	9.2
23	522	15	8.8	7.2	—	—	—	—	—	—

[a] Reference to raw data in *NCHRP Report 144* (3).
[b] Assuming a free-field propagation loss of 3 dBA per doubling of distance.
[c] D_E=107.5 [d] L_{50} only. [e] D_E=137.5 ft. [f] D_E=187.5 ft. [g] D_E=287.5 ft.

TABLE C–2

MEASURED AND PREDICTED NOISE REDUCTIONS FOR ELEVATED ROADWAY CONFIGURATION

			NOISE REDUCTION (dBA) AS MEASURED [b] AND PREDICTED AT VARIOUS DISTANCES FROM ROADSIDE					
			125 FT [c]			250 FT [d]		
		MICRO-	MEASURED			MEASURED		
RUN NO.[a]	TRAFFIC VOLUME (VPH)	PHONE HT. (FT)	L_{50}	L_{10}	PRED.	L_{50}	L_{10}	PRED.
6	10,410	1	17.0	17.2	14.4	13.0	12.8	10.4
12	14,070	1	14.7	14.5	14.4	10.0	9.8	10.4
1	13,650	5	16.4	15.6	13.3	8.8	8.8	9.8
5	11,280	5	15.6	15.7	13.3	10.7	11.1	9.8
11	13,140	5	13.5	13.5	13.3	8.6	8.6	9.8
2	13,110	10	12.9	13.3	12.2	7.9	8.7	9.0
7	10,560	10	12.8	11.5	12.2	9.8	10.2	9.0
10	14,070	10	11.3	9.2	12.2	7.5	6.5	9.0
3	12,360	15	11.7	11.6	10.7	7.6	7.8	8.1
4	13,080	20	9.0	9.3	9.0	5.9	6.9	7.3
8	12,090	20	10.9	10.5	9.0	8.9	9.0	7.3
9	13,080	20	8.6	8.5	9.0	6.4	6.9	7.3

[a] Reference to raw data in *NCHRP Report 144* (*3*).
[b] Assuming a free-field propagation loss of 3 dBA per doubling of distance.
[c] D_E=167.4 ft. [d] D_E=292.4 ft.

TABLE C–3

MEASURED AND PREDICTED NOISE REDUCTIONS FOR DEPRESSED ROADWAY CONFIGURATION

			NOISE REDUCTION (dBA) AS MEASURED [b] AND PREDICTED AT VARIOUS DISTANCES FROM ROADSIDE								
			134 FT [c]			184 FT [d]			284 FT [e]		
		MICRO-	MEASURED			MEASURED			MEASURED		
RUN NO.[a]	VEHICLE VOLUME (VPH)	PHONE HT. (FT)	L_{50}	L_{10}	PRED.	L_{50}	L_{10}	PRED.	L_{50}	L_{10}	PRED.
1	5484	1	6.6	7.9	9.1	9.2	10.6	10.3	—	—	—
9	8772	1	6.7	7.3	9.1	9.6	10.2	10.3	—	—	—
2	6000	2.5	6.9	8.0	8.3	9.9	10.9	9.8	—	—	—
10	15198	2.5	7.5	7.9	8.3	9.8	10.3	9.8	—	—	—
3	6303	5	6.9	7.2	7.1	9.9	10.4	9.2	—	—	—
5	6318	5	5.8	7.8	7.1	9.4	10.7	9.2	—	—	—
12	8130	5	7.2	7.7	7.1	10.0	10.8	9.2	—	—	—
4	6144	7.5	—	—	—	9.4	10.5	8.3	—	—	—
5	6318	10	—	—	—	9.1	10.3	7.5	—	—	—
6	6636	10	—	—	—	—	—	—	11.9	13.1	9.8
13	6234	10	—	—	—	9.4	10.5	7.5	—	—	—
14	5784	10	—	—	—	—	—	—	8.7	10.5	9.8
7	7236	15	—	—	—	—	—	—	11.8	13.2	8.9
15	5622	15	—	—	—	—	—	—	7.1	9.4	8.9
8	8136	20	—	—	—	—	—	—	11.0	11.9	8.0
16	6312	20	—	—	—	—	—	—	6.3	8.1	8.0
17	5772	25	—	—	—	—	—	—	5.3	7.1	7.1

[a] Reference to raw data in *NCHRP Report 144* (*3*).
[b] Assuming a free-field propagation loss of 4.5 dBA per doubling of distance.
[c] D_E=170.3 ft. [d] D_E=220.3 ft. [e] D_E=320.3 ft.

TABLE C-4

DESCRIPTION OF HIGHWAY CONFIGURATION FOR CONSTRUCTION COST DATA

(a) GENERAL DESCRIPTION, ALL CONFIGURATIONS

SITE NO.	SITE STATE	SECTION TYPE [a]	LGTH. (MI)	AVG. ELEV. OR DEPTH (FT)	NO. LANES	LANE WIDTH (FT)	MED. WIDTH (FT)	SHDR. WIDTH (FT)	ROW WIDTH (FT)	SLOPE OF FILL OR CUT
1	CA	G–T	1	0	8	12	30	10	246	—
2	CA	D–T	1	20	8	12	30	10	256	2:1
3	CA	E–T	1	20	8	12	20	13	262	2:1
4	CA	S–T	1	24	8	12	30	10	178	—
5	CA	D–A	1.3	35	10	12	64	13	320	2:1
6	CA	E–A	1.8	25	10	12	64	13	320	2:1
7	CA	S–A	0.5	30	10	12	64	10	236	—
8	CO	G–T	—	0	6	12	16	10	150	—
9	CO	D–T	—	20	6	12	12	10	300	3:1
10	CO	E–T	—	20	6	12	10	10	300	— [b]
11	CO	S–T	—	20	6	12	12	10	100	—
12	CT	G–A	0.2	0	6	12	90	10	362	—
13	CT	D–A	1.1	20	6	12	90	10	362	—
14	CT	E–A	0.7	20	6	12	90	10	362	— [b]
15	CT	S–A	0.1	16	2	12	0	8	NA	—
16	IL	G–A	2.3	0	4	12	46	11	500	—
17	IL	S–A	0.5	30	4	12	50	6	250	—

(b) DETAILED DESCRIPTION, ACTUAL CONFIGURATIONS

SITE NO.	SITE STATE	DESCRIPTION
5	CA	Rt. 105 (Century Freeway) in Los Angeles between Wilton St. and Vermont Ave., Sta. 434+07 to 503+75; median includes future bus lanes.
6	CA	Rt. 105 (Century Freeway) in Los Angeles between State St. and Atlantic Blvd., Sta. 730+14 to 824+26; median includes future bus lanes.
7	CA	Rt. 105 (Century Freeway) in Los Angeles between Mona St. and Santa Fe St., Sta. 688+58 to 717+111; median includes future bus lanes; details on supports not available.
12	CT	Newington-Wethersfield-Rocky Hill area; no further details provided.
13	CT	Newington-Wethersfield-Rocky Hill area; no further details provided.
14	CT	No details provided.
15	CT	Newington-Wethersfield-Rocky Hill area; average span between verticals, 154 ft; diameter of supports, 4 ft; mean roadway height above columns, 7.5 ft; height of curbing, 6 and 8 in.
16	IL	I–74 in Moline from south of 7th Ave. to north of John Deere Expressway.
17	IL	I–74 in Moline from end of Iowa-Illinois Memorial Bridge to south of 7th Ave.; median is opening between two separate structures; average span between verticals, 98 ft; diameter of supports, 4 to 5.5 ft; mean roadway height above column tops, 5.8 ft; height of curbing, 2.2 to 2.9 ft.

[a] G=at grade, D=depressed, E=fill elevated, S=elevated structure, T=theoretical section, A=actual section; see Table C-4(b) for further details on actual (A) sections.

[b] 2:1, 6:1.

TABLE C–5

RIGHT-OF-WAY ACQUISITION COSTS, PER ACRE

STATE, SITE; LAND USE	PRICE YEAR	COST ($1000/ACRE) AND PERCENTAGE OF TOTAL[a] BY COST CATEGORY							
		LAND	STRUCTURES	LIQUIDATION DAMAGES	LEGAL EXPENSES	MOVING AND RELOCATION	UTILITY ADJUSTMENTS	MISC.	TOTAL
CA, 1–4; mixed	1973	54 (24)	127 (55)	5 (2)	12 (5)	2.5 (1)	7 (3)	22 (10)	229
CA, 1–4; residential	1973	—	—	—	—	—	—	—	262
CA, 1–4; commercial	1973	—	—	—	—	—	—	—	503
CA, 1–4; industrial	1973	—	—	—	—	—	—	—	537
CA, 1–4; farm land	1973	—	—	—	—	—	—	—	30
CA, 5; 90% res. 5% comm., 5% pub. land	1972	68 (39)	60 (35)	2.4 (1)	8.4 (5)	11.3 (6)	3.1 (2)	21 (12)	174
CA, 6; 90% res., 10% comm.	1972	82 (30)	118 (43)	3.5 (1)	32 (12)	28 (10)	4.2 (1)	8.5 (3)	276
CA, 7; 25% res., 75% indus.	1972	97 (24)	257 (63)	25 (6)	9.7 (2)	5.4 (1)	4.7 (1)	10 (3)	409
CO, 8–11; 20% res., 10% comm., 70% indus.	1973	33 (70)	11 (23)	2.2 (5)	0.2 (<1)	0.1 (<1)	0.3 (<1)	—	47
CT, 12–15; mixed	1969	100 (58)	68 (40)	— (0)	0.9 (<1)	1.1 (<1)	2 (1)	—	172
IL, 16–17; residential	71–72	3 (64)	0.33 (7)	0.9 (20)	0.01 (2)	0.01 (2)	0.25(5)	—	4.7
IL, 16–17; commercial	69–70	125 (46)	107 (40)	2.6 (1)	1.4 (<1)	25.6 (10)	9.5 (3)	—	270
IL, 16–17; farm land	70–71	0.3 (38)	nil (<1)	0.3 (38)	nil (1)	nil (<1)	0.2 (22)	—	0.8

[a] In parentheses.

TABLE C–6

HIGHWAY CONSTRUCTION COSTS, PER MILE

SITE: STATE	SITE: NO.	PRICE YEAR	COST ($1000/MILE) BY COST CATEGORY: ROADWAY	DRAINAGE	PAVEMENT OR STRUCTURE	SHOULDERS	ROADWAY APPURT.	UTILITY ADJUST.	LANDSCAPING	LIGHTING	SIGNING	MISCELLANEOUS	TOTAL
CA	1	73	170	146	511	239	200	—[a]	144	59	29	602	2100
CA	2	73	62	250	408	192	111	—[a]	122	—[a]	150	1160	2400
CA	3	73	16	507	370	94	181	—[a]	110	—[a]	54	416	1748
CA	4	73	15	408	12600	11	13	—[a]	78	—[a]	265	1400	14790
CA	5	72	87	3161	511	239	111	—[a]	144	—[a]	50	1405	5708
CA	6	72	20	804	462	117	181	—[a]	124	—[a]	54	660	2422
CA	7	72	20	448	13997	11	13	—[a]	109	—[a]	265	1537	16400
CO	8	72	50	90	285	—[b]	48	120	100	70	2	—	765
CO	9 or 10	72	250	270	436	—[b]	150	150	200	70	2	—	1528
CT	12–15[c]	73	1664[d]	425	765[d]	155	130	110	125	9	12	2205	5600
IL	16	68	535	446	588	118	252	71	141	31	11	—	2193
MI	18	72	52	210	525	76	229	170	25	190	43	—	1520

[a] Not reported separately; apparently included under miscellaneous costs.
[b] Included in cost of pavement.
[c] Mixed.
[d] Cost of structure may be included in roadway cost.

TABLE C-7

HIGHWAY RAMP AND STREET CROSSING COSTS

SITE			ON-OFF RAMPS				STREET CROSSINGS			
				NO. PER MILE				NO. PER MILE		
STATE	NO.	PRICE YEAR	COST PER RAMP ($1000)	URBAN	SUBURBAN	RURAL	COST PER CROSSING ($1000)	URBAN	SUBURBAN	RURAL
CA	1	71–72	1450	2	1	1/3	450	4	2	1
CA	2	71–72	1450	2	1	1/3	510	4	2	1
CA	3	72	1450	2	1	1/3	400	4	2	1
CA	4	72–73	1980	2	1	1/3	400	4	2	1
CA	5	72	2600	2	1	1/3	—	4	2	1
CA	6	72	1980	2	1	1/3	—	4	2	1
CA	7	72	803	2	1	1/3	—	4	2	1
CO	8	72	—	8	8	2	100	6	4	1
CO	9	72	25	8	8	2	—	6	4	1
CO	10	72	25	8	8	2	—	6	4	1
CT	12	73	—	1	—	—	87	3	—	—
CT	13	73	62	1	—	—	87	3	—	—
CT	14	73	—	1	—	—	87	3	—	—
IL	16	70	—	—	—	—	687	1	1/2	1/4
IL	17	72	—	—	—	—	603	1	1/2	1/4
MI	18	72	45	8	4	1	—	—	—	—

APPENDIX D

SUPPLEMENTAL DATA FOR VEHICLE NOISE DIRECTIVITY SURVEYS

The basic data acquired during the free-field traffic noise directivity studies are presented in Tables D-1 through D-3. The maximum noise levels measured for individual passing vehicles at site A (Canoga Park, Calif.) are given in Table D-1. Similar data for site B (California R-14) are given in Table D-2. The vehicle identifications and speeds are also included in these tables, along with the distortion factor, Δ, and average level, $\overline{P}$, as defined in Eqs. 94 and 95 in the text. The environmental conditions observed during the measurements are given in Table D-3.

TABLE D-3

ENVIRONMENTAL CONDITIONS DURING DIRECTIVITY MEASUREMENTS

		WIND				
SITE	DATE	SPEED (MPH)	DIRECTION	TEMP. (°F)	REL. HUMID. (%)	REMARKS
A	3–3–73	2–5, gusts	West	78	55	Clear
A	5–4–73	4–12, gusts	West	72	50	Clear

TABLE D–1

MAXIMUM NOISE LEVELS FROM INDIVIDUAL PASSING VEHICLES AT SITE A

EVENT NO.	NOISE LEVEL (dBA) CORRECTED TO 45.7 FT AT VARIOUS ANGLES 6°	19°	32°	45°	AVER. $\overline{P}$	DISTORT. FACTOR, Δ	SPEED (MPH)	VEHICLE TYPE [a]
12	—	68.5	68.5	70.0	69.3	−0.5	39.5	CA
13	—	66.0	66.5	68.0	67.2	0.0	33.3	SW
14	—	72.0	72.0	72.5	72.5	−1.0	34.6	T
15	—	79.5	80.0	80.0	80.2	−0.75	—	CA
16	—	71.5	70.5	76.5	73.2	0.75	—	—
17	—	72.5	80.5	81.0	80.7	0.0	34.0	T
18	—	68.0	68.5	69.0	68.8	−0.5	30.5	PU
19	—	82.0	82.5	83.0	82.8	−0.5	32.8	T
20	—	82.5	81.5	82.5	82.5	−1.25	32.8	T
21	—	72.0	72.0	73.5	72.8	−0.5	41.0	CA
22	—	74.0	71.5	72.5	73.3	−2.75	40.0	CA
23	—	68.5	68.5	69.0	69.0	−1.0	36.7	CA
24	—	68.0	67.5	68.0	68.2	−1.5	44.5	CA
25	81.0	81.0	81.0	79.5	80.6	−0.75	33.0	T
26	70.5	70.0	70.0	69.5	70.0	−0.5	35.2	T
27	74.0	73.0	74.0	74.5	73.9	0.75	46.8	SW
28	70.0	69.5	69.5	69.0	69.5	−0.5	36.0	PU
29	68.0	67.5	68.0	68.0	67.9	+0.25	38.3	SW
30	70.0	69.0	69.5	69.5	69.5	0.0	50.7	CA
31	66.0	64.5	65.5	66.0	65.5	0.5	39.1	SW
32	65.0	64.0	65.0	65.0	64.8	0.5	39.5	SW
33	72.0	71.0	71.5	72.0	71.6	+0.25	40.4	CA
34	70.0	69.0	69.0	69.5	69.4	−0.25	38.2	PU
35	84.5	84.0	85.0	84.0	84.4	+0.25	36.0	T
36	66.0	65.5	65.5	65.0	65.5	−0.5	36.0	CA
37	65.0	65.0	65.0	64.0	64.8	−0.5	33.3	CA
38	66.0	66.0	66.0	65.5	65.6	−0.75	41.3	CA
39	69.5	69.0	69.0	69.5	69.3	+0.0	43.8	CA
40	69.5	68.0	69.0	70.0	69.1	0.75	—	—
41	84.0	83.5	81.5	81.5	82.6	−2.25	—	CA
42	65.0	65.0	65.5	65.5	65.3	0.5	36.0	SW
43	69.0	68.0	68.5	69.0	68.6	+0.25	36.0	CA
44	69.0	68.0	69.0	69.0	68.8	0.5	—	—
45	64.0	64.5	65.5	66.5	65.1	1.75	30.0	CA
46	68.0	66.5	67.0	66.5	67.0	−0.5	35.0	CA
47	71.0	70.0	71.5	70.0	70.4	−0.25	33.0	CA
48	68.0	68.5	68.5	68.0	68.3	0.0	49.0	BS
49	67.5	66.5	66.5	67.5	67.0	0.0	37.0	CA
50	66.0	66.0	67.5	67.5	66.8	1.5	38.0	CA
51	69.0	68.0	69.0	69.0	68.8	0.5	—	T
52	66.5	66.5	67.5	67.5	67.0	1.0	33.0	SW
53	64.0	62.5	63.5	64.0	63.5	0.5	30.0	CA
54	—	—	—	—	—	—	—	T
55	63.0	63.0	66.5	66.5	64.5	1.5	32.0	CA
56	61.0	61.5	63.5	65.0	62.8	3.0	—	CA
57	69.0	69.0	71.0	73.0	70.5	3.0	—	CA
58	69.0	69.5	69.5	71.0	70.0	0.5	45.0	CA
59	73.0	71.5	71.5	75.0	73.0	0.1	40.0	CA
60	73.0	72.5	72.5	74.0	73.0	0.5	46.0	PU
61	—	—	—	—	—	—	40.0	PU
62	82.0	83.5	85.5	84.0	83.8	3.0	—	T
63	69.0	68.5	71.0	70.0	69.6	1.75	—	—
64	68.0	67.5	68.5	69.0	68.3	1.0	—	CA
65	69.0	70.5	70.5	71.0	70.3	1.0	45.0	CA
66	75.0	74.0	71.5	73.0	72.4	−2.25	38.0	CA
67	74.0	73.5	74.5	76.0	74.5	1.5	39.0	CA
68	68.0	67.5	68.5	71.0	68.8	1.0	38.0	CA
69	79.0	78.5	79.0	81.0	79.4	1.25	53.0	MC
70	—	—	—	—	—	—	—	PU
71	72.0	71.5	72.5	72.0	72.0	0.5	60.0	CA
72	71.0	69.5	70.5	69.5	70.1	−0.25	43.0	CA
73	88.0	86.5	87.5	88.0	87.5	0.5	55.0	MC
74	72.0	72.5	73.5	72.5	72.6	0.75	60.0	CA
(38′)	76.0	74.0	74.5	73.5	74.6	−0.75	—	MC
(57′)	89.0	89.5	90.0	90.0	89.6	0.75	—	MC

[a] CA=passenger car, SW=station wagon, T=truck, PU=pick-up truck, MC=motorcycle.

TABLE D-2

MAXIMUM NOISE LEVELS FROM INDIVIDUAL PASSING VEHICLES AT SITE B [a]

EVENT NO.	NOISE LEVELS (dBA) CORRECTED TO 45.7 FT AT VARIOUS ANGLES					DISTORT. FACTOR, Δ	SPEED (MPH)	NO. WHLS, N	EXHT. TYPE,[b] E	STD. DEV., σ
	6°	19°	32°	45°	AVER. $\overline{P}$					
1	87.0	88.5	89.3	87.0	88.0	0.4	—	18	5	0.99
2	84.6	84.6	84.9	82.9	84.3	−0.7	63.4	6	1	0.37
3	77.5	78.0	78.5	77.0	77.8	0.0	68.2	6	1	0.56
4	84.0	84.6	85.5	84.3	84.6	0.6	56.3	14	5	0.56
5	92.0	92.7	93.3	91.5	92.4	0.05	68.2	18	5	0.68
6a	85.1	86.2	86.7	85.7	85.9	0.55	—	—	5	0.59
6b	84.2	84.4	85.7	85.0	84.8	1.05	—	—	—	0.58
6c	83.0	82.8	84.2	83.8	83.5	1.1	—	—	1	0.57
7	88.4	88.3	89.0	89.0	88.7	0.65	61.4	18	5	0.32
8	80.5	81.4	82.5	81.0	81.4	0.8	61.4	10	5	0.74
9	82.2	82.5	83.2	81.1	82.3	−0.2	56.6	10	1	0.76
10	87.1	87.0	87.7	86.5	87.1	0.05	60.6	18	3	0.43
11	85.5	85.7	87.3	86.4	86.2	1.25	61.7	18	5	0.70
12	82.2	83.3	84.5	83.9	83.5	1.45	58.7	10	5	0.85
13	82.6	84.5	85.4	84.4	84.2	1.35	57.3	18	5	1.0
14	84.0	83.9	84.7	83.2	84.0	0.0	62.6	18	5	0.53
15	86.3	86.5	86.0	85.1	86.0	−0.85	60.3	10	4	0.54
16	87.1	87.7	89.5	89.9	88.6	2.3	64.9	18	5	1.18
17	90.2	89.8	90.7	90.0	90.2	0.35	65.6	18	5	0.33
18	86.0	86.5	88.3	86.9	86.9	1.35	66.2	18	5	0.99
19	84.8	85.5	86.3	84.0	85.2	0.0	67.5	18	5	0.85
20	86.0	85.9	87.3	86.0	86.3	0.7	56.3	18	1	0.58
21	85.2	85.5	87.2	86.4	86.1	1.45	61.4	18	5	0.79
22	84.0	83.7	85.0	84.3	84.3	0.8	65.6	18	5	0.48
23	86.3	86.6	88.0	86.8	86.9	0.95	64.9	18	5	0.65
24	84.9	85.0	85.3	84.0	84.8	−0.3	60.3	18	5	0.48
25	85.4	84.7	85.9	85.0	85.3	0.4	62.6	10	1	0.45
26	83.5	83.5	84.5	83.0	83.6	0.25	61.4	18	3	0.54
27	86.7	86.6	88.4	88.2	87.5	1.65	59.3	18	4 or 5	0.83
28	84.1	84.0	84.8	83.8	84.2	0.25	64.0	14	5	0.38
29	86.9	87.3	88.5	87.3	87.5	0.8	62.6	18	5	0.60
30	82.0	82.0	84.0	84.1	83.0	2.05	66.2	18	5	1.03
31	88.3	88.5	89.5	89.3	88.9	1.0	71.0	18	1	0.51
32	84.0	83.5	85.0	84.0	84.1	0.75	50.5	18	5	0.54
33	89.1	89.3	90.5	89.3	89.6	0.7	56.3	18	5	0.55
34	86.5	87.0	88.3	87.7	87.4	1.25	66.8	18	5	0.68
35	89.5	89.5	92.4	92.0	90.9	2.7	59.8	18	5	1.36
36	89.1	89.4	90.6	90.2	89.8	1.15	68.5	18	5	0.60
37	88.0	87.5	88.5	88.1	88.0	0.55	60.6	18	3	0.36
38	81.0	80.8	82.5	81.9	81.6	1.3	61.7	18	5	0.69
39	87.5	87.2	88.8	87.4	87.7	0.75	53.5	18	4	0.63
40	79.4	79.7	82.5	83.1	81.2	3.25	62.3	10	5	1.64
41	84.7	84.5	86.7	90.5	86.6	4.0	60.9	12	3	2.41
42	85.1	85.0	86.8	86.0	85.7	1.35	69.2	18	5	0.73
43	90.0	90.5	92.3	90.5	90.8	1.15	57.3	18	5	0.88
44	82.8	81.5	83.3	83.0	82.7	1.0	59.3	6	1	0.69
45	80.0	79.6	81.7	81.1	80.6	1.6	45.6	10	1	0.84
46	84.3	84.1	85.5	84.7	84.7	0.9	66.8	18	4	0.54
47	79.7	80.5	81.4	79.8	80.4	0.5	61.4	6	1	0.68
48	81.8	81.5	83.1	81.5	82.0	0.65	60.6	16	1	0.66
49	87.0	88.5	89.9	88.5	88.5	1.45	59.3	18	5	1.03
50	84.0	84.3	84.9	84.1	84.3	0.35	61.4	18	5	0.35
51	88.4	88.0	88.6	88.0	88.3	0.1	66.2	18	5	0.26
52	82.0	81.7	83.7	83.6	82.8	1.8	55.2	14	1	0.91
53	87.3	86.8	88.2	87.2	87.4	0.65	62.6	14	1	0.51
54	90.8	90.5	91.1	89.8	90.6	−0.2	65.9	18	5	0.48
55	83.6	83.9	84.0	82.1	83.4	−0.7	69.2	6	1	0.76
56	84.2	84.0	85.5	86.0	84.9	1.65	61.4	10	5	0.85
57	88.5	88.5	89.9	89.0	89.0	0.95	68.5	18	4	0.57
58	89.0	88.8	90.5	89.3	89.4	1.0	75.8	18	5	0.66
59	87.0	86.8	88.0	86.3	87.0	0.25	63.7	18	3	0.62
60	83.5	83.5	84.5	84.9	84.1	1.2	62.6	18	3	0.62
61	84.5	85.0	86.5	86.7	85.7	1.85	63.7	18	3	0.94
62	87.0	87.5	88.1	87.5	87.5	0.55	64.6	18	5	0.39
63	84.0	84.0	85.5	83.5	84.3	0.5	62.3	6	1	0.75
64	86.0	85.6	86.8	86.8	86.3	1.0	58.3	10	5	0.52
65	88.0	87.5	89.2	87.0	87.9	0.35	56.3	18	5	0.82
66	82.7	82.5	84.5	82.3	83.0	0.8	58.8	6	1	0.88
67	86.9	85.9	87.5	88.3	87.2	1.5	59.8	18	5	0.88

[a] Trucks only.
[b] 1=exhaust under chassis; 2=single stack, left side; 3=single stack, middle; 4=two stacks, each side; 5=single stack, right side.

APPENDIX E

SUPPLEMENTAL DATA FOR TRUCK DRIVE-BY NOISE SURVEYS

The basic data acquired during the truck drive-by noise studies are presented in Tables E-1 through E-7. The following code is used to define the types of trucks detailed in these tables:

TT—tractor-trailer; all multiple-unit trucks (excluding vehicle carriers) with a tractor-drawn semitrailer and/or trailers—AASHTO designations 2-S1, 2-S2, 3-S2, 3-2, and 2-S1-2.

ST—straight truck; all single-unit trucks, excluding dump trucks and truck tractors—AASHTO designation SU.

VC—vehicle carrier; those multiple-unit trucks designed to carry motor vehicles—primarily AASHTO designation 2-S1.

DT—dump truck; those single-unit trucks designed to haul dirt, gravel, etc., and to unload by tilting the cargo area—AASHTO designation SU.

TO—tractor only; truck tractors without a trailer or semitrailer.

Note that no data were obtained for buses or motorhomes. The environmental conditions observed during the measurements at each site are given in Table E-8.

As noted in the text, the five catagories used to classify trucks were selected to facilitate the desired noise evaluations. These catagories generally do not agree with the classification procedures used by the various state highway departments.

TABLE E-1

PEAK DRIVE-BY NOISE LEVELS AT SITE 1[a]

VEHICLES		VEHICLE SPEED (MPH)		PEAK NOISE LEVEL (dBA)[b]	
TYPE	NO.	MEAN	STD. DEV.	MEAN	STD. DEV.
TT-type trucks	232	51.2	5.4	84.8	3.4
ST-type trucks	142	51.2	6.1	80.8	2.8
VC-type trucks	5	49.6	5.8	85.0	3.1
DT-type trucks	5	54.8	2.8	82.2	2.2
TO-type trucks	4	55.7	6.3	83.5	1.0
High-exhaust trucks	249	51.4	5.5	84.4	3.7
Low-exhaust trucks	139	51.0	6.1	81.3	2.8
2-Axle trucks	83	52.3	6.5	80.6	2.6
3-Axle trucks	87	50.4	5.5	81.6	3.1
4-Axle trucks	31	49.9	4.6	82.7	1.9
5-Axle trucks	185	51.5	5.5	85.4	3.4
6+-Axle trucks	2	48.0	7.1	86.0	2.8
All trucks	388	51.3	5.7	83.3	3.7

[a] California.
[b] Measured 50 ft from axis of vehicle motion.

TABLE E-2

PEAK DRIVE-BY NOISE LEVELS AT SITE 2[a]

VEHICLES		VEHICLE SPEED (MPH)		PEAK NOISE LEVEL (dBA)[b]	
TYPE	NO.	MEAN	STD. DEV.	MEAN	STD. DEV.
TT-type trucks	184	52.8	7.0	86.6	3.4
ST-type trucks	106	50.1	6.8	81.3	4.2
VC-type trucks	5	41.4	2.3	84.2	1.8
DT-type trucks	7	50.6	6.5	83.4	5.6
TO-type trucks	4	54.5	6.6	84.2	2.9
High-exhaust trucks	134	53.0	7.0	86.8	2.9
Low-exhaust trucks	122	49.5	6.8	81.2	4.3
2-Axle trucks	84	51.1	6.4	80.5	4.4
3-Axle trucks	43	48.9	6.9	84.0	2.6
4-axle trucks	27	48.3	7.2	84.7	4.5
5-Axle trucks	147	53.4	7.0	87.0	3.0
6+-Axle trucks	5	49.4	8.6	88.2	2.4
All trucks	306	51.6	7.1	84.6	4.4

[a] Colorado.
[b] Measured 50 ft from axis of vehicle motion.

TABLE E-3

PEAK DRIVE-BY NOISE LEVELS AT SITE 3[a]

VEHICLES		VEHICLE SPEED (MPH)		PEAK NOISE LEVEL (dBA)[b]	
TYPE	NO.	MEAN	STD. DEV.	MEAN	STD. DEV.
TT-type trucks	770	57.4	4.6	88.6	4.6
ST-type trucks	96	55.2	5.8	83.0	3.6
VC-type trucks	58	56.9	3.6	88.3	3.1
DT-type trucks	10	58.0	4.7	86.6	2.1
TO-type-trucks	14	58.6	4.2	83.3	2.4
High-exhaust trucks	782	57.6	4.5	88.8	4.5
Low-exhaust trucks	166	55.1	5.4	83.8	3.6
2-Axle trucks	74	55.9	5.9	82.1	3.0
3-Axle trucks	62	55.7	4.7	85.3	3.3
4-Axle trucks	91	55.6	5.4	86.1	3.7
5-Axle trucks	710	57.6	4.4	89.0	4.6
6+-Axle trucks	11	56.2	4.2	89.8	2.4
All trucks	948	57.2	4.7	87.9	4.8

[a] Illinois.
[b] Measured 50 ft from axis of vehicle motion.

TABLE E–4

PEAK DRIVE-BY NOISE LEVELS AT SITE 4[a]

VEHICLES		VEHICLE SPEED (MPH)		PEAK NOISE LEVEL (dBA)[b]	
TYPE	NO.	MEAN	STD. DEV.	MEAN	STD. DEV.
TT-type trucks	466	62.3	4.8	89.1	3.1
ST-type trucks	114	58.0	6.1	82.4	3.4
VC-type trucks	15	57.4	3.5	89.1	3.6
DT-type trucks	0	0.0	0.0	0.0	0.0
TO-type trucks	11	59.5	7.3	83.0	3.2
High-exhaust trucks	416	62.6	4.8	89.3	3.1
Low-exhaust trucks	190	58.5	5.6	84.2	4.1
2-Axle trucks	106	57.8	6.3	81.9	3.1
3-Axle trucks	28	59.5	5.4	85.7	3.3
4-Axle trucks	66	60.9	4.9	87.1	3.1
5-Axle trucks	403	62.5	4.8	89.5	3.0
6+-Axle trucks	3	61.7	9.2	88.7	4.0
All trucks	606	61.3	5.4	87.7	4.2

[a] Kentucky.
[b] Measured 50 ft from axis of vehicle motion.

TABLE E–5

PEAK DRIVE-BY NOISE LEVELS AT SITE 5[a]

VEHICLES		VEHICLE SPEED (MPH)		PEAK NOISE LEVEL (dBA)[b]	
TYPE	NO.	MEAN	STD. DEV.	MEAN	STD. DEV.
TT-type trucks	251	60.6	5.2	89.5	2.7
ST-type trucks	137	58.6	6.6	84.4	3.3
VC-type trucks	19	59.4	5.6	89.8	2.4
DT-type trucks	13	54.5	6.3	85.8	3.7
TO-type trucks	6	64.5	4.8	86.2	1.9
High-exhaust trucks	238	61.2	4.2	89.8	2.3
Low-exhaust trucks	188	58.0	7.1	85.1	3.6
2-Axle trucks	127	59.0	6.4	84.0	3.2
3-Axle trucks	43	56.5	7.4	87.7	2.8
4-Axle trucks	75	58.9	6.2	88.0	2.8
5-Axle trucks	180	61.4	4.2	90.2	2.3
6+-Axle trucks	1	66.0	0.0	91.0	0.0
All trucks	426	59.8	5.9	87.7	3.8

[a] New York.
[b] Measured 50 ft from axis of vehicle motion.

TABLE E–6

PEAK DRIVE-BY NOISE LEVELS AT SITE 6[a]

VEHICLES		VEHICLE SPEED (MPH)		PEAK NOISE LEVEL (dBA)[b]	
TYPE	NO.	MEAN	STD. DEV.	MEAN	STD. DEV.
TT-type trucks	218	57.7	6.8	85.7	3.7
ST-type trucks	100	54.1	8.3	78.2	4.3
VC-type trucks	6	57.3	4.9	85.5	3.2
DT-type trucks	44	52.5	5.4	77.0	4.1
TO-type trucks	11	56.5	5.1	83.0	4.6
High-exhaust trucks	197	57.4	7.0	86.2	3.6
Low-exhaust trucks	182	54.7	7.3	78.8	4.5
2-Axle trucks	135	54.0	7.5	77.4	3.9
3-Axle trucks	30	54.7	6.9	82.9	4.4
4-Axle trucks	39	55.9	6.7	83.0	3.3
5-Axle trucks	175	58.0	6.8	86.6	3.3
6+-Axle trucks	0	0.0	0.0	0.0	0.0
All trucks	379	56.1	7.3	82.6	5.5

[a] Texas.
[b] Measured 50 ft from axis of vehicle motion.

TABLE E–7

PEAK DRIVE-BY NOISE LEVELS AT SITE 7[a]

VEHICLES		VEHICLE SPEED (MPH)		PEAK NOISE LEVEL (dBA)[b]	
TYPE	NO.	MEAN	STD. DEV.	MEAN	STD. DEV.
TT-type trucks	256	56.8	5.9	84.3	3.2
ST-type trucks	73	56.7	6.4	79.5	4.0
VC-type trucks	11	51.1	6.6	88.7	3.2
DT-type trucks	13	52.8	7.5	80.5	4.4
TO-type trucks	4	56.2	6.2	81.7	6.6
High-exhaust trucks	207	57.1	5.6	84.9	2.9
Low-exhaust trucks	150	55.6	6.8	81.1	4.4
2-axle trucks	66	56.7	6.4	78.6	3.7
3-Axle trucks	27	54.9	6.5	82.6	3.1
4-Axle trucks	39	55.3	6.8	81.4	3.3
5-Axle trucks	222	56.9	5.8	85.1	3.0
6+-Axle trucks	3	50.3	14.6	85.3	4.7
All trucks	357	56.5	6.2	83.3	4.1

[a] Texas.
[b] Measured 50 ft from axis of vehicle motion.

TABLE E–8

ENVIRONMENTAL DATA FOR TRUCK DRIVE-BY NOISE SURVEYS

SITE NO.	ROUTE NO.	ROUTE DIR.	LOCATION[a]	DATE	WIND SPEED (MPH)	TEMP. (°F)	REL. HUM. (%)	HWY. GRADE (%)
1	101	W	Canoga Park, Calif.	7–24–73	0–7	68–94	58–70	0.5
2	I25	S	Denver, Colo.	7–2–73	0–5	60–80	65–72	0.0
3	I270	E	Edwardsville, Ill.	6–26–73	5	77–92	70–63	0.3
4	I71	S	Lagrange, Ky.	6–28–73	5	78	56	0.5
5	I87	N	Albany, N.Y.	6–20–73	5	—	—	0.7
6	I20	E	Dallas, Tex.	6–27–73	2–6	95	65	0.0
7	I10	E	Houston, Tex.	6–28–73	2–6	85	65	0.0

[a] Nearest city.

APPENDIX F

MODEL OF TRAFFIC NOISE

This appendix presents a summary of the derivation of the basic equation used to calculate the equivalent level, L_{eq}, for an infinite line source. In addition, the appendix presents a discussion of all of the adjustments that must be made to the infinite line source to simulate real roadway conditions. Finally, the relationship between L_{eq} and L_{10} levels is discussed.

BASIC EQUIVALENT LEVEL EQUATIONS

Infinite Line Source Model

The exposure level for a single event, or SEL, at a fixed distance, D_o, is defined as

$$L_{ex} = 10 \log_{10} \frac{1}{t'} \int_{t_1}^{t_2} 10^{\frac{L(t)}{10}} dt \qquad \text{(F-1)}$$

where $L(t)$ is the sound pressure level, in dB(A), at time t and $t' = 1$ sec. This is equivalent to

$$L_{ex} = L_{max} + 10 \log_{10} d_{eff} \qquad \text{(F-2)}$$

where L_{max} is the maximum value of $L(t)$ and d_{eff} is the effective duration of the square pulse of equivalent energy.

For multiple events, the equivalent level over a time, T, is

$$L_{eq_1} = 10 \log_{10} \frac{1}{T} \int_0^T 10\left(\frac{L(t)}{10}\right) dt \qquad \text{(F-3)}$$

For a fixed distance

$$L_{eq_2} = 10 \log_{10} \sum 10^{(L_{ex}/10)} + 10 \log \frac{1}{T} \qquad \text{(F-4)}$$

If the exposure level, L_{ex}, is assumed to be constant for all vehicles, the noise due to traffic flow becomes

$$L_{eq_T} = L_{ex} + 10 \log_{10} N + 10 \log \frac{1}{T} \qquad \text{(F-5)}$$

If $T = 3{,}600$ sec and N is the number of vehicles per time, T (here the volume, V), the hourly equivalent level is

$$L_h = L_{ex} + 10 \log V - 35.6 \qquad \text{(F-6)}$$

To evaluate the exposure level, the effective duration, d_{eff}, is determined for an omnidirectional source radiating in a half-space, for a given speed, S ft/sec, and distance, D, in ft, or

$$d_{eff} = \frac{\pi D}{S} \qquad \text{(F-7)}$$

Then,

$$L_{ex} = L_{max} + 10 \log \frac{\pi D}{S} \qquad \text{(F-8)}$$

Combining Eq. F-6 and F-8 gives

$$L_h = L_{max} + 10 \log \frac{VD}{S} - 30.6 \qquad \text{(F-9)}$$

where L_{max} is evaluated at $D = D_o$.

At any distance, D,

$$L_h = L_{max} + 10 \log \frac{VD}{S} - 30.6 + 10 \log (D_o/D)^2 \qquad \text{(F-10)}$$

where no excess attenuation has been taken into account. If $D_o = 50$ ft,

$$L_h = L_{max} + 10 \log \frac{V}{SD} + 3.4 \qquad \text{(F-11)}$$

Because S is expressed in miles per hour rather than feet per second,

$$L_h = L_{max} + 10 \log \frac{V}{SD} + 1.7 \qquad \text{(F-12)}$$

In practice, the value of L_{max} in each vehicle class varies slightly among individual vehicles. To account for this variation of individual vehicles the emission level, EL, for each vehicle class is defined as the root-mean-square of the distribution of individual maximum sound levels for a large random distribution of vehicles of a specified class.

For distributions of sound level maxima, the emission level is given by

$$\text{EL} = L_{50} + 0.115\, \sigma^2 \qquad \text{(F-13)}$$

where L_{50} is the median and σ the standard deviation.

The final result for the hourly equivalent level is

$$L_h = \text{EL} + 10 \log \frac{V}{SD} + 1.7 \text{ dB(A)} \qquad \text{(F-14a)}$$

which may be rounded to

$$L_h = \text{EL} + 10 \log \frac{V}{SD} + 2 \text{ dB(A)} \qquad \text{(F-14b)}$$

For each class of vehicle, the emission level will be assigned the following values, at a distance, D_o, = 50 ft.

Autos	$\text{EL}_1 = 22 + 30 \log S$	dB(A)	(F-15a)
Medium trucks	$\text{EL}_2 = 32 + 30 \log S$	dB(A)	(F-15b)
Heavy trucks	$\text{EL}_3 = 90$	dB(A)	(F-15c)

These values are based on average experimental studies of drive-by's of single vehicles.

A further adjustment is needed to ensure that the model leads to values that are comparable to actual measurements of highway noise under free-field conditions. Comparisons performed against the data acquired under a previous research project (*3*) show that the present model tends to overpredict, which can be attributed to the fact that a number of phenomena have been neglected. The assumptions that traffic flow may be represented by a line source and that no shielding of one vehicle by another takes place may account for the error.

Therefore, a constant has to be introduced into the model on an empirical basis. The source level, SL, will be defined as the *effective level* emitted by a source under actual traffic conditions, or

$$\mathrm{SL} = \mathrm{EL} - 4\ \mathrm{dBA} \tag{F-16}$$

Eq. F-14a then becomes

$$L_h = \mathrm{SL} + 10 \log \frac{V}{DS} + 2\ \mathrm{dBA} \tag{F-17}$$

where the source level is obtained from the emission level.

When necessary, the present model can be altered to reflect changes in the emission levels of vehicles. The creation and enforcement of new laws as well as the progressive introduction of quieter vehicles may warrant such a modification. In particular, for long-range predictions, revised emission levels should be considered.

Corrections Due to a Finite Attenuated Line Source

In the previous section the equivalent level for an infinite line source was determined assuming single-hemispherical spreading (i.e., 3 dB/doubling of distance). The model must now be modified for the case when the attenuation for an infinite line source is 4.5 dB/doubling of distance. The reasons for this value are discussed in the text. In fact, because the line source is normally separated into finite length elements, its attenuation must be evaluated in a differential form, then when all the elements are finally integrated to form a line source the intensity will be of the form

$$I \propto 1/D^{1.5} \tag{F-18}$$

This will force the sound pressure levels to vary with distance, as

$$L = \text{constant} - 15 \log D \tag{F-19}$$

In Figure F-1, an infinite line source lies along the x axis. Consider, then, a differential element of the source (from x to $x + dx$) of length dx. Assuming hemispherical spreading from this source element, the resulting intensity at the receiver shown would be

$$dI = \frac{\rho dx}{2\pi r^2} \tag{F-20a}$$

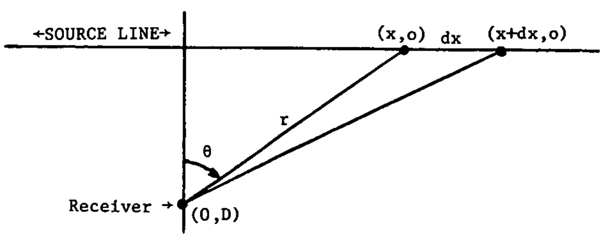


Figure F-1.

where ρ is the power generated per unit length and r is as shown. This expression for dI assumes no propagation losses other than geometrical spreading between source and receiver, and uniform directivity of the source.

If Eq. F-20 is modified to read

$$dI = f(r)\frac{\rho dx}{2\pi r^2} \tag{F-20b}$$

then integrated and solved for $f(r)$ to force a fit to Eq. F-18,

$$I = \int_{-\infty}^{\infty} \frac{f(r)\rho dx}{2\pi r^2} = \frac{\rho}{2\pi}\int_{-\infty}^{\infty} \frac{f(r)dx}{r^2} \tag{F-21}$$

To change to polar coordinates, $\tan\theta = \frac{x}{D}$ and $\sec\theta = \frac{r}{D}$. Then

$$x = D\tan\theta \qquad r = D\sec\theta$$
$$dx = D\sec^2\theta\, d\theta \qquad r^2 = D^2\sec^2\theta$$

hence

$$I = \frac{\rho}{2\pi}\int_{-\pi/2}^{\pi/2} \frac{f(D\sec\theta)\ D\sec^2\theta d\theta}{D^2\sec^2\theta}$$
$$= \frac{\rho}{2\pi D}\int_{-\pi/2}^{\pi/2} f(D\sec\theta)\,d\theta \tag{F-22}$$

Consider the case $f(r) = 1$; i.e., no excess attenuation. Then

$$I = \frac{\rho}{2\pi D}\int_{-\pi/2}^{\pi/2} d\theta = \frac{\rho}{2D} \tag{F-23}$$

which is the expected result.
To force Eq. F-18, we must force

$$\int_{-\pi/2}^{\pi/2} f(D\sec\theta)\,d\theta \propto \frac{1}{\sqrt{D}}$$

It is sufficient to set

$$f(D\sec\theta) = \frac{B\sqrt{D_o}}{\sqrt{D\sec\theta}} \tag{F-24}$$

where D_o is the distance at which the attenuated and mathematical intensities are equal, and solve for B to achieve this condition.

Then

$$I = \frac{\rho B\sqrt{D_o}}{2\pi D}\int_{-\pi/2}^{\pi/2} \frac{d\theta}{\sqrt{D\sec\theta}}$$
$$= \frac{\rho B\sqrt{D_o}}{2\pi D^{1.5}}\int_{-\pi/2}^{\pi/2} \sqrt{\cos\theta}\,d\theta \tag{F-25}$$
$$= \frac{\rho B\sqrt{D_o}}{\pi D^{1.5}}\int_{0}^{\pi/2} \sqrt{\cos\theta}\,d\theta, \text{ since } \sqrt{\cos\theta} \text{ is even in } \theta.$$

Now

$$\int_0^{\pi/2} \sqrt{\cos\theta}\,d\theta = \frac{(2)^{3/2}}{[\Gamma(1/4)]^2} = 1.198, \text{ hence}$$

$$I = \frac{1.198\rho B\sqrt{D_o}}{\pi D^{1.5}} \tag{F-26}$$

To summarize, the calculated intensity due to the infinite line will vary as $1/D^{1.5}$ by forcing the differential element's intensity to vary as $1/r^{2.5}$. Therefore,

$$dI = \frac{\rho dx}{2\pi r^2} B \sqrt{\frac{D_o}{r}}$$

giving 7.5 dB/distance doubling from a point source. Specifically,

$$dI = \frac{B\sqrt{D_o}}{\sqrt{r}} \frac{\rho dx}{2\pi r^2} = \frac{B\rho\sqrt{D_o}dx}{2\pi r^{2.5}}$$

The constant, B, has been preserved in the formulation so that the intensities can be matched at some preferred distance, D_o, as calculated with and without the excess attenuation.

Therefore, from Eqs. F-23 and F-26,

$$\frac{\rho}{2D_o} = \frac{1.198\rho B\sqrt{D_o}}{\pi(D_o)^{1.5}} \qquad \text{(F-27)}$$

and $B = \dfrac{\pi}{2(1.198)} = 1.31$

In summary, Eqs. F-20, F-24, and F-27 combine to

$$dI = \frac{1.31\sqrt{D_o}\rho dx}{2\pi r^{2.5}} \qquad \text{(F-28)}$$

For a point source, this is modified to

$$I_{\text{point}} = \frac{1.3.\sqrt{D_o}\,\Pi}{2\pi r^{2.5}} \qquad \text{(F-29)}$$

where Π is the power generated by the point source.

Also, combining equations F-26 and F-27 for an infinite source yields

$$I_{\text{line}} = \frac{\rho\sqrt{D_o}}{2D^{1.5}} \qquad \text{(F-30)}$$

This is shown graphically in Figure F-2.

From Eq. F-24, $f(r) = 1 = \dfrac{B\sqrt{D_o}}{\sqrt{r_o}}$

and

$$r_o = B^2 D_o = 1.71 D_o \qquad \text{(F-31)}$$

This is shown graphically in Figure F-3.

Thus, the propagation from each differential source to the receiver has been modified by a factor of

$$f(r) = \frac{1.31\sqrt{D_o}}{\sqrt{r}} = 1.31\sqrt{\frac{D_o}{r}}$$

Then

$$(L_{\text{point}})_{\text{atten.}} = (L_{\text{point}})_{\text{not atten.}} + 10 \log f(r)$$

With the foregoing information, the correction due to an attenuated roadway differential element may be determined as follows:

$$\begin{aligned} A_p &= \text{excess propagation atten.} \\ &= 10 \log f(r) \\ &= 1.2 - 5 \log (r/D_o) \end{aligned} \qquad \text{(F-32)}$$

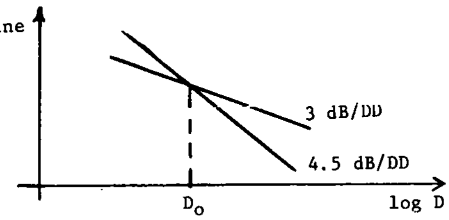


Figure F-2.

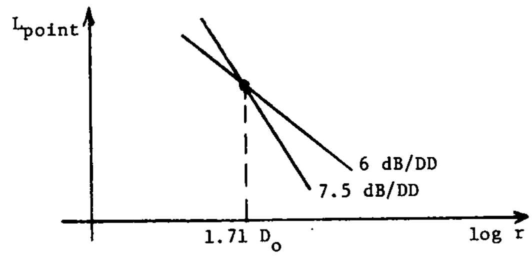


Figure F-3.

So far, only differential elements have been considered in the model. However, the computer program will divide the infinite highway into elements of constant propagation attenuation, A_p (in 1-dB intervals). Each constant propagation attenuation element is a combination of a number of differential elements;

$$A_{p_2} - A_{p_1} = 1\ dB = 1.2 - 5 \log \frac{r_2}{D_o} - 1.2 + 5 \log \frac{r_1}{D_o} \qquad \text{(F-33)}$$

Therefore, $r_1/r_2 = 1.6$ (see Fig. F-4 for an example) and each element, 1, 2, 3, . . ., has now a single propagation attenuation.

For a finite element, Eq. F-17 must be modified to take into account the reduction in equivalent level. If θ is the subtended angle (in radians) under which the element is seen from the observer, the decrease will be 10 log (θ/π). Inasmuch as this approximate approach fails for small angles, it will be used for angles larger than 5°. Then the finite attenuated line source becomes

$$L_{l_\theta} = \text{SL} + 10 \log \frac{V}{SD} + 2 + \left[1.2 - 5 \log \frac{r_N}{D_o}\right] - 10 \log \frac{\pi}{\theta} \qquad \text{(F-34)}$$

with $\theta > 5°$, where r_N and r_F are the distances (in feet)

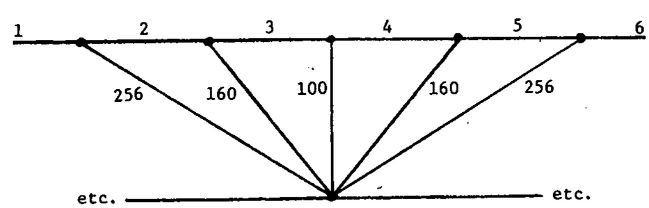


Figure F-4.

from the observer to the closest and farthest element points, respectively. This equation is correct only if the ratio r_F/r_N is equal to or smaller than 1.6.

Correction Due to Small Subtended Angle ($\theta < 5°$)

It is physically reasonable to expect virtually no change in L_{eq} for receivers in the "end zone" as shown in Figure F-5. This follows automatically from the mathematics. Consider the geometry of Figure F-6. The first step is to compute the noise level at the receiver (O,D) and then take the limit at $D \to 0$. The limit is expected to be bounded and to be approached very slowly. Both the 3-dB/DD and the 4.5-dB/DD cases are considered; they are called, for brevity, nonattenuated and attenuated and take into account the absence or presence of excess attenuation due to the ground. Intuitively, for the 3-dB/DD case, as $D \to 0$ the infinite-road level rises 3 dB for each halving of D. Also, the angle $\theta_2 - \theta_1$ halves for each halving of D, so that the angle adjustment exactly cancels the 3-dB increase.

It is hoped that this cancellation also occurs in the 4.5-dB/DD case.

For the 4.5-dB/doubling of distance case, Eq. F-25 is rewritten with different angular limits. Thus,

$$I = \frac{\rho A\sqrt{D_o}}{2\pi D^{1.5}}\int_{\theta_1}^{\theta_2}\sqrt{\cos\theta}\, d\theta \qquad \text{(F-35)}$$

Let $\alpha \equiv \pi/2 - \theta$. Then $\sin\alpha = \sin(\pi/2 - \theta) = \cos\theta$, and $d\alpha = -d\theta$. Furthermore, as $D \to 0$, $\sin\alpha \to \alpha$. Hence,

$$I = \frac{-\rho A\sqrt{D_o}}{2\pi D^{1.5}}\int_{\alpha_1}^{\alpha_2}\sqrt{\alpha}\, d\alpha = \frac{\rho A\sqrt{D_o}}{2\pi D^{1.5}}\int_{\alpha_2}^{\alpha_1}\sqrt{\alpha}\, d\alpha \qquad \text{(F-36)}$$

The integral equals

$$\tfrac{2}{3}\,\alpha^{3/2}\Big|_{\alpha_2}^{\alpha_1} = \tfrac{2}{3}\,(\alpha_1^{1.5} - \alpha_2^{1.5})$$

Now as $D \to 0$, $\alpha_1 \to D/r_N$ and $\alpha_2 \to D/r_F$. Hence, the intensity in the attenuated case becomes

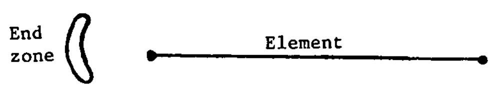


Figure F-5.

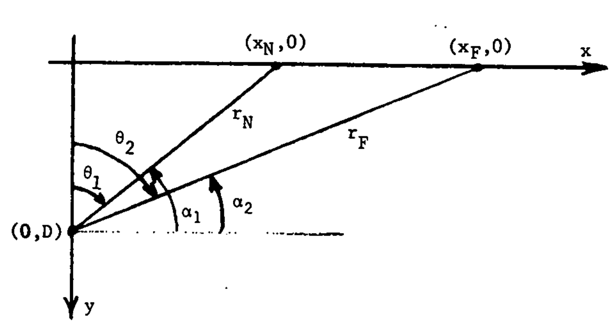


Figure F-6.

$$I_{atten} \to \frac{\rho A\sqrt{D_o}}{2\pi D^{1.5}}\left|\,\tfrac{2}{3}\left(\frac{D^{1.5}}{r_N^{1.5}} - \frac{D^{1.5}}{r_F^{1.5}}\right)\right|$$
$$= \frac{\rho A\sqrt{D_o}}{3\pi}\left(\frac{1}{r_N^{1.5}} - \frac{1}{r_F^{1.5}}\right) \qquad \text{(F-37)}$$

It is independent of D.

Using Eq. F-23 with modified limits, the intensity can be computed for the nonattenuated case:

$$I = \frac{\rho}{2\pi D}\int_{\theta_1}^{\theta_2} d\theta = \frac{\rho}{2\pi D}(\theta_2 - \theta_1)$$
$$= \frac{\delta}{2\pi D}(\alpha_1 - \alpha_2)$$

Again, $\alpha_1 \to D/r_N$ $\alpha_2 \to D/r_F$. Hence,

$$I_{nonatten} \to \frac{\rho}{2\pi D}\left(\frac{D}{r_N} - \frac{D}{r_F}\right)$$
$$= \frac{\rho}{2\pi}\left(\frac{1}{r_N} - \frac{1}{r_F}\right) \qquad \text{(F-38)}$$

Then

$$\frac{I_{atten}}{I_{nonatten}} = \frac{2A\sqrt{D_o}}{3}\,\frac{\left(\dfrac{1}{r_N^{1.5}} - \dfrac{1}{r_F^{1.5}}\right)}{\left(\dfrac{1}{r_F} - \dfrac{1}{r_F}\right)} \qquad \text{(F-39)}$$

As a special case, let $r_F \to \infty$. Then

$$\frac{I_{atten}}{I_{nonatten}} = \frac{2A}{3}\frac{D_o}{r_N}$$
$$= 0.873\, D_o/r_N.$$

Therefore, the attenuated (4.5 dB/DD) and nonattenuated (3.0 dB/DD) intensities will differ significantly only for very small r_N's.

For small angles ($\theta < 5°$), Eq. F-17 will be modified and D is replaced by $D_o = 50$ ft. A correction factor will be included, having the form

$$10\log\left(\frac{1}{r_N} - \frac{1}{r_F}\right) + K \qquad \text{(F-40)}$$

where $K = 12$ dBA.

Thus, this correction factor, referenced at 50 ft, will take the place of both the angular and distance adjustments for both the attenuated and nonattenuated cases.

Summary of Traffic Noise Models

In summary, the equations and various corrections are as follows for $D_o = 50$ ft. Note that all the equations are presented in terms of source levels (SL) due to the reasons presented earlier.

1. Infinite line, nonattenuated (3.0 dB/doubling of distance)

$$L_h = \text{SL} + 10\log\frac{V}{SD} + 2\text{ dB(A)} \qquad \text{(F-17)}$$

2. Infinite line, attenuated (4.5 dB/doubling of distance)

$$L_h \doteq \text{SL} + 10\log\frac{V}{SD} + 2 - 5\log\frac{D}{50} \qquad \text{(F-41)}$$

3. Finite line source length ($\theta > 5°$), nonattenuated

$$L_{h\theta>5°} = \mathrm{SL} + 10 \log \frac{V}{SD} + 2 - 10 \log \frac{\pi}{\theta} \qquad \text{(F-42)}$$

where θ is measured in radians.

4. Finite line source length ($\theta > 5°$), attenuated

$$L_{h\theta>5°} = \mathrm{SL} + 10 \log \frac{V}{SD} + 2 + 2 + \left[1.2 - 5 \log \frac{r_N}{50}\right] - 10 \log \frac{\pi}{\theta} \qquad \text{(F-43)}$$

5. Finite line source length ($\theta \leq 5°$), nonattenuated

$$L_{h\theta\leq5°} = \mathrm{SL} + 10 \log \frac{V}{S(50)} + 2 + 10 \log \left(\frac{1}{r_N} - \frac{1}{r_F}\right) + 12 \qquad \text{(F-44)}$$

6. Finite line source length ($\theta \leq 5°$), attenuated

$$L_{h\theta\leq5°} = \mathrm{SL} + 10 \log \frac{V}{S(50)} + 2 + \left[1.2 - 5 \log \frac{r_N}{50}\right] + 10 \log \left(\frac{1}{r_N} - \frac{1}{r_F}\right) + 12 \qquad \text{(F-45)}$$

DETERMINATION OF L_{10} LEVELS

From the equivalent levels obtained earlier, the L_{10} levels may be determined, taking into consideration the characteristics of the statistical distribution of sound pressure levels.

The statistics of the system are related to the ratio $\frac{VD}{S}$, where V is the volume in vehicles per second, D the equivalent distance in meters, and S the speed in meters per second. A correction is made ultimately so that the U.S. customary units can be used.

First, the parameter, A, is defined as $A = \frac{VD}{S}$, in consistent units. Then $L_{10} - L_{eq}$ is determined in two regimes: (1) for large A (approaching infinity), where the level distribution is expected to be normal; and (2) for small A (approaching zero), for which the vehicles are separable and the distribution is skewed.

L_{10}-Level Conversion for Large A

Using Kurze's (95) results first, which assumed that the sound emission of every source is equal, nondirectional, and uncorrelated with other sources, the second cumulant of the intensity distribution (normalized by the mean intensity) is given by

$$K_2 = \frac{1}{\lambda D(\alpha_2 - \alpha_1)^2} \int_{\alpha_1}^{\alpha_2} \cos^2 \alpha d\alpha \qquad \text{(F-46)}$$

where λ is the average number vehicles per unit length of roadway and the geometry is shown in Figure F-7. Integrating gives

$$K_2 = \frac{1}{\lambda D(\alpha_2 - \alpha_1)^2} \left[\frac{\sin\alpha \cos\alpha}{2} + \frac{\alpha}{2}\right]_{\alpha_1}^{\alpha_2} \qquad \text{(F-47)}$$

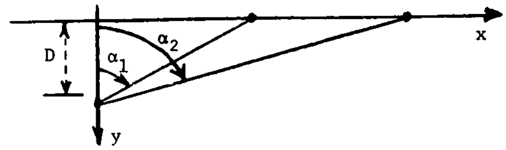


Figure F-7.

For an infinite roadway, $\alpha_1 = -\pi/2$, $\alpha_2 = \pi/2$, $\alpha_2 - \alpha_1 = \pi$. Therefore, since $\lambda = V/S$ Eq. F-47 becomes

$$K_2 = \frac{1}{\lambda D \pi^2}\left[\frac{\pi}{2}\right] = \frac{1}{2\lambda D\pi} = \frac{S}{2VD\pi} \qquad \text{(F-48)}$$

After approximation of the level distribution as an Edgeworth series, Kurze finds that

$$\sigma_L = \frac{10}{\ln 10} \sqrt{\ln(1 + K_2)} = 4.35 \sqrt{\ln\left(1 + \frac{1}{2\pi A}\right)} \qquad \text{(F-49)}$$

For a normal level distribution

$$L_{10} - L_{eq} = 1.28\,\sigma_L - 0.115\sigma_L^2 \qquad \text{(F-50)}$$

Hence,

$$L_{10} - L_{eq} = 5.57 \sqrt{\ln\left(1 + \frac{1}{2\pi A}\right)} - 2.18 \ln\left(1 + \frac{1}{2\pi A}\right) \qquad \text{(F-51)}$$

At high values of A, $L_{10} - L_{eq}$ is slightly underestimated, because the variability of emission levels within any one vehicle type is ignored. Now, consider the case where the standard deviation, σ_{ref}, of each vehicle class is included.

Again, by using results reported by Kurze (95) the second cumulant of the intensity distribution can be written as follows:

$$K_2 = \frac{C_1\left(\frac{\lambda}{D^3}\right) 10^{2L_{ref/10}}\, e^{1/2\left(2\sigma_{ref}\frac{\ln 10}{10}\right)^2}}{\left[(\alpha_2 - \alpha_1)\left(\frac{\lambda}{D}\right) 10^{L_{ref/10}}\, e^{1/2\left(\sigma_{ref}\frac{\ln 10}{10}\right)^2}\right]^2} \qquad \text{(F-52)}$$

where

$C_1 = \frac{1}{2}\,[\sin\alpha_2 \cos\alpha_2 - \sin\alpha_1 \cos\alpha_1 + \alpha_2 - \alpha_1]$

$= \frac{\pi}{2}$ for infinite roadway;

$\lambda = V/S$; and

$\sigma_{ref} =$ standard deviation of the vehicle noise level.

Therefore, Eq. F-52 becomes

$$K_2 = \frac{1}{2\pi A}\, e^{\left(\sigma_{ref}\frac{\ln 10}{10}\right)^2} \qquad \text{(F-53)}$$

Using the results obtained in Chapter Three for the noise emission levels of vehicles, the standard deviation, σ_{ref}, here was chosen to be 4 dB. Then $K_2 = \frac{2.33}{2\pi A}$ and in Eq. F-51 the term $\left(1 + \frac{1}{2\pi A}\right)$ should be replaced by $\left(1 + \frac{2.33}{2\pi A}\right)$.

Based on the foregoing, Eq. F-51 may be modified as follows:

$$L_{10} - L_{eq} = 5.57\sqrt{\ln\left(1 + \frac{0.371}{A}\right)} - 2.18 \ln\left(1 + \frac{0.371}{A}\right) \quad \text{(F-54)}$$

L_{10}-Level Conversion for Small A

Use of Eq. F-14a, where the ratio $\frac{V}{SD}$ is expressed in units of m^{-2}, gives

$$L_{eq} = 28.6 + \text{EL} + 10 \log\left(\frac{V}{SD}\right), \quad \text{(F-55)}$$

where the excess attenuation, $5 \log (D/D_o)$, has been omitted from the model and EL is defined as the emission level. Eq. F-55 may be re-written as

$$L_{eq} = 28.6 + \text{EL} + 10 \log\left(\frac{VD}{S}\right) - 20 \log D \quad \text{(F-56)}$$

To derive the L_{10} level, space the vehicles uniformly on the roadway. The level history during passbys is shown schematically in Figure F-8, where l is the average spacing between adjacent vehicles ($= 1/\lambda = S/V$). For this equal-spacing (periodic) model, the L_{10} can be obtained from examination of the interval, l, as shown. It is evident that the L_{10} occurs when a single vehicle is at a distance of $l/20$ down the road from the receiver. The plan view is shown in Figure F-9. From the geometry,

$$r^2 = D^2 + \frac{S^2}{400V^2} = \frac{400V^2D^2 + S^2}{400V^2} \quad \text{(F-57)}$$

Then

$$L_{10} = \text{EL} - 10 \log\left(\frac{r^2}{D_{\text{EL}}{}^2}\right) \quad \text{(F-58)}$$

where D_{EL} is the distance at which the emission level was determined; i.e., 15.2 m (50 ft).

From Eqs. F-57 and F-58 it follows that

$$L_{10} = \text{EL} - 10 \log\left(\frac{400V^2 D^2 + S^2}{400V^2 D^2_{\text{EL}}}\right) = \text{EL} - 10 \log \frac{\left(\frac{20VD}{S}\right)^2 + 1}{\left(\frac{20VD_{\text{EL}}}{S}\right)^2} \quad \text{(F-59)}$$

Hence, combining Eqs. F-56 and F-59 gives

$$L_{10} - L_{eq} = 20 \log\left(\frac{20VD_{\text{EL}}}{S}\right) - 10 \log\left[\left(\frac{20VD}{S}\right)^2\right] + 1 - 28.6 - 10 \log \frac{VD}{S} + 20 \log D \quad \text{(F-60)}$$

where D is now in meters because

$$20 \log\left(\frac{20VD_{\text{EL}}}{S}\right) = 20 \log\left[\left(\frac{20VD}{S}\right)\left(\frac{D_{\text{EL}}}{D}\right)\right] \quad \text{(F-61)}$$

Eq. F-60 can be rewritten as

$$L_{10} - L_{eq} = 21 + 10 \log A - 10 \log [(20A)^2 + 1] \quad \text{(F-62)}$$

This equation is based on the assumption that the sources have equal power and are equally spaced: because these conditions will lead to the higher limits of the L_{10} values, and in view of the complexity of the problem of considering random sources with variable emission levels, Eq. F-62 is used as such.

Summary of $L_{10} - L_{eq}$ Conversion

For convenience, it is desirable to express the foregoing results in terms of the units used by highway engineers; namely, (a) V, in vehicles per hour; (b) D, in feet; and (c) S, in miles per hour. Making the proper unit transformations, Eqs. F-51 and F-62 become

For Low A

$$L_{10} - L_{eq} = 21 + 10 \log\frac{A}{5{,}280} - 10 \log\left[\left(20\frac{A}{5{,}280}\right)^2 + 1\right] \quad \text{(F-63)}$$

For Large A

$$L_{10} - L_{eq} = 5.57 \sqrt{\ln\left[1 + \frac{(0.371)5{,}280}{2\pi A}\right]} - 2.18 \ln\left[1 + \frac{(0.371)5{,}280}{2\pi A}\right] \quad \text{(F-64)}$$

Eqs. F-63 and F-64 are plotted in Figure F-10 with $\frac{VD}{S}$ in ft/mile.

These equations are used in two ways. First, for the computer method of predicting levels it is convenient to replace the curves of Figure F-10 by the steplike function shown in Figure F-11. Seven classes are used, with the values of $L_{10} - L_{eq}$ tabulated as follows $\left(\frac{VD}{S} \text{ in ft/mile}\right)$:

CLASS	RANGE OF A	$L_{10} - L_{eq}$
I	$16000 \leq \frac{VD}{S}$	1
II	$3000 \leq \frac{VD}{S} < 16000$	2
III	$200 \leq \frac{VD}{S} < 3000$	3
IV	$50 \leq \frac{VD}{S} < 200$	1
V	$25 \leq \frac{VD}{S} < 50$	−2
VI	$10 \leq \frac{VD}{S} < 25$	−5
VII	$\frac{VD}{S} < 10$	—

These values for $L_{10} - L_{eq}$ are approximate. The error for quasi-normal distributions will not exceed 2 dB; however, for $\frac{VD}{S} < 200$ the error can become substantially greater, depending on the actual time history of the traffic.

Second, the L_{10} nomograph developed in the "short method" in the Design Guide (*131*) assumes a single value

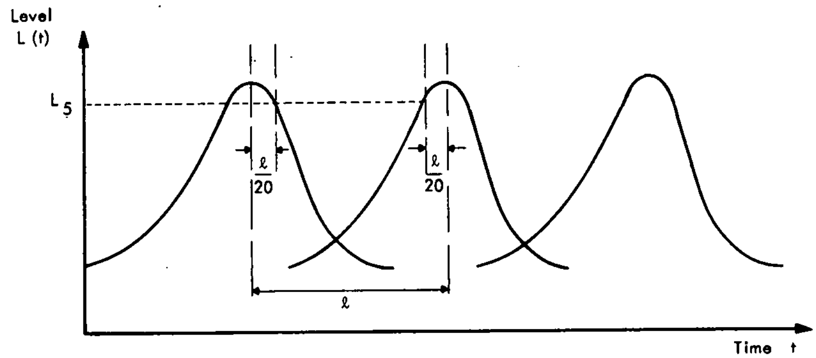


Figure F-8. Time history of uniformly spaced drive-bys.

of $L_{10} - L_{eq}$. A value of 3 dB for $L_{10} - L_{eq}$ was chosen because it is desirable to overpredict L_{10} levels by that method, as explained in the Design Guide (*131*).

ADJUSTMENT AND ELEMENT IDENTIFICATION CRITERIA

The traffic noise models developed so far assume a straight-line source lying at grade on a flat, level terrain. Apart from the flow parameters, the only variables included are the observer distance and the angular dependence. To accommodate such real-life parameters as changes in gradients, traffic parameters, roadway width, etc., it is necessary to develop adjustments to the basic models developed in the first section of this appendix.

The objective of this section is to set forth the mathematical reasons on which these adjustments are based. The resulting rules are then used either to divide the infinite line source into finite elements of constant characteristics (that may be treated using the traffic noise models) or to modify or adjust the values of the traffic noise models as appropriate. All of the rules developed in the following are based on a maximum error of 2 dB(A).

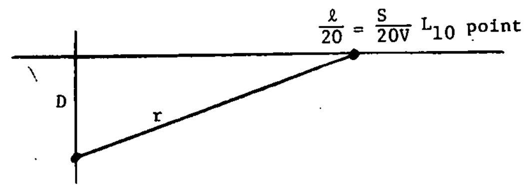


Figure F-9.

The following analysis uses the model adopted in the prediction method; namely, emission levels (in dB(A)).

$$EL_1 = 22 + 30 \log S$$
$$EL_2 = 32 + 30 \log S$$
$$EL_3 = 90$$

for automobiles, medium trucks, and heavy trucks, respectively.

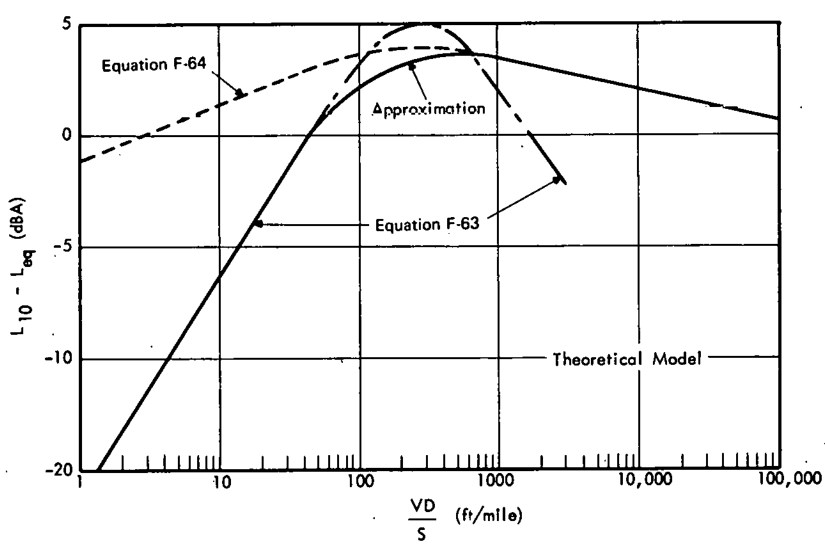


Figure F-10. Conversion from equivalent level to L_{10} ($\rho_{ref} = 4$ dB).

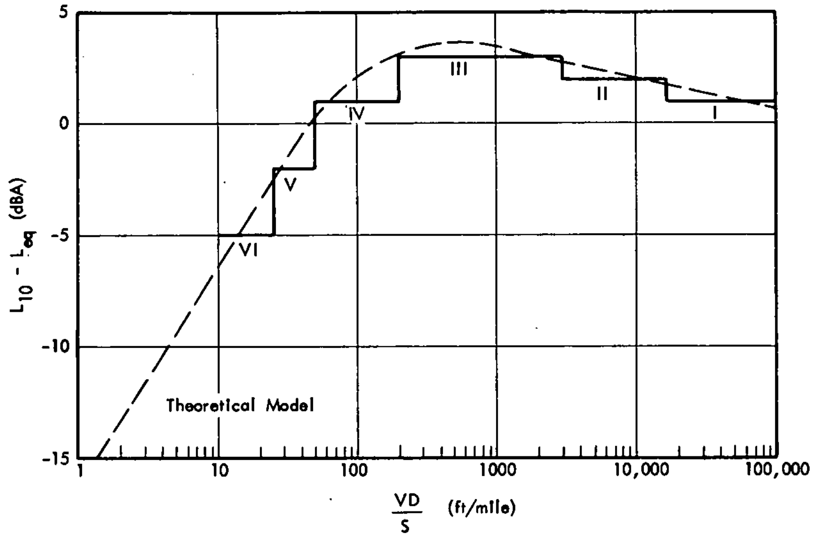


Figure F-11. Conversion from equivalent level to L_{10}, computer model.

Element Identification Criteria: Transverse Splitting

Effect of Volume and Speed Variations

The sound pressure at the observer's location is inversely proportional to the spacing between vehicles and proportional to their noise emission levels.

Other portions of this study have determined the speed dependence of noise emission levels. If it is expressed as the nth power of the speed, n assumes the values of:

3 for cars and medium trucks
0 for heavy trucks

The spacing is equal to S/V, where S is the speed and V is the vehicle volume.

The equivalent level, L_{eq}, can be given the functional form as

$$L_{eq} = k + 10 \log \left(\frac{V}{S} S^n \right) \qquad N = 0, 3 \qquad \text{(F-65)}$$

if all the variables but S and V are assumed constant.

Looking at the variations of L_{eq} with speed and volume,

$$\frac{\partial L_{eq}}{\partial S} = \frac{10}{\ln 10} \left[\frac{1}{VS^{n-1}} \right] (n-1)\, VS^{n-2}$$

$$= \frac{10}{\ln 10} \frac{n-1}{S} \simeq 4 \frac{n-1}{S} \qquad \text{(F-66)}$$

and

$$\Delta L_{eq} = 4 \left(\frac{n-1}{S} \right) \Delta S \qquad n = 0, 3 \qquad \text{(F-67)}$$

Similarly, taking the partial differential with respect to V,

$$\frac{\partial L_{eq}}{\partial V} = \frac{10}{\ln 10} \frac{1}{VS^{n-1}} S^{n-1} = \frac{10}{\ln 10} \frac{1}{V} = \frac{4}{V} \qquad \text{(F-68)}$$

and

$$\Delta L_{eq} = \frac{4}{V} \Delta V \qquad \text{(F-69)}$$

If a 2-dB variation is allowed in L_{eq}, the variations allowed for V and S can be determined, as given in Table F-1.

In conclusion, a change in volume of more than 50 percent will require a new roadway element. A change of speed of 20 percent is a reasonable choice for all three categories. A conservative value is chosen for S, because truck tire noise, which is speed dependent, has been neglected in the model.

Effect of Width Variations

Transverse splitting may be required when the width of the roadway changes by a large amount. The criterion is based on the maximum variation of the roadway-observer distance, D_C, that does not affect the mean energy level by more than 2 dB(A).

For the actual calculation, the distance D_C is replaced by the equivalent distance, D_E, defined as the geometric mean of the near-lane distance, D_N, and the far-lane distance, D_F. The width, W, is the difference between D_N and D_F.

Using the fact that the equivalent level decreases by 4.5 dB per doubling of distance, in the most common case:

$$L_{eq} = k - 15 \log D_E = k - 6.5 \ln D_E \qquad \text{(F-70)}$$

then, by differentiation,

$$\frac{\partial L_{eq}}{\partial D_E} = - \frac{6.5}{D_E} \qquad \text{(F-71)}$$

If L_{eq} is allowed to vary by 2 dB(A), $\Delta D_C / D_C \simeq 0.3$ and D_C is allowed to vary by no more than 30 percent.

To compute the change of equivalent distance corresponding to a change of width,

$$D_e = \sqrt{D_N D_F} = \sqrt{D_N(D_N + W)} \quad \text{(F-72)}$$

and

$$\frac{\partial D_e}{\partial W} = + \tfrac{1}{2}\,(D_N^2 + D_N W)^{-1/2}\,D_N \quad \text{(F-73)}$$

The permitted change in D_e is $\Delta D_e = 0.3 D_e$.
If D_N is assumed constant,

$$\Delta W = \frac{\Delta D_e}{\dfrac{\partial D_e}{\partial W}} = (0.3 D_e)\frac{2(D_N^2 + D_N W)^{1/2}}{D_N} = \frac{6 D_F}{10} \quad \text{(F-74)}$$

If D_F is assumed constant,

$$\Delta W = \frac{6 D_N}{10} \quad \text{(F-75)}$$

More conservatively,

$$\Delta W < \frac{6(D_N - \Delta W)}{10}, \text{ or } \Delta W < 0.4\, D_N \quad \text{(F-76)}$$

$$\Delta W < 0.4\, D_N$$

This indicates that a change in width of more than 40 percent of the near-lane distance would require creation of new element.

Effect of Gradients

The effect of gradients on traffic noise is complex, because the multiple sources that constitute motor vehicular noise vary in many and sometimes opposite ways. For example, for an up-grade condition, engine noise increases. At the same time the speed drops and so does tire noise. Therefore, to determine the effect of gradients, tire noise must be separated from other noise sources.

If the actual speed is used on a grade, the corrections for truck tire noise and for automobiles will be implicitly taken into account and it is only necessary to correct for exhaust and engine noise emission levels of heavy trucks. The latter is based on the fact that the power required is different on a grade from what it is on a level roadway; the noise level correction is

$$10 \log\left(\frac{\text{Power on a grade}}{\text{Power at grade}}\right) \quad \text{(F-77)}$$

An empirical equation can be obtained using data on the power required at various speeds, on different grades (*132*). The correction is

$$\Delta_G = 6.6 - 3.3 \log S + G \qquad \text{in dB(A)} \quad \text{(F-78)}$$

where S is the speed in miles per hour and G is the percent grade.

The correction is further complicated by the fact that the speed is affected by the length of the up-grade section (*135*). However, for the purpose of identifying elements it is sufficient to set the following rule: In a single element, G cannot undergo a change greater than 100 percent (beyond ½ percent).

TABLE F–1

VARIATIONS ALLOWED FOR V AND S

VEHICLE TYPE	n	$\frac{\Delta L_e}{\Delta V}$	$\frac{\Delta L_e}{\Delta S}$	ΔV	ΔS	$\%V$	$\%S$
Heavy trucks	0	$4/V$	$-4/S$	$V/2$	$-(S/2)$	50	50
Autos and medium trucks	3	$4/V$	$8/S$	$V/2$	$S/4$	50	25

Effect of Curves

The rule for curves is simply based on the maximum change allowed for D_E; that is, 30 percent. A detailed technique for curve division is given in the complete method.

Effect of Different Pavement Characteristics

Noise emission levels depend on the type of roadway pavement. Three broad categories are introduced in the method, with corresponding adjustments (see Table F-2). Whenever the pavement characteristics change from one category to another, a new roadway element must be considered.

A recent survey of the existing data (see Chapter Two) shows that these adjustments are approximately corroborated by experimental results. These, however, remain quite inaccurate because of the effects of tire type, tire wear, and pavement characteristics, which are only weakly accounted for.

Element Identification Criteria: Longitudinal Splitting

The rules for longitudinal splitting are based on the same criteria on L_{eq} and D_E as for transverse splitting.

Effect of Median

The two directions of flow on a highway are often simulated by a single line source when the vehicles are uniformly distributed along the highway width. When the roadways are widely separated, the single line source model loses it accuracy, inasmuch as distance attenuation and

TABLE F–2

NOISE EMISSION LEVEL ADJUSTMENTS FOR VARIOUS PAVEMENT SURFACES

NO.	SURFACE TYPE	SURFACE DESCRIPTION	ADJUSTMENT (dB)
1	Normal	Moderately rough asphaltic and concrete surface	0
2	Smooth	Very smooth, seal-coated, asphaltic pavement	−5
3	Rough	Rough asphaltic pavement with large voids≥½-in. diameter); grooved concrete	+5

shielding attenuation have significantly different effects on the two sides of the roadway.

Based on the maximum error of 2 dBA if the median exceeds 200 ft wide, the two flows should be treated as separate line noise sources.

Effect of Unbalanced Directional Flow

In a perfectly balanced flow, one-half of the traffic would go in one direction and one-half in the other. However, when the volume is not distributed evenly in both directions, it may become mandatory to divide the roadway into two line sources.

Consider an equivalent distance weighted by traffic:

$$D_e = \frac{V_F}{V_N + V_F}\left[\sqrt{(D_N + W + M)(D_N + 2W + M)} - \sqrt{D_N(D_N + W)}\right] + \sqrt{D_N(D_N + W)}$$
$$= \frac{K}{1+\alpha} + \sqrt{D_N(D_N + W)} \qquad \text{(F-79)}$$

where V_F and V_N are the traffic volumes on the roadways, respectively, far from the observer and near the observer; D_N is the distance from the observer to the near lane; W is the width of the near roadway and also of the far roadway; and M is the median width.

The traffic imbalance, α, is defined as the ratio of V_N and V_F. Then

$$\frac{\partial D_e}{\partial \alpha} = -\frac{K}{(1+\alpha)^2} \qquad \text{(F-80)}$$

and

$$\Delta\alpha = -\frac{\Delta D_e\,(1+\alpha)^2}{K} \qquad \text{(F-81)}$$

Inasmuch as

$$\Delta D_e = 0.3\,D_e = 0.3\sqrt{D_N(D_N + 2W + M)},$$
$$\Delta\alpha = \frac{0.3\sqrt{D_N(D_N + 2W + M)}\,(1+\alpha)^2}{K} \qquad \text{(F-82)}$$

and

$$\Delta\alpha \simeq \frac{0.3\sqrt{D_N(D_N + 2W + M)}\,(1+\alpha)^2}{\sqrt{D_N + W + M}\,\sqrt{D_N + 2W + M} - \sqrt{D_N(D_N + W)}} \qquad \text{(F-83)}$$

If the median width, M, is more than 200 ft, the roadway should be divided for other reasons than traffic imbalance. Therefore, the most unfavorable case for $M =$ 200 ft is that of a close observer ($D_N = 50$ ft). Setting the width, W, at 60 ft,

$$\Delta\alpha \simeq 0.15\,(1+\alpha)^2 \qquad \text{(F-84)}$$

A severe traffic imbalance, with $V_N = 30\%\ V$, would lead to $\alpha = V_{NR}/V_{FR} = 3/7 \rightarrow \Delta\alpha = 0.3$. Therefore, a 30 percent departure from perfectly balanced traffic requires longitudinal division of the roadway.

Effect of Directional Average Speed

It was shown earlier that a 20 percent change in average speed results in a variation of L_{eq} of the order of 2 dB. The same principle applies to longitudinal division: if the difference in directional average speeds exceeds 20 percent, the two directions of flow should be treated separately.

Effect of Barriers

If a barrier in the median may provide an attenuation in excess of 5 dB(A), the two roadways should be divided.

The attenuation provided by an obstacle can always be found using the barrier nomograph; see Design Guide (*131*), Chapter Five.

Effect of Directional Flow Elevation

It may be necessary to consider two parallel roadways separately whenever there is a significant difference in elevation between them. A conservative procedure would include dividing the roadways whenever the elevations of the two directional flows differ by 5 ft or more. This figure is based on the minimum barrier height that is considered to be efficient.

Effect of Pavement Surfaces

If the surfaces of the two roadways belong to different surface types, according to the definitions presented previously, they should be considered separately. The speed to be used on grades is the actual speed of each vehicle class.

Adjustments

A number of adjustments are also provided in the complete method (see Design Guide (*131*), Chapter Six). They are based on the same principles as the foregoing criteria and include the surface and gradient adjustments, the element and ground attenuation adjustments, and the various adjustments for shielding by barriers, structures, and vegetation.

Finally, some considerations are set forth on the eventual adjustment of emission levels.

Element and Ground Attenuation Adjustment

The adjustments for angle subtended and for the excess attenuation provided by the ground were introduced in the first section of this appendix. The standard value is 4.5 dBA per doubling of distance, which takes into account, in addition to the attenuation due to hemispherical spreading, an excess attenuation due to the ground. However, when the surface of the terrain is highly reflective, which is the case with asphalt or concrete, a value of 3 dB per doubling of distance should be used, reflecting only the geometric spreading. Similarly, for receivers high above the ground the effect of attenuation by the ground cover becomes negligible and the 3 dB per doubling of distance shall be used. These conditions are built into the computer program.

Surface Adjustment

The corrections for different types of road surface are:

SURFACE TYPE	CORRECTION
Normal	0
Smooth	−5
Rough	+5

The computer program includes this adjustment. A detailed description of these surface types is included in the design guide. However, it should be noted that under most circumstances this correction is zero (normal surface) unless one of the other two surface types is specifically identified in the design.

Gradient Adjustment

At a given speed, S, and percent gradient, G, the correction is given by

$$\Delta_G = 6.6 - 3.3 \log S + G \qquad \text{dB(A)} \qquad \text{(F-85)}$$

and applies only to heavy trucks.

For a two-way highway, calculated as a single line source, the correction is applied to all the heavy trucks. However, if each direction is treated as a line source, a more accurate picture can be obtained by assigning the adjustment only to heavy trucks going up grade.

Shielding Adjustments

(a) *Barriers.*—The effects of barriers on the propagation of highway noise have been analyzed both theoretically and experimentally (*3*). The model chosen here for the calculation of barrier attenuation is based on the Kurze-Anderson model (*136*).

The equations to be used are the following:

$$\text{NR}_\text{B} = \begin{cases} 0 & \text{for } N \leq -0.2 \\ 20 \log \dfrac{\sqrt{2\pi N}}{\tan \sqrt{2\pi N}} + 5 \text{ dB} & \text{for } -0.2 < N \leq 0 \\ 20 \log \dfrac{\sqrt{2\pi N}}{\tanh \sqrt{2\pi N}} + 5 \text{ db} & N > 0 \\ 20 \text{ dB maximum} & \end{cases} \qquad \text{(F-86)}$$

where NR_B is the noise reduction provided by the barrier and N is the Fresnel number for a frequency of about 500 Hz.

$$N = 2\frac{\delta}{\lambda} \simeq \delta \qquad \text{(F-87)}$$

where δ is the path length difference.

(b) *Structures.*—The shielding provided by structures is computed according to the results of a recent study (*3*), which assigns a certain attenuation for each row of structures, as tabulated earlier. To determine whether a row of structures is actually an effective acoustic shield, the user must determine that the gaps between structures do not constitute more than 50 percent of the row length. Once this is established, the following corrections apply:

STRUCTURE SHIELDING	NOISE REDUCTION (*dBA*)
First row	4.5
Additional row	1.5 each
Maximum	10

The correction applies only if the line of sight is interrupted by the row. This condition is checked automatically by the computer.

(c) *Vegetation.*—In general, planting either at the roadside or in the terrain between the roadway and the observer position has little influence on the propagation of traffic noise (*1*). Bushes, trees, and similar foliage can attenuate sound only if the growth is dense enough and the depth of the foliage is great, as some experimental measurements (*137, 138, 139*) indicate.

A single line of trees, or a depth of trees of less than 50 to 100 ft, will provide little actual attenuation; rather, the visual isolation may reduce a person's awareness of the noise to a great extent.

A design value of 5 dB(A) noise reduction for every 100 ft of planting depth is to be used if these trees are at least 15 ft tall and sufficiently dense so that no visual paths between observer and roadway exist. This attenuation should not exceed a maximum of 10 dB(A). In the computer program, this correction is taken into account only if the vegetation actually interrupts the line of sight between observer and roadway.

Efficient tree belts can be conceived provided the underbrush is thick enough to prevent sound propagation under the canopy and that a mixture of deciduous and evergreens is used to ensure that the efficiency of the belt is not seasonal.

Emission Level Adjustments

The emission levels (EL) used in the model are based on recent measurements summarized in Chapter Three.

Because no information is available on the variety of emission levels, corresponding to different areas and to different times that may be used in the future, no option is left to the user in this regard. However, whenever the effect of new regulations and new noise control technologies is felt, the user will be able to introduce revised emission levels in the computer program.

APPENDIX G

SUMMARY OF TYPICAL EXTERIOR BUILDING CONSTRUCTIONS

A. SINGLE-FAMILY RESIDENCE

1. *Existing Structures*

(a) *Structural frame:* Wood-framed walls and roof. Wall may be masonry in South.
(b) *Exterior walls:* Conventional stud wall with stucco, lightweight siding, or brick veneer on exterior, and plaster (or drywall) on interior. Stucco predominant in South, and brick veneer in North. Light- or medium-weight masonry wall with furred plaster on interior may be found in South.
(c) *Windows:* Single- or double-strength glass in operable sash. Sliding sash window predominant in South. Double-hung or hinged sash predominant in Middle and North. Storm sash or insulating glass also used in North zone. Window sash in Middle and North are moderately weatherstripped.
(d) *Exterior doors:* Single, hinged, lightweight wood doors at entrances in South and Middle, and heavy wood door with storm door in North. Two doors separated by vestibule also found in North. Doors in North may be moderately weatherstripped. Also, sliding glass door in at least one room of dwelling in South and Middle.
(e) *Roof/Ceiling:* Lightweight roofing on wood sheathing over vented attic space and plaster ceiling below. Roofing on spaced board sheathing in South, continuous sheathing in Middle and North. Dwelling in South may have at least one room with exposed roof deck.
(f) *Underfloor:* Slab on grade or wood floor over vented crawl space in South. Wood floor over crawl space or unoccupied basement in Middle. Basement in North.
(g) *Environmental control:* Typically, dwellings not air conditioned. Central gas heater units with forced-air duct system and through-the-wall air-conditioning unit in one or two rooms in dwelling in South. Gas- or oil-fired furnace and forced hot air in Middle. Central furnace with hot-water convector, steam radiator, or forced-air ducts in North.

2. *Planned Structures*

Exterior construction basically the same as that of existing structures, except the majority of dwellings in South have sliding sash windows only, and exposed wood plank roof deck in at least one room and no through-the-wall unit. Also, the majority of dwellings in North have gas- or oil-fired furnaces with forced-air duct distribution system or terminal convectors in each room.

B. MULTI-FAMILY DWELLING

1. *Existing Structures*

(a) *Structural frame:* Two- or three-story wood-framed walls and roof. Load-bearing masonry walls also found in Middle and North.
(b) *Exterior walls:* Majority of dwellings have conventional stud wall with stucco, lightweight siding, or brick veneer on exterior, and plaster (or drywall) on interior. Stucco predominant in South, and brick veneer in North. Light- or medium-weight masonry wall with furred plaster on interior may be found in South. Medium- or heavyweight masonry also in Middle or North.
(c) *Windows:* Single- or double-strength glass in operable sash. Sliding sash window predominant in South. Double-hung or hinged sash predominant in Middle and North. Storm sash or insulating glass also used in North zone. Window sash in Middle and North are moderately weatherstripped.
(d) *Exterior doors:* Single, hinged, lightweight wood doors at entrances in South and Middle, and heavy wood door with storm door in North. Two doors separated by vestibule also found in North. Doors in North may be moderately weatherstripped. Also, sliding glass door in at least one room of dwelling in South and Middle.
(e) *Roof/Ceiling:* Lightweight flooring on wood sheathing over vented attic space and plaster ceiling below. Roofing on spaced board sheathing in South, continuous sheathing in Middle and North. Dwelling in South may have at least one room with exposed roof deck; many dwellings have ceilings fastened to bottom of roof rafters with flat or sloped roofs.
(f) *Underfloor:* First floor on concrete slab on grade or wood floor over vented crawl space in South. Wood floor over crawl space or unoccupied basement in Middle. Basement in North.
(g) *Environmental control:* Typically, dwellings not air conditioned, but heated only. Central gas heater units with forced-air duct system and through-the-wall air-conditioning unit in one or two rooms per dwelling units in South. Some dwellings in the South have central station equipment with terminal units in each dwelling. Gas- or oil-fired furnace and forced hot air in Middle. Central furnace with hot-water convector, steam radiator, or forced-air ducts in North.

2. *Planned Structures*

Exterior construction basically the same as that of existing structures, except majority of dwelling units in South have sliding sash windows only and no through-the-wall units.

Also, the majority of dwellings in North have gas- or oil-fired furnaces with forced-air duct distribution system or terminal convectors in each room.

C. HIGH-RISE APARTMENT

1. **Existing Structures**

(a) *Structural frame:* Steel and/or concrete.
(b) *Exterior walls:* In South, stucco on metal studs with plaster on interior, or light- to medium-weight masonry panels with furred plaster on interior. Light- to medium-weight masonry panels or veneer with furred plaster on interior found in Middle and North. Also, many structures with curtain-wall construction found in all zones.
(c) *Windows:* Double-strength, crystal, or plate glass in fixed or operable sash. Sliding sash predominant in South, and hinged or double-hung predominant in Middle and North. Windows most likely weather-stripped.
(d) *Exterior doors:* One sliding glass door to balcony in South and Middle.
(e) *Roof/Ceiling:* Built-up roofing on concrete slab with plaster ceiling applied directly to bottom surface of slab.
(f) *Underfloor:* First floor on concrete slab over parking or unoccupied basement.
(g) *Environmental control:* Central-station equipment with terminal units supplying year-around heating and cooling to each apartment.

2. *Planned Structures*

Exterior building construction is basically the same as that of existing structures, except more structures in North may have sliding doors to balconies.

D. SCHOOLS

1. *Existing Structures*

(a) *Structural frame:* Wood- or steel-framed walls and roof, or load-bearing masonry wall.
(b) *Exterior walls:* In South, conventional stud wall with stucco or wood siding on exterior and plaster on interior is predominant. In the Middle, stucco or brick veneer is predominant. Also, some structures in Middle and North have medium- to heavyweight masonry with plaster furred on the interior. Some recent schools in all zones have curtain-wall construction.
(c) *Windows:* Double-strength glass in double-hung or hinged sash. In North, insulating glass in some window sash. Sash in Middle and North often moderately weatherstripped.
(d) *Exterior doors:* In South and Middle, single heavy metal or wood hinged door for each classroom on ground floor. Doors are moderately weatherstripped. Classrooms in North do not have exterior doors.
(e) *Roof/Ceiling:* Lightweight roofing on continuous wood sheathing over vented attic or rafter space with plaster ceiling below or ceiling fastened directly to bottom of roof rafters. Built-up roofing on flat roofs in Middle and North.
(f) *Underfloor:* First floor on concrete slab on grade or over vented crawl space. Slab of school in North on grade or over unoccupied basement.
(g) *Environmental control:* Classrooms typically are not air conditioned, but heated only. Central-station equipment with terminal convectors or fan coil units serving each classroom.

2. *Planned Structures*

Exterior construction is basically the same as that of existing structures.

E. CHURCH

1. *Existing Structures*

(a) *Structural frame:* Wood-framed roof and load-bearing masonry walls.
(b) *Exterior walls:* Medium- or heavyweight masonry or stone wall exposed to the interior or with furred plaster on interior. Some structures in South have conventional stud wall with stucco on exterior.
(c) *Windows:* Double-strength or plate glass in fixed sash with small area of hinged operable sash.
(d) *Exterior doors:* Main entrance through double wood doors separated by vestibule. Side exits through single wood doors. Doors in North have moderately airtight gaskets.
(e) *Roof/Ceiling:* Lightweight roofing on wood plank deck on wood beams. Majority of structures have exposed roofs on interior.
(f) *Underfloor:* Slab on grade.
(g) *Environmental control:* Majority of structures not air conditioned, but heated only. Central-station equipment and terminal convector or forced-air ducted system.

2. *Planned Structures*

Exterior building construction is basically the same as that of existing structures.

F. AUDITORIUM

1. *Existing Structures*

(a) *Structural frame:* Masonry walls and steel frame.
(b) *Exterior walls:* Heavy masonry with or without interior furred plaster.
(c) *Windows:* Majority do not have windows.
(d) *Exterior doors:* Entrance through double doors separated by vestibule. Some have direct-exit single doors from stage area.
(e) *Roof/Ceiling:* Built-up roofing on lightweight concrete on metal deck on steel trusses with no plaster ceiling below.
(f) *Underfloor:* Slab on grade.
(g) *Environmental control:* Center-station equipment, ducted forced-air, providing year-around heating and air conditioning.

2. *Planned Structures*

Exterior building construction is basically the same as that of existing structures.

G. HOSPITAL

1. *Existing Structures*

(a) *Structural frame:* Steel and/or concrete.
(b) *Exterior walls:* Masonry panels or veneer with plaster furred on interior. In South, some structures have stucco on metal studs with plaster on the interior.
(c) *Windows:* Double-strength or plate glass in fixed or operable sash. Sliding sash predominant in South. Hinged or double-hung sash predominant in Middle and North, and such sash with moderately efficient weatherstripping.
(d) *Exterior door:* None to patient room.
(e) *Roof/Ceiling:* Built-up roofing on concrete with plaster ceiling suspended below.
(f) *Underfloor:* Slab on grade or slab over unoccupied basement.
(g) *Environmental control:* Central-station equipment with forced-air duct system or terminal units supplying year-around heating and air conditioning.

2. *Planned Structures*

Exterior building construction is basically the same as that of existing structures, except some structures with glass curtain-wall construction and ceiling on top floor may have suspended acoustical tile instead of plaster.

H. LOW-RISE MOTEL

1. *Existing Structures*

(a) *Structural frame:* Wood-framed walls and roof. Load-bearing masonry walls in Middle and North.
(b) *Exterior walls:* Conventional stud wall with stucco in South, brick veneer or lightweight siding in Middle and North, with plaster on interior. Some structures have masonry units with furred interior plaster.
(c) *Windows:* Double-strength glass in operable sash. Sliding sash predominant in South. Hinged or double-hung sash predominant in Middle and North. Windows in Middle and North moderately efficient weatherstripping on sash. In South, sliding glass door to balcony often used in lieu of window.
(d) *Exterior doors:* Single heavy wood door to each guest room in South and Middle. Typically, guest room in North has no exterior door.
(e) *Roof/Ceiling:* Lightweight roofing on wood sheathing with plaster ceiling below an attic space or fastened to bottom of roof rafter.
(f) *Underfloor:* Slab on grade.
(g) *Environmental control:* Through-the-wall air handling unit or central-station equipment with terminal units in each room supplying year-around heating and air conditioning.

2. *Planned Structures*

Exterior building construction is basically the same as that of existing structures.

I. HIGH-RISE HOTEL

1. *Existing Structures*

(a) *Structural frame:* Steel or concrete.
(b) *Exterior walls:* Masonry panels or veneer with furred plaster on interior. Some structures in the South have stucco on exterior of metal studs, and plaster on interior. Some recent structures have curtain-wall construction.
(c) *Windows:* Double-strength or plate glass in operable hinged sash or fixed sash. Sliding sash predominant in South. Hinged or double-hung sash predominant in Middle and North. Windows in Middle and North have moderately efficient weatherstripping on sash.
(d) *Exterior doors:* Some structures have sliding glass doors to balconies in lieu of windows. Majority of guest rooms are without exterior doors.
(e) *Roof/Ceiling:* Built-up roofing on concrete slab, no ceiling below.
(f) *Underfloor:* Concrete slab over unoccupied basement.
(g) *Environmental control:* Through-the-wall air-handling unit or central-station equipment with terminal units in each room supplying year-around heating and air conditioning.

2. *Planned Structures*

Exterior building construction is basically the same as that of existing structures, except more structures have curtain-wall construction.

J. HIGH-RISE COMMERCIAL

1. *Existing Structures*

(a) *Structural frame:* Steel and/or concrete.
(b) *Exterior walls:* Glass curtain wall; or masonry, brick veneer, or panels with plaster furred on interior.
(c) *Windows:* Plate glass in fixed sash.
(d) *Exterior doors:* None on high-rise floors.
(e) *Roof/Ceiling:* Built-up roofing on concrete slab. Plaster or acoustical tile ceiling suspended below.
(f) *Underfloor:* Concrete slab over unoccupied basement.
(g) *Environmental control:* Central-station equipment with ducted forced-air system and/or terminal units supplying year-around heating and air conditioning.

2. *Planned Structures*

Exterior building construction is basically the same as that of existing structures, except most exterior walls are glass curtain walls, and ceiling on top floor is suspended acoustical tile ceiling.

K. LOW-RISE COMMERCIAL

1. *Existing Structures*

(a) *Structural frame:* Wood or steel wall or roof framing, or load-bearing masonry walls.
(b) *Exterior walls:* Structures in South, conventional stucco and stud wall or light- to medium-weight masonry block wall with plaster furred on interior. In Middle and North, masonry walls or brick veneer on studs plus plaster on interior. Some recent structures have glass curtain wall.
(c) *Windows:* Double-strength or plate glass in operable sash or fixed sash. Sliding sash predominant in South. Hinged double-hung sash predominant in Middle and North. Windows in Middle and North have moderately efficient weatherstripping on sash.
(d) *Exterior doors:* In South and Middle, single lightweight hinged door. In North, two hinged doors separated by vestibule.
(e) *Roof/Ceiling:* Lightweight roofing on continuous sheathing or lightweight concrete on metal deck. Plaster ceiling fastened to bottom of roof rafters or acoustical tile ceiling suspended below roof structure.
(f) *Underfloor:* Slab on grade.
(g) *Environmental control:* Majority with central-station equipment or packaged air-handling unit with forced-air system or terminal units supplying year-around heating and air conditioning.

2. *Planned Structure*

Exterior building construction is basically the same as that of existing structures.

L. INDUSTRIAL PLANT

1. *Existing Structures*

(a) *Structural frame:* Wood or steel wall and roof frame. Also load-bearing masonry walls.
(b) *Exterior walls:* Masonry units, heavy concrete or metal insulated panels on exterior with no plaster on interior. Some structures in South have stucco or metal siding.
(c) *Windows:* Minimum number of operable windows. Some with glass skylights. Double-strength glass in hinged sash.
(d) *Exterior doors:* Large sliding or roll-up metal service doors. Also lightweight metal hinged doors in South and Middle and heavyweight metal doors in North. Typical doors are not weatherstripped.
(e) *Roof/Ceiling:* In South and Middle, lightweight roofing on metal or plywood deck with no ceiling below. In North, lightweight roofing or lightweight concrete on metal or plywood deck with no ceiling below.
(f) *Underfloor:* Slab on grade.
(g) *Environmental control:* Indoor spaces not air conditioned or treated by central system. Typically, spaces are ventilated by unit fans and heated by gas or electric unit heaters.

2. *Planned Structures*

Exterior building construction is basically the same as that of existing structures, except exterior wall most likely constructed of precast concrete panels or masonry.

M. CONCLUDING COMMENTS

The foregoing descriptions of exterior constructions consider the following items:

1. Interior surfaces of exterior walls and ceilings are described as being plaster (on lath). These interior surfaces may be drywall (gypsum board) construction. Constructions ten or more years old most likely include plaster walls. Structures not more than five years old most likely include drywall construction. Planned construction most likely will include drywall, not plaster, construction.

2. Glass of windows is described as being single thickness. However, insulating (double) glass may be used in windows in the North zone for thermal insulation. Nevertheless, in analyzing noise reduction, all glass is considered to be single thickness. The acoustical performance of insulating glass is similar to single-thickness glass. The acoustical benefits provided by double-glazed construction are not realized with insulating glass because the airspace between panes of insulating glass is only a fraction of an inch.

3. Basements are considered to be unoccupied or noncritical spaces. If basement areas are used as living or commercial spaces, recommended modifications to windows and doors on floors above grade also apply to basement construction.

4. Low-cost apartment structures housing low social-economic groups most likely are not air conditioned. Such existing structures should be provided with air-conditioning systems when modified, even though other similar structures have year-around air-treatment system. Of course, planned low-cost structures should include central year-around systems.

APPENDIX H

DESCRIPTION OF CONVENTIONAL EXTERIOR CONSTRUCTION COMPONENTS AND MATERIALS

A. MAIN STRUCTURAL FRAME

1. *Framing Members*

(a) *Vertical members:* Column, walls, and studs.
(b) *Horizontal members:* Roof deck or slab, girder or beam, roof purlin or rafter, ceiling or floor joist.

2. *Material*

Concrete, steel, masonry, or wood.

B. EXTERIOR WALLS

1. *Stud Wall*

(a) *Lightweight siding:* Wood, wood fiber, plywood, hardboard, light-gauge metal or steel, asphalt or cement asbestos board weighing 3 psf or less. Typically applied over sheathing.
(b) *Heavyweight siding:* Heavy-gauge metal or asbestos board weighing 4 psf or greater.
(c) *Brick or stone veneer:* Brick or stone weighing 30 psf or greater. Brick typically applied over sheathing.
(d) *Exterior plaster:* ¾- to 1-in. stucco.
(e) *Exterior sheathing:* Wood board, wood fiberboard, plywood, or gypsum board.
(f) *Studs:* Wood or metal, minimum 3½ in. deep.
(g) *Insulation between studs:* Glass-fiber or mineral-wool blanket insulation.
(h) *Interior wall:* Gypsum board (drywall) or plaster on metal or gypsum lath (wood-strip lath in old structures).
(i) *Conventional stud walls:* Lightweight siding on sheathing on exterior of studs, and drywall or plaster on interior of studs. Brick or stone veneer fastened to exterior of studs or to sheathing on exterior of studs, and drywall or plaster on interior of studs. Stucco on exterior of studs, and drywall or plaster on interior of studs. Insulation not necessarily provided between studs in the above stud walls.

2. *Masonry Walls*

(a) *Types of masonry units:* Stone block; clay tile or brick; hollow, lightweight concrete block (with light aggregate); solid lightweight concrete block; hollow heavyweight concrete block (with heavy aggregate); solid heavyweight concrete block; and hollow concrete block with cells filled with sand or grout (also considered solid block construction).
(b) *Solid concrete:* Precast or poured-in-place with lightweight aggregate of approximate 100-pcf density; precast or poured-in-place stone-aggregate concrete of approximate 150 pcf density.
(c) *Lightweight masonry:* Masonry wall with a surface weight of 20 to 40 psf, such as clay tile, 4-in.-wide brick (veneer) or hollow lightweight concrete block.
(d) *Mediumweight masonry:* Masonry wall with a surface weight of 41 to 60 psf, such as hollow heavyweight concrete block or solid lightweight concrete or concrete unit.
(e) *Heavyweight masonry:* Masonry wall with a surface weight of greater than 60 psf, such as solid heavyweight concrete or concrete block, or brick 8 in. or more wide.
(f) *Furred interior wall:* Drywall or plaster-on-lath on wood or metal furring or studs.

3. *Glass Curtain Wall*

Modular nonload-bearing bay walls containing window and exterior wall panels. Windows generally are fixed sash. Panels below window sill and above window head are of opaque glass or metal. Insulated metal panels contain two light-gauge metal surfaces separated by a small air space filled with thermal insulation.

C. WINDOWS

1. *Glass Thickness*

(a) *Single strength:* 3/32 in.
(b) *Double strength:* ⅛ in.
(c) *Crystal:* 3/16 in.
(d) *Plate:* ¼ in.
(e) *Insulating glass:* Two panes of glass separated by approximately ¼-in. airspace.

2. *Window Frame Material*

Wood, steel, or aluminum

3. *Window Sash*

(a) *Operable sash:* Louvered sash; sliding sash (horizontal sliding); hinged sash, casement (side hinged), awning (top hinged), or hopper (bottom hinged); single or double-hung (vertical sliding); pivoted sash.
(b) *Fixed sash:* Nonoperable sash.
(c) *Storm sash:* Removable sash fastened to window frame over operable or fixed sash.

4. *Weatherstripping*

(a) *Materials:* Metal, vinyl, or vinyl-coated weatherstripping for hinged sash and wool pile for sliding sash.
(b) *Moderately airtight weatherstripping:* Loosely fitted with small air gaps.
(c) *Reasonably airtight weatherstripping:* Tightly fitted with no air gaps or minimum air gaps.

D. DOORS

1. *Single Hinged Door* (side-swinging door)

Lightweight hollow-core wood or metal door; heavy solid-core wood or heavy-gauge metal door; or wood or metal door with large panel of glass light.

2. *Double Hinged Doors*

Hinged door plus wood or glass storm door hinged to same frame; or two hinged doors separated by a vestibule.

3. *Sliding Doors*

Glass in sliding frame; or metal or wood sliding door.

4. *Roll-Up Doors*

Metal or wood roll-up doors, generally in large door openings.

5. *Weatherstripping or Gaskets*

(a) *Materials:* Metal, vinyl, or rubber weatherstripping (or gasketing) for side-swinging doors, and wool pile and vinyl or rubber weatherstripping for sliding doors.
(b) *Moderately airtight weatherstripping:* Loosely fitted with some air gaps.
(c) *Reasonably airtight weatherstripping:* Tightly fitted gasket with no air gaps or minimum air gaps.

E. ROOF/CEILING

1. *Roofing Materials*

(a) *Lightweight roofing:* Wood shingle or shake; asphalt shingle; copper, aluminum, or tin panels; corrugated steel; 3-ply ready roofing each weighing 3 psf or less.
(b) *Heavyweight roofing:* Slate and clay tile shingles weighing 10 psf, or 3- to 5-ply felt and gravel built-up roofing weighing 6 psf or greater.

2. *Roof Sheathing*

(a) *Spaced-board sheathing:* One-inch thick wooden boards spaced with an opening between boards greater than 1 in.
(b) *Continuous sheathing:* Wooden boards, plywood, gypsum board, or fiberboard butted tightly edge-to-edge.

3. *Roof Deck*

(a) *Metal deck:* Corrugated metal or steel decking.
(b) *Cement asbestos:* Cement-asbestos panels.
(c) *Wood plank:* Tongue-and-groove wood plank.
(d) *Lightweight concrete slab:* Poured-in-place or precast concrete panels weighing 10 to 30 psf.
(e) *Mediumweight concrete slab:* Poured-in-place or precast concrete panels weighing 35 to 50 psf.
(f) *Heavyweight concrete slab:* Poured-in-place or precast concrete panels weighing 55 psf or greater.

4. *Ceilings*

Acoustical tile or board; gypsum board (drywall); or plaster on metal or gypsum lath (woodstrip lath in old structures).

5. *Insulation*

Lightweight rigid fiber or foamed board on top of roof, or deck. Glass-fiber or mineral-wool blanket or blown-in insulation above ceiling between rafters or joists.

6. *Conventional Roof/Ceiling Constructions*

(a) *Exposed roof:* Flat or sloped roof with light- or heavyweight roofing on wood plank, metal deck, or concrete deck having bottom side of roof exposed to the interior space (no ceiling).
(b) *Ceiling fastened to roof rafters:* Flat or sloped roof with light- or heavyweight roofing, on roof sheathing or other roof deck with drywall or plaster ceiling fastened directly to the bottom of roof rafters or joists.
(c) *Ceiling below attic space:* Sloped roof with lightweight roofing on sheathing over a vented (with exterior vent openings) attic space and drywall or plaster ceiling fastened to ceiling joists.
(d) *Suspended ceiling:* Flat or sloped roof and ceiling suspended from roof structure.

F. UNDERFLOOR

1. *Slab-on-Grade*

Concrete slab poured on grade, no crawl space below.

2. *Crawl Space*

Floor raised above grade over a crawl space of about 2 ft. Crawl space vented by openings in the foundation wall.

3. *Basement*

First floor at or above grade and full-height basement below.

4. *Floor over Outdoor Space*

Floor over outdoor parking or other space.

G. INDOOR ENVIRONMENTAL CONTROL AND CONDITIONING

1. *Central-Station Equipment*

(a) *Heating units:* Gas, oil, or coal-fired furnaces, boiler, and electrical coil.

(b) *Cooling units:* Condensing units, cooling tower, and chillers.
(c) *Central air handling:* Fan forcing air through heating and/or cooling coils.
(d) *Central packaged units:* Single unit containing heating and/or cooling units plus air handling.

2. *Distribution System*

(a) *Ducted system:* Central fan forces treated (or untreated) air through ducts to interior space. Also, warm air forced through ducts by air convection.
(b) *Piping system:* Hot or chilled water, or steam, piped to room terminal units.

3. *Terminal Units*

(a) *Fan-coil units:* Fan forces air through heating or cooling coils directly into room or through ducts to room.
(b) *Air mixing or velocity reducing box:* Terminal unit that mixes hot and cold air or reduces air velocity in high-velocity duct system.
(c) *Induction units:* Ducted treated air induces circulation of room air. Induced room air flows through heating or cooling coils in unit.
(d) *Radiators, convectors, or baseboard radiation:* Hot water or steam passes through a shell radiator or tube and radiates heat to room air via heat convection.
(e) *Radiant-panel heating:* Hot water pipes or electrical

APPENDIX I

MODIFICATIONS[a] REQUIRED IN EXTERIOR CONSTRUCTIONS OF EXISTING STRUCTURES TO EFFECT VARIOUS NOISE REDUCTIONS

		MODIFICATION REQUIRED				
NOISE REDUCTION IMPROVEMENT (dB)	EXTERIOR CONSTRUCTION	SINGLE-FAMILY RESIDENCE	MULTI-FAMILY DWELLING	HIGH-RISE APARTMENT	SCHOOL	CHURCH
		(a) Structures in South Zone				
5	Exterior walls	None	None	None	None	None
	Windows	WM–2	WM–2	WM–2 or 4	WM–2	WM–2 or 4
	Exterior doors	DM–2 or 3 [c] DM–1 [f]	DM–2 or 3 [c] DM–1 [f]	DM–1	DM–1	DM–1
	Roof/ceiling	RM–2	RM–2	None	RM–2	None
	Underfloor	None	None	None	None	None
	Envir. control	CM–2, 3 and 4	CM–2, 3 and 4	CM–1 and 3	CM-2 and 3	CM–2
10	Exterior walls	EM–2 [h, i]	EM–2 [h, i]	EM–2 [h] EM–1 or 2 [j]	EM–2	EM–2
	Windows	WM–5 or 6	WM–5 or 6	WM–5 or 6	WM–3 or 6	WM–5 or 6
	Exterior doors	DM–4 [c] DM–5 [f]	DM–4 [c] DM–5 [f]	DM–5	DM–4	DM–1 [l] DM–4 [n]
	Roof/ceiling	RM–1 or 3 RM–4 [p]	RM–1 or 3 RM–4 [p]	None	RM–1 or 3	RM–1, 4 or 7
	Underfloor	None	None	None	None	None
	Envir. control	CM–2, 3 and 5	CM–2, 3 and 5	CM–1 and 3	CM–2 and 3	CM–2
15	Exterior walls	EM–4	EM–4	EM–4 [h, q] EM–3 [j]	EM–4	EM–4
	Windows	WM–7 or 8	WM–7 or 8	WM–7 or 8	WM–7 or 8	WM–7
	Exterior doors	DM–7 [c] DM–6 or 8 [f]	DM–7 [c] DM–6 or 8 [f]	DM–6 or 8	DM–7	DM–1 [l] DM–7 [n]
	Roof/ceiling	RM–1 and 2, or RM–6 RM–5 [u]	RM–1 and 2, or RM–6 [s] RM–6 [v] RM–5 [p]	None	RM–1 or 2, or RM–6	RM–5 or 7
	Underfloor	UM–2	UM–2	UM–3 and 4	UM–1 or 2	UM–1 or 2
	Envir. control	CM–2, 3 and 5	CM–2, 3 and 5	CM–1 and 3	CM–2 and 3	CM–2

coils imbedded in ceiling or floor radiate heat into room.

(f) *Unit heaters:* Individual units containing fan that forces room air over gas flame or through electrical coils.

4. *Through-the-Wall Air Handling Unit*

Packed unit contains cooling unit plus air-handling unit. Unit relies on outdoor air for heat exchange at condensing unit and fresh-air ventilation. Unit is placed in opening in exterior wall or open window.

HOSPITAL	LOW-RISE COMMERCIAL	HIGH-RISE COMMERCIAL	LOW-RISE MOTEL	HIGH-RISE HOTEL	AUDITORIUM	INDUSTRIAL BUILDING
None	None	None	None	None	None	EM–1 [b]
WM–2 or 4	WM–1 or 2	WM–3 or 4	WM–2	WM–1 or DM–1	None	WM–2
None	DM–1 or 3	None	DM–1	— [d]	DM–1	DM–1 [e] DM–3 [e]
None	RM–2 [g]	None	None	None	RM–7	None
None	None	None	None	None	None	None
CM–1	CM–1 and 3	CM–3	CM–4	CM–3 and 4	CM–3	CM–2 and 3
EM–3 [h] EM–1 or 2 [j]	EM–2 [h] EM–1 or 2 [j]	EM–1 or 2 [j]	EM–2 [h]	EM–2 [h, j]	None	EM–1 [k]
WM–3, 5 or 6	WM–3, 5 or 6	WM 5 or 7	WM–3 or 6	WM–5 or 6, or DM–5	None	WM–5 or 6
None	DM–4	None	DM–4 [m] DM–5 [f]	— [d]	DM–1	DM–1 [e] DM–3 [e]
None	RM–4 or 8	None	RM–1 or 3	None	RM–7	RM–4 or 7
None	None	None	None	None	None	None
CM–1 and 3	CM–1 and 3	CM–3	CM–2, 3 and 5	CM–2, 3 and 5	CM–3	CM–2 and 3
EM–3 [j] EM–4 [r]	EM–3 [j] EM–4 [r]	EM–3 [j] EM–4 [r]	EM–4	EM–3 [j] EM–4 [r]	None	EM–3
WM–7 or 8	WM–7 or 8	WM–7	WM–7 or 8	WM–7 or 8	None	WM–7 or 8
None	DM–7	None	DM–7 [m] DM–6 or 8 [f]	DM–6 or 8	DM–3 [l] DM–4 [o]	DM–9 [e] DM–4 [e]
None [t] RM–6 or 8 [w]	RM–5 or 8	None	RM–1 and 2, or RM–6	None	RM–7	RM–7
None	None	UM–3 and 4	None	None	None	None
CM–1 or 3	CM–1 and 3	CM–3	CM–2, 3 and 5	CM–2, 3 or 5	CM–3	CM–2 and 3

NOISE REDUCTION IMPROVEMENT (dB)	EXTERIOR CONSTRUCTION	MODIFICATION REQUIRED SINGLE-FAMILY RESIDENCE	MULTI-FAMILY DWELLING	HIGH-RISE APARTMENT	SCHOOL	CHURCH
		(b) Structures in Middle Zone				
5	Exterior walls	None	None	None	None	None
	Windows	WM–2 or 4	WM–2 or 4	WM–2 or 4	WM–2	WM–2 or 4
	Exterior doors	DM–2 or 3 [c] DM–1 [f]	DM–2 or 3 [c] DM–1[f]	DM–1	DM–1	DM–1
	Roof/ceiling	RM–2	RM–2	None	None	None
	Underfloor	UM–3 [x]	UM–3 [x]	None	None	None
	Envir. control	CM–2 and 3	CM–2 and 3	CM–1 and 3	CM–2 and 3	CM–2
10	Exterior walls	EM–2 [h, i]	EM–2 [h, i]	EM–1 or 2 [j]	None	None
	Windows	WM–5 or 6	WM–5 or 6	WM–5 or 6	WM–3 or 6	WM–5 or 6
	Exterior doors	DM–4 [c] DM–5 [f]	DM–4 [c] DM–5 [f]	DM–5	DM–4	DM–1 [l] DM–4 [n]
	Roof/ceiling	RM–1 or 3	RM–3	None	RM–1 or 3	RM–1, 4 or 7
	Underfloor	UM–3 and 5, or UM–5 [x]	UM–3 and 5 [x]	None	None	None
	Envir. control	CM–2 and 3	CM–2 and 3	CM–1 and 3	CM–2 and 3	CM–2
15	Exterior walls	EM–4	EM–4	EM–4 [cc] EM–3 [j]	EM–4	EM–4
	Windows	WM–7 and 8	WM–7 and 8	WM–7 and 8	WM–7 and 8	WM–7
	Exterior doors	DM–7 [c] DM–6 or 8 [f]	DM–7 [c] DM–6 or 8 [f]	DM–6 or 8	DM–7	DM–1 [l] DM–7 [n]
	Roof/ceiling	RM–1 and 2 or 6 [s] RM–6 [v]	RM–1 and 2 or 6 [s] RM–6 [v]	None	RM–1 and 2 or 6	RM–5 or 7
	Underfloor	UM–3, 4 and 5 [x] UM–1 or 2 [z]	UM–3 or 5 [x] UM–1 and 2 [z]	None	UM–1 or 2	None
	Envir. control	CM–2 and 3	CM–2 and 3	CM–1 and 3	CM–2 and 3	CM–2
		(c) Structures in North Zone				
5	Exterior walls	None	None	None	None	None
	Windows	WM–2 or 4	WM–2 or 4	WM–2 or 4	WM–2	WM–2 or 4
	Exterior doors	DM–1	DM–1	None	None	DM–1
	Roof/ceiling	None	None	None	None	None
	Underfloor	UM–3	UM–3	None	None	None
	Envir. control	CM–2 and 3	CM–2 and 3	CM–1 and 3	CM–2 and 3	CM–2
10	Exterior walls	EM–3 [i]	EM–3 [i]	EM–1 or 3 [j]	None	None
	Windows	WM–5 or 6	WM–5 or 6	WM–5 or 6	WM–3 or 6	WM–5 or 6
	Exterior doors	DM–1 [aa]	DM–1 [aa]	None	None	DM–1 [l] DM–4 [n]
	Roof/ceiling	RM–1 or 3	RM–1 or 3	None	RM–2	RM–1, 4 or 7
	Underfloor	UM–3 and 5 or 4	UM–3 and 5	None	None	None
	Envir. control	CM–2 and 3	CM–2 and 3	CM–1 and 3	CM–2 and 3	CM–2
15	Exterior walls	EM–4 [i]	EM–4 [i]	EM–4 [bb] EM–2 [j]	EM–4	None
	Windows	WM–7 and 8	WM–7 and 8	WM–7 or 8	WM–7 or 8	WM–7
	Exterior doors	DM–7	DM–7	None	None	DM–1 [l] DM–4 [n]
	Roof/ceiling	RM–1 and 2, or RM–6	RM–1 and 2, or RM–6 [s, v]	None	RM–1 and 2, or RM–6	RM–5 or 7
	Underfloor	UM–3, 4 and 5	UM–3 and 5	None	None	None
	Envir. control	CM–2 and 3	CM–2 and 3	CM–1 and 3	CM–2 and 3	CM–2

[a] See Appendix K for code to modification symbols. [b] If metal siding. [c] At hinged door. [d] See windows. [e] At roll-up door. [f] At sliding door. [g] Above acoustical tile ceiling. [h] If stucco. [i] If siding. [j] If curtain wall. [k] If metal siding or panel. [l] At main entrance. [m] At entrance to lobby. [n] At side door. [o] At stage house exit. [p] If exposed roof deck. [q] If masonry. [r] Other than curtain wall. [s] If attic space. [t] If high-rise. [u] At exposed roof. [v] If flat roof. [w] If low-rise. [x] If basement. [y] If wall unit. [z] If crawl space. [aa] Both door and storm door. [bb] If masonry panels. [cc] If masonry.

HOSPITAL	LOW-RISE COMMERCIAL	HIGH-RISE COMMERCIAL	LOW-RISE MOTEL	HIGH-RISE HOTEL	AUDITORIUM	INDUSTRIAL BUILDING
None	None	None	None	None	None	None
WM-2 or 4	WM-1 or 2	WM-3 or 4	WM-2	WM-1 or DM-1	None	WM-2
None	DM-1	None	DM-1	—[d]	DM-1	DM-1[c] DM-3[c]
None	None	None	None	None	RM-7	None
None	None	None	None	None	None	None
CM-1	CM-1 and 3	CM-3	CM-4	CM-3 and 4	CM-3	CM-2 and 3
EM-1 or 2[j]	EM-1 or 2[j]	EM-1 or 2[j]	EM-2[h]	EM-1 or 2[j]	None	EM-1 or 2[k]
WM-3, 5 or 6	WM-3, 5 or 6	WM-5 or 7	WM-3 or 6	WM-5 or 6, or DM-5	None	WM-5 or 6
None	DM-3	None	DM-4	—[d]	DM-3[l] DM-4[o]	DM-9[c] DM-4[c]
None	RM-8	None	RM-1 or 3	None	RM-7	RM-4 or 7
None	None	None	None	None	None	None
CM-1 and 3	CM-1 and 3	CM-3	CM-2 and 5[y]	CM-2, 3 and 5	CM-3	CM-2 and 3
EM-4[cc]	EM-3[j]	EM-3[j]	EM-4	EM-3[j]	None	EM-3
EM-3[j]	EM-4[r]	EM-4[r]		EM-4[r]		
WM-7 or 8	WM-7 or 8	WM-7	WM-7 or 8	WM-7 or 8 or DM-6 or 8	None	WM-7 or 8
None	DM-7	None	DM-7	—[d]	DM-7	DM-7
None[t] RM-6 or 8[w]	RM-6 or 8	None	RM-1 and 2 or 6	None	None	None
None	None	None	None	None	None	None
CM-1 and 3	CM-1 and 3	CM-3	CM-3 CM-2 and 5[y]	CM-2, 3 and 5	CM-3	CM-2 and 3
None	None	None	None	None	None	None
WM-2 or 4	WM-2	WM-3 or 4	WM-2	WM-1 or DM-1	None	WM-2
None	DM-1	None	None	—[d]	DM-1	DM-1[c, e]
None	None	None	None	None	RM-7	None
None	None	None	None	None	None	None
CM-1	CM-1 and 3	CM-3	CM-4	CM-3 and 4	CM-3	CM-2 and 3
EM-1 or 3[j]	EM-1 or 2[j]	EM-1 or 2[j]	None	EM-1 or 2[j]	None	EM-1 or 2[k]
WM-3, 5 or 6	WM-3, 5 or 6	WM-5 or 7	WM-3 or 6	WM-5 or 6, or DM-5	None	WM-5 or 6
None	DM-3	None	None	—[d]	DM-3[l] DM-4[o]	DM-9[c] DM-4[c]
None	RM-8	None	RM-1 or 3	None	RM-7	None
None	None	None	None	None	None	None
CM-1 or 3	CM-1 and 3	CM-3	CM-3 CM-2 and 5[y]	CM-2, 3 and 5	CM-3	CM-2 and 3
EM-2[j]	EM-3[j]	EM-3[j]	EM-4	EM-3[j]	None	EM-3
EM-4[q]	EM-4[r]	EM-4[r]		EM-4[r]		
WM-7 or 8	WM-7 or 8	WM-7	WM-7 or 8	WM-7 or 8, or DM-6 or 8	None	WM-7 and 8
None	DM-7	None	None	—[d]	DM-3[m] DM-7[o]	DM-10[c] DM-7[c]
None[t] RM-6 or 8[w]	RM-6 or 8	None	RM-1 and 2, or RM-6	None	RM-7	RM-7
None	None	None	None	None	None	None
CM-1 and 3	CM-1 and 3	CM-3	CM-2 and 5[y]	CM-2, 3 and 5	CM-3	CM-2 and 3

APPENDIX J

REQUIRED CONSTRUCTIONS [a] FOR PLANNED STRUCTURES TO EFFECT VARIOUS NOISE REDUCTIONS

		CONSTRUCTION REQUIRED				
NOISE REDUCTION IMPROVEMENT (dB)	EXTERIOR CONSTRUCTION	SINGLE-FAMILY RESIDENCE	MULTI-FAMILY DWELLING	HIGH-RISE APARTMENT	SCHOOL	CHURCH
		(a) Structures in South Zone				
5	Exterior walls	EC–1, 3 or 5	EC–1, 3 or 5	EC–3, 5 or 10	EC–1 or 3	EC–3, 5 or 7
	Windows	WC–1	WC–1	WC–1	WC–1	WC–1
	Exterior doors	DC–1 and 4	DC–1 and 4	DC–4	DC–1	DC–1
	Roof/ceiling	RC–5 RC–1 [c]	RC–3 and 5 RC–1 [c]	RC–10	RC–3 RC–5 or 8	RC–1
	Underfloor	UC–1 or 2	UC–1 or 2	UC–6	UC–1 or 2	UC–1
	Envir. control	CC–1, or CC–2 and 3	CC–1, or CC–2 and 3	CC–1 and 3	CC–1 and 3	CC–1
10	Exterior walls	EC–2, 3 or 5	EC–2, 3 or 5	EC–3, 5 or 11	EC–2 or 3	EC–3, 5 or 7
	Windows	WC–4	WC–4	WC–4	WC–4	WC–4
	Exterior doors	DC–2 and 5	DC–2 and 5	DC–5	DC–2	DC–3 [d] DC–2 [e]
	Roof/ceiling	RC–5 RC–2 [c]	RC–4 and 5 RC–2 [c]	RC–10	RC–5 or 9	RC–2
	Underfloor	UC–1 or 2	UC–1 or 2	UC–6	UC–1 or 2	UC–1
	Envir. control	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1
15	Exterior walls	EC–4, 6 or 8	EC–4, 6 or 8	EC–4, 6 or 12	EC–4	EC–4, 8 or 9
	Windows	WC–5	WC–5	WC–5	WC–5	WC–5
	Exterior doors	DC–3 [f]	DC–3 [f]	None	DC–3	DC–3 [d, e]
	Roof/ceiling	RC–4, 6 or 7	RC–4 and RC–6 or 7	RC–10	RC–4, 7 or 9	RC–4 or 9
	Underfloor	UC–1 or 3	UC–1 or 3	UC–6	UC–1, 3 or 6	UC–1
	Envir. control	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1	CC–1 and 3
		(b) Structures in Middle Zone				
5	Exterior walls	EC–1, 3 or 6	EC–1, 3 or 6	EC–5 or 10	EC–3, 5 or 6	EC–5 or 7
	Windows	WC–1	WC–1	WC–1	WC–1	WC–1
	Exterior doors	DC–1 and 4	DC–1 and 4	DC–4	DC–1	DC–1
	Roof/ceiling	RC–5	RC–3 and 5	RC–10	RC–3, 5 or 8	RC–1
	Underfloor	UC–2 or 4	UC–2 or 4	UC–6	UC–1 or 2	UC–1
	Envir. control	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1
10	Exterior walls	EC–2, 3 or 6	EC–2, 3 or 6	EC–5 or 11	EC–3, 5 or 6	EC–5 or 7
	Windows	WC–4	WC–4	WC–4	WC–4	WC–4
	Exterior doors	DC–2 and 5	DC–2 and 5	DC–5	DC–2	DC–3 [d] DC–2 [e]
	Roof/ceiling	RC–5	RC–4 and 5	RC–10	RC–5 or 9	RC–2
	Underfloor	UC–2 or 4	UC–2 or 4	UC–6	UC–1 or 2	UC–1
	Envir. control	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1
15	Exterior walls	EC–4 or 6	EC–4 or 6	EC–6 or 12	EC–4 or 6	EC–6, 8 or 9
	Windows	WC–5	WC–5	WC–5	WC–5	WC–5
	Exterior doors	DC–3 [f]	DC–3 [f]	None	DC–3	DC–3 [d, e]
	Roof/ceiling	RC–6 or 7	RC–4 and 6 or 7	RC–10	RC–4, 6, 7 or 9	RC–4 or 9
	Underfloor	UC–2 or 5	UC–2 or 5	UC–6	UC–1, 3 or 6	UC–1
	Envir. control	CC–1 or 3	CC–1 or 3	CC–1 or 3	CC–1 or 3	CC–1

HOSPITAL	LOW-RISE COMMERCIAL	HIGH-RISE COMMERCIAL	LOW–RISE MOTEL	HIGH-RISE HOTEL	AUDITORIUM	INDUSTRIAL BUILDING
EC–3, 5 or 10	EC–3, 5 or 7	EC–10	EC–3 or 5	EC–3, 5 or 10	EC–7	EC–3, 7 or 10
WC–1 or 2	WC–1 or 2	WC–1	WC–1	WC–1 or DC–4	None	WC–1
None	DC–1	None	DC–1 or 4	—[b]	DC–1	DC–1 and 6
RC–3 or 8	RC–3 or 8	RC–8 or 10	RC–3 or 5	RC–10	RC–9	RC–3 or 12
UC–1 or 6	UC–1 or 2	UC–6	UC–1 or 2	UC–6	UC–1 or 6	UC–1
CC–1 and 3	CC–1	CC–1	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1 and 3
EC–3 or 5	EC–3, 5 or 7	EC–11	EC–3 or 5	EC–3, 5 or 11	EC–7	EC–3, 7 or 11
WC–4	WC–4	WC–4	WC–2 or 4	WC–4 or DC–5	None	WC–4
None	DC–2	None	DC–2 or 5	—[b]	DC–2	DC–2 and 7
RC–5, 9 or 10	RC–4 or 9	RC–9 or 10	RC–4 or 5	RC–10	RC–9	RC–9 or 13
UC–1 or 6	UC–1 or 2	UC–6	UC–1 or 2	UC–6	UC–1 or 6	UC–1
CC–1 and 3	CC–1	CC–1	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1 and 3
EC–4, 6 or 8	EC–4, 6 or 8	EC–12	EC–4 or 8	EC–4, 6 or 12	EC–8 or 9	EC–9 or 12
WC–5	WC–5	WC–5	WC–5	WC–5	None	WC–5
None	DC–3	None	DC–3[g]	None	DC–3	DC–3 and 7
RC–7, 9 or 10	RC–4 or 9	RC–9 or 10	RC–4, 6 or 7	RC–10	RC–11	RC–9 or 14
UC–1 or 6	UC–1 or 2	UC–6	UC–1 or 2	UC–6	UC–1 or 6	UC–1
CC–1	CC–1	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1 and 3
EC–5 or 10	EC–5, 7 or 10	EC–10	EC–3 or 5	EC–5 or 10	EC–7	EC–7 or 10
WC–1	WC–1 or 2	WC–1	WC–1	WC–1 or DC–4	None	WC–1
None	DC–1	None	DC–1	—[b]	DC–1	DC–1 and 6
RC–3 and 8	RC–3 or 8	RC–10	RC–3 or 5	RC–10	RC–9	RC–3 or 12
UC–1 or 6	UC–1	UC–6	UC–1	UC–6	UC–1 or 6	UC–1
CC–1 and 3	CC–1	CC–1	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1 and 3
EC–5 or 11	EC–5, 7 or 11	EC–11	EC–3 or 5	EC–5 or 11	EC–7	EC–7 or 11
WC–4	WC–4	WC–4	WC–2 or 4	WC–4 or DC–5	None	WC–4
None	DC–2	None	DC–2	—[b]	DC–2	DC–2 and 7
RC–5, 9 or 10	RC–4 or 9	RC–10	RC–4 or 5	RC–10	RC–9	RC–9 or 13
UC–1 or 6	UC–1	UC–6	UC–1	UC–6	UC–1 or 6	UC–1
CC–1 or 3	CC–1	CC–1	C–1 and 3	CC–1 and 3	CC–1 and 3	CC–1 and 3
EC–6 or 12	EC–6, 8 or 12	EC–12	EC–4, 6 or 8	EC–6 or 12	EC–8 or 9	EC–9 or 12
WC–5	WC–5	WC–5	WC–5	WC–5	None	WC–5
None	DC–3	None	DC–3[g]	None	DC–3	DC–3 and 7
RC–7, 9 or 10	RC–4 or 9	RC–10	RC–4, 6 or 7	RC–10	RC–11	RC–9 or 14
UC–1 or 6	UC–1	UC–6	UC–1	UC–6	UC–1 or 6	UC–1
CC–1 or 3	CC–1	CC–1	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1 and 3

NOISE REDUCTION IMPROVEMENT (dB)	EXTERIOR CONSTRUCTION	CONSTRUCTION REQUIRED SINGLE-FAMILY RESIDENCE	MULTI-FAMILY DWELLING	HIGH-RISE APARTMENT	SCHOOL	CHURCH
		(c) Structures in North Zone				
5	Exterior walls	EC–1 or 6	EC–1 or 6	EC–5 or 10	EC–5 or 6	EC–7 or 8
	Windows	WC–1 or 3	WC–1 or 3	WC–1	WC–1	WC–1
	Exterior doors	DC–1	DC–1	DC–4	DC–1	DC–1
	Roof/ceiling	RC–5	RC–3 and 5	RC–10	RC–3, 5 or 8	RC–2
	Underfloor	UC–4	UC–4	UC–6	UC–1 or 6	UC–1
	Envir. control	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1 or 3	CC–1
10	Exterior walls	EC–2 or 6	EC–2 or 6	EC–5 or 11	EC–5 or 6	EC–7 or 8
	Windows	WC–4	WC–4	WC–4	WC–4	WC–4
	Exterior doors	DC–2	DC–2	DC–5	DC–2	DC–3 [d] DC–2 [e]
	Roof/ceiling	RC–5	RC–4 and 5	RC–10	RC–5 or 9	RC–2
	Underfloor	UC–4	UC–4	UC–6	UC–1 or 6	UC–1
	Envir. control	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1
15	Exterior walls	EC–6	EC–6	EC–6 or 12	EC–6	EC–8 or 9
	Windows	WC–5	WC–5	WC–5	WC–5	WC–5
	Exterior doors	DC–3	DC–3	None	DC–2	DC–3 [d, e]
	Roof/ceiling	RC–6 or 7	RC–4 and RC–6 or 7	RC–10	RC–4, 6, 7 or 9	RC–4 or 9
	Underfloor	UC–5	UC–5	UC–6	UC–1 or 6	UC–1
	Envir. control	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1 or 3	CC–1

[a] See Appendix L for construction code. [b] See windows. [c] If exposed. [d] At main entrance. [e] At side entrance. [f] And no sliding doors. [g] Or no door.

APPENDIX K

CODE FOR RECOMMENDED MODIFICATIONS TO EXISTING STRUCTURES (To Be Used in Interpreting Appendix I)

A. EXTERIOR WALLS *

EM-1: Install new drywall or plaster wall on inside of existing wall and on new studs. Also provide acoustical installation between studs.

EM-2: Install new resiliently furred drywall or plaster on inside of existing wall. Also provide insulation between furring members.

EM-3: Same as EM-1, except mount drywall resiliently to stud.

EM-4: Remove existing interior drywall or plaster surface and install new resiliently mounted drywall on interior of studs or furring. Also provide insulation between studs.

* Most new interior constructions include drywall (gypsumboard) construction, not plaster. Consequently, drywall construction is described in modifications to walls and ceilings.

B. WINDOWS

1. *Single-Glazed*

WM-1: Retain existing window and glass, and fix and seal operable sash airtight to frame *or* install efficient weatherstripping to perimeter of sash.

WM-2: Remove existing sash and/or glass and install new single pane of minimum plate glass, and fix and seal operable sash airtight to frame *or* install efficient weatherstripping to perimeter of sash.

WM-3: Same as WM-2, except install new single pane of acoustical laminated glass.

2. *Double-Glazed*

WM-4: Retain existing window and install new tightly fitted storm sash in existing window frame and in series with existing window.

WM-5: Same as WM-4, except space glass of storm sash

HOSPITAL	LOW-RISE COMMERCIAL	HIGH-RISE COMMERCIAL	LOW–RISE MOTEL	HIGH-RISE HOTEL	AUDITORIUM	INDUSTRIAL BUILDING
EC–5 or 10	EC–5, 7 or 10	EC–5 or 10	EC–5 or 7	EC–5 or 10	EC–7	EC–7 or 10
WC–1 or 3	WC–1 or 2	WC–1	WC–1	WC–1	None	WC–1
None	DC–1	None	DC–1	None	DC–1	DC–1 and 6
RC–3 or 8	RC–3 or 8	RC–10	RC–3 or 5	RC–10	RC–9	RC–3 or 12
UC–1 or 6	UC–1	UC–6	UC–1 or 6	UC–6	UC–1 or 6	UC–1
CC–1 and 3	CC–1	CC–1	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1 and 3
EC–5 or 11	EC–5, 7 or 11	EC–5 or 11	EC–5 or 7	EC–5 or 11	EC–7	EC–7 or 11
WC–4	WC–4	WC–4	WC–2 or 4	WC–4	None	WC–4
None	DC–2	None	DC–2	None	DC–2	DC–2 and 7
RC–5, 9 or 10	RC–4 or 9	RC–10	RC–4 or 5	RC–10	RC–9	RC–9 or 13
UC–1 or 6	UC–1	UC–6	UC–1 or 6	UC–6	UC–1 or 6	UC–1
CC–1 or 3	CC–1	CC–1	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1 and 3
EC–6 or 12	EC–6, 8 or 12	EC–6, 8 or 12	EC–6 or 8	EC–6 or 12	EC–8 or 9	EC–9 or 12
WC–5	WC–5	WC–5	WC–5	WC–5	None	WC–5
None	DC–3	None	DC–3	None	DC–3	DC–3 and 7
RC–7, 9 or 10	RC–4 or 9	RC–10	RC–4, 6 or 7	RC–10	RC–11	RC–9 or 14
UC–1 or 6	UC–1	UC–6	UC–1 or 6	UC–6	UC–1 or 6	UC–1
CC–1 or 3	CC–1	CC–1	CC–1 and 3	CC–1 and 3	CC–1 and 3	CC–1 and 3

at least 2 in. from existing window glass and seal storm sash airtight or provide efficient weatherstripping.

WM-6: Retain existing window, extend frame, and install second operable sash in series with existing window. Separate existing and new glass by deep (4 in. or greater) airspace. Provide efficient weatherstripping at perimeter of new sash. New glass minimum "crystal" in thickness.

WM-7: Same as WM-6, except fix and seal both existing and new sash *or* provide efficient weatherstripping at perimeter of both sash.

WM-8: Remove existing sash, extend frame, and install two new sash separated by deep airspace. Fix and seal each sash airtight or provide efficient weatherstripping on each sash. New glass minimum "crystal" in thickness. Factory sealed and fabricated double-glazed window desirable.

C. EXTERIOR DOORS

DM-1: Gasket existing door with efficient weatherstripping.

DM-2: Install new tightly fitted storm door in series with existing door.

DM-3: Remove existing door and install new heavy wood or metal door. Provide door with efficient gaskets.

DM-4: Same as DM-3, except add storm door with efficient weatherstripping *or* install single acoustical sound-isolating door.

DM-5: Retain existing sliding door and install second sliding-frame glass door in series with existing door. Separate glass by deep airspace.

DM-6: Remove existing sliding glass door and install two new double sliding doors with efficient weatherstripping. Separate glass by deep airspace.

DM-7: Remove existing door(s), construct vestibule if required, and install two efficiently gasketed heavy wood or metal doors at each end of the vestibule, *or* remove existing door and install single "acoustical" door with high transmission loss rating.

DM-8: Remove existing sliding door and install door DM-7 and window WM-7 or WM-8 in the sliding door opening.

DM-9: Remove existing door and install new single heavy-gauge roll-up door with efficient weatherstripping.

DM-10: Same as DM-9, except install two roll-up doors separated by a deep airspace or vestibule.

D. ROOF/CEILING

RM-1: Lay heavyweight roofing (slate or tile) over eixsting roof.

RM-2: Lay or blow insulation in attic space and provide lined transfer ducts at main vent openings.

RM-3: Install resiliently furred drywall on the bottom of existing drywall or plaster ceiling (or bottom of exposed roof deck). Also provide insulation above the new ceiling between furring members.

RM-4: Install drywall ceiling directly to the bottom of roof rafters. Provide insulation above ceiling between rafters. If acoustical tile ceiling exists, remove tile ceiling first.

RM-5: Same as RM-4, except resiliently mount drywall ceiling to bottom of roof rafter, and provide insulation above ceiling. Also provide lined transfer ducts at main vent openings.

RM-6: Remove existing drywall or plaster ceiling and install resiliently mounted drywall to the bottom of roof rafters or ceiling joists, and provide insulation above ceiling. Also provide lined transfer ducts at main vent openings.

RM-7: Suspend drywall ceiling below roof and deep airspace. Also provide insulation above ceiling.

RM-8: Same as RM-7, except first remove existing ceiling.

E. UNDERFLOOR

UM-1: Install insulation to bottom of floor.

UM-2: Install lined transfer duct in crawl space over each vent opening.

UM-3: Fix and seal, or efficiently weatherstrip, existing basement windows, or install new tightly fitted sash in series with existing basement window.

UM-4: Remove existing basement door and install new efficiently gasketed heavy door.

UM-5: Install new heavy wood door at interior of vestibule between basement and groundfloor spaces.

F. ENVIRONMENTAL CONTROL

CM-1: Make minor modifications to existing mechanical system to improve year-around indoor air treatment.

CM-2: Make major modifications to existing mechanical system or install new system to provide year-around indoor air treatment.

CM-3: Line outside-air intake duct to fan plenum or air-handling unit and acoustically treat room exhaust duct.

CM-4: Remove existing through-the-wall air-conditioning unit and install new sound-isolating unit.

CM-5: Remove existing through-the-wall unit, fill opening with existing or modified exterior wall construction and provide new central air-handling system providing year-around air treatment.

APPENDIX L

CODE FOR RECOMMENDED CONSTRUCTIONS IN PLANNED STRUCTURES (To Be Used in Interpreting Appendix J)

A. EXTERIOR WALLS

EC-1: Conventional stud wall with lightweight siding on sheathing on exterior of 3½-in. minimum studs, ½-in. minimum drywall * on interior of studs, and insulation in space between studs.

EC-2: Same as EC-1, except resiliently mount minimum ½-in. drywall to interior of studs.

EC-3: Conventional stud wall with minimum 1-in. stucco on exterior of minimum 3½-in. wood or metal studs, minimum ½-in. drywall on interior of studs, and insulation in space between studs.

EC-4: Same as EC-3, except resiliently mount drywall to interior of studs.

EC-5: Minimum lightweight masonry plus drywall furred to inside of masonry over minimum 2-in.-deep furring member and insulation between furring.

EC-6: Conventional stud wall with minimum lightweight masonry veneer on exterior of minimum 3½-in.-deep studs, drywall on interior of studs, and insulation in space between studs, *or* same as EC-5 except resilently mount drywall to furring.

EC-7: Minimum 6-in. medium- or heavyweight masonry wall.

EC-8: Mediumweight masonry plus drywall furred to inside of masonry and insulation between furring members.

EC-9: Minimum 6-in. heavyweight masonry wall.

EC-10: Insulated metal panel with two 18-gauge or heavier sheet-steel panels separated by minimum 3-in. airspace containing minimum 2-in. low-density glass-fiber insulation.

EC-11: Same as EC-10, plus drywall resiliently furred to inside surface of panel. Also insulation behind drywall between furring.

EC-12: Same as EC-10, plus drywall resiliently mounted to stud over inside surface of panel. Also insulation behind drywall between studs.

* Most new interior constructions includes drywall (gypsumboard) construction, not plaster. Consequently, drywall is described in wall and ceiling constructions.

B. WINDOWS

WC-1: Single pane of minimum 3⁄16-in. glass in a fixed and sealed sash, *or* in an operable sash with highly efficient weatherstripping.

WC-2: Single pane of minimum 3⁄8-in. acoustical laminated glass in a fixed and sealed sash.

WC-3: Two operable sash windows with glass separated by a minimum 3-in. airspace, and moderately efficient weatherstripping on perimeter of each sash. Sash contain minimum 1⁄8-in. thick glass.

WC-4: Two operable sash windows, each with highly efficient weatherstripping or fixed glass, separated by minimum 4-in. airspace. Sash contain minimum 3⁄16-in.-thick glass.

WC-5: Two panes of glass in fixed and sealed sash separated by minimum 4-in. airspace. Sash contain minimum 3⁄16-in.-thick glass.

C. EXTERIOR DOORS

DC-1: Heavyweight wood or metal door, fully gasketed with efficient gaskets.

DC-2: Two doors hung to the same frame and separated by minimum 2-in. airspace. One or both doors to be heavyweight; one door may be glass storm door. Both doors to be fully gasketed, *or* acoustical door STC-35.

DC-3: Two heavyweight doors separated by a minimum 3-ft vestibule. Both doors to be fully gasketed, *or* acosutical door STC-45.

DC-4: Single sliding glass door with efficient gaskets around sliding frame.

DC-5: Two sliding glass door units separated by a minimum 4-in. airspace. Each door with efficient gaskets around sliding frame.

DC-6: Heavy-gauge steel roll-up industrial door fully gasketed with efficient gaskets.

DC-7: Two heavy-gauge roll-up doors separated by a minimum 3-ft airspace.

D. ROOF/CEILING

RC-1: Heavyweight roofing on continuous 1-in. wood roof deck with no ceiling below.

RC-2: Heavyweight roofing on continuous minimum 2-in. wood or lightweight concrete roof deck with no ceiling below.

RC-3: Minimum heavyweight roofing on continuous sheathing or metal deck, plus drywall mounted directly to bottom of rafters and insulation above ceiling between rafters, *or* RC-1 plus drywall mounted to bottom of rafters.

RC-4: Same as RC-3, except resiliently mount drywall to bottom of rafters.

RC-5: Minimum lightweight roofing on continuous sheathing or metal deck, attic space of average 3-ft, height plus drywall ceiling below, and insulation in attic space above ceiling. All transfer ducts at main vent openings.

RC-6: Same as RC-5, except heavyweight roofing tiles.

RC-7: Same as RC-5, except resiliently mount drywall ceiling to joists.

RC-8: Heavyweight roofing on plywood or metal deck or lightweight concrete deck plus acoustical tile ceiling suspended below.

RC-9: Same as RC-8, except suspend drywall ceiling minimum 2-ft below roof deck *or* resiliently mount drywall ceiling to bottom of roof joists.

RC-10: Mediumweight concrete roof deck.

RC-11: Mediumweight concrete roof deck plus drywall ceiling furred or suspended below and insulation above ceiling, *or* heavyweight concrete roof deck.

RC-12: Built-up roof on insulated pane of two 18-gauge or heavier sheet-steel panels separated by minimum 3-in. airspace containing minimum 2-in. low-density glass-fiber insulation.

RC-13: Heavy build-up roofing on metal roof deck plus drywall ceiling suspended minimum 24 in. below and insulation above ceiling.

RC-14: Same as RC-12 plus drywall ceiling suspended below plus insulation.

E. UNDERFLOOR

UC-1: Slab on grade.

UC-2: Crawl space.

UC-3: Crawl space with lined transfer duct on inside of each vent opening or insulation in crawl space.

UC-4: Full-height basement with efficiently weatherstripped windows and DC-1 exterior doors.

UC-5: Gasketed heavy door between basement and first floor.

UC-6: Slab over unoccupied basement or garage.

F. INDOOR ENVIRONMENTAL CONTROL SYSTEM

CC-1: Central-station equipment and appropriate distribution system and/or terminal units to provide yeararound air treatment of indoor environment. Also acoustically lined fresh-air intake and exhaust-air ducts to central fans.

CC-2: Efficient through-the-wall air-conditioning units (such as Zoneline by G.E.)

CC-3: Acoustically treat room exhaust ducts (such as kitchen or toilet).

APPENDIX M

DESCRIPTIONS OF ACOUSTICAL TREATMENTS IN SOUND-REDUCTION CONSTRUCTIONS

A. EXTERIOR WALL

1. *Conventional Wall*

   Conventional stud wall with brick veneer or stucco or conventional masonry walls. Studs minimum 3½ in. deep.

2. *Resilient Mounts*

   Resilient metal channels or clips to resiliently fasten interior drywall or plaster to studs.

3. *Interior Drywall*

   Minimum ½- to 1-in. drywall (gypsumboard) or plaster on lath on interior of stud or furring member. If furred to exterior wall, furring member minimum 2 in. deep.

4. *Acoustical Insulation*

   Two- to 4-in. glass-fiber or mineral-wool conventional building insulation.

5. *Airtight Construction*

   Exterior surfaces treated airtight in conventional manner. In masonry construction use full-depth, carefully struck joints and provisions against cracking. Also pargeting, plastering, or through painting over porous masonry units. Overlapping building paper and continuous sheathing behind siding, or taped joints of sheathing panels. Joints at sill, header, and jamb between window and door frames and exterior wall treated airtight with an acoustical sealant (nonhardening, nonshrinking and noncracking caulking compound). Interior walls should be finished airtight and sealed at the base with acoustical sealant.

B. WINDOWS

1. *Fixed Sash*

   Nonoperable sash fastened to window frame and sealed airtight to permit no infiltration of air. Also glass set in airtight glazing compound or gasket.

2. *Efficient Weatherstripping (or Gasket)*

   Airtight vinyl, vinyl-coated metal, vinyl-covered foam-rubber or closed-cell neoprene or foam-rubber weatherstripping or gaskets that permit minimum infiltration of air (no air gap) when operable sash is closed.

3. *Single-Pane Acoustical Glass*

   Specially manufactured laminated glass with moderately high sound transmission loss.

4. *Double-Glazed Window Unit*

   Two panes of glass separated by 3-in. or greater airspace. Panes of glass of unequal thickness. Also sound-absorbing material on perimeter frame between panes of glass.

C. EXTERIOR DOORS

1. *Solid-Core Door*

   Solid-core wood or heavy metal door.

2. *Acoustical Door*

   Specially manufactured sound-isolating doors supplied with gaskets, frames, and other hardware. Moderate-sound-isolating door has sound transmission loss rating of STC-35. High-sound-isolating door has rating of STC-40 or greater.

3. *Double Doors*

   Two doors separated by an airspace or vestibule.

4. *Efficient Gasketing*

   Same as efficient weatherstripping for windows.

D. ROOF/CEILING

1. *Conventional Roof*

   Conventional roof of heavyweight roofing, continuous sheathing, wood plank or concrete deck, or with a deep attic space between roof deck and ceiling.

2. *Resilient Mounts or Hangers*

   Resilient metal channels or clips to resiliently fasten drywall ceiling to roof rafters or ceiling joists. Resilient hanger mounts to resiliently support suspended ceiling from roof structure.

3. *Drywall Ceiling*

   One-half- to 1-in. drywall or plaster-on-lath.

4. *Acoustical Insulation*

   Two- to 4-in. glass-fiber or mineral-wool building insulation with no paper or foil face in space between roof and ceiling and between rafters or joists.

5. *Airtight Construction*

   Seal all penetrations of the roof by pipes or ducts in an airtight manner. Finish ceiling airtight.

E. MISCELLANEOUS TREATMENTS

1. *Vent Mufflers*

   Internally lined transfer duct at vent openings in attic or crawl space.

2. *Duct Liner*

   Minimum 1-in. coated glass-fiber duct liner.

3. *Exhaust Ducts*

   Acoustically treat exhaust duct that connects interior space directly to the outdoors. Line duct or acoustical baffle at opening of duct.

4. *Sound-Isolating Through-the-Wall Unit*

   Off-the-shelf, through-the-wall air-conditioning unit that provides better-than-average sound transmission loss through the unit.

APPENDIX N

STUDY TASK DESCRIPTIONS AND PROCEDURES

This appendix presents descriptions of the various field and analytical studies conducted during the course of the project. The first four studies relate to the findings presented in Chapter Three, "Propagation and Control of Highway Noise." The fifth study relates to Chapter Four, "Community Measures to Reduce Noise Impact." The last two study procedures described here led to the findings of Chapter Five, "Economic Evaluation of Noise-Reduction Strategies."

FREE-FIELD NOISE PROPAGATION STUDIES

The approach here was to collect and evaluate free-field noise data measured along well-traveled highways at sites with various types of ground cover. The sites selected for survey, the data collection procedures, and the basic data reduction techniques are outlined in the following.

Measurement Sites

The three sites selected for the field measurement program represent terrain with three widely different types of ground cover, as follows:

Site 1—Freshly plowed farmland on the north side of the Santa Ana Freeway between Red Hill Drive and Myford Road near Tustin, Calif. (Fig. N-1(a)).

Site 2—Planted farmland with 3- to 4-ft growth of asparagus on the north side of the Santa Ana Freeway between Myford Road and Culver Drive near Tustin, Calif. (Fig. N-1(b)). Figure 5(b) is a pictorial view.

Site 3N—Parkland with grass and scattered small trees on the north side of the Pomona Freeway between the Rio Hondo River and Rosemead Boulevard near El Monte, Calif. (Fig. N-2(a)).

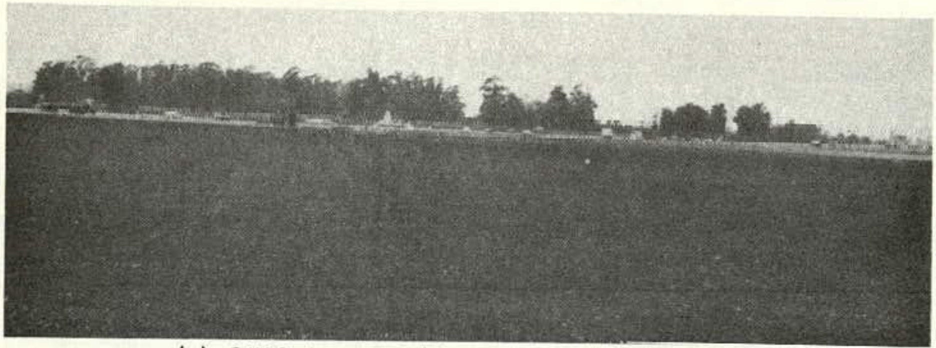
Site 3S—Parkland with grass and scattered shrubs on the south side of the Pomona Freeway between Rosemead Boulevard and Santa Anita Avenue near El Monte, Calif. (Fig. N-2(b)).

Although they are at different locations, Sites 3N and 3S are considered a single site, inasmuch as they represent the same type of ground cover (typical parkland).

All three of these sites lay along well-traveled highways that are level with the surrounding terrain and have no significant grades or curves within 2,000 ft on either side of the sites. Furthermore, the sites are level and free of buildings and other obstructions for at least 2,500 ft from the highways. Hence, the sites provide good conditions for a free-field traffic noise survey.

Measurement Procedures and Instruments

At each site, traffic noise levels were recorded at each of six locations (50, 100, 200, 400, 800, and 1,600 ft from the edge of the roadway) along a normal to the roadway, and at each of three heights (5, 10, and 15 ft) above the ground, as detailed in Figure N-3 (a). The recordings at the 50- and 1,600-ft locations were made using digital monitoring systems, as shown in Figure N-3(b), whereas the recordings at



(a) SITE 1 - Freshly Plowed Farmland

(b) SITE 2 - Planted Farmland (An Asparagus Field)

Figure N-1. Sites 1 and 2 (farmland).

(a) SITE 3N - Parkland With Grass and Small Trees

(b) SITE 3S - Parkland With Grass and Shrubs

Figure N-2. Site 3 (parkland).

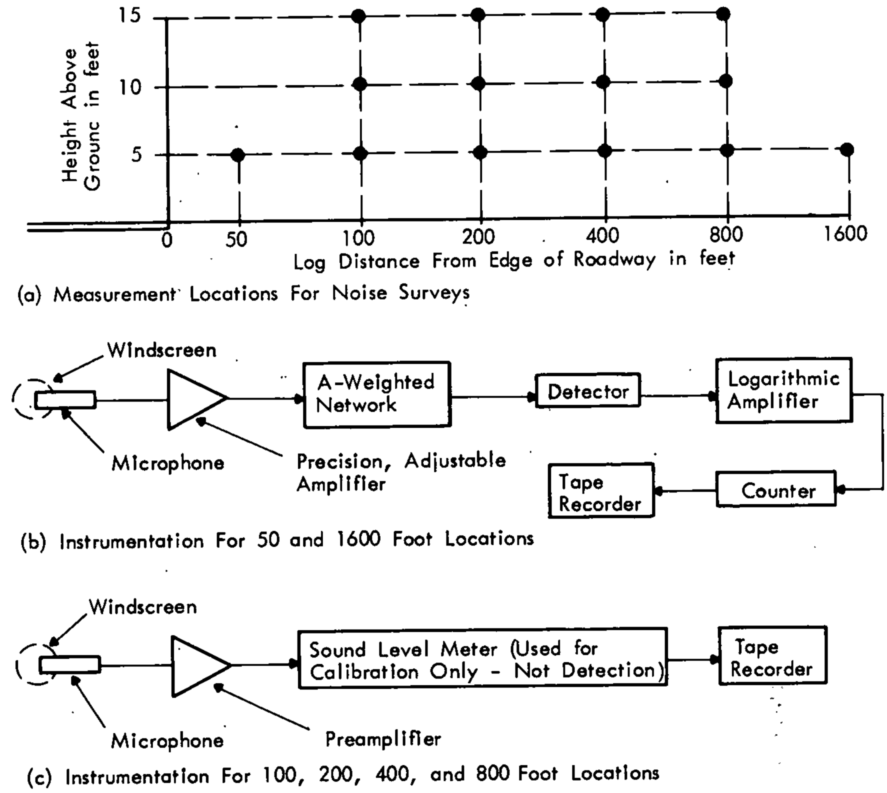


Figure N-3. Measurement locations and instrumentation for free-field noise propagation studies.

the other locations were made with analog monitoring systems, as shown in Figure N-3(c).

The measurements were made by simultaneously recording the noise levels at all six locations (distances from the roadway) with a common microphone height for a period of 10 min. The microphones at the locations 100, 200, 400, and 800 ft from the roadway were then changed to a different common height, and the noise levels at the six locations were again recorded. The microphones at the 50- and 1,600-ft locations were left at the 5-ft height for all measurements. Each set of six simultaneous noise level recordings constituted a "measurement run." Such measurement runs were repeated intermittently over a period of two days at Site 1, and one day each at Sites 2 and 3. During each run, the average traffic volume and truck mix were estimated by visual count. The traffic speed was estimated by clocking the time required for selected vehicles to pass between two markers.

Data Reduction

Each 10-min tape recording of traffic noise was reduced to a distribution of dBA values by the following procedure. The sound pressure level signal was converted to a running averaged dBA level signal using an A-weighted logarithmic detector circuit (calibrated in dBA) with an averaging time constant of 0.1 sec. The dBA level signal was then converted to discrete digital values using a sampling rate of 2 sps and a quantization interval of one dBA. Hence, a total of 1,200 sample values of dBA noise levels were generated from each 10-min record. These data reduction operations were performed on line (in the field) for the noise levels measured at the 50- and 1,600-ft locations, as shown in Figure N-3(b). At all other locations, however, sound pressure levels were directly recorded in the field, as indicated in Figure N-3(c), and the data reduction was performed later in the laboratory.

Given the 1,200 sample dBA values for each traffic noise record, the values were then ranked and grouped to arrive at an empirical distribution function using a special digital computer progam designed for this purpose. Four percentage levels of interest (L_{01}, L_{10}, L_{50}, and L_{90}) were then interpolated from the empirical distribution function. The equivalent level, (L_{eq}), was also calculated from

$$L_{eq} = 10 \log \left[\frac{1}{n} \sum_{i=1}^{n} \text{antilog} \, (AL_i/10) \right] \qquad \text{(N-1)}$$

where AL_i is the value of the ith sample, in dBA, and n is the sample size.

As in any statistical estimation problem, some consideration must be given to the accuracy of the percentage level estimates produced by the foregoing data reduction procedure. A review of the statistical accuracy of percentage level estimates is included in Appendix A. In summary, if it is assumed that the sampled dBA values of traffic noise determined at 0.5-sec intervals over a period of 10 min are (a) uncorrelated, and (b) distributed in an approximately Gaussian manner, 95 percent confidence limits for the true percentage levels based on the estimated percentage levels are given by

$$\begin{array}{l} \pm 0.21\sigma \text{ for } L_{01} \\ \pm 0.10\sigma \text{ for } L_{10} \\ \pm 0.07\sigma \text{ for } L_{50} \\ \pm 0.10\sigma \text{ for } L_{90} \end{array} \qquad \text{(N-2)}$$

where σ is one standard deviation of the dBA noise level distribution. For exmple, the standard deviation for truck traffic noise is about 4 dBA. For this case, Eq. N-2 gives 95 percent confidence limits of about ± 0.3 dBA for L_{50} estimates and ± 0.8 dBA for L_{10} estimates.

The validity of the assumptions used to arrive at Eq. N-2 is discussed in Appendix A. In general, the assumptions are dependable only for high traffic volumes; specifically, for volumes where the number of vehicles per unit time is greater than the number of samples per unit time. For the sampling rate of 2 sps used for the measurements herein, this corresponds to a volume of at least 7,200 vph. For smaller traffic volumes, the accuracy of various percentage point estimates would be more a function of the number of vehicles than the number of samples over the 10-min observation time, meaning the confidence limits for percentage point estimates probably would be greater than suggested by Eq. N-2.

HIGHWAY NOISE-REDUCTION MEASURES

No new measurements were needed for these studies. Instead, basic data acquired during a previous NCHRP project (*3*) were employed for the desired evaluations. Specifically, the data for three sites representing three different noise reduction measures were selected for evaluation, as follows:

1. Roadside barrier configuration (I-680, Milpitas, Calif.)
2. Elevated roadway configuration (U.S. 101, Encino, Calif.)
3. Depressed roadway configuration (I-35W, Minneapolis, Minn.)

Cross sections of the three sites and measurement locations are presented in Figures C-1, C-2, and C-3. Detailed descriptions of the sites and measurement procedures are available from *NCHRP Report 144* (*3*) and are not repeated here. It is necessary only to point out that the terrain adjacent to both the Milpitas barrier site and the Encino elevated roadway site was freshly plowed farmland; i.e., the terrain was similar to Site 1 for the traffic noise propagation studies discussed in the previous section. On the other hand, the Minneapolis depressed roadway site was in a well-established residential area, where the adjacent terrain was more like the parkland of Site 3 for the traffic noise propagation studies.

The approach in these studies was as follows. The noise reductions provided by the three types of construction were computed using the sound levels measured at various locations around the sites, and assuming a propagation loss factor as determined empirically for similar terrain during the current study. These computed noise reductions were then compared to the theoretical noise reductions predicted by the incoherent line source model in accordance with Figure N-4. The predictions were made assuming the noise source had a wavelength of 2 ft (so that $N_{max} = \delta$ in Fig. N-4), and that it lay along a line on the surface of the roadway at an equivalent distance $D_E = \sqrt{D_N D_F}$ from the noise-reduction construction. Here, D_N and D_F are the distances to the near lane and far lane, respectively, measured from the highest point on the noise-reduction construction.

To simplify the noise reduction predictions and make them independent of traffic noise levels, no correction was introduced for trucks. However, to suppress possible errors introduced by this simplification, later comparisons of measured and predicted noise reductions were limited to locations well below the line-of-sight to the source where the efficiency of a given noise reduction measure is least influenced by the possible differences in the source height of trucks versus automobiles. This action, plus the fact that the truck mix ratio was relatively small for most of the traffic noise measurements, should permit reasonably accurate comparisons between the measurements and simplified predictions.

The second phase of this task involved collection of cost data needed for the cost-effectiveness studies in this report. This was pursued by soliciting basic cost data for the construction of at-grade, elevated, and depressed roadways, as well as roadside barriers, from various state highway departments. Detailed right-of-way acquisition cost data were also requested. Five states (California, Colorado, Connecticut, Illinois, and Michigan) responded with at least some cost figures. The California Department of Highways, in particular, provided valuable data.

VEHICLE NOISE DIRECTIVITY STUDIES

The approach here was to collect and evaluate free-field noise measurements with a vertical microphone array that would permit determination of a directivity pattern for passing vehicles (primarily trucks). The sites selected for survey, the data collection procedures, and the basic data reduction techniques are now outlined.

Measurement Sites

Two measurement sites were selected for the surveys. Site A (Fig. N-5(a)), located in Canoga Park, was selected to conduct preliminary measurements on various types of vehicles for the purpose of comparing directivity patterns and testing the equipment. A vertical array of microphones was erected 32 ft from the center of the near lane. The road surface was new asphalt, almost unpolished by traffic.

Site B (Fig. N-5(b)) is a section of the Antelope Valley Freeway (Calif. 14 northbound). The vertical array of microphones was again erected 32 ft from the center of the near lane, and a reference microphone was placed 45.4 ft from the center of the near lane. The freeway at that location is level and has a wide shoulder. The surface is new concrete, almost unpolished by traffic.

Measurement Procedures and Instrumentation

Four microphones were placed at various heights above the ground as shown in Figure N-6(a). One microphone was placed 5 ft above the ground and 45.4 ft from the center

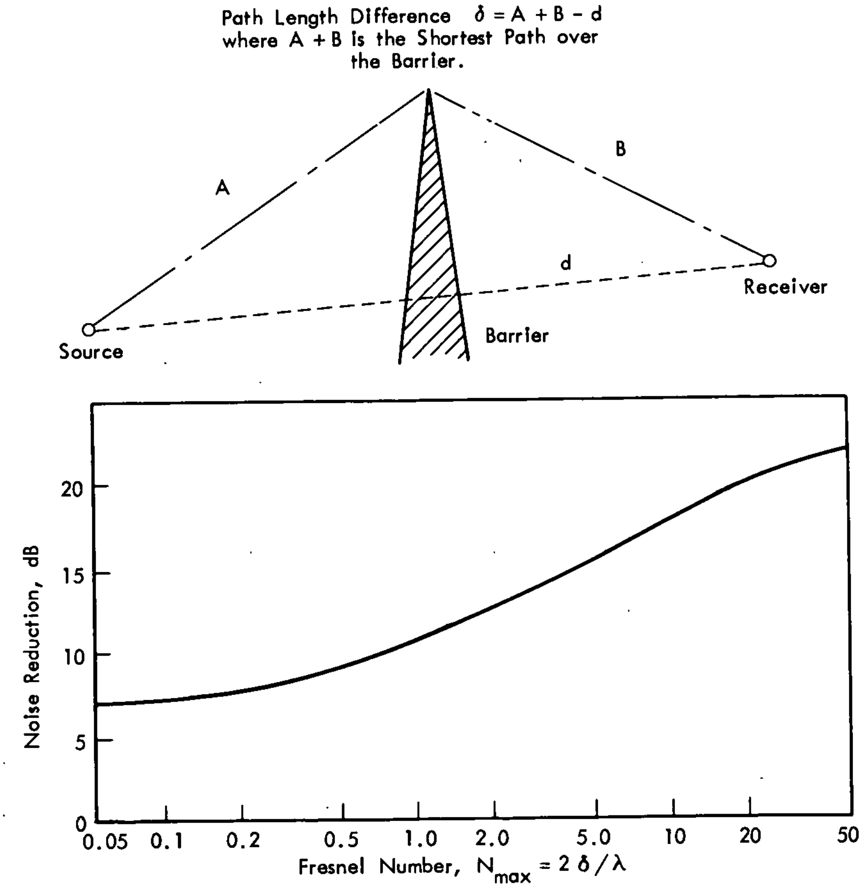


Figure N-4. Noise reductions for infinitely long barrier running parallel to an incoherent line source.

of the near lane. The three remaining microphones were hung on a vertical tower at a horizontal distance of 32 ft from the center of the near lane. The positions of the microphones were chosen in such a way that a circular pattern, with four equally spaced points, could be constructed by making the proper distance correction (6 dB/ doubling of distance). The angles measured from the horizontal were 6°, 19°, 32°, and 45°.

The measurements were made by simultaneously recording the noise levels at all four locations. The equipment consisted of four identical channels, each composed of a condenser microphone protected by a windscreen, a preamplifier, and a high-fidelity tape recorder, as shown in Figure N-6(b). A switch was available to superimpose a reference mark simultaneously on all four tapes. Calibration was performed on each system by recording a 124-dB signal at the beginning and at the end of each tape.

Each measurement run consisted of a simultaneous recording of the noise levels at all four locations during the passage of a single vehicle. Marks were superimposed on the tape to indicate assage of the vehicle by two reference points. The marks were used to synchronize the tapes and also to determine the speed of the vehicle. A picture of each vehicle was taken for identification.

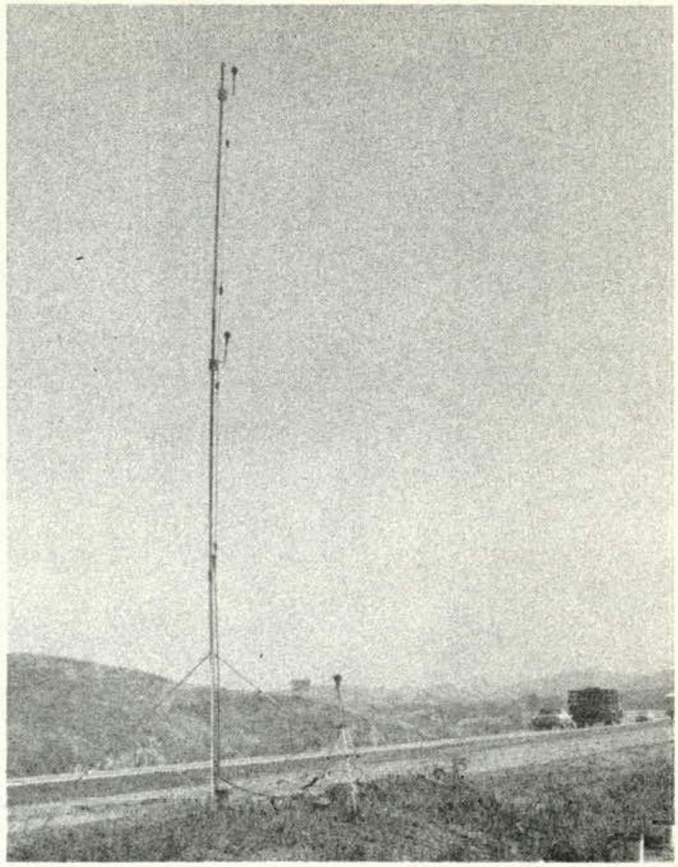
Data Reduction

Each tape recording of vehicle noise was analyzed in the laboratory as follows. The signal was processed through an A-weighted network and plotted on a chart-recorder, using an averaging time constant of 0.1 sec, corresponding to the "fast" setting of a sound level meter. The resulting chart was used to determine the peak dBA value. The measurements at positions 2 and 3 were corrected to a distance of 45.7 ft from the source. Hence, the four measurements then corresponded to four points on an arc of a circle with a radius of 45.7 ft. (The data may be normalized to the usual distance of 50 ft by subtracting 0.8 dBA from all values reported.) A spectral analysis of some of the data was also performed using one-third-octave band spectral analysis equipment.

TRUCK DRIVE-BY NOISE STUDIES

These studies were pursued by collecting measurements of the peak drive-by noise levels of individual trucks, together with descriptions of (a) the speed, (b) the size in terms of number of axles, and (c) the location of exhausts. The sites selected for the survey and the data collection procedures are described in the following.

SITE A: Canoga Park, California



SITE B: State Highway 14, California

Figure N-5. Sites for noise directivity measurements.

Measurement Sites

A total of seven measurement sites in six states were selected, as follows:

Site 1—California: on Route 101 westbound near Canoga Park; grade $< 0.5\%$.

Site 2—Colorado: on I-25 southbound near Denver; grade $= 0\%$.

Site 3—Illinois: on I-270 eastbound near Edwardsville; grade $= 0.3\%$.

Site 4—Kentucky: on I-71 southbound near Lagrange; grade $< 0.5\%$.

Site 5—New York: on I-87 northbound near Albany; grade $= 0.7\%$.

Site 6—Texas: on I-20 eastbound near Dallas; grade $=$ 0%.

Site 7—Texas: on I-10 eastbound near Houston; grade $=$ 0%.

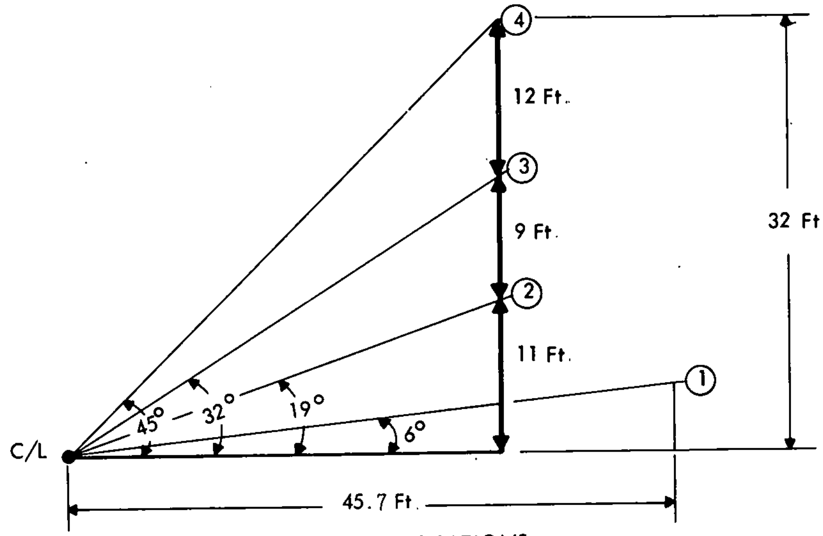
The sites were chosen in areas where the highway grade was less than 1% and the ambient noise level was at least 10 dBA below the lowest vehicle drive-by sound pressure level expected during the survey. The terrain at all sites was relatively level and clear of obstructions.

Measurement Procedures and Instrumentation

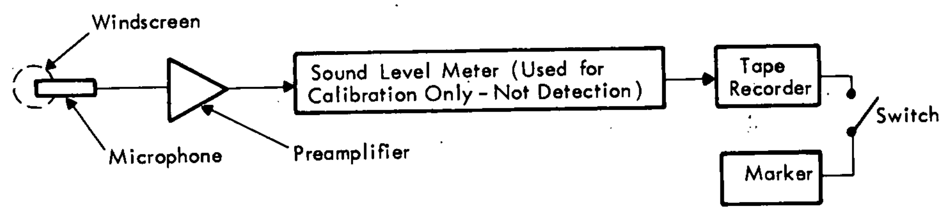
At each site, one microphone with a windscreen was mounted 4 ft above grade and 50 ft from the center line of the nearest lane (the lane most often used by trucks). For each individual vehicle drive-by, the peak A-weighted sound pressure level was read directly in dBA from a Type 1 sound level meter on the "fast" setting. The microphone-sound level meter system was calibrated at regular intervals with a pistonphone. The measurements were obtained primarily for vehicles passing in the near lane. However, a vehicle of interest did occasionally pass in the second lane. In such cases, the peak level was measured and later corrected, assuming 6 dBA per doubling of distance, to normalize all data to a 50-ft distance.

During each drive-by for which a peak noise measurement was made, additional data were collected, as follows:

1. Type of vehicle; (a) tractor-trailer, (b) straight truck, (c) vehicle carrier, (d) dump truck, (e) bus, (f) tractor only, (g) motorhome.
2. Make of vehicle.
3. Number of axles.
4. Exhaust location; (a) high, (b) low.
5. Lane of highway; (a) first lane, (b) second lane.
6. Speed.



(a) MEASUREMENT LOCATIONS



(b) MEASUREMENT INSTRUMENTATION

Figure N-6. Measurement locations and instrumentation for noise directivity studies.

The speed of each vehicle was measured with a conventional speed Doppler-shift radar. All other parameters were determined by visual inspection, although many of the drive-bys were photographed for positive identification. Only those vehicles with six or more wheels were counted as trucks. All two-axle vehicles with four wheels are considered to be automobiles for the purposes of this study. Furthermore, the trucks were classified into categories considered most useful from the noise evaluation viewpoint, although these categories generally do not agree with the classification procedures used by the various state highway departments. However, any other classification scheme can be easily compared to the one used, as given under Item 1.

IMPROVED BUILDING NOISE INSULATION STUDIES

In developing recommended modifications to existing structures or designs for future structures required to achieve additional noise reduction, the following factors must be considered:

1. The geographic location within the United States.
2. The types of structures of interest.
3. Basic construction materials and components.
4. The amount of interior noise reduction desired.

To make the problem tractable, various assumptions and simplifications related to these four factors are necessary.

Geographic Zones

For analysis purposes, the United States is divided into three zones: north, middle and south, as shown in Figure N-7. The basic constructions of buildings within each zone are assumed to be the same. The boundaries of the zones, although based on climatic conditions, are quite general and do not account for mountains and other local geographic and weather conditions that affect construction. Nevertheless, the three zones broadly correlate with differences in building exterior constructions.

The zone boundaries defined in Figure N-7 are not based on cost differences. However, the average construction and modification costs generally differ from zone to zone. The costs also vary from rural areas to large cities and from city to city, but these variations are ignored. For this analysis, the average construction costs within a zone are assumed to be similar.

Types of Structures

Twelve major building types are considered for analysis. The types of structures vary with type of occupancy, indoor functional activity, and building construction. Other building types not listed should be considered similar to one of the major categories based on similar occupancy or construction. General descriptions of the major building types are as follows:

Single-family residence—A single-story dwelling with three bedrooms, 1,500 sq ft of floor area, and 3.5 occupants on the average.

Multifamily dwelling (low-rise apartment building)—A two- or three-story structure with 12 or more dwelling units, each having two bedrooms, 900 sq ft of floor area, and three occupants on the average.

High-rise apartment building—A structure eight stories or more high with six or more apartments per floor. A typical apartment has two bedrooms, 1,000 sq ft of floor area, and three occupants on the average.

School—The majority of recent school structures are single story. Many older structures, especially in the north, are two or three stories high. Each school contains general classrooms plus supporting spaces (laboratories, library, auditorium, offices). The typical classroom has 900 sq ft of floor area, a 10- to 12-ft-high ceiling, and serves 30 students on the average. Only classrooms are considered in the analysis. The construction of offices and other spaces is similar to equivalent building structures.

Church—A typical church has approximately 4,000 to 7,000 sq ft of floor area and seats 250 to 500 people. The nave and sanctuary contain side walls 15 ft or more high with a high ceiling or exposed roof structure. The construction of the rectory, classrooms, and church office space is similar to equivalent building structures.

Auditorium—The main body of the auditorium has a long-span structure and high ceiling. A typical hall seats 1,000 people and, with stage, has an area of 12,000 sq ft.

Hospital—A structure four stories high and containing patient rooms, each with two beds and approximately 200 sq ft of floor area. The area of supporting medical spaces is about twice as large as the total patient room area.

Low-rise motel—A structure two to four stories high containing guest rooms, each with 200 sq ft of floor area on the average.

High-rise hotel—A structure five stories or more high containing guest rooms with 200 sq ft of floor area each on the average.

High-rise commercial building—A structure four or more stories high where most of the floor area consists of office space. Typical floors contain private as well as large open offices.

Low-rise commercial building—A structure one to three stories high containing offices, shops, restaurants, etc., where office spaces make up 50 percent of building floor area. The typical private office has 150 sq ft of floor area.

Industrial building—A one- or two-story structure with large open manufacturing or assembly areas.

Construction Materials and Components

The exterior building components that have the greatest effect on noise reduction are the exterior walls, windows, doors, and roof-and-ceiling construction. Exterior noise is transmitted through these significant building components and is radiated directly into the interior building spaces. Noise can also flank these components and enter the interior through vent openings in attic or crawl spaces, and then through the ceiling or floor to indoor spaces. Exterior noise can also enter a basement through windows and doors, and then be transmitted to interior spaces along connecting passageways or through exhaust or fresh-air intake ducts. Typically, there are direct and/or indirect paths between the outdoors and interior spaces via supply, return, or ex-

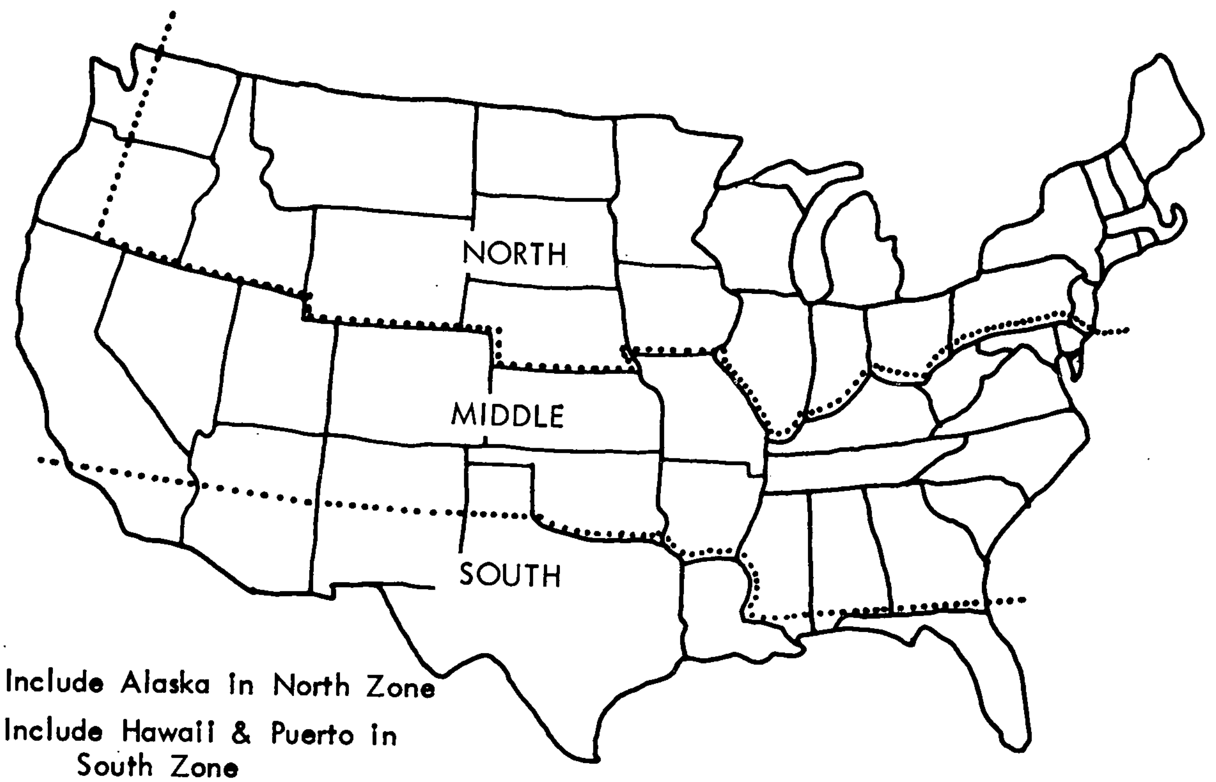


Figure N-7. Geographic zone boundaries for different types of building construction.

haust duct systems. Therefore, in addition to the significant exterior constructions, attic space vents and interior duct systems must be considered in the description of conventional exterior building constructions.

Indoor air-treatment systems must also be considered in the description of building constructions. Under most conditions, windows and doors must be closed to achieve increased noise reduction. This means that the interior building spaces should be provided with year-round air treatment. Therefore, building air-treatment systems are generally reqired as part of any noise reduction construction. In this report, the air-treatment system is referred to as the "indoor environmental control system."

Desired Noise Reduction

Noise reduction due to the exterior building construction is defined as the difference between the average sound pressure level outdoors near the structure and the average sound pressure level inside the structure. The indoor sound pressure level represents the acoustical summation of sound transmitted directly through the various significant exterior construction components, and indirectly through flanking paths. The sound pressure level transmitted through individual building components is based on the sound transmission loss property of the component, its surface area, and the size and absorption quality of the indoor space.

Three increments of noise-reduction improvement are considered; specifically, 5, 10, and 15 dB of improvement in terms of A-weighted sound levels (dBA). The 5-dBA increment is selected for analysis because it represents a change in noise level that is readily distinguishable to occupants of structures, as well as to acoustical measuring instruments. An improvement of 15 dBA is considered the practical limit beyond which the required constructions become difficult and excessively expensive to incorporate.

The incremental improvements in noise reduction for modifications to existing structures represent dBA improvements in the noise reduction above that value provided by the existing construction with windows and doors closed. The incremental improvements for new constructions represent the noise reductions beyond that expected if the new structure were built without special acoustical considerations.

NOISE-REDUCTION ESTIMATING PROCEDURES

If the various traffic noise-reduction strategies are to be compared in terms of their costs and benefits, a necessary first step is to establish the noise-reduction potential for each strategy. This is done assuming the fullest practical applications of current technology, as summarized in Chapters Two, Three, and Four. To make the ultimate cost-benefit models tractable, all noise-reduction assessments are made in terms of "A-weighted" sound pressure levels (dBA), which provide a convenient single-number description of the potential abatement.

Vehicle Noise-Reduction Potential

The basic data for assessing the noise reductions that might be achieved for automobiles and trucks using current technology are extracted largely from the research results of Chapter Two, as summarized in Tables N-1 and N-2. In both tables, the noise data for full-throttle acceleration in accordance with appropriate SAE standards were extracted from measurements, whereas the data for constant-speed cruise on level grade at 55 to 65 mph were generated by prediction models. In Table N-2, the 55-to-65-mph cruise data for heavy trucks were computed assuming a fully loaded truck (4,500 lb/tire) with two drive axles powered by a four-stroke, turbo-charged, diesel engine.

Table N-1 indicates that the noise-reduction potential for conventional passenger automobiles and light trucks driving full-throttle acceleration is about 10 dBA; however, for cruise at 55 to 65 mph the potential is only about 4 dBA. The collapse in noise reduction at cruise speeds is due to the fact that tire noise, which dominates the individual noise sources at higher speeds, cannot be significantly reduced with current technology, assuming straight-rib tires (NBS tread pattern B or C) are used.

TABLE N-1

AUTOMOBILE AND LIGHT TRUCK NOISE ABATEMENT POTENTIAL

	NOMINAL LEVEL (dBA AT 50 FT)		NET REDUCTION (ΔdBA)		REDUCED LEVEL (dBA AT 50 FT)	
NOISE SOURCE	SAE J986a	CRUISE 55-65 MPH	SAE J986a	CRUISE 55-65 MPH	SAE J986a	CRUISE 55-65 MPH
Engine casing	73	60	5	5	68	55
Exhaust system	81	72	18	18	63	54
Fan	76	66	13[a]	21[a]	63[a]	45[a]
Intake	74	—	6	6	68	—
Tires	60	72.5	0	0	60	72.5
Other sources	72	72	6	6	66	66
Total	83.6	77.4	—	—	73.3	73.5

[a] High-performance slow fan (0.6 engine speed).

Neutral-rib tires would reduce the tire noise slightly, but not sufficiently to make their use a practical alternative in view of the associated safety hazard. Of course, tire noise can also be significantly reduced (or increased) by modifications of the highway pavement surface, but this approach is considered as a highway design strategy rather than a vehicle strategy.

Table N-2 indicates that the noise-reduction potential for a conventional heavy diesel truck is about 14 dBA during full-throttle acceleration and about 8 dBA during cruise at 55 to 65 mph. It is assumed that similar results could be obtained for heavy gasoline trucks. This substantial abatement potential at cruise speeds is very important, inasmuch as truck noise often dominates the total noise level produced by highway traffic. Specifically, the average heavy truck is about 12 dBA noisier than the average passenger automobile or light truck. This means that the contribution of heavy trucks to traffic noise will exceed the contribution of automobiles and light trucks if the truck mix ratio is greater than about 6 percent.

Highway Noise-Reduction Potential

The noise-reduction potential of various highway designs is assessed by application of conventional diffraction theory, as described in Chapter Three. Specifically, if the highway traffic is assumed to be an infinitely long line of incoherent point sources, and the highway noise-reduction measure is assumed to be a barrier blocking the line-of-sight between the line source and a point receiver, the noise reduction at the receiver can be estimated in terms of an associated Fresnel Number, $N_{max} = 2\delta/\lambda$, where δ is the path length difference and λ is the noise wavelength, as shown in Figure N-4. It follows that the noise reduction provided by a given highway configuration is a function of the frequency, $f = c/\lambda$, where c is the speed of sound. However, when traffic noise levels are measured in terms of A-weighted sound pressure levels (dBA), experimental studies (Chap. Three) indicate that reasonably accurate noise-reduction predictions are obtained by assuming that the traffic noise is concentrated at about $f = 550$ Hz, corresponding to a wavelength of $\lambda = 2$ ft. Hence, approximate noise-reduction predictions in dBA can be made by applying the prediction curve of Figure N-4 with $N_{max} = \delta$. Such a simplification is used in these studies.

Even with this simplification, there are additional problems associated with the assessment of highway noise-reduction measures. In particular, the noise reduction provided by a given configuration varies with the location of the receiver; see Table 65 (p. 89), which summarizes the noise reductions at observer locations 5 ft above grade and 100 and 500 ft from the highway right-of-way for various elevated and depressed roadway and roadside barrier configurations. It should be noted that the noise reductions available from the elevated roadway and the roadside barrier configurations tend to decrease with increasing distance from the highway, whereas the noise reductions from the depressed roadway configuration increase with increasing distance from the highway. This fact complicates direct comparisons among the various highway noise-reduction strategies, as well as between a highway strategy and a vehicle source or community strategy.

To provide a firm basis for comparisons among strategies, all cost-benefit evaluations in this study are based on the noise reductions at a point 100 ft from the edge of the right-of-way and 5 ft above grade. A fixed distance from the edge of the right-of-way, rather than from the edge of the highway pavement, is used because the right-of-way boundary, not the highway location, determines how close the community structures and activities might approach the highway. The distance of 100 ft corresponds to the approximate location of the closest row of structures that might be constructed along the highway and, hence, the region where noise reduction is most needed. Of course, the noise reduction at this location will be slightly augmented for those highway constructions requiring wider rights-of-way than normal (for example, depressed roadways or earth berms) simply because of the increased spreading loss of the traffic noise due to the increased dis-

TABLE N-2

HEAVY DIESEL TRUCK NOISE ABATEMENT POTENTIAL

	NOMINAL LEVEL (dBA AT 50 FT)		NET REDUCTION (ΔdBA)		REDUCED LEVEL (dBA AT 50 FT)	
NOISE SOURCE	SAE J366	CRUISE 55-65 MPH	SAE J366a	CRUISE 55-65 MPH	SAE J366	CRUISE 55-65 MPH
Engine casing	82	83	14	14	68	69
Exhaust system	82	81	19	19	63	62
Fan	81	82	13[a]	21	68	61
Intake	74	74	12	12	62	62
Tires	71	85	4[b]	4[b]	67	81
Transmission	75	75	20	20	55	55
Total	87.1	89.3	—	—	73.3	81.4

[a] High-performance slow fan (0.6 engine speed) with thermatic or viscous clutch not engaged.

[b] Assumes cross-rib tires are replaced by straight rib tires; new tires on good quality portland cement or asphaltic concrete pavement.

tance from the source. This additional noise-reduction factor is reflected in the values given in Table 65.

As an additional point of clarification, the predicted noise reductions in Table 65 vary with the heavy truck mix ratio (the percentage of heavy trucks in the total traffic volume) because the effective height of the traffic noise source above the pavement is greater for heavy trucks than for automobiles and light trucks. The values in Table 65 were arrived at assuming the source height to be 8 ft above the pavement for heavy trucks and at the pavement surface for automobiles and light trucks. This procedure is consistent with the prediction techniques recommended in the "Design Guide" (*131*). Furthermore, the calculations were made using the nominal source noise levels for unsilenced trucks and automobiles during cruise at 55 to 65 mph, as presented in Tables N-1 and N-2.

A final noise-control strategy considered under highway design measures involves the pavement surface, which significantly influences the generation of tire noise. For the case of a new highway design, it is assumed that the highway engineer would consider tire noise problems, among other things, in his selection of a pavement surface. Because the cost difference between a "quiet" pavement (for example, open-graded asphaltic concrete) and a "noisy" pavement (for example, dense-graded, medium-coarse-finished asphaltic concrete) is generally trivial relative to the over-all cost of a new highway, it follows that cost probably would not play an important roll in this selection. For the case of existing highways, however, where tire noise is magnified by pavement deterioration (for example, old pitted or rough pavements), repaving with a "quiet" surface, such as open-graded asphalt, constitutes a reasonable noise-control alternative. Indeed, surface repavement is one of only two reasonable strategies (the other being the construction of roadside barriers) applicable to an existing highway.

A summary of available tire noise data for various pavement surfaces (Chapter Two) indicates that repaving an old pitted or rough portland cement concrete pavement with open-graded asphalt will reduce tire noise at highway speeds by about 6 dBA. Using the vehicle source noise data in Tables N-1 and N-2, it can be shown that a 6-dBA reduction in tire noise (assuming straight-rib tires) would reduce the over-all source noise of an automobile or truck by about 1.5 dBA. However, if the automobiles and trucks were quieted in other ways, as detailed in Tables N-1 and N-2, the potential over-all noise reductions would be 4 dBA and 5 dBA, respectively.

Community Noise-Reduction Potential

The construction changes required to achieve 5, 10, and 15 dBA of additional noise reduction in the interior of typical community structures are presented in Chapter 4 and Appendixes I, J, K, L, and M. The structures considered include single- and multiple-family dwellings, high-rise apartments, schools, churches, auditoriums, hospitals, low- and high-rise motels, low- and high-rise commercial buildings, and industrial plants. Full construction details are presented for modifications to existing structures, as well as design changes of planned structures, for the northern, central, and southern regions of the United States. It is necessary here only to note that reductions of up to 15 dBA in the interior noise levels are readily achievable for community structures of all types. However, the construction techniques required to provide more than 15 dBA of noise reduction are not considered practical at the present time.

As noted previously, there are at least two other logical noise-control strategies that might be taken at the community level. These involve restricting the use of land bordering on the right-of-way to (a) high-rise structures that would serve as a partial noise barrier for the rest of the community and (b) those structures involving activities least sensitive to intruding noise. For the second case, the only physical noise reduction provided is that due to increasing the distance of family dwellings from the highway. Because the comparisons in this study emphasize the noise reductions at locations near the highway (100 ft from the right-of-way), it appears that this strategy can be evaluated only in qualitative terms. However, the first case involves interior noise reduction within the high-rise structures along the right-of-way, as well as some additional noise reduction throughout the community due to the shielding provided by the structures. The amount of additional noise reduction to be expected from this shielding is difficult to estimate, because it clearly would be dependent on the height and, more important, the density of the high-rise structures. One previous study (Chapter Four) suggests that a single row of one-story homes might be expected to provide about 4.5 dBA of additional noise reduction, whereas a second study (*7*) indicates that closely spaced two-story structures should produce about 10 dBA of additional noise reduction. As a first-order estimate, it is assumed that a row of high-rise structures will provide 0 to 6 dBA more noise reduction than a row of single-story houses, depending on the amount of open area between the structures.

COST ESTIMATION PROCEDURES

When costs and benefits, or inputs and consequences, can each be measured in terms of dollars, the usual procedure for analysis of the relative economy of the alternatives for attaining the objective is to calculate an equivalent uniform annual cost, net present worth of the cash flows, benefit/cost ratio, or rate of return (*8*). For the problem at hand, where noise reduction is the desired benefit, there is no available technique for placing market prices on the benefits received through a reduction in the dBA noise level within a community. The cost of inputs can be expressed in terms of dollars, but the consequences of the input dollars cannot be dollar priced. The procedure, then, must involve a cost-effectiveness analysis in terms of the dollar costs required to make a specific reduction in the dBA noise level. This cost can be normalized to dollars per dBA of noise reduction; however, the total amount of noise reduction must also be stated, because some strategies will provide more noise reduction than others.

The several alternatives for achieving a reduction in noise level need to be reduced to a common standard of measurement in order to make meaningful comparisons. A mile of highway length is the common factor normally used in comparing highway capital costs and highway operation and maintenance costs. The traffic is normally expressed in number of vehicles flowing per unit of time, usually a specific hour or a day of 24 hours. With these traditional units of measurement in mind, the analyses of cost-effectiveness are made on a highway-mile as the basic unit. When the traffic stream is a factor in the analysis, it is expressed in terms of vehicles per hour or vehicles per day for the one-mile section.

Basic Cost Evaluation Technique

For the purposes of this study, the equivalent uniform annual cost is considered the most appropriate descriptor for assessing noise-reduction costs. The equivalent uniform annual cost (EUAC) is defined by

$$\text{EUAC} = (I - T)(\text{CR}, r, n) + P + M + rT \qquad \text{(N-3)}$$

where

- I = capital investment at time zero, in dollars;
- T = estimated terminal value of I at the end of n years, in dollars;
- CR = capital recovery factor;
- r = money time discount factor per year;
- n = useful service life or analysis period, in years;
- P = equivalent uniform expense per year for operation, in dollars; and
- M = equivalent uniform expense per year for maintenance, in dollars.

The capital recovery factor, CR, combines return of capital (depreciation) with return on capital (investment return) at the discount rate of r for n years. This compound interest factor is given by

$$\text{CR} = \frac{r(1 + r)^n}{(1 + r)^n - 1} \qquad \text{(N-4)}$$

which is based on the sinking fund concept that provides for an increasing yearly depreciation return and a decreasing yearly investment return, such that the sum of the two factors is constant over n years.

It should be noted that the cost terms in Eq. N-3 represent the change in cost due to the noise-reduction measure, rather than an absolute cost. For example, the change in cost associated with quieting a heavy truck is the cost of the quiet truck minus the cost of a similar truck without noise-reduction equipment. It follows that some of the cost changes might be negative, reflecting a cost reduction due to the noise-reduction measure. For example, use of a thermatic or viscous fan clutch as a noise-reduction measure on a heavy truck actually will reduce the operating cost for the truck because it reduces the horsepower consumed by the fan.

Finally, because the costs of concern must be measured in terms of a change from an existing situation or baseline design, it is necessary to define the baseline designs to which noise-control measures are applied. The baseline designs assumed for the purposes of this study are as follows:

1. For motor vehicles, the baseline design is that generally prevailing in the 1973 models, including such specific designs that are for safety and emission controls. Straight-rib tires are considered within the baseline design for automobiles and light trucks, but cross-rib tires (NBS tread patterns D through F) are assumed in the baseline design for heavy trucks.
2. For highways, the baseline design is the one the highway department would construct with the gradeline at ground level on the basis that no feature of the design would be specifically directed to reduction of noise.
3. For community structures along the highway route, the baseline design is the one being constructed in that locality without specific features to prevent the penetration of noise to the interior of the structures. Any insulation for space heating or space cooling now standard is considered within the baseline design, even though such insulation provides interior noise reduction. However, central air conditioning is not considered within the baseline design for residential dwellings.

Assessment of Vehicle Noise-Reduction Costs

For the motor vehicle noise-reduction measures considered in this study, the equivalent uniform annual cost is computed using the following assumptions:

1. The money time discount factor is $r = 0.10$.
2. The terminal value of the noise-reduction equipment on new automobiles is $T = 0$ after $n = 11$ years.
3. The terminal value of the noise-reduction equipment on new light trucks is $T = 0$ after $n = 8$ years.
4. The terminal value of the noise-reduction equipment on either new or retrofitted heavy trucks is $T = 0$ after $n = 2$ to 8 years, depending on the specific equipment.

The first assumption is consistent with the discount factor currently used by the U.S. Department of Transportation. The second and third assumptions suggest that the noise-reduction equipment (excluding mufflers) for automobiles and light trucks is good for the useful life of the vehicle. The average useful life of automobiles is estimated from recent Department of Transportation data (*124*) to be about 120,000 miles at an average use of 11,000 miles per year for 11 years. The average useful life of light trucks is coarsely estimated to be about 160,000 miles at an average use of 20,000 miles per year for 8 years. Of course, the annual use of both automobiles and light trucks is heavily dependent on their age; the annual use is much higher, on the average, for new vehicles than for old vehicles. However, this does not influence the desired economic calculations, so long as it is assumed that the noise-reduction equipment is good for the life of the vehicle.

Concerning the last assumption, discussions with representatives of both a heavy truck manufacturer and a trucking company lead to the following conclusions. The average heavy truck is operated about 125,000 miles per year for 4 to 6 years by its first owner. During this period, the engine is overhauled two or three times, which is generally the limit for continued reliable and efficient performance. The truck is then often sold to a second owner, who may use the truck only for the remaining engine life, or may replace the engine and use the truck for several additional years. It follows that a heavy truck might outlive much of its noise-reduction equipment. Hence, the equivalent uniform annual cost of the equipment should be computed item by item. The alternative would be to carry the equipment replacement costs as a maintenance expense. However, this approach would ignore the interest costs, which are substantial for some of the more expensive items.

For the case of new trucks, the useful lives of equipment items are assumed to be (a) 8 years for items good for the life of the truck, (b) 5 years for items good for the life of the engine, and (c) 2 years for all others, as detailed later. For the case of existing trucks that are retrofitted, it is assumed that the average truck is 2 years old when the equipment is installed. Hence, the useful lives of equipment items good for the life of the truck and engine are 6 and 3 years, respectively.

Based on the foregoing assumptions, the capital recovery factors for vehicle noise-reduction equipment are as follows:

1. New automobiles; CR = 0.154.
2. New light trucks; CR = 0.187.
3. New heavy trucks; CR = 0.576 for $n = 2$,
   CR = 0.264 for $n = 5$,
   CR = 0.187 for $n = 8$.
4. Existing heavy trucks; CR = 0.576 for $n = 2$,
   CR = 0.402 for $n = 3$,
   CR = 0.230 for $n = 6$.

With these capital recovery factors and appropriate cost data for given degrees of noise reduction, an equivalent uniform annual cost (EUAC) for vehicle noise-reduction measures can be calculated by Eq. N-3. However, the resulting EUAC figures do not provide a firm basis for cost comparisons with other traffic noise-reduction strategies, because they do not relate directly to the desired base unit of measure; i.e., one mile of highway length. There is no totally satisfying way, from the viewpoint of basic economic theory, to convert vehicle noise-reduction costs in units of dollars per vehicle-year to units of dollars per highway-mile. Nevertheless, there is at least one practical approach acceptable for the purposes of this study. Specifically, convert the EUAC in dollars/vehicle-year to an EUMC (equivalent uniform mileage cost) in dollars/vehicle-mile by dividing the EUAC by the average yearly use in vehicle-miles. Now convert the EUMC in dollars/vehicle-mile back to an EUAC in dollars/highway-mile by multiplying the EUMC by the traffic volume in vehicles/year. The result is an effective equivalent uniform annual cost ($EUAC_e$) in dollars per highway-mile, which may be expressed as

$$EUAC_e = (EUMC)V = (EUAC)V/M \quad \text{(N-5)}$$

where:

V = traffic volume, in vehicles per year, over a given mile of highway;
M = average vehicle use, in miles per year;
EUAC = equivalent uniform annual cost, in dollars per vehicle-year, as given by Eq. N-3;
EUMC = equivalent uniform mileage cost, in dollars per vehicle-mile, = EUAC/M; and
$EUAC_e$ = equivalent uniform annual cost, in dollars per highway-mile-year.

Application of Eq. N-5 poses one serious problem; specifically, the definition of an appropriate value for M (the average vehicle use). On the one hand, it might be argued that this value should reflect only the miles per year spent by the average vehicle on a highway passing through a community where traffic noise is a major problem. This approach, however, would totally ignore the benefits of vehicle noise reduction during operation on city streets or in rural areas. The logical alternative is to let M equal the total annual miles the vehicle is driven. Of course, this technique would bill the noise-reduction costs equally to all miles of operation, including those miles that might be driven on rural roads where the demand for noise reduction is not as great as in urban areas.

Although neither of these definitions for M is wholly satisfying, it is believed that the definition based on total annual use is the more desirable of the two. Hence, in this study, vehicle noise-reduction costs are computed using Eq. N-5, where M is the total average vehicle use in miles per year. It should be clearly understood, however, that this approach effectively asserts that a dBA of vehicle noise reduction is as valuable on a mile of city street or country road, as on a mile of urban highway. This assertion is particularly critical for the case of heavy interstate trucks, where more than 90 percent of the total operating miles might be on highways through sparsely populated areas. If the total cost of heavy truck noise-reduction measures were billed against only those miles spent on urban highways, the resulting computed noise-reduction cost per mile would be increased by perhaps an order of magnitude. Hence, the assumption greatly influences the apparent cost-effectiveness of this noise-reduction strategy.

For those strategies involving use of vehicle noise-reduction equipment, there is no change in travel time, inasmuch as the speed and route of the vehicle are not altered. However, this is not true for the strategy of diverting all heavy trucks to an alternate route. In this case, there is no change in capital costs resulting from the strategy. Furthermore, assuming the alternate route has curvatures, grades, and traffic interference similar to the normal route, there is no change in the operating and maintenance costs on a per mile basis. On the other hand, there is a change (usually an increase) in the time and distance the truck must travel. It follows that an $EUAC_e$ for this noise-reduction strategy may be estimated by

$$EUAC_e = C_o V(D_a - D_n)/D_n \quad \text{(N-6)}$$

where:

C_o = truck operating cost, in dollars per mile, including the value of travel time;
V = truck traffic volume on the alternate route;
D_a = total length, in miles, of alternate route diverted to; and
D_n = total length, in miles, of normal route diverted from.

Eq. N-6 assumes that the alternate and normal routes are equal in their effects on the operating cost of trucks. Furthermore, application of Eq. N-6 requires the assumption that an alternate route is available through an area where no noise reduction is needed, and that there are no starting or termination points for the trucks along that section of the normal route being diverted.

Assessment of Highway Noise-Reduction Costs

For the highway noise-reduction measures considered in this study, the equivalent uniform annual cost is computed using the following assumptions:

1. The money time discount factor is $r = 0.10$.
2. The terminal value of a highway pavement is $T = 0$ after $n = 20$ years.
3. The terminal value of noise-reduction constructions, excluding highway repavement, is $T = 0$ after $n = 40$ years.
4. The increase in right-of-way width required for construction of elevated and depressed highway configurations, as well as roadside earth berms, is equal to the width of slopes required to construct the roadway fill, depression, or roadside berms.
5. No increase in right-of-way width is required for construction of masonry or steel roadside barriers.

The first assumption is consistent with the factor currently used by the U.S. Department of Transportation. The second assumption is consistent with general data for asphalt pavements (*8*). It follows that the capital recovery factor for repaving is CR = 0.117. The third assumption is considered a reasonable lower bound on the useful service life of the noise-reduction constructions of interest. The constructions of concern here are only those required to add shielding to a normal ground-level highway; specifically, land excavations and fills, elevated structures, roadside barriers, and additional right-of-way, but not the pavement, signs, and other constructions that would be required for a ground-level highway. Many of these added constructions (additional right-of-way, for example) might have a useful service life far in excess of 40 years. Fortunately, for $r = 0.10$, the capital recovery factor is not very sensitive to the assumed service life beyond 40 years (for example, at $n = 40$, CR = 0.102, whereas at $n = \infty$, CR = 0.100).

The last two assumptions (concerning the right-of-way width) are critical. Because right-of-way acquisition costs are often the largest single cost factor in construction of highways through densely populated cities, the actual change in required right-of-way width caused by a noise-reduction measure could have a profound impact on the resulting cost of the strategy. Assumptions 4 and 5 are required to obtain quantitative results for evaluation. Furthermore, they are generally reasonable assumptions. However, it should be emphasized that highway designers often suppress the increased right-of-way requirements for fill elevations, depressions, and earth berms by reducing the median width and/or the distance between the edge of the construction (including slopes) and the right-of-way boundary. In such cases, the effective capital cost of the noise-reduction construction might be significantly reduced.

With the foregoing assumptions and appropriate cost data for a given degree of noise reduction, an equivalent uniform annual cost (EUAC) for the various highway noise-reduction measures can be calculated from Eq. N-3. The resulting figures directly provide a firm basis for cost comparisons with other traffic noise-reduction strategies.

Assessment of Community Structures Noise-Reduction Costs

For the community noise-reduction measures involving the sound treatment of occupied structures, the equivalent uniform annual cost is computed using the following assumptions:

1. The money time discount factor is $r = 0.10$.
2. The terminal value of the noise-reduction construction is $T = 0$ after $n = 40$ years.

The justification for these two assumptions is exactly the same as presented for the highway noise-reduction constructions. They further lead to the same capital recovery factor; namely, CR = 0.102.

With these assumptions and appropriate cost data for a given degree of noise reduction, an equivalent uniform annual cost (EUAC) for the sound treatment of individual structures can be calculated from Eq. N-3. Of course, there is still the problem of relating the EUAC for individual structures to an EUAC per highway-mile. This final step requires a specific configuration for the type of structures along the right-of-way, as well as some limit on the distance from the highway where noise control is considered necessary. However, for any given configuration and stated distance limit, an appropriate EUAC per highway-mile is readily calculated by summing the EUAC figures for the individual structures.

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