NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT **311**

PREDICTING STOP-AND-GO TRAFFIC NOISE LEVELS

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TO: CHIEF ADMINISTRATIVE OFFICERS
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FROM: Thomas B. Deen
Executive Director

SUBJECT: National Cooperative Highway Research Program Report 311
"Predicting Stop-and-Go Traffic Noise Levels"
Final Report on Project 25-2 of the FY '88 Program.

I am enclosing one copy of the final report resulting from research conducted by Vanderbilt University, Nashville, Tennessee. In accordance with the selective distribution system of the Transportation Research Board, all persons who have selected the Highway Transportation mode and subject areas of Planning; Energy and Environment; Environmental Design; Operations and Traffic Control; and Traffic Flow, Capacity, and Measurements will receive copies of this document.

The NCHRP staff has provided a foreword that succinctly summarizes the scope of the work and indicates the personnel who will find the results of particular interest. This will aid in the distribution of the report within your department and in practical application of the research findings on predicting traffic noise under stop-and-go conditions, for example, at intersections and highway ramps.

Enclosure

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **311**

PREDICTING STOP-AND-GO TRAFFIC NOISE LEVELS

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

AREAS OF INTEREST

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Operations and Traffic Control
Traffic Flow, Capacity, and Measurements
(Highway Transportation)

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. NOVEMBER 1989

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

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

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 the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

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

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

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation officials, or the Federal Highway Administration, U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

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FOREWORD

By Staff
Transportation Research Board

In this report, a method is advanced for predicting stop-and-go traffic noise levels that occur during interrupted traffic flow, such as at signalized or signed intersections and on ramps. Individuals involved in project development and the assessment of noise impacts will find the report of interest. In particular, it will be of interest to location and design engineers, traffic engineers, and environmental engineers who can adapt the method for their special use. Researchers will also want to review the findings to help refine the application of the method and further the overall development of noise predictions and impact assessments.

STAMINA 2.0 has become the standard computer-based noise prediction model to aid in the assessment of existing and future noise levels on highway projects. This Federal Highway Administration supported computer model has the versatility to use several ranges of factors (or data) to predict noise levels for many types of conditions. However, STAMINA deals with free flowing traffic traveling at least 30 miles per hour. It does not have the capability of dealing with stop-and-go conditions that are frequently encountered in urban areas and can be very different from normal free flow traffic conditions.

Noise analysts using STAMINA have been attempting to predict noise levels for stop-and-go conditions by using various approximations and engineering judgments, based on often differing results of previously published material. The analyst who assesses existing and future noise levels for environmental impact statements (EISs) or environmental assessments (EAs) using STAMINA has no formally recognized basis for adjusting the program to adequately reflect stop-and-go conditions. The error resulting from the use of these approximations can be significant. Consequently, research was needed to develop standard procedures for accurately assessing stop-and-go noise levels through a careful review of the literature, new controlled measurements of truck emission levels, and analysis and field validation of the results.

Vanderbilt University, Nashville, Tennessee, as contractor for NCHRP Project 25-2, "Predicting Stop-and-Go Traffic Noise Levels," developed procedures and algorithms for use with the national emission level equations used in STAMINA, as well as for adaption to local conditions and further verification. The procedures will be useful immediately, but even more so when STAMINA 2.0 has been modified by others to incorporate the algorithms.

Readers will note that not all appendixes are published herein but are, instead, contained in a separate agency report titled, "Supplement to NCHRP Report 311, Predicting Stop-and-Go Traffic Noise Levels." Copies of the agency-prepared supplemental report have been sent to all NCHRP sponsors, namely the state highway agencies. Others wishing to obtain the additional details found in the supplemental report (available for $3.00) should contact the Publications Office, Transportation Research Board, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

CONTENTS

ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 25-2 by the Vanderbilt Engineering Center for Transportation Operations and Research (VECTOR), part of the School of Engineering of Vanderbilt University.

William Bowlby, Associate Professor of Civil Engineering, was the principal investigator. Roger L. Wayson, Research Instructor in Transportation Engineering, and Robert E. Stammer, Jr., Associate Professor of Civil Engineering, were the co-authors.

Of great assistance to the authors during most phases of the work were Hung-Ming Sung, research assistant, and Mark L. Greenwood, experimental equipment technician. Also assisting in the data collection and reduction were Wendell Osbey, Ted Hildreth, Ram Subramaniam, Li Jinsheng, Derrick Gregg, Yuri Imanishi, Yoshi Imanishi, Mani Agrawal, Emily Goodenough, and Brennan Smith.

PREDICTING STOP-AND-GO TRAFFIC NOISE LEVELS

SUMMARY

In compliance with the National Environmental Policy Act and other Federal and State procedures for processing highway projects, traffic noise analyses are required as part of the environmental process relating to highway project development. A key feature of the analysis is the prediction of worst hour, future noise levels near the project. The most commonly used prediction method is the Federal Highway Administration (FHWA) STAMINA 2.0 computer program, which incorporates the algorithms of the FHWA Highway Traffic Noise Prediction Model. The model is based on vehicles traveling at constant speeds. Acceleration and deceleration situations where speeds change, however, are not accounted for in the model. These situations regularly occur on interrupted flow facilities (signalized or signed intersections) or on ramps. This research developed a methodology for using the STAMINA 2.0 program in these changing speed situations. Use of the methodology should lead to more accurate traffic noise predictions, which, in turn, should result in better assessments of impact and better decisions on noise abatement.

Development of the prediction method was based on a detailed analysis of the literature and the collection of new field data. The literature review indicated that most traffic noise prediction models developed and refined, in the United States, have focused on constant speed traffic. A good deal of the data acquired on constant speed vehicle emission levels from those works, generally, show that cruise-mode emission levels for automobiles, medium trucks, and heavy trucks are speed dependent, although to a lesser degree than the emission levels in the FHWA STAMINA model. The data also support extension of the FHWA model equations for cruise conditions to lower speeds than the current 30-mph limit.

Most of the data collected on accelerating or decelerating vehicles were for purposes other than computer modeling, such as for assessing the impacts of regulations and, thus, were not directly usable in this research. One source of information, however, was through the U.S. Environmental Protection Agency (EPA) National Roadway Traffic Noise Exposure Model. The data describe four modes of operation—cruise, acceleration, deceleration, and idle. The cruise data match the FHWA STAMINA model cruise emission levels. The acceleration and deceleration emission levels are presented as time-averaged levels over the duration of the acceleration/deceleration event, for an observer assumed to be moving alongside the vehicle at a 50-ft offset distance. These averages were given for a series of final and initial speeds. By assuming vehicle acceleration and deceleration rates, the full-event levels can be broken down into a series of intermediate steps or stages to allow simulation of changing levels during the event.

Other research in the literature has addressed the changing speed problem by developing time simulation models that relate noise level to speed, position, and mode of operation. These models allow determination of acoustical profiles (depictions of how the average level changes as a function of distance along the line of travel). The profiles are particularly useful in demonstrating the effects of acceleration and deceleration on the received level. However, these simulation models have not been used extensively in this country and are based on foreign vehicles.

The literature reported a limited amount of field data collected specifically to address level changes with distance from a traffic control device. Those data sources support the results of the simulation models, which depict levels decrease rapidly with decreasing speed during deceleration and increase during acceleration. Whether the level during acceleration exceeds the final cruise level depends on the final speed. Levels during acceleration were roughly equivalent to levels emitted during cruise at speeds of 40 to 45 mph.

In the development of the method for this research, the sound exposure level (SEL), a measure of the total acoustic intensity of an event, such as a vehicle pass-by, was found to be a good surrogate measure for effects on the one-hour time-averaged level, L_{eq}.

An analysis of EPA acceleration data showed that the automobile sound exposure level was speed-dependent, while the medium truck sound exposure level was independent of speed (equivalent to a 43-mph cruise event based on the FHWA STAMINA model equations). Field data collected in this research showed that the heavy truck sound exposure level was relatively constant over the first 600 ft of an acceleration event, about 2 dB below the sound exposure level of a 60-mph cruise pass-by. Beyond 600 ft, the level was largely a function of tire noise and followed the cruise emission level pattern—although it was less speed dependent than the FHWA model.

Levels during deceleration changed much more rapidly with speed than during acceleration. Analysis of the EPA data showed that the automobile sound exposure level averaged over the 20-mph to 0-mph deceleration stage was 15 dB below the sound exposure level for cruise at 60 mph. Half of the drop occurs in the last 100 ft of the event.

Analysis of deceleration field data assembled in this research showed an 8-dB drop in the heavy truck sound exposure level from a 60-mph cruise event compared to deceleration pass-bys in the 20-mph range. In the final stage of deceleration the sound exposure level was about 12 dB below the value at 60 mph.

Because the goal of this study was to develop a method to predict stop-and-go levels with the constant-speed STAMINA 2.0 model, some means of accounting for speed-related level changes was needed. The concept of zones of influence was used.

A zone of influence (ZOI) was simply defined as an area where levels are affected by acceleration and deceleration. There are two approaches that can then be taken to define levels in these zones: (1) direct adjustments to the cruise speed levels can be made, or (2) the level can be predicted by an equivalent constant speed that will produce the desired level differences relative to cruise. The direct use of level adjustments proved cumbersome because the acceleration and deceleration effects were dependent on the vehicle type, and STAMINA 2.0 does not report levels in such a manner. Use of equivalent speeds proved to be more workable because the STAMINA 2.0 input does require speed to be given by vehicle type. Acceleration areas can be modeled by as few as one or two zones of influence, depending on the vehicle type and final speed.

Deceleration areas can also be modeled by one or two zones of influence. The lengths of such zones were carefully chosen in the research after comparing the results to a more finely detailed modeling strategy and to field evaluation data.

Although the different vehicle types reached final cruising speed over different distances, the results could still be combined to maintain the concept of using only one or two zones of influence per mode of operation. The results showed that when the initial or final cruise speed was 45 mph or below, only one zone of influence needed to be defined for acceleration or deceleration. Also, for speed changes on ramps where both the initial and final speeds were nonzero, only one zone of influence needed to be defined.

A series of equivalent constant speeds was developed for each vehicle type for each zone of influence. The STAMINA 2.0 program was modified to accept speeds below 30 mph and a sensitivity analysis of the methodology was conducted. By defining a series of receiver points along the roadway, acoustical profiles could be developed.

The predicted results followed what was reported in the literature for many of the simulation models: levels decreased in the decelaration area and increased in the acceleration zone. For final speeds below 45 mph, the acceleration level decreased back down to a cruise level. For final speeds over 45 mph, the level continued to increase until the cruise level was reached.

A drop in the levels of more than 6 dB was predicted for the most sensitive case (100 percent automobiles, 60-mph cruise speed, all vehicles stopping, receivers at 50 ft). The introduction of a certain percentage of traffic modeled as cruising through the intersection changed the results significantly. For example, for a 50 percent split between cruise and interrupted flow traffic, the difference in levels between the zones of influence and the full cruise areas beyond them was reduced to less than 2 dB. Introduction of traffic flowing in the opposite direction tended to make the predicted acoustical profiles more symmetrical around the intersection because accelerating traffic was now being modeled in the same region as deceleration traffic, and vice-versa. The modeling also showed that as receiver distance from the road increased, the magnitude of the level difference between full cruise and interrupted flow decreased. However, the affected region widened as contributions from adjacent modeled roadways became more important in computing the total level.

Validation of the methodology at two signalized intersections led to adjustments in the lengths of the zones of influence. Validation also showed that when the percentage of nonslowing, cruise-through traffic was less than 25 percent, the best results were obtained if all traffic was modeled as interrupted flow. Final predictions of hourly L_{eq} values were within 1 dB of measured levels.

The resultant design guide defined three types of analysis situations: (1) signalized intersections, (2) unsignalized intersections (STOP signs), and (3) loop ramps or slip ramps where both the initial and final speeds were nonzero. For signalized intersections, an average point of stop is determined for all modeled vehicles as being located one-half the expected queue length back from the stop line. For unsignalized intersections, all vehicles are assumed to stop at the stop line, and the final deceleration zone of influence includes the distance to decelerate to the end of the expected queue plus the length of the queue.

The methodology was not developed to predict sound levels in unstable flow situations, such as level-of-service F on highways or level-of-service E or level-of-service F at intersections, where frequent failures in clearing the queue occur. Also, it was beyond the scope of the research to use the methodology in highly reverberant urban "canyon" areas because of limitations in the STAMINA 2.0 algorithms.

However, the methodology should offer a solution to the needs of traffic noise analysts for prediction along suburban arterials where cruise conditions can be achieved between traffic signals, along roads with STOP signs, and near highway tollbooths and ramps.

Because the methodology is more complicated than a free-flow traffic analysis with STAMINA, potential users may wish to do an initial screening using the free-flow technique to see if the problem warrants more detailed analysis.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

RESEARCH PROBLEM

Over the last 20 years, a great deal of effort in the United States has been devoted to the development of traffic noise prediction models. The principal use of these models has been the assessment and control of potential impacts from proposed federal-aid highway projects, as required by the National Environmental Policy Act, the 1970 Federal-Aid Highway Act, and subsequent federal regulations. As such, the initial prediction modeling focused on highway traffic and on design year conditions operating as continuously flowing traffic at level-of-service C (or better). Subsequent modeling efforts have evolved from this initial work with the underlying assumption of this continuous flow. The assumption of continuous flow, or more precisely, constant speed, greatly simplifies the prediction algorithms.

However, not all situations requiring noise assessment involve continuous flow (or constant speed). Examples include highway entrance and exit ramps, arterials, toll booth areas, STOP signs, and local street networks. When faced with these situations, noise analysts have made various types of adjustments and approximations within the continuous flow models, with varying degrees of success.

Part of the problem stems from the fact that very little effort has been aimed at modeling nonfree flow during the development of the models approved for use by the Federal Highway Administration (FHWA). As a consequence, there has been no formally recognized basis for considering the interrupted-flow situation. The result of not having such a procedure can be inaccurate predictions of traffic noise levels. The consequence of such predictions can lead to improper assessment of impact, followed by improper decisions on the need for noise abatement or on the amount of abatement.

The research in this project was directed toward overcoming these problems by developing nonfree flow adjustments for the most commonly used traffic noise prediction program STAMINA 2.0 [Bowlby et al., 1982]. The following subsections expand on the definition of the problem. The remainder of this chapter defines the objectives and scope of the research, and describes the approach that was used to study the problem. Chapter Two describes the findings. Their application to traffic noise studies is covered in Chapter Three. Chapter Four includes conclusions and recommended future research. Details of the literature review are given in Appendix A. The analysis and development of the methodology are discussed in full, in Appendix B. The design guide for the methodology is provided in Appendix C. The contents of Appendixes D, E, and F are contained in a supplement entitled, "Predicting Stop-And-Go Traffic Noise Levels—Supplement to NCHRP Report 311." Appendix D describes the noise measurement site and the equipment and procedures used in the measurements. It also tabulates the various measurement periods. Appendix E documents the time-average data collected during model validation at a subset of the sites. It also discusses changes that were made to the original methodology based on a comparison of the measured and predicted levels. Finally, Appendix F presents tables of raw data and statistical analyses for each measurement period, as well as figures presenting summaries of the data on a day-by-day basis. (See Foreword for information on availability of the Supplement.)

STOP-AND-GO TRAFFIC

Common terms used in traffic noise analysis to describe the noncontinuous traffic flow condition are "interrupted flow" or "stop-and-go traffic." In this study, these terms have broader meanings to include other conditions in which speed varies with distance, but a full stop may not occur. Therefore, the first step in understanding the problem is to define the universe of what is meant by "stop-and-go" traffic situations. From that universe, the scope is narrowed to what is particularly important and achievable through this project. It should be noted that traffic engineers use the term "interrupted flow" to apply to a facility, such as an arterial, that has traffic control devices. An "uninterrupted flow" facility would be a highway without traffic control devices; such a facility may still have stop-and-go traffic during periods of extreme congestion.

The universe of stop-and-go situations on public roads includes five major areas: (1) extreme congestion with unstable flow (level-of-service (LOS) F on highways or LOS E or LOS F on interrupted flow facilities such as a signalized intersection); (2) entrance ramps and exit ramps for highways; (3) arterials with widely spaced, traffic control devices in nonurbanized or nonreverberant areas; (4) urban city street networks with traffic controls; and (5) areas in the vicinity of toll booths.

The first category (unstable flow) is not a situation toward which a highway engineer designs, and it cannot be accurately predicted as to when and where the situation will occur. Design work and the requirements for traffic noise studies revolve around the use of the less constrained traffic flow for LOS C (or LOS D). If, for some reason, an agency is required to study noise levels on highways or streets with unstable flow, the agency should make field measurements of the noise levels at similar sites and, then, determine site-specific effects of the constrained traffic on the sound levels.

The second category—entrance ramps and exit ramps—can be further divided by the type of ramp and type of traffic control (if any) at the end of the ramp. As an example, for entrance ramps, one can define at least three subcategories: (a) acceleration from stop to highway speed, such as from a traffic signal on a diamond ramp; (b) acceleration from low speed to highway speed, such as at a diamond interchange channelization or on slip ramps; and (c) acceleration from low speed to high speed with a possible section of constant speed travel, such as on a loop ramp.

Similarly, the category of exit ramps can be further subdivided: (a) deceleration to a stop, such as along a diamond interchange ramp with a traffic control device at the end; (b) deceleration followed by acceleration, such as on a ramp with channelization at the end; and (c) deceleration with a period of constant speed operation, then acceleration, such as on a loop ramp.

The third category of stop-and-go traffic occurs when arterials in nonreverberant situations are controlled by traffic control devices. This category is one of the more common situations where noise analysts find current prediction modeling to be deficient.

The fourth stop-and-go category is that of the city street network controlled by traffic control devices (signs, signals, and the like). This category, a subset of the third category, is one that is not modeled by STAMINA because of its inability to consider multiple reflections or reverberation that occurs in built-up areas. Even if one were to develop emission levels for the city street traffic, STAMINA alone should not be used in these situations. It is beyond the scope of this study to develop a multiple reflections algorithm for STAMINA for urban street canyons. However, the adjustments that have been derived through this study could well be used in conjunction with an urban propagation model, such as that developed by Anderson [1979] for FHWA. That work allows the user to develop urban insertion loss contours for cross-street and midblock sound propagation as a function of many geometric parameters at a site. Anderson recognized the need for an improved emission model in these situations for use in conjunction with the insertion loss model. Accordingly, the results of this research may be combined with an insertion loss model, such as Anderson's, to predict urban noise levels under certain traffic flow situations.

The category of tollbooths along freeways could also be considered a subset of the third category (the suburban arterial with widely spaced traffic control devices) and can be predicted in the same way.

Traffic Noise Models

The next step in understanding the problem is to have some background on the evolution of the prediction models in use today on federal-aid work. There were two main streams of model development in the late 1960's and the 1970's: research sponsored by NCHRP and research conducted directly for USDOT (through the Transportation Systems Center (TSC) and the FHWA).

The initial NCHRP work studied the traffic noise phenomenon (*NCHRP Report 78*) [Galloway et al., 1969] and led to the development of a detailed design guide manual for traffic noise prediction (*NCHRP Report 117*) [Gordon et al., 1971]. *NCHRP Report 117* gave a simple method for accounting for interrupted flow. However, field validation of the *NCHRP Report 117* method produced enhancements of the method that was the subject of *NCHRP Report 144* [Kugler and Piersol, 1973]. The enhanced NCHRP method was subsequently computerized by the Michigan DOT [Grove, 1974], and many other state DOT's made their own modifications to suit their needs [New York State Department of Transportation, 1975].

Concurrent with NCHRP work, the USDOT TSC developed another noise prediction methodology, a computer program commonly referred to as the TSC model [Wesler, 1972]. The TSC model underwent a series of changes including use of a new database for truck emission levels, and evolved into the TSC MOD-04 model [Rudder and Lam, 1977a] by the mid-1970's.

Work under NCHRP sponsorship also continued in this period. A major effort resulted in *NCHRP Report 173* [Bolt Beranek and Newman 1976] and *NCHRP Report 174* [Kugler et al., 1976]. *NCHRP Report 173* examined traffic noise generation and control in detail and provided the basis for a revised design guide prediction methodology and computer program, which was then published as *NCHRP Report 174.*

The two streams of method development—NCHRP and TSC—used different assumptions and often led to widely differing answers. However, both were approved by FHWA for use on federal-aid project studies. With the goal of unifying the traffic noise prediction methodology, Barry and Reagan led a major effort, within FHWA, to draw upon the best features of the NCHRP and TSC work, which resulted in the FHWA Highway Traffic Noise Prediction Model [Barry and Reagan, 1978]. This model was computerized initially as two programs, a "simplified method" called SNAP 1.0 [Rudder and Lam, 1977b] (later revised as SNAP 1.1 [Bowlby, 1980]) and a "detailed method" called STAMINA 1.0 [Rudder et al., 1979a] (later revised as STAMINA 2.0 [Bowlby et al., 1982]). The STAMINA programs used the TSC program code as a framework, modifying the emissions and propagation algorithms but maintaining the geometric calculations routines. The FHWA traffic noise regulations embodied in the *Federal-Aid Highway Program Manual,* Volume 7, Chapter 7, Section 3 (FHPM 7-7-3) [Federal Highway Administration, 1982] now state that any prediction method used in traffic noise studies must be consistent with the FHWA Highway Traffic Noise Prediction Model. While many states have made revisions to different aspects of the model, the STAMINA 2.0 program remains the most widely used method for project noise analysis and noise barrier design [American Society of Civil Engineers, 1986].

As noted earlier, all of these models are based on assumptions of freely flowing traffic. Little effort was put into describing how to model interrupted flow. *NCHRP Report 117* suggests a +2-dB correction to cruise levels for automobiles and a +4-dB correction for trucks (added to the predicted 10 percent exceedance level, L_{10}). *NCHRP Report 174* gives brief guidance on the choice of appropriate constant speeds to model levels on highway ramps. For the FHWA model, Barry and Reagan suggest using emission levels based on speeds of 30 mph for automobiles and medium trucks, and 60 mph for heavy trucks, while using the actual operating speed for the calculation of the traffic density effect.

In an effort to deal separately with the stop-and-go problem in reverberant urban areas, FHWA sponsored development of a stop-and-go model by Slutsky et al. [1983, p. i]. A computer program was developed that takes into account the effects of "urban building structures on multiple reflection and diffuse scattering, of vehicle types, mixes in traffic signalization on microscopic flow behavior, of vehicle acceleration as well as speed and type of vehicle source strength." The model uses as a preprocessor a modified mainframe computer version of the Federal Highway Administration [1980] Network Simulation Model (NETSIM). The procedure for using the stop-go noise program first includes running the modified NETSIM program, then running an intermediate program called POSTNET, and finally running the stop-go noise program. Separately and independently, FHWA made extensive changes to the original mainframe NETSIM to adopt it for microcomputer use, and shifted technical support to the microcomputer version. As a result, potential users of the stop-go model are faced with having to work with an unsupported, difficult-to-use mainframe version of NETSIM. Thus, while the stop-go model offers a potentially useful and valuable approach for modeling urban traffic noise, a great deal of additional effort will be required, prior to implementation, with emphasis on adaptation to the FHWA-supported microcomputer version of NETSIM.

To summarize the problem addressed by this research, virtually all traffic noise prediction models developed in the United States for highway project studies have been based on continuous flow, with little attention to interrupted flow. Also, the work focusing on stop-and-go traffic [Slutsky et al., 1983; and subsequent related efforts] has not been implemented by FHWA, and requires further development before it might be. A need exists to provide guidance to noise analysts in addressing interrupted flow situations to improve their studies and to ultimately improve noise abatement decisions and designs.

RESEARCH OBJECTIVE AND SCOPE OF WORK

The objective of this project was to develop a method to accurately predict stop-and-go traffic noise levels that could be used with the STAMINA 2.0 computer noise program. The method needed to be one that could easily be used, with relatively simple adjustments, by the noise analyst familiar with STAMINA 2.0. In addition, it was required that the adjustments be based on common traffic engineering and highway design methodologies and terminology, so that the noise analyst could easily obtain needed traffic input parameters, from traffic engineering specialists, or needed design information, from accepted charts and tables.

The work accomplished in this study was also required to be compatible with the STAMINA 2.0 program. It was not the intent of the research to either develop a separate new model or make extensive changes to the STAMINA program code. Instead, what was sought after were a series of adjustments to the predicted levels or modifications to the procedures by which a problem would be modeled with STAMINA.

The research was to consist of a critical evaluation of the key literature and the collection and analysis of field data to supplement the literature.

The methodology to be developed would apply to a variety of interrupted flow traffic situations, as well as to acceleration and deceleration on freeway ramps, but would not attempt to consider highly congested traffic conditions in urbanized areas. The STAMINA model itself is inadequate for predicting levels in such situations because it does not compute reverberation effects.

ABBREVIATIONS AND NOTATIONS

a	Constant term in a linear expression
a_{acc}	Constant term in a linear expression for an acceleration adjustment
a_{dec}	Constant term in a linear expression for a deceleration adjustment
A	Automobile
AZOI	Acceleration zone of influence; see also ZOI
b	Coefficient of an independent variable in an expression
b_{acc}	Coefficent of an independent variable in an acceleration adjustment
b_{dec}	Coefficient of an independent variable in a deceleration adjustment
dBA	The sound pressure levels in decibels measured with a frequency weighting network corresponding to the "A-scale" on a standard sound level meter; also A-weighted sound level; also DBA
D	Perpendicular distance from the center of a source lane to an observer, in feet (or meters)
DBA	A-weighted sound level
DZOI	Deceleration zone of influence; see also ZOI
D_o	Reference distance of 50 ft, or 15.2 m
D_1	In an acceleration adjustment, the distance from an observer to the low speed end of a segment
D_2	In an acceleration adjustment, the distance from an observer to the high speed end of a segment
E	Sound exposure of an event, in pasques (or pascal-squared seconds)
E.Q.	End of queue
E_o	Reference sound exposure of 4×10^{-10} pasques
HT	Heavy truck
L_{AE}	Level of total received acoustic intensity
L_{eq}	Also $L_{eq}(t) = L_{eq}(t_2 - t_1)$ = equivalent sound level (time-averaged level) over some time period
L_{max}	Also L_o or L_{AFmax}, the maximum A-weighted sound level (fast response) of a vehicle pass-by at a distance of 50 ft
$(\overline{L_o})_E$	Energy-average of a series of L_o measurements
$L_{eq}(1\text{ hr})$	Time-averaged level over a period of 1 hour
$L(i)$	Level of ith event or ith period
$L(\text{total})$	Result of combining two or more levels
$L(x\text{–}y\text{ mph})$	Time-averaged level over the duration of an acceleration event from x to y mph for an observer moving alongside the vehicle at an offset distance of 50 ft
MT	Medium truck
n	Number of events
NB	Northbound
p_o	Reference sound pressure of 20 micropascals
$p(t)$	Sound pressure at time t
P.S.	Point of stop
r	Correlation coefficient
s	Standard error of a sample
S	Vehicle speed, in miles per hour, kilometers per hour, feet per second, meters per second
S_{ref}	A reference speed from which adjustment is made or calculated
SB	Southbound
S.E.	Standard error of an estimate
SEL	Sound exposure level; also level of total received acoustic intensity; also L_{AE}
S_{final}	Speed at end of an acceleration event
$S_{initial}$	Speed at beginning of a deceleration event
$S_{i,AZOI(j)}$	Equivalent speed for the ith vehicle type in the jth AZOI
$S_{i,DZOI(j)}$	Equivalent speed for the ith vehicle type in the jth DZOI

t, t_1, t_2	Time in seconds
T	Time period for time-averaging in FHWA Highway Traffic Noise Prediction Model
ZOI	Zone of influence; also area in which levels are affected by acceleration and deceleration

RESEARCH APPROACH

To accomplish the objectives of this research, the work was divided into three major tasks: (1) Review existing information to determine usability of stop-and-go traffic noise data. (2) Develop and conduct field measurements coupled with existing information that would produce an adequate database from which stop-and-go noise prediction procedures could be formulated and evaluated. (3) Develop a methodology for accurately predicting stop-and-go noise levels.

Reviewing Existing Information

A preliminary literature review during proposal preparation revealed a number of sources of potentially useful information. One difficulty in using data collected by others is the uncertainty regarding the techniques or factors that might affect the results. Thus, even the very interesting sources of data had to be approached with caution. In some instances data may be imperfect, but the theory and methodology are sound. The reverse may also be true. That is not to say, however, that these sources would not be useful. Accordingly, the researchers took great care in obtaining all pertinent sources possible and in performing a careful review of methods, theory, and data from which to build a solid base for the project.

Field Measurement Study

The preliminary literature review revealed that much data on low-speed and stop-and-go noise emission levels and time-averaged levels have been collected over the last 15 years. It was not clear until the first task was well underway as to which data were actually available and how useful that information was for this study. In any case, the additional field data were collected with the specific objectives of this study in mind. There were three thrusts to the field data collection effort: (1) initial measurement of equivalent sound levels, L_{eq}, for different modes of vehicle operation (focusing on heavy trucks); (2) the measurement of emission levels for heavy trucks, medium trucks, and automobiles during the different modes of operation; and (3) initial validation of the stop-and-go adjustment methodology.

The purpose of the initial L_{eq} measurements was to gain additional insight into the phenomena and into the findings of the previous studies. Using sound level analyzers, the measurement team collected short-term L_{eq} data near a highway truck weigh station.

For the first test, three analyzers were used to simultaneously measure in areas where the vehicles were primarily operating in a single mode—one each for cruise, acceleration, and deceleration. The second set of tests was at three positions along the acceleration ramp at the truck weigh station and at a cruise speed position to gain insight into acceleration effects on L_{eq}.

Most of the emission level measurements were also made at the truck weigh station. The site permitted good isolation of the different modes of operation for the purpose of emission level determination, and provided a random selection process of the fleet. The use of multiple analyzers permitted simultaneous measurement at several different points along the deceleration and acceleration lanes. An additional analyzer was set up a mile from the sites to provide a reference point when the vehicles were in the cruise condition. With sampling accomplished at several points along the deceleration or acceleration lane, the data were studied for trends in noise levels as a function of speed and/or distance from the stopping point. Careful statistical analysis allowed trends to be identified and to be used in the methodology development.

The third thrust of the field data collection was a limited model validation. It had been proposed to check the performance of the methodology at two or more typical sites. Four sound level analyzers were used to measure time-average equivalent sound levels simultaneously at four points—one in the free-flow region and three at different points in the area of influence.

Methodology Development

In this task, the results of the detailed evaluation of the literature and the field measurements were used as the basis for a stop-and-go sound-level adjustment methodology for STAMINA 2.0. A main criterion for the methodology was the requirement that the procedures be easy to use, for the noise analyst familiar with STAMINA 2.0, and at the same time also be consistent with traffic engineering and highway design methods.

For those reasons, it was planned to tie the stop-and-go adjustment to data or calculations from the familiar AASHTO Green Book [American Association of State Highway and Transportation Officials, 1984] or *Highway Capacity Manual* (HCM) [Transportation Research Board, 1985].

As was found in the preliminary literature review, stop-and-go traffic noise depends on many factors. However, the only factors of concern to the noise analyst would be obtaining from the traffic engineer or highway designer the relevant traffic parameters consisting of: (1) the type of stop-and-go situation; (2) the size or extent of the area of influence of the traffic control device which would be a function of the initial or final speeds; and (3) the appropriate set of vehicle noise emission levels adjustments.

The first factor could be easily determined from the geometrics and type of project: slip ramp, spiral or loop ramp, traffic signal, STOP sign, and so on. The second and third factors are not as easily determined, but were emphasis areas of this study. The area of influence depends on such factors as number of lanes, capacity, hourly flow rate, approach and final speed grade, type of traffic control (if any), percentage of trucks, and traffic signal cycle if a signal is present. Several of these factors are used in equations to determine an average length of queue, which is used in locating the areas of influence.

A goal of this work was to reduce the methodologies in the HCM or the AASHTO Green Book to a tabular format that would reveal to the noise analyst where the influence area begins so that the analyst could start a new STAMINA "roadway" at that point. The parameters were required to be readily available on project plans or be obtainable from the traffic engineer. STAMINA currently allows 30 roadways, which would be sufficient to allow for additional "area of influence" roadways.

Several methods of defining vehicle characteristics needed to be investigated: adjustments to cruise levels, use of equivalent speeds to produce desired levels or adjustments, definition of new vehicle types with new emission levels, and use of emission levels based on parameters other than vehicle speed. The chosen method could not place too many demands on the user during input file creation or else it would likely go unused.

In other words, the methodology needed to reflect careful consideration of the effects of traffic parameters on the size of the area of influence and on the vehicle emission levels within the area—but in a manner requiring minimal additional effort on the part of the noise analyst using STAMINA. The analyst would need to obtain some basic flow parameters for the study site from the traffic engineer and then use these data to look up in tables where to start and end the influence area "roadways" and which vehicle characteristics to specify in the STAMINA file.

CHAPTER TWO

FINDINGS

INTRODUCTION

This chapter reports the findings from investigation of both the existing literature and new measurements done as part of this research. Highlights of the methodology for predicting interrupted flow traffic noise levels using the STAMINA 2.0 computer program, which was developed, evaluated, and tested against field data, are also covered. The literature review, the analysis of the field data, and the development and evaluation of the methodology are presented in full in the appendixes. The discussion in this chapter is complete enough to give an understanding of the results and their use without overburdening with too much detail.

REQUIREMENTS

To understand this work, it is necessary to know how it will be used. Federal regulations require traffic noise studies as part of the environmental impact analysis process. The regulations say that this impact assessment should be done in terms of hourly averages. Specifically, the worst (perceived) noise hour of the day or the noisiest (actual) hour should be examined. However, traffic noise varies with time as vehicles continually approach and pass a study site.

Describing how this varying noise level at a particular site will impact people has been accomplished in various ways over years of research and study on this topic. First, the noise at any point at any moment in time may be described in terms of its intensity at that point relative to a reference intensity. Intensity is a function of the square of the pressure in the air produced by the traveling sound wave. A logarithmic function was used to condense the range of possible squared sound pressure ratios to workable numbers. The resulting relationship of squared sound pressure to squared reference sound pressure was termed the sound pressure level and expressed in the unit of decibels (dB). Because the human ear hears different components of the sound spectrum in different ways, electronic filters were developed for measurement instruments to measure levels that related to human response. One such filter, termed the A-filter, has become accepted as the standard way of adjusting the sound pressures of typical environmental sounds, including traffic noise, to replicate how the human ear perceives the sounds. The overall effect of reducing or boosting these sound pressure levels across the sound spectrum is termed A-weighting. The composite of these adjusted levels is termed the A-weighted sound level, also measured in decibels (and typically written as dBA).

Initially, a statistical approach was taken to describe the variation in noise levels over the hour being studied. A tenth-percentile exceedance level was defined as a good descriptor for assessing traffic noise impacts. This level, written L_{10}(1 hour), could be determined from measurements by examining the cumulative distribution curve and could be predicted by knowing the distance to the receiver, the volume and speed of traffic (assuming equal vehicle spacing), and the average maximum level of each type of vehicle in the traffic stream.

Later, an approach of averaging the sound energy was adopted for describing time-varying levels and assessing impacts. This approach did not require special assumptions, such as equal vehicle spacing for predictions, and allowed levels from different sources to be combined in a mathematically correct way. As noted in the beginning of this discussion, the term level represents a logarithm function of a ratio of sound intensities (or squared pressures). More precisely, the sound pressure level at any time t, $L_p(t)$, is defined as:

$$L_p(t) = 10 \log [p(t)^2/p_o^2] \quad (1)$$

where $p(t)$ is the sound pressure at time t and p_o = 20 micropascals.

The averaging of these squared pressure ratios is done by summing them over some duration (t_2-t_1) and then dividing by that duration. The level of the averaged square pressures ratio is ten times the logarithm of the average squared pressure. This level is called the time-averaged level or "equivalent level" and is typically abbreviated as $L_{eq}(t_2-t_1)$. The duration (t_2-t_1) could be any value of interest, but for traffic noise prediction and impact assessment, it is defined as one hour (or 3,600 sec). L_{eq}(1 hr) is often abbreviated simply by L_{eq}, but it is always important to know that some duration is being implied. Mathematically, $L_{eq}\,(t_2-t_1)$ is defined as:

$$L_{eq} = 10 \log \left\{[1/(t_2 - t_1)] \int_{t_1}^{t_2} [p(t)^2/p_o^2]dt\right\} \quad (2)$$

This quantity may be determined by measurement using an analyzer that detects the sound pressure and performs the foregoing calculation. However, predicting L_{eq} for highway project studies requires an expression that is a function of the typical parameters available to the engineer—traffic volumes, speeds, and distances from the road, among other items.

Traffic noise prediction has been the subject of much research. Most of the research as it relates to highway project studies has been based on the assumption of constant speed traffic above a speed of 30 miles per hour (mph). These research works will be discussed shortly. In general, prediction of the time-averaged level of a stream of traffic begins with the prediction of the level of a single vehicle at each point in its passage by a receptor. Then, these levels are combined to give some single measure of the contribution of that passage to the total level over the hour. Next the contributions of all vehicles passing by the point in the hour are combined.

There are two important ways to describe the level of the passage of the vehicle. The first is simply the maximum level, L_{max}, which occurs when the vehicle is at or near its closest point to the observer. To simplify predictions, all of the vehicles are divided into three categories, automobiles, medium (2-axle, 6-tire) trucks, and heavy trucks (3 or more axles). The average L_{max} of each vehicle class is used. These averages are called "energy-averages" and are actually the level of the average maximum intensity of each vehicle class. An expression for this average level, which is also denoted as $(\overline{L_o})_E$ to denote energy-average of maximum levels (L_{max} or L_o) measured at a reference distance is

$$(\overline{L_o})_E = 10 \log \left[(1/n) \sum_{i=1}^{n} 10^{(0.1\, L_{\max,i})}\right] \quad (3)$$

where n is the number of events and $L_{max,i}$ is the maximum level of the ith event. If the distribution of the maximum levels is normal (or Gaussian), an approximation may be derived [Barry and Reagan, 1978]:

$$(\overline{L_o})_E = L_o + 0.115(s)^2 \quad (4)$$

where $(\overline{L_o})$ is the arithmetic average of the maximum levels of the n events and s is the standard error of the measured maxima.

These levels are termed "reference energy mean emission levels" in the literature, and are typically the quantities used in traffic noise prediction.

The $(\overline{L_o})_E$ term makes no account of the duration of the pass-by event, which is important in determining the total contribution to the L_{eq} from the pass-by. Duration may be accounted for elsewhere in the prediction model equations in a relatively straightforward manner if the speed is constant. However, when speed varies, such as in acceleration or deceleration, which are two of the key modes in interrupted flow situations, then the relationship of L_{max} to L_{eq} is not as easily described. Instead, it is useful to consider another way of representing the event, the sound exposure level, or SEL. SEL represents the level of the total intensity of the event integrated over its duration. It is determined by computing or measuring the level at each point in the pass-by, converting the level to an energy representation, summing these energies and converting back to a level. It is directly related to L_{eq} in that SEL represents the level of the total energy of the event, while L_{eq} is the level of the average energy. Thus:

$$L_{eq}(t_2 - t_1) = \text{SEL}(t_2 - t_1) + 10 \log [1/(t_2 - t_1)] \quad (5)$$

Because SEL represents the total energy of the event, generally only that time when the level of the vehicle is within 10 dB of the maximum needs to be considered in computing SEL. The energy contributed for those times in the pass-by before and after the "10-dB down" time contributes little to the total, and SEL tends to no longer increase. Thus, the following relationship can be shown:

$$L_{eq}(1 \text{ hr}) = \text{SEL} - 35.6 \text{ dB} \quad (6)$$

where 35.6 is a function of the number of seconds in an hour. For example, if the SEL of a truck passage was 90 dB, the L_{eq}(1 hr) for that single truck would be 54.4 dB. The effect of multiple trucks can then be easily computed.

This relationship was of direct use in this study. What was ultimately desired was the effect of nonconstant speed traffic on L_{eq}(1 hr). While the total L_{eq}(1 hr) from a stream of traffic could be measured under such a condition, there would be no way of using that measurement to quantify the effects of individual vehicle types—the measured L_{eq} would have all effects combined for all vehicle types. However, the SEL of individual vehicles could also be measured, allowing disaggregation of the effects by vehicle type. Then, these individual effects could be used as building blocks to predict L_{eq}(1 hr) from a mixed flow of vehicles.

The objective of this study was to develop a way to predict nonconstant speed levels using a constant speed model, the FHWA Highway Traffic Noise Prediction Model [Barry and Reagan, 1978], that had been computerized first as STAMINA 1.0 [Rudder et al., 1979a], and subsequently revised as STAMINA 2.0 [Bowlby et al., 1982]. Thus, by establishing how SEL was affected by nonconstant speed traffic, adjustments could be determined to allow use of the constant speed model.

One final useful relationship is that between SEL and $(\overline{L_o})_E$ for the constant speed model:

$$(\overline{L_o})_E = \text{SEL} + 10 \log (S) - 22.4 \text{ dB} \quad (7)$$

where S is the vehicle speed in kilometers per hour. This aspect of the measurement program focused on the relationship of SEL and $(\overline{L_o})_E$ (computed from the L_{max} data) in acceleration and deceleration conditions in an attempt to solve the problem of dealing with a time-varying speed in a constant speed model. The remainder of this chapter will build on the concepts presented in this introductory section.

LITERATURE REVIEW FINDINGS

The literature that was examined focused on two areas: (1) effects on individual vehicle emission levels for constant and varying speed vehicles, and (2) combined effects on overall traffic flows. The individual vehicle data are discussed first for cruise, acceleration, and deceleration conditions. Then, the literature dealing with the combined effects is highlighted.

The literature review overwhelmingly shows that cruise emission, for all vehicle types, is a function of speed. The FHWA $(\overline{L_o})_E$ values for cruise conditions were confirmed from several.

independent sources. At the lower end of the FHWA-defined speed range (50 kph) values from many researchers were very close to the FHWA values and showed, in general, that for the lower defined speed range (cruise conditions), the FHWA $(\overline{L_o})_E$ curve could generally be extended below 50 kph. Vehicles during the idle mode have the lowest emission levels. As speeds increased above 50 kph, several states produced their own $(\overline{L_o})_E$ values and less speed dependence was shown than by the FHWA $(\overline{L_o})_E$ curves. Accordingly, $(\overline{L_o})_E$ values derived by the State DOT's tend to be less than those of FHWA at higher speeds.

Tire noise became significant with increasing cruise speeds and was the primary cause of increased noise levels associated with high-speed cruise. High-speed cruise was shown to be the mode with the greatest amplitude. For automobiles, tire noise became significant at approximately 30 mph. For medium heavy trucks, tire noise became significant at approximately 40 to 45 mph. Accordingly, at lower speeds the engine and exhaust noise components dominate the total noise level.

During the cruise mode the vehicle engine noise is steady. If acceleration occurs, engine noise increases and become variable. Gear shifts increase this variability. Because of the increased amplitude with engine rpm and power output, wide open throttle (WOT) tests have been used extensively to determine maximum noise emissions from vehicles under hard acceleration [Whitney, 1980]. However, these WOT emission levels were shown not to be typical of urban acceleration [Hillquist and Scott, 1975]. Therefore, these reported data were not of use for this project.

Other data have been presented on urban acceleration. The data of Sharp, Olson, Miller, Anderson, Prahl, Close, Hruska, Hillquist, and Whitney provided absolute values and trends. The trends were supported by foreign researchers. However, the database assembled by Plotkin [1979] and presented by Rudder et al. [1979b] was complete and well documented. This work, done for the EPA, in efforts to develop a national exposure model, also presented data for all modes, a shortcoming of many of the other databases. For example, the EPA data for decelerating vehicles showed a very strong speed dependence. This deceleration generally occurs over relatively short distances [American Association of State Highway and Transportation Officials, 1984] and varies with vehicle type. Idle values shown by the data are lower limits to the emission data, as expected.

Accordingly, the EPA database provides a complete database for all four modes (idle, acceleration, deceleration, and cruise), which provides the consistency needed to develop stop-and-go models. When the EPA cruise values are compared to those used in STAMINA 2.0 (the FHWA model), good agreement is shown. It would follow, then, that the other mode data would also be consistent if used in the FHWA prediction model. However, STAMINA 2.0 is a speed-dependent model and can predict only for a given speed. Acceleration and deceleration are varying speed events and are not predicted well by STAMINA.

Different approaches have been taken to overcome this difficulty. The most common, and also the method suggested in the FHWA Model report and used by many researchers, is the use of constant emission levels for interrupted flow [Barry and Reagan, 1978]. This logic is generally based on the fact that interrupted flow is a mixture of all four modes with wide variations in the emission levels. Accordingly, the emission level should be a constant value, derived by consideration of many variables (gear-shift pattern, modal contributions, and so on). The determined constant value can then be estimated with a derived constant speed. However, depending on the modeling approach used, research has shown that mode dependence and measures of traffic dispersion may affect this assumption [Lewis, 1978].

For most modeling situations, the same modes occur with repetition (i.e., deceleration on an exiting ramp; deceleration before an intersection, and acceleration after an intersection). Acoustical profiles (graph of L_{eq} or L_{max} as a function of receiver distance from an intersection at a constant offset distance from the road) have been determined which show this effect [Favre, 1978]. Favre developed a simulation model to allow emission levels to vary with nonconstant speed and other variables, such as engine speed. A similar method was also used by Slutsky [Slutsky et al., 1983]. For cruise, Slutsky used a speed-dependent function in his simulation model. For acceleration and deceleration he used a distance-dependent relationship. This allowed his emission levels to vary per predefined acoustical profiles.

Unfortunately, STAMINA 2.0 is not suited for reprogramming as a simulation model. Future development should include defining $(\overline{L_o})_E$ values as a function of distance. In this way, the determined acoustical profile could be programmed by the distance from a stop point, which would allow characterization of intersections or other areas dominated by modal contributions (i.e., ramps).

In the interim, STAMINA 2.0 may still be used by the derivation of equivalent speeds and zones-of-influence. These ZOI are the defined zones (roadway segments) where one mode is considered dominant (e.g., a deceleration or acceleration ZOI, and can be determined by vehicle and road geometry characteristics).

To determine the characteristic acoustical profile, consideration must be given to mode and vehicle-type contributions. For vehicle types, the data previously discussed could be used (i.e., EPA). For modal contributions traffic parameters must be considered such as queue length, acceleration and deceleration rates, approach speeds, departure speeds, vehicle counts, and the dominant mode per defined roadway. In some cases, modal contributions may not be significant, such as when idle and cruise occur equal amounts of time in a deceleration ZOI. These variables would have to be allowed to vary, based on location from a relative point (i.e., the point of stop, P.S.). Most of the traffic parameters have been established by long-term observations [American Association of State Highway and Transportation Officials, 1984] and could be used directly.

The literature reviewed showed, for the different modes of vehicle operation, that the noise contribution of each mode, along with traffic considerations, may be used to establish the acoustical profile for the area of concern (ZOI dominated by single modal contributions). Simulation models have been used with some success, but are not applicable to this research. The use of other variables rather than speed with a reprogramming of STAMINA 2.0 may be a viable future enhancement. In the interim, emission level step functions, defined by ZOI's may be used with "equivalent" speeds to produce the desired acoustical profiles.

The basis for these models is the absolute values presented in the literature. To confirm these levels and to verify trends, measurements were also conducted and are discussed in the next section. The following section also describes the findings from investigating the phenomenon of accelerating and decelerating vehicles, both in terms of the literature and the measurements.

METHODOLOGY DEVELOPMENT

The development of the methodology began with a detailed examination of the levels from an accelerating automobile to gain a better understanding of the problem. The EPA database [Rudder et al. 1979b] was particularly useful. The data were presented in terms of levels averaged over the full duration of an acceleration event (from 0 mph to a final speed) for a hypothetical observer moving alongside the vehicle at an offset distance of 50 ft. Thus, any trends of how the level changed with distance from the stop line were hidden in the averaged level. However, the data were still useful and good approximations of levels for intermediate 10-mph speed ranges could be determined, as will be described shortly.

The relationship between longitudinal distance from the start of acceleration and emitted level implies that the only totally accurate way to compute the level at a receiver is to do a time-step simulation of the received level as the vehicle proceeds along the acceleration path. Thus, for each incremental time *t*, of the acceleration event, one would determine: (1) the speed, (2) the resultant emission level alongside the vehicle, (3) the longitudinal distance from the stop line, (4) the distance from the receiver to the vehicle, (5) the distance propagation loss, and (6) the resultant received level. Then, one can integrate these received levels over the duration of the event to determine a SEL, at the receiver. This SEL will change with receiver position along the acceleration zone—the closer the receiver position is to the start point, the lower the SEL; the closer to the end point, the nearer the SEL will be to the cruise SEL.

A spreadsheet model was set up to permit this type of analysis. As a starting point,the recommendations in Appendix I of the FHWA model report [Barry and Reagan, 1978] were followed:

$(L_o)_E$ = 38.1 log (speed, kph) − 2.4 dB, for speeds above 30 mph
$(L_o)_E$ = 62 dB at or below 30 mph

A two-step acceleration rate was used, changing at 30 mph, as an approximation to acceleration curves given in the AASHTO Green Book [American Association of State Highway and Transportation Officials, 1984]. The resulting sound level time histories were predicted at different longitudinal distances from the stop line for an offset distance from the road of 50 ft. From these time histories, the SEL and L_{max} of the event were computed. These levels were then compared to levels from constant speed events.

Figure 1 shows one of the sets of time histories for a receiver located 100 ft from the stop line. The two curves are for an automobile accelerating from 0 to 60 mph and for an automobile cruising at 60 mph. (Appendix B gives a more detailed explanation of the curves.) However, one may note the symmetrical shape of the constant speed sound level curve compared to the skewed shape of the accelerating vehicle's curve. The skewing is caused by the changing speed as the vehicle accelerates. One may also note that while the maximum levels differ by 11 dB, the SEL only differs by 6 dB.

These differences indicate a key point about the effect of speed on SEL and, hence, on L_{eq}. A slower moving vehicle does not pass by the observer as quickly as a faster moving vehicle; thus, the sound level rises and falls more slowly. More time elapses when the levels are within 10 dB of the maximum, allowing more of the received sound energy to affect the total level. As a result, when speed decreases, the SEL and L_{eq} do not decrease as rapidly as does the maximum level; stated differently, SEL and L_{eq} are less speed dependent than L_{max}. This effect turns out to be very important and, actually, simplifies the modeling of noise from accelerating vehicles quite a bit.

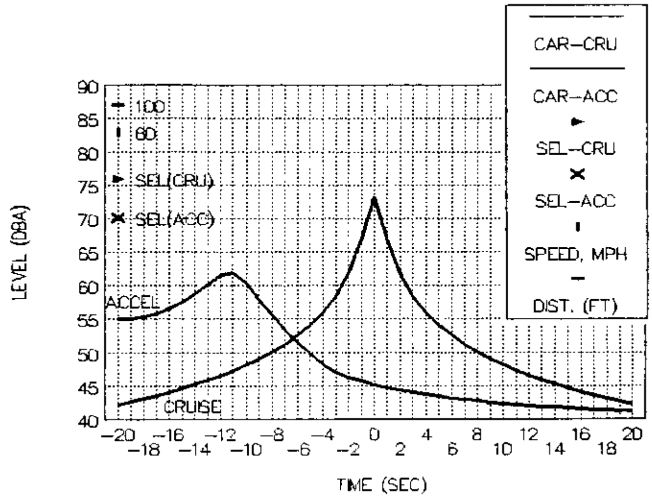

Figure 1. Time history of car cruise and acceleration (speed = 60 mph; distance = 100 ft).

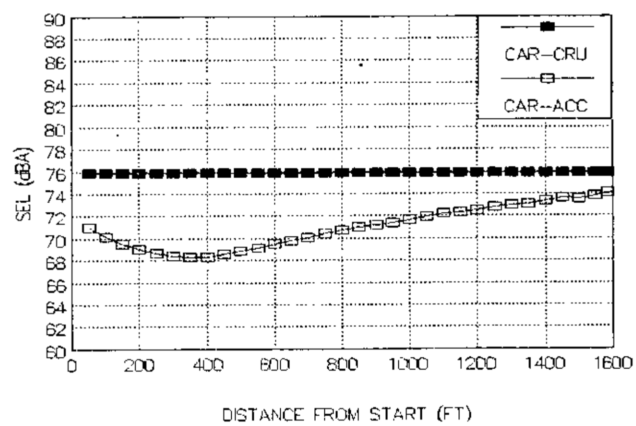

Figure 2. SEL at various distances from start: car cruise at 60 mph and acceleration at constant 62 dBA.

Figure 2 presents the calculated SEL for distances ranging from 50 ft to 1,600 ft from the stop line for a series of 50-ft offset receiver points. This type of curve was referred to in the literature review as an acoustical profile. Also shown is the constant level that would occur at the receivers for a 60-mph cruise event. Of importance is that the SEL for an accelerating automobile—based on the assumptions of the FHWA model emission level recommendations and a two-stage acceleration rate—only varies by less than 6 dB over the entire range of receiver points. The SEL is shown to first decrease and then to increase. The decrease is caused by the assumption of a constant emission level below 30 mph coupled with an ever-increasing speed that shortens the pass-by time as distance from the stop line increases. A 6-dB variation is large enough, however, to cause concern that use of a single equivalent constant speed might produce unacceptable errors.

The implication for more accurate STAMINA predictions is clear: either the acceleration road must be broken into a series of shorter length roads, each with its own emission level, or a receiver-dependent sound level adjustment must be developed. Neither alternative is attractive, the first from the user's perspective and the second from the programmer's perspective. However, if the number of shorter roads could be minimized, the first approach would be the easiest to implement.

At this point in the analysis, it was decided to study the EPA database in more detail to examine how to break the acceleration roadway into smaller segments. Based on EPA time-averaged levels over the duration of acceleration events ranging from 0 to 20 mph to 0 to 60 mph, the following approach was taken. If the averaged level from 0 to x mph was $L(0–x)$ and the averaged level from 0 to y mph was $L(0–y)$, an averaged level to accelerate from x to y, $L(x–y)$ could be approximated by knowing the times to accelerate from 0 to x (t_x) and 0 to y (t_y) and the levels $L(0–x)$ and $L(0–y)$. This approximation would be computed using rules for level combination. Specifically:

$$L(x-y) = 10 \log \{[1/(t_y - t_x)][(t_y)10^{0.1L(0-y)} + (t_x)10^{0.1L(0-x)}]\} \quad (8)$$

For example, consider the data for 0 to 30-mph and 0 to 60-mph events. For a constant acceleration rate, the time to accelerate from 0 to 60 mph will be twice that to accelerate from 0 to 30 mph. If L(0–30 mph) is 62.8 dB and L (0–60 mph) is 67.4 dB, L(30–60 mph) will be approximated by Eq. 8 as 69.6 dB. This level can be defined for the same "moving" observer as the EPA values were for the 0 to 30-mph and 0 to 60-mph events.

Thus, a mechanism was available for approximating intermediate levels of acceleration events, and these events, in turn, could be divided into stages. For example, a 0 to 60-mph event could be divided into two stages, 0 to 30 mph and 30 to 60 mph. Then, approximate averaged emission levels could be assigned to each stage. Distances that the vehicle traveled in each stage could be computed to define two sequential roadways, each with its own averaged emission level. Equivalent constant speeds, then, could be computed using the FHWA model equation that would produce the same SEL as the time-step model of the acceleration event. Definition of these sequential roadways with their stepped levels, thus, would reduce the size of errors caused by the use of constant levels to represent the type of distance-dependent curve shown in Figure 2.

Several scenarios were examined in detail for the 0 to 60-mph case, including use of a constant acceleration rate and a two-step acceleration rate. Further calculations were made with the EPA data to approximate time-averaged emission levels in 10-mph bands above the initial 0 to 20-mph segment (e.g., 20 to 30, 30 to 40, 40 to 50 and 50 to 60 mph). These data were also used in the time-step simulation model to define two "roadways" that could be used to simulate the 0 to 60-mph acceleration event. It was found that the best comparison to the time-step data was achieved using the two-step acceleration rate as an approximation of the AASHTO acceleration curve. Also, the acceleration distance could be divided into two segments for the 0 to 60-mph event with acceptable results. Putting the break point at a distance of 1,000 ft from the stop line and using an equivalent constant speed of 42 mph would produce SEL within ± 1 dB of the time-step simulation results using the stepped emission levels computed from the EPA data. The second segment should run from this 1,000-ft point to where the vehicle would reach 60 mph, which according to AASHTO would be at 2,200 ft. Use of a constant equivalent speed of 50 mph on this second 1,200-ft long section would produce SEL within +2.4 dB and −2.2 dB of the time-step levels. The acceptability of such errors would depend on the situation being studied. For example, on an acceleration ramp, noise from the main lanes would probably dominate the ramp contributions and deemphasize their importance. These two segments are called acceleration zones of influence (AZOI).

Similar examinations were made for other final speeds in 5-mph increments from 30 to 55 mph. It was found that for a final speed of 45 mph or less, only one AZOI needed to be defined. The lengths of these zones were a function of the final speeds. Table 1 presents the results. The errors from the use of constant speeds are about 1 dB or less for the first AZOI compared to the time-step model. For the second AZOI, the errors were under ± 2 dB compared to the time-step model. These initial results were only from the standpoint of automobiles. When the other vehicle types were considered, it was found that certain shifts and changes could be made to simplify the modeling process.

A limited amount of accelerating automobile emission level data was collected to study the phenomenon (the major thrust of data collection was for heavy trucks). Thirty automobiles accelerating from a STOP sign were measured at three 50-ft offset points past the sign and at a cruise point further downstream. SEL, L_{max}, and duration were measured. Also, a sampling of speeds was taken as the vehicles passed each measurement point.

The site (Figure 3) was a wide open grassy area, but traffic in the opposing direction and on the crossroad posed difficulties in getting uncontaminated pass-by events at the acceleration sites, and many potential events had to be rejected. Also, of the successfully measured events, the measurement durations at the point closest to the crossroad (110 ft from the stop line and 75 ft from the crossroad) had to be shorter than ideal, in an attempt to avoid crossroad traffic contamination. Typically a 6-dB rise and fall was all that could be achieved. As a result, the measured SEL were lower than if longer durations could have been measured.

Calculations using the time-step simulation spreadsheet showed that the difference in computed SEL using only a 4-sec event duration (typical of the measurements) compared to full 10-dB down duration would be 3.3 dB at the closest measured site. Differences of 1 to 2 dB were computed for the other two pass-by points. If the measured data were adjusted by these differences, the results would be within 1 to 2 dB of those computed by use of the FHWA model with this study's recommended equivalent cruise speed of 42 mph. Table 2 illustrates these adjustments and comparisons. Note that the FHWA model equation predicted the cruise SEL with no error. The overprediction at the acceleration sites is a direct consequence of approximating the first 1,000 ft of acceleration by a single zone of influence. If a study demanded more accuracy close to the intersection, it is recommended that the 1,000-ft zone of influence be broken into more segments, each with its own emission level and equivalent speed.

The deceleration data for automobiles were also taken from

Table 1. **Initial automobile acceleration zones of influence.**

Speed Range mph	L_{max} at Cruise (dB)	SEL at Cruise (dB)	First Acceleration Zone Length (ft)	Speed (mph)	SEL (dB)	Second Acceleration Zone Length (ft)	Speed (mph)	SEL (dB)
0-30	61.7	67.1	500	38	70.0	none	n/a	n/a
0-35	64.3	69.0	600	39	70.4	none	n/a	n/a
0-40	66.5	70.7	800	40	70.7	none	n/a	n/a
0-45	68.5	72.2	1000	42	71.3	none	n/a	n/a
0-50	60.2	73.5	1000	42	71.3	1400	48	73.0
0-55	71.8	74.7	1000	42	71.3	1800	50	73.5
0-60	73.1	75.9	1000	42	71.3	2200	53	74.2

Table 2. Comparison of measured and predicted accelerating automobile SEL.

Site Name	Distance from Stopline (ft)	Mean Speed (mph)	Measured Energy-Averaged SEL (dB)	Duration Adjustment (dB)	Adjusted Measured SEL (dB)	Predicted SEL at Equiv. Speed
AE110	110	20	66.4	3.3	69.7	71.3
AE170	170	25	68.4	2.0	70.4	71.3
AE270	270	29	68.1	1.2	69.3	71.3
CE	cruise	42	71.3	0.0	71.3	71.3

the EPA database results. As with acceleration, those data were presented as time-averaged levels over the full duration of a deceleration event. Levels for events ranging from 60 to 0 mph to 20 to 0 mph in 10-mph steps were given. Intermediate speed range levels were computed based on use of a constant deceleration rate approximated from AASHTO curves.

Two important findings differed from the acceleration case: (1) the event occurred over a much shorter distance (e.g., 470 ft for 60 to 0 mph compared to 2,200 ft for 0 to 60 mph); and (2) the change in levels from one end of the event to the other was much greater for deceleration (the time-averaged level for the last stage of deceleration from 20 to 0 mph was more than 21 dB below the 60-mph cruise level, which equated to about a 15-dB difference in SEL).

The second finding implies that the deceleration event should be broken into many separate zones of influence to minimize the change in emission level between adjacent zones. However, the first finding makes it impractical to consider the use of many zones—the zones would be too short to make it worthwhile to model each of them individually.

The idea of limiting the problem to two deceleration ZOI was appealing from a practical point of view. Examination of the data showed that the greatest drop in time-averaged levels occurred in the last stages of the event. For example, the level dropped 12 dB from the value for cruise at 60 mph to the value computed for the 30-mph to 20-mph stage and the 20-mph to 0-mph stage. These data suggested that a split in zone at the 20-mph point would be appropriate, which would occur at about 80 ft from the stop line.

Calculations showed that the use of an equivalent constant speed of 18 mph for the 20-mph to 0-mph zone would result in an emission level about 20 dB below the 60-mph cruise level, with a 15-dB difference in SEL (and, hence, L_{eq}). An equivalent speed of 41 mph for the 60-mph to 20-mph zone would produce a SEL midway between that at 60 mph and that computed for the 30-mph to 20-mph stage, with a 4-dB error at each end. This large error from using a single constant level for this "roadway" would not be as big a problem as might seem in an actual analysis scenario because the user would typically define adjacent roadway segments (for the cruise and 20-mph to 0-mph stages) each with its own emission level. The level predicted at any wayside receiver would be the combination of levels from all three segments, smoothing out differences at each end of the center segment.

Table 3 presents the deceleration ZOI determined for automobiles using the 20-mph break point for each initial speed scenario. As with acceleration, these data were modified when

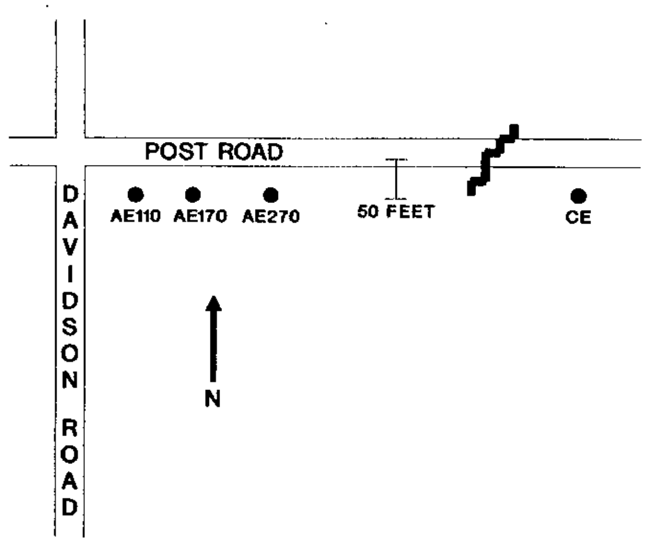

Figure 3. Automobile single event measurement sites.

Table 3. Initial automobile deceleration zones of influence.

Speed Range mph	L_{max} at Cruise (dB)	SEL at Cruise (dB)	First Deceleration Zone Length (ft)	Speed (mph)	SEL (dB)	Second Deceleration Zone Length (ft)	Speed (mph)	SEL (dB)
60-0	73.1	75.9	370	41	71.0	80	18	60.8
50-0	70.2	73.5	260	38	70.0	80	18	60.8
40-0	66.5	70.7	150	34	68.6	80	18	60.8
30-0	61.7	67.1	90	29	66.7	80	18	60.8
20-0	51.3	62.1	80	18	60.8	none	n/a	n/a

the different vehicle types were examined together in the methodology development.

The second vehicle category to be examined was medium trucks. As with automobiles, the EPA database was very valuable. Also, a limited amount of field data was collected as part of this study. The EPA data were presented in terms of time-

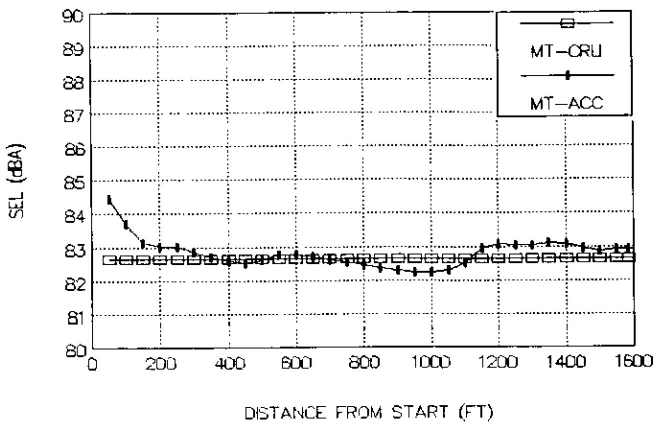

Figure 4. SEL at various distances from start: medium truck cruise = 43 mph, acceleration per EPA data = 0.07 g.

averaged levels over the duration of an acceleration or deceleration event between 0 mph and a cruise speed for a receiver moving alongside the vehicle at a 50-ft offset. Levels were given for 10-mph increments in the cruise speed between 20 and 60 mph. From these data, intermediate stage levels (in 10-mph bands) were computed using acceleration or deceleration rates approximated from AASHTO data. An assumption was made that the intermediate stage levels were good approximations of the energy-averaged emission level for a stationary observer located along the section of roadway on which that portion of the acceleration or deceleration event took place. Based on that assumption and the rate of speed change, pass-by SEL were computed at a range of longitudinal distances from the start of the event.

Figure 4 shows the results of one such set of computations for an accelerating medium truck for a 50-ft offset distance from the center of the travel lane. Overlaid on the curve is a constant SEL of 82.7 dB computed using the FHWA model with an equivalent cruise speed of 43 mph. The results indicate that the medium truck acceleration SEL—based on the EPA acceleration noise level data—showed virtually no speed dependence beyond the first 50 ft of acceleration. The SEL was within ±0.5 dB of the SEL from a 43-mph cruise event for distances of 100 ft to 1,600 ft from the stop line. Thus, up to a speed of about 45 mph, only one acceleration roadway needs to be defined for STAMINA, with an equivalent cruise speed of 43 mph.

The limited medium truck field data gathered during the heavy truck measurements fully supported this calculation finding. Nineteen data points were obtained representing 13 medium trucks measured at one or more points that ranged between 75 ft and 610 ft from the stop line (at a 50-ft offset distance). While the individual SEL ranged from 78.2 dB to 88.4 dB, the energy-averaged SEL of the data was 82.8 dB, only 0.1 dB different from the SEL predicted by the assumed constant speed of 43 mph. (The energy-averaged L_{max} of the acceleration data was 77.9 dB, which would be the $(L_o)_E$ predicted by the FHWA model for a speed of 40 mph.) The measured acceleration SEL was 2.7 dB below an energy-averaged measured SEL of 85.5 dB for 11 medium trucks cruising at an average speed of 60 mph. (The energy average of the cruise L_{max} data was 84.3 dB.

Table 4. Initial medium truck deceleration zones of influence.

Speed Range mph	L_{max} at Cruise (dB)	SEL at Cruise (dB)	First Deceleration Zone Length (ft)	First Deceleration Zone Speed (mph)	First Deceleration Zone SEL (dB)	Second Deceleration Zone Length (ft)	Second Deceleration Zone Speed (mph)	Second Deceleration Zone SEL (dB)
60-0	83.7	86.3	550	36	80.7	100	13	70.0
50-0	81.0	84.3	400	34	80.1	100	13	70.0
40-0	77.7	81.9	275	30	79.2	100	13	70.0
30-0	73.5	78.8	150	26	77.7	100	13	70.0
20-0	67.5	74.5	100	13	70.0	none	n/a	n/a

The FHWA model predicts an $(L_o)_E$ of 83.6 dB (0.7 dB less) at the measured mean speed of 60 mph).

The EPA data were also used for decelerating medium trucks. The data were in terms of time-averaged levels for deceleration events for speed ranges of 20 to 0 mph up to 60 to 0 mph in 10-mph increments. Intermediate speed stages were defined and time-averaged levels were approximated based on assumed deceleration rates. The data indicated, as they had for automobiles, the need to consider at least two major deceleration zones of influence—from cruise speed to 20 mph and from 20 mph to a stopped position. A series of equivalent constant speeds was computed that would produce the same SEL using the FHWA model medium-truck cruise equation as using the staged EPA deceleration levels. Table 4 presents the resulting data for the medium truck deceleration zones of influence.

Nine decelerating medium trucks were measured during the heavy truck measurements, with matched data being obtained at two or more points for eight of the trucks. Both the deceleration SEL and L_{max} showed distance-from-stop line dependences, although the sample size was small and the scatter was very large. The mean deceleration SEL of all the data points was 75.9 ± 3.4 dB (the large error representing the large scatter in the data). This mean was 8.9 dB below the measured mean cruise SEL for the medium trucks: that difference was consistent with the difference found for decelerating heavy trucks.

Thus, in sum, the medium truck field data, while too limited to be conclusive, do support the findings for the larger database for heavy trucks, as well as the use of the EPA time-averaged levels in a staged manner. It was concluded that medium trucks could be treated in a similar manner as heavy trucks, with the appropriate lower levels.

The main focus of the field data collection was on heavy trucks because of their usually dominant contribution to the total noise levels at nearby receivers. More than 600 trucks were measured during the course of several field trips, most simultaneously at 3 or 4 different points. The measurement sites were at and near a pair of truck weigh stations on I-65—Portland, Tennessee, just south of the Kentucky border (see Figure 5). Typically, two or three sound level analyzers would be set at varying distances from the stop line at a 50-ft offset from the exit or entrance ramp; an additional analyzer would be placed about a mile from the weigh station, again at a 50-ft offset, to measure trucks in the cruise mode. Thus, comparisons could be made not only of the mean values measured at each site but also of the differences between pairs of data measured for the same trucks.

SEL and L_{max} were measured at the cruise sites for 269 trucks. The mean cruise SEL was 87.2 ± 1.8 dB (± 1 standard error)

I-65 WEIGH STATION

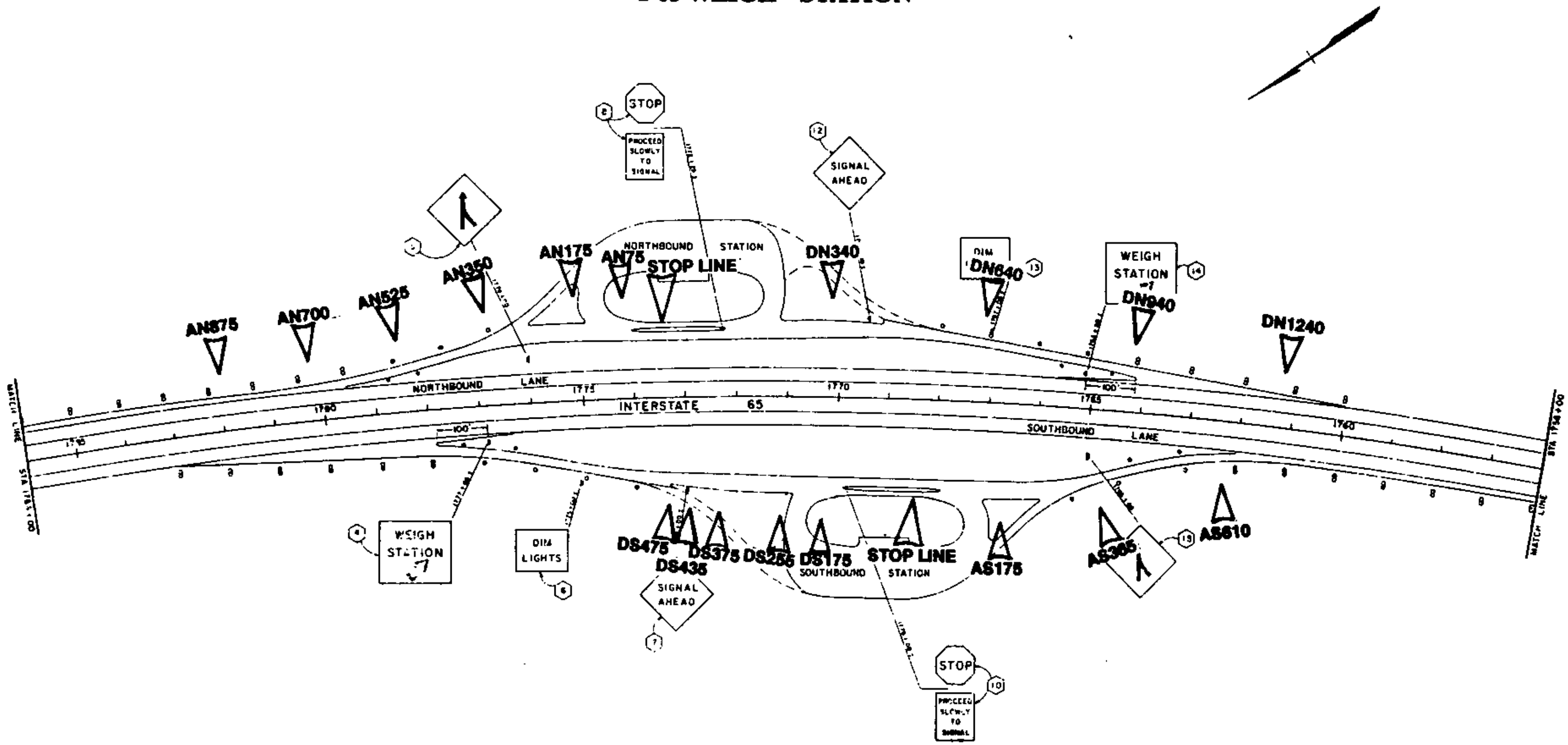

Figure 5. Heavy truck noise measurement sites.

for an energy averaged SEL of 87.6 dB. The mean cruise L_{max} was 85.1 ± 2.4 dB (energy average of 85.5 dB). A mean speed of 59.5 ± 3.2 mph was measured for 50 cruise events; use of the FHWA heavy truck emission level equation with this speed yields an energy mean emission level of 87.2 dB, which is 1.4 dB above the measured value of 85.8 dB. This slight overprediction of heavy trucks by the FHWA model is typical of what others have reported, as described in the literature review section.

Figure 6 shows the mean SEL and L_{max} with indicators for plus/minus one standard error for each of the acceleration sites, as well as for the cruise data. Statistical analyses of the differences in the means at each site, as well as the means of the differences in levels for the same trucks at paired sites, showed virtually all differences to be significant at the 5 percent level of significance. Indeed, a slight dependence of SEL on distance from the stop line is apparent in the data in Figure 6. However, the magnitude of these statistically significant differences was, in reality, quite small. The change in mean SEL from 75 ft from the stop line to 610 ft was only about 1 dB.

The objective of the research was to develop a methodology to use the constant-speed STAMINA computer program to model changing speed situations Each time speed changes, new "roadway" must be defined by the STAMINA user, which complicates data input and analysis. It was therefore decided to see if the acceleration data could be aggregated in a useful manner. For 633 acceleration data points covering distances from the stop line ranging from 75 ft to 875 ft, a mean SEL of 84.8 ± 2.4 dB was computed (95 percent confidence intervals of ± 0.2 dB). The standard error of 2.4 dB was quite comparable to the standard errors associated with the cruise emission level data in the FHWA model, indicating that aggregation was a reasonable idea. The energy-averaged SEL of the aggregated data was 85.5 dB, which is 2.1 dB below the energy-averaged SEL of 82.6 dB of the measured cruise data.

Given that the standard error of the mean acceleration SEL was comparable to the standard errors for the cruise data in the FHWA model, it was concluded that a constant SEL of 84.8 ± 2.4 dB (or an energy-averaged SEL of 85.5 dB) may

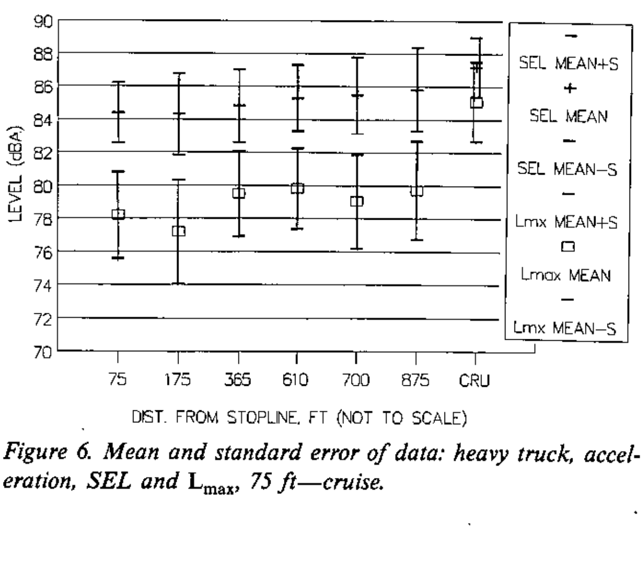

Figure 6. Mean and standard error of data: heavy truck, acceleration, SEL and L_{max}, *75 ft—cruise.*

be used to characterize the SEL at all of the acceleration measurement sites in this study. This directly implies that the variation in the L_{eq}(1 hr) of a stream of accelerating heavy trucks would be of the same order of magnitude.

Further, the 2.1-dB difference between the mean energy-averaged cruise SEL and the mean energy-averaged acceleration SEL describes the difference in L_{eq}(1 hr) that may be expected at those same measurement points. In other words, the L_{eq}(1 hr) from a stream of accelerating heavy trucks would be 2.1 dB less than the L_{eq}(1 hr) of the same trucks at the measured mean cruise speed of 59.5 mph. Within the error indicated by the ±2.4-dB standard error and ±0.2 dB 95 percent confidence limits on the mean for the acceleration data, this relationship would hold true for any point along the acceleration lane.

While the individual site data, especially the paired SEL differences, seemed to indicate a distance-from-stop line effect on SEL, linear regression of SEL as a function of log (distance) only had a correlation coefficient of 0.21 (r^2 of 0.046). It is thus concluded that the distance relationship is small enough to be totally outweighted by the ability to develop a relatively simple method for predictions based on the FHWA model theory and use of the STAMINA 2.0 computer code. Two approaches were taken for addressing this 2.1-dB difference in SEL between accelerating and cruising heavy trucks. The first approach was to develop an L_{eq} acceleration adjustment as a function of the cruise speed and the heavy truck emission level equation. Then, knowing the cruise speed, the analyst could predict the cruise L_{eq} and the acceleration adjustment and combine them to get the acceleration L_{eq}. The adjustment was developed for both the FHWA model heavy truck, reference energy, mean emission level equation and for a general emission level expression. For the FHWA model, the acceleration adjustment is:

$$\Delta_{acc,HT} = 26.8 - 14.6 \log (S_{final}, \text{kph}) \tag{9}$$

where S_{final} is any final cruise speed in kilometers per hour and would be added to the L_{eq} at S_{final} to get the L_{eq} for the same stream of trucks in an acceleration mode.

The more general expression would be:

$$\Delta_{acc,HT} = 1.978(b - 10) - 2.1 + (b - 10) \log (S_{final}, \text{kph}) \tag{10}$$

where b is the coefficient of the log (speed) term in the general emission level expression:

$$(\overline{L_o})_E = a + b \log(\text{speed, kph}). \tag{11}$$

The second approach to using the 2.1-dB acceleration/cruise SEL difference was the same approach used for the automobiles and medium trucks: compute an equivalent constant speed that would produce a SEL (and, hence, the same L_{eq}(1 hr)) that is 2.1 dB below the 60-mph cruise SEL. That speed was computed as 68.4 kph, or about 43 mph.

For emission level equations that differ from the FHWA model, the reader can use the general computation procedure discussed in Appendix C to determine an appropriate equivalent speed.

According to AASHTO curves, a heavy truck would not reach 43 mph until 2,500 ft from the start of acceleration (from rest). However, the paired difference data between the cruise sites and the 875-ft acceleration site showed a mean difference of only 0.6 dB, which was not different from 0 dB at the 5 percent level of significance (the mean truck speed was 32 mph at the 875-ft point). Thus, it did not seem appropriate to apply the −2.1-dB adjustment all the way to 2,500 ft from start. Instead, an acceleration zone of influence (AZOI) roadway break point between 800 ft to 1,000 ft seemed more appropriate. Then, a second AZOI could be defined from that point to where the truck would reach final speed. Some speed between 43 mph and the final speed would need to be assigned to this second AZOI. Because the difference in the SEL at 43 mph and 60 mph is only 2.1 dB, use of an average speed seemed to be a simple accurate assumption. For final speeds below 43 mph, only one AZOI would need to be defined with an equivalent cruise speed of 43 mph. The length of the AZOI would be determined from AASHTO curves.

A similar type of analysis was done for the deceleration data. First, an observation needs to be made about the deceleration events (there was much more variability in the deceleration rates and speeds than for acceleration). Where a truck began its deceleration depended largely on the size of the queue of trucks, if any, already at the weigh station. For example, on one of the measurement days, the queue length ranged from 0 to 15 trucks within the same 15-min period. As a result, the approach speed profile varied considerably and the ability to get uncontaminated pass-by levels was limited to conditions when only a small queue existed.

Figure 7 shows the mean L_{max} and SEL at each measurement site, along with standard error bars. The cruise data are shown for comparison at the far right of the figure. A first observation on these data is that there was much more of a distance dependence on the L_{max} than there was for the acceleration case. As shown, there was nearly a 7-dB difference in the mean L_{max} in a span of only 300 ft. Furthermore, the mean deceleration L_{max} was 8 dB to 15 dB the mean cruise L_{max}.

However, the SEL data showed much less distance dependence between the deceleration sites except at the closest point. There was only a 2-dB difference between the mean SEL from 475 ft to 255 ft. These SEL were approximately 8 dB below the mean cruise SEL. The data at the closest point were about 12 dB below the cruise SEL. The data suggested that some level of aggregation might be possible. When all of the deceleration data at all of the sites were aggregated together, the following results were obtained:

SEL = 78.6 ± 2.6 dB (n = 239, energy-averaged SEL = 79.4)

L_{max} = 74.0 ± 3.8 dB (n = 191, energy-averaged L_{max} = 75.7)

The 95 percent confidence limits on these two means are 0.3 dB and 0.5 dB, respectively.

As was the case with the acceleration data, the 2.6-dB standard error on the mean SEL for the combined deceleration data was similar to the standard error on the cruise emission levels in the FHWA model. Thus, as a first approximation, it was concluded that the energy-averaged SEL, and, hence, L_{eq}(1 hr), of decelerating trucks at 175 ft to 475 ft from the stop line was 8.2 dB below the 81.6-dB energy-averaged cruise level for heavy trucks.

The trade-off in such an approximation in terms of accuracy

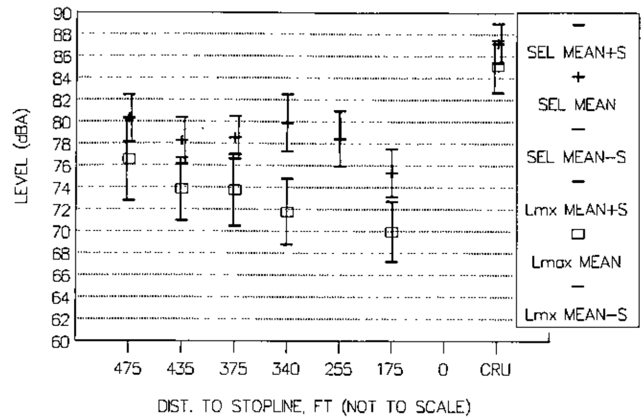

Figure 7. Mean and standard error of data: heavy truck, deceleration, SEL and L_{max}.

at either end of the section needs to be viewed in the context of the larger scenario where traffic on the main lanes would tend to dominate the total received levels. Indeed, this very fact made it difficult to obtain valid pass-by measurements of the decelerating trucks, even though the main line traffic consisted almost entirely of automobiles (as virtually all of the trucks had exited into the weigh station).

It was later found that when combining the results for the three vehicle types, it was better not to aggregate all of the data, but to separate them into two groups because of the large changes in levels toward the end of the deceleration event.

Nonetheless, it was decided to use approaches similar to those that were used for the heavy truck acceleration data. First, an adjustment was developed based on the 8.2-dB difference between the 60-mph cruise SEL and the mean deceleration SEL as a function of the initial cruise speed for the particular problem of interest. That expression for the FHWA model heavy truck equation was:

$$\Delta_{dec,\mathrm{HT}} = 20.7 - 14.6 \log(S_{\mathrm{initial}}, \mathrm{kph}) \qquad (12)$$

where S_{initial} is the cruise speed prior to deceleration.

This adjustment would be added to the predicted cruise L_{eq} at S_{initial} to get an approximation of the deceleration L_{eq}.

Secondly, an equivalent cruise speed was computed that would produce a SEL and, hence, L_{eq}(1 hr), 8.2 dB below the mean SEL at 60 mph. That speed was 16 mph (26 kph).

More insight into levels at the low end of the heavy truck deceleration events was gained from some additional data collected at one of the sites during a series of 4-min L_{eq} measurements. A number of observations were made of maximum levels as trucks passed the site at 340 ft from the stop line, but no SEL were measured. The events included "fast" pass-bys with rapid deceleration (when no queue existed), "slow" pass-by decelerations when a queue existed, unspecified decelerations, idling noise when several trucks were in queue in front of the microphone, and a combination of short periods of acceleration, deceleration, and idle as trucks moved up in the queue. The fast, slow, and unspecified decelerations were clean events (at

Table 5. Summary of L_{max} observations during various types of deceleration: heavy trucks, 6/1/88.

Type of Event	Mean L_{max} (dB)	S.E. (dB)	No. of Samples
Fast pass-by, rapid deceleration	70.8	2.6	29
Slow pass-by, slow deceleration	68.3	1.9	5
Unspecified pass-by & deceleration	69.1	2.4	26
Idle of several trucks in queue	68.0	2.3	27
Acclaration/Deceleration/Idle of Trucks Moving up in Queue	71.1	2.3	15

least 6-dB rise and fall); the other events had influence from other trucks in the queues.

The levels of these additional events are summarized in Table 5. Of interest is that all of the means are in the 68 dB to 71 dB range, within which would fall the EPA time-averaged level over the 20-mph to 0-mph deceleration event of 69 dB. "Fast" deceleration levels were about 2.5 dB higher than "slow" deceleration levels. Referring back to Figure 5, one notes that these means fall at or below the mean L_{max} measured at the sites nearest the stop line.

The idle level of 68 dB included the combined effect of several trucks and represented the maximum level when one of the tractor cabs was directly in front of the microphone. An idle level of a single truck could be approximated as about 64 dB from that data by assuming that all of the trucks have equal idle levels and that the spacing between cabs was 50 ft. Rudder reported a similar level of 65 dB. Also, several other idling trucks were measured during this study, with an average level of 65 dBA.

These extra deceleration data indicate that in true congested stop-and-go situations the L_{eq} at 50 ft from a stream of heavy trucks will be in the 68-dB to 71-dB range. This type of information is very useful as an indicator of the lower limit of the possible heavy truck noise levels, but would be a very difficult result to try to program into a model like STAMINA.

Thus the findings of the literature review coupled with the analysis of the acceleration and deceleration modes for each vehicle type laid the foundation for a stop-and-go methodology for the STAMINA 2.0 program.

The next chapter will show how these findings were used to develop the overall methodology, considering three vehicle types in the same problem. The results of sensitivity analysis of the methodology will also be described, as well as the preliminary evaluation of the methodology at two field sites and the resulting modifications of the methodology.

CHAPTER THREE

INTERPRETATION, APPRAISAL, APPLICATIONS

INTRODUCTION

This research has led to a methodology for predicting nonconstant speed traffic noise levels using the Federal Highway Administration STAMINA 2.0 computer program. The development of the methodology was based on detailed analyses of information from the literature (particularly the EPA database [Rudder et al., 1979b]) and of field data collected during the research. The next step was to combine the results into a procedure that could be used directly with the STAMINA 2.0 computer program.

This chapter describes the combination of results into a single methodology, the sensitivity analyses that were performed to examine the effects of various important parameters on the predicted levels, the field evaluation, and the subsequent modifications that were made to the final methodology. The use of the methodology on actual project studies and the assumptions and limitations in its use are also described.

COMBINING FINDINGS FOR EACH VEHICLE TYPE

The previous chapter summarized the findings for the individual vehicle types with little attempt to blend the individual results together. However, the analysis was done with the hypothesis that a multiple zone of influence (ZOI) method would prove possible and workable. A discussion of the combined results and the changes to STAMINA 2.0 follows.

Requirements for STAMINA 2.0

To use the STAMINA 2.0 program, the engineer first must define a series of roadways (each of which could represent one or more lanes of traffic). Each roadway may be divided into segments based on the geometry of the site. Traffic volumes and speeds on that roadway are assumed constant within each vehicle-type category. Different speeds may be specified for each vehicle type; however, each time a speed change is required for any vehicle type, an entirely new roadway must be defined. Repeatedly having to define new roadways is time-consuming, cumbersome, and generally undesirable.

The analysis of the data showed that as speed changes during acceleration or deceleration, the emission levels will change in different ways. For example, the medium truck SEL remained quite constant during acceleration, while the automobile SEL during deceleration from 60 mph to 0 mph dropped more than 20 dB. Nonetheless, certain commonalities seemed to exist. It appeared reasonable (and desirable) to divide the acceleration or deceleration region on a ramp or near a signal or STOP sign into one or two zones of influence, depending on the initial (or final) speed, the extent of the changing levels, and the distances each vehicle type traveled to reach certain speeds. To fit within the STAMINA 2.0 framework, each zone had to be defined as a constant speed "roadway." The speed would not necessarily be an average operating speed through the zone, but would be determined from the noise level data to produce a certain difference in level relative to the known cruise levels.

The Analyzed Data

In the case of the EPA database, average levels were given for full acceleration events from a stopped position and full deceleration events to a stopped position for various cruise speeds. From these full-event averaged levels, levels for intermediate stages during these events were deduced based on assumptions about the speed change rates and the definition of L_{eq}. The assumption was then made that the vehicle emission levels could be predicted during each particular stage with a constant value over the distance traveled during that stage. Thus, a step function of emission level as a function of speed and mode could be defined for each vehicle type. From these step functions, a computation could be made of the sound exposure level at a wayside receiver during an acceleration or deceleration event. Then, the FHWA model equations (which form the basis for the STAMINA 2.0 calculations) could be used to calculate the equivalent constant speed that would produce the same SEL as the changing speed/changing level step function.

In the case of the newly collected field data, differences in observed SEL at various points during acceleration or deceleration were compared to the cruise SEL to compute equivalent constant speeds in the acceleration or deceleration zones that would replicate these differences.

Combining Acceleration Data

The acceleration data were examined in 5-mph increments of the final speed (from 30 mph to 60 mph) based on a starting speed of 0 mph. Also, cases for nonzero initial speeds were examined, starting from 20 mph and increasing in 10-mph increments. Each vehicle type was examined for each speed range.

As an example of the process, consider a road where vehicles are accelerating to 30 mph from a stopped position. Automobiles will reach 30 mph in 500 ft per AASHTO [American Association of State Highway and Transportation Officials, 1984], but medium trucks and heavy trucks take about 700 ft and 800 ft, respectively. Thus, automobiles need to be modeled as accelerating from 0 to 500 ft, but cruising beyond 500 ft. If a conservative approach is made to assume that the medium trucks will not reach 30 mph until the same point as the heavy trucks, the trucks need to be modeled as accelerating to 800 ft and cruising at 30 mph beyond that point. Thus, the two defined acceleration zones of influence would be:

AZOI(1): extending from 0 to 500 ft, all vehicle types accelerating.

AZOI(2): extending from 500 to 800 ft, automobiles cruising at 30 mph, medium and heavy trucks accelerating.

In a similar manner, the individual vehicle-type data were analyzed and combined for the other speeds. Only one ZOI needed to be defined when the initial speed for an acceleration event was 30 mph or higher.

Combining Deceleration Data

The deceleration data were examined in a similar manner as the acceleration data. As was noted in Chapter Two, during the discussion for each individual vehicle type, deceleration events occurred over shorter distances than acceleration and with greater sound level changes. Most of the sound level change occurred in the last stage of deceleration (estimated from the available data to be the 20 mph to 0-mph range). The distance covered in this last stage varied from about 80 ft to 100 ft, depending on vehicle type, according to AASHTO [1984] data. Thus, a zone of influence common to the three vehicle types could be defined for this last stage of deceleration, with the 100-ft distance being chosen for convenience (pending the results of the initial validation). Again using AASHTO data, the length of the first zone of influence could be determined as a function of initial speed. For the speed changes to a nonzero final speed (such as on a loop ramp), only one ZOI needed to be defined.

SENSITIVITY ANALYSIS

The next step was to do a sensitivity analysis to see how the various parameters affected the L_{eq} predicted by STAMINA. Four basic scenarios were established for the testing: (1) one-way flow, where all vehicles decelerate from cruise to a stop and then accelerate back to cruise speed; (2) one-way flow, but where a certain percentage of vehicles travel through the site at cruise speed; (3) two-way flow, all vehicles decelerating to a stop and then accelerating; and (4) two-way flow, with a percentage cruising through.

Description of the Example Scenario

The easiest way to introduce the sensitivity analysis and begin to describe the effects of the prediction parameters on L_{eq} is through an example. Numerous variations on the basic scenario are then used in the analysis.

The scenario represents a situation similar to a STOP sign or tollbooth. Vehicles are modeled on a hypothetical one-way, one-lane road as decelerating from a cruise speed to a stop and accelerating back to cruise speed. The cruise speed is 60 mph, and the hourly traffic flow consists of 1,000 automobiles, 50 medium trucks, and 100 heavy trucks (a total hourly flow of 1,150 vehicles consisting of 87 percent automobiles, 4.3 percent medium trucks, and 8.7 percent heavy trucks). It is assumed that all vehicles stop at the same point and that no queue develops. The site is defined as acoustically soft and a series of receivers are defined along the road at a 50-ft offset from the centerline. From 1,200 ft before the STOP sign to 2,400 ft after it, the receivers are spaced 100 ft apart. This basic scenario will be referred to as "accel/decel only" (despite the cruise at each end).

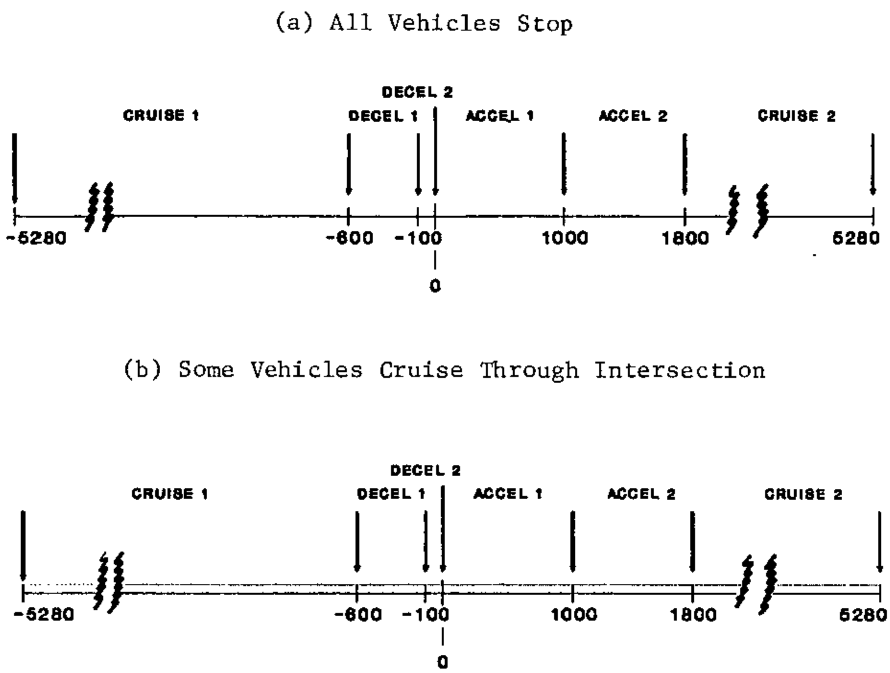

Figure 8. Sensitivity analysis scenarios for one-way flow: (a) all vehicles stop; (b) some vehicles cruise through intersection.

Other Scenarios

The first variation of this scenario will represent a signalized intersection where only some of the vehicles will be modeled stopping. This latter situation will be referred to as "mixed mode." One sensitivity test varied the percentage of stopped vehicles (referred to as "percent interrupted flow," or its converse, "percent cruise"). These two scenarios assume one-way traffic. The next two scenarios represent two-way versions of the first two assuming a 50-ft separation between the two directions: "two-way accel/decel only" and "two-way mixed mode." A second sensitivity test varied the width of this median separation.

Other sensitivity tests included: (1) variation of the cruise speed, (2) variation of the offset distance, (3) isolation of individual vehicle type effects, and (4) comparison of hard site to soft site.

Modeling the Example Scenario

All scenarios were modeled using a version of STAMINA 2.0 with subroutine input modified to allow cruise speeds below 30 mph. For the "accel/decel only" case, six STAMINA roadways were defined using the guidance in Appendix B for speeds and lengths of corresponding roadways. The location and lengths of the zones of influence are shown in Figure 8(a), as follows:

1. Cruise prior to deceleration: from −5,280 ft to −600 ft; speeds of 60 mph for all three vehicle types.
2. Deceleration ZOI(1): from −600 ft to −100 ft; speeds of 41, 36, and 33 mph from automobiles, medium trucks, and heavy trucks, respectively.
3. Deceleration ZOI(2): from −100 ft to the stop line; speeds of 18, 13, and 10 mph for the three vehicle types.
4. Acceleration ZOI(1): from stop line to +1,000 ft; speeds of 42, 43, and 43 mph for the three vehicle types.
5. Acceleration ZOI(2): from +1,000 ft to +1,800 ft; speeds of 50, 52, and 52 mph.
6. Cruise after acceleration: from +1,800 ft to +5,280 ft; speeds of 60 mph.

The resulting L_{eq} for each receiver are plotted in Figure 9, showing vehicle type contributions as well as the total. In effect, the curves give graphical representations of the adjustment tables, while showing how the levels from adjacent roadways are combined at the break points (see the 1,000 and 1,800 ft points for example). This combination of levels tends to smooth out the transitions from one step adjustment to the next, giving a somewhat better approximation of the real world. The shapes of the curves are similar for each vehicle type, as expected from the values in the tables. The data for the combined vehicle types show a 6.5-dB difference from the L_{eq} at cruise of 75 dB and the L_{eq} at −100 ft, the low point for deceleration.

Choice of a 100-ft separation between receivers disguises what would be modeled for receivers located between −100 ft and the stop line. Further modeling showed the L_{eq} to decrease an additional 1.5 dB at the −50 ft point. The level does not decrease further despite the readjustments being −12 dB for heavy trucks and −20 dB for automobiles (with regard to 60 mph) for this deceleration section because even at −50 ft from the stop line, the contribution from the first acceleration roadway is significant.

However, one needs to consider whether the predicted drop at −100 ft is modeled realistically. The assumption that all vehicles stop at the same point is only an approximation. Some queueing will develop, causing deceleration to begin earlier and to create a roadway section of mixed acceleration, idle, and deceleration as the vehicles move up in the queue. Contiguous roadways may influence predicted levels as noted previously. It

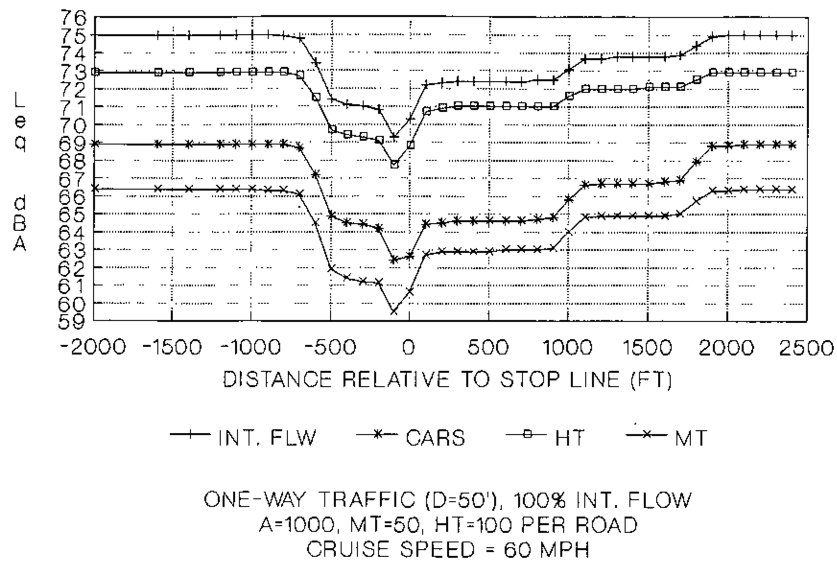

Figure 9. Sound level contributions by vehicle type: 100 percent interrupted flow traffic for cruise speed of 60 mph.

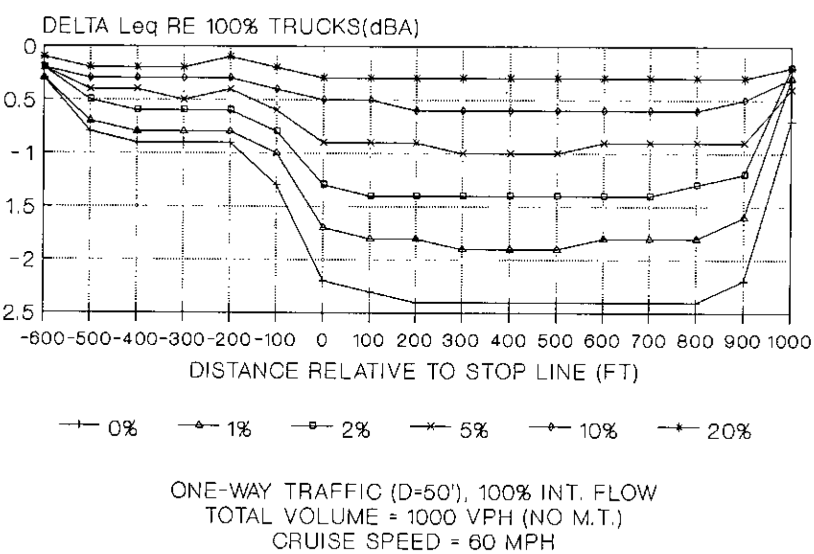

Figure 10. Change in level differences between cruise and interrupted flow relative to 100 percent trucks.

is quite likely, then, that the dip in the curve at −100 ft will need to be considered carefully throughout the sensitivity analysis and the validation to allow proper modeling and good predictive results.

The results indicate that the vehicle mix does not have a major effect on the trends. For heavy trucks only, the L_{eq} at −100 ft is 5 dB below cruise, while for automobiles only, the decrease is 7 dB.

Effects of Truck Percentage

To study further the effects of vehicle mix, the basic scenario was modified to exclude medium trucks and to set the total volume to 1,000 vph. Heavy truck percentage was varied from 0 percent to 100 percent. The data were then normalized to account for differences in the total cruise L_{eq}, which increased as the percentage of trucks increased. The differences in normalized levels at each receiver point between the 100 percent trucks case and each other case were computed and plotted in Figure 10 over a range of −600 ft to +1,000 ft from the stop line. As an example of how to read Figure 10, consider a receiver position of +400 ft from the stop line for the case of 1 percent trucks. The curve shows that the difference between full cruise L_{eq} and the L_{eq} at this point is 1.9 dB less than the same difference for the case of 100 percent trucks. The data show that for truck percentages above approximately 10 percent, there is less than 0.5-dB difference in levels relative to full cruise levels when compared to the 100 percent truck case. This low difference implies that separate roadway break points for automobiles are not needed when truck percentages exceed 10 percent; the hourly volume of automobiles still needs to be used to predict the proper total L_{eq}, but a lower cruise speed may be modeled simply as low speed cruise.

In total, the maximum normalized level difference between 100 percent automobiles and 100 percent trucks was only 2.5 dB. This small difference indicates that while the absolute L_{eq} was sensitive to truck mix, the acceleration/deceleration effects were relatively insensitive to mix.

Effect of Cruise Speed on the Example Scenario

The example scenario was based on a cruise speed of 60 mph. Of interest are how the effects vary with cruise speed. Figure 11 shows the total L_{eq} as well as the contributions from each vehicle type based on initial and final speeds of 30 mph. The curves still show a drop at the end of deceleration, although its size is decreased to only 2 dB because of the lower cruise level. The absolute level of the dip is also about 2 dB below the low point for the 60-mph case, reflecting the decreased contribution from the lower speed cruise roadway for this receiver. The curves also show a predicted acceleration effect of several dB for several hundred feet beyond the intersection until the vehicles reach cruise speed. Because the automobiles are assumed to reach cruise sooner than the trucks, the predicted automobile level for the second acceleration section is equal to the predicted cruise level. The total difference in predicted L_{eq} between receivers in the deceleration and acceleration zones is shown as about 4.5 dB.

Figure 12 combines the total L_{eq} curves at 30 mph and 60 mph along with curves for cruise speeds of 40 mph and 50 mph to show the sensitivity of L_{eq} to cruise speed. Again, these curves are for the given mix of traffic on a hypothetical one-way road with all vehicles stopping for receivers at 50-ft offsets and for soft sites.

Effects of Mixed Mode of Operation

In the case of a traffic signal, and less than congested flow, not all of the vehicles will have to stop. A certain percentage, which is a function of volume, capacity, cycle split, and other variables, will be able to drive through the intersection either near cruise speed or at a reduced speed.

To examine the effects of mixed mode on the prediction methodology, six scenarios were run, with the percentage of cruise-through vehicles set equal to 0, 10, 25, 50, 75, and 100 percent. The scenarios were based on the mixed traffic of 1,000 automobiles, 50 medium trucks, and 100 heavy trucks at a speed of 60 mph. The same six roadways were modeled as in Figure 8(a), but, in addition, a cruise roadway throughout the area of analysis was included as shown by Figure 8(b).

Figure 13 shows the results for the assumed 50 percent cruise case. The top curve represents the total predicted L_{eq} at each receiver. The two lower curves represent the component contributions from the cruise-through traffic and the interrupted flow traffic. Because the traffic is evenly split, the L_{eq} for the interrupted flow traffic, while at cruise speed, equals the L_{eq} for the full cruise case, both being 72 dB.

Figure 14 shows the predicted L_{eq} for the 25 percent cruise case (75 percent interrupted flow) in terms of the total and the component contributions. Because only 25 percent of the total traffic is in the full cruise mode, the L_{eq} from the cruise traffic is predicted to be 6 dB (10 log (0.25)) below 100 percent cruise level of 75 dB. Likewise, the L_{eq} for the cruise portion of the interrupted flow traffic is predicted to be only 1.25 dB below the 100 percent cruise level (10 log (0.75)). Note that the cruise-

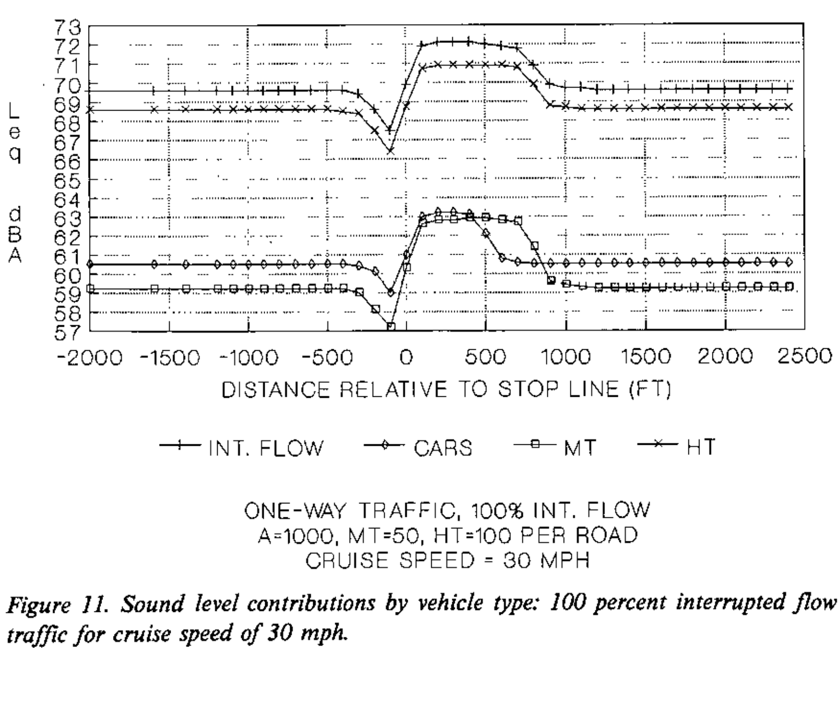

Figure 11. Sound level contributions by vehicle type: 100 percent interrupted flow traffic for cruise speed of 30 mph.

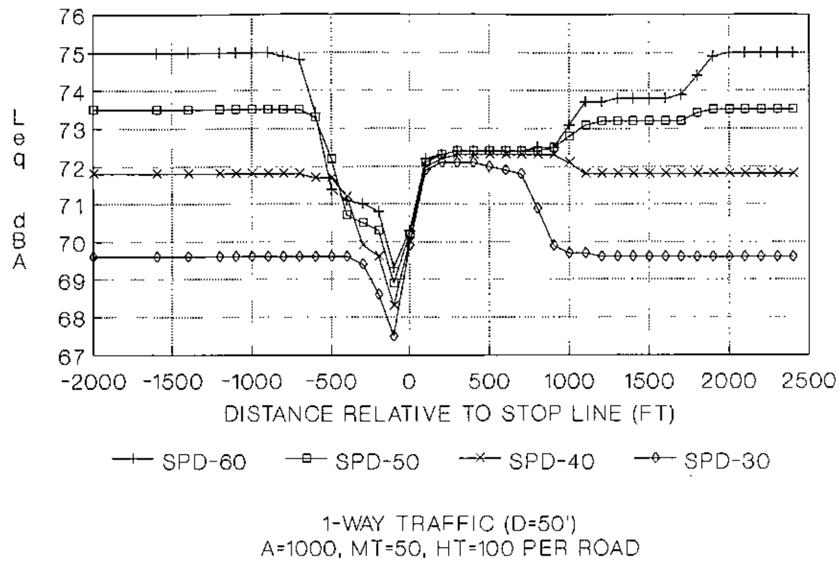

Figure 12. Sensitivity study for speeds of 30 and 60 mph, one-way traffic, 100 percent interrupted flow.

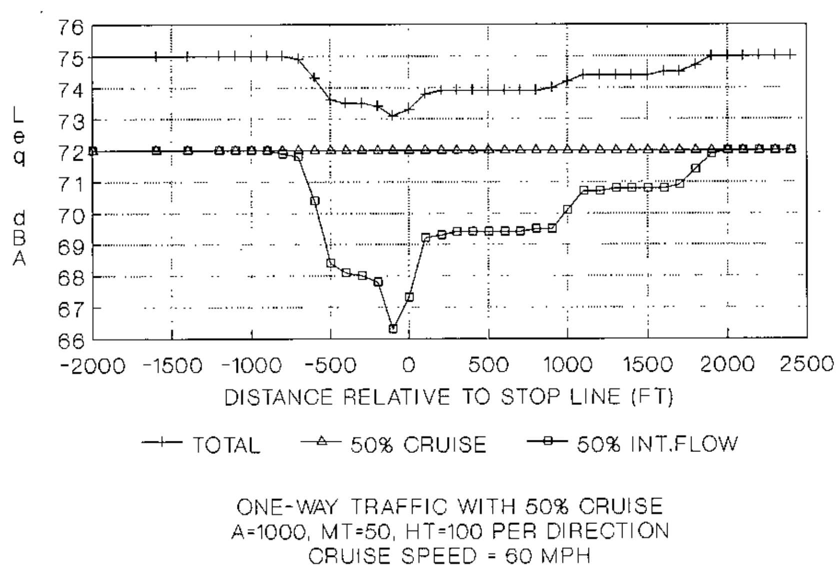

Figure 13. Sound level contributions by operating mode for 50 percent of interrupted flow.

through traffic has a significant effect on the total L_{eq} in the vicinity of the stop line, where the contribution from the interrupted flow traffic is a low point.

Figure 15 presents the 75 percent cruise case. Now, the L_{eq} for the cruise-through traffic is predicted as 6 dB below that total. As a result, the cruise-through traffic noise contribution dominates the total predicted L_{eq} in the vicinity of the intersection, reducing the net predicted effect of the interrupted flow traffic on the total L_{eq} to about 1 dB.

Figure 16 shows the total L_{eq} curves for the three foregoing cases as well as the 0, 10, and 100 percent cruise cases. The extremes represent the 100 percent cruise condition at a constant level of 75 dB and the 0 percent cruise curve (previously shown as the combined curve in Figure 9), which shows a 5.7-dB drop at the −100 ft point. As the percentage of cruise increases, the curve flattens out because of the increased effect of the constant cruise sound level in the predictions. At and above 50 percent cruise, the total difference on levels between the accel/decel zone and full cruise is predicted to be less than 2 dB.

Figure 17 presents the same cruise percentages, but based on 30-mph cruise speeds. In this case, the acceleration/deceleration effects are predicted to be less than 1.5 dB when the cruise percentage equals or exceeds 50 percent.

While the magnitude of these calculated differences will vary

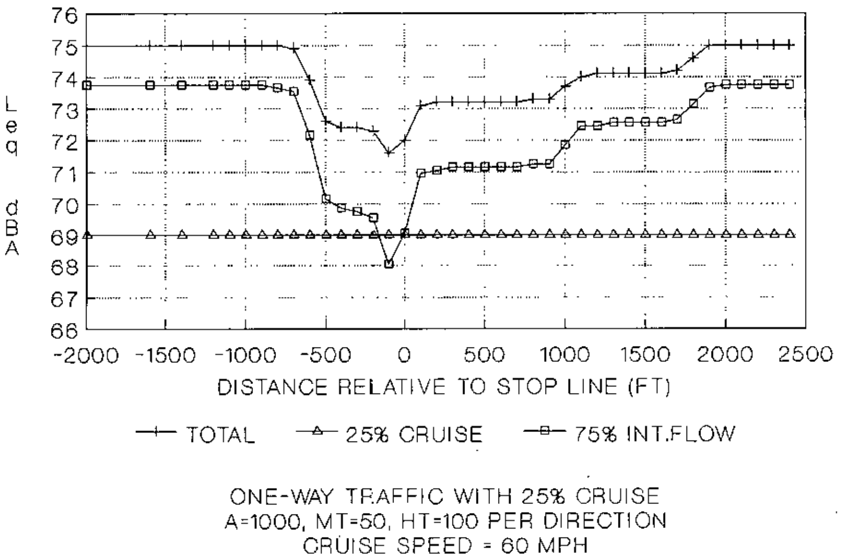

Figure 14. Sound level contributions by operating mode for 75 percent of interrupted flow.

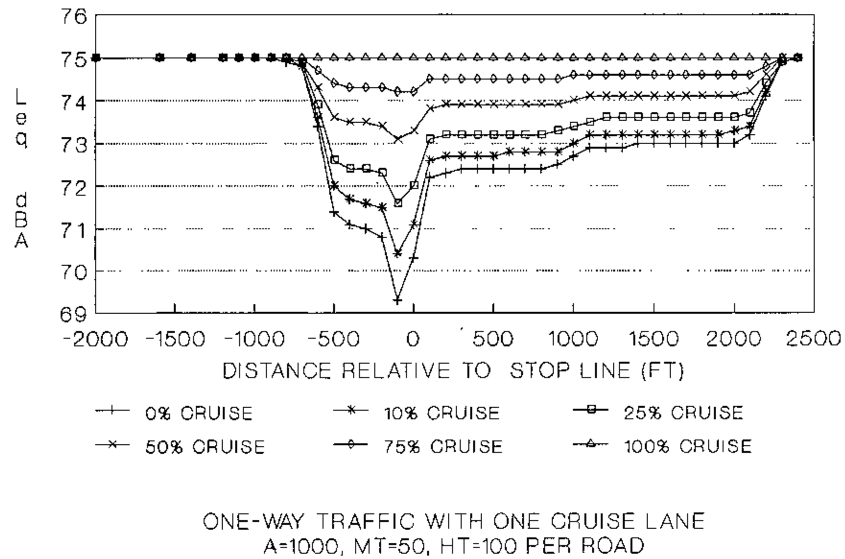

Figure 16. Sensitivity study for percent of cruise: cruise speed of 60 mph.

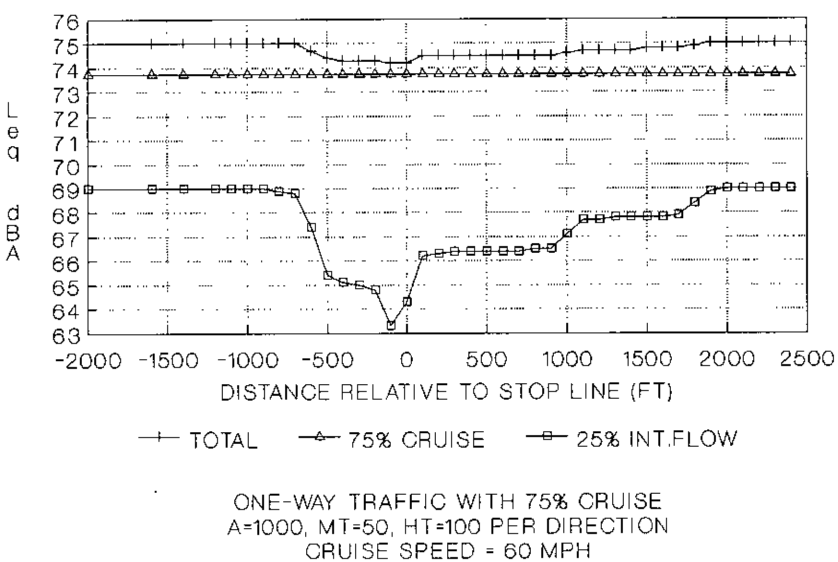

Figure 15. Sound level contributions by operating mode for 25 percent of interrupted flow.

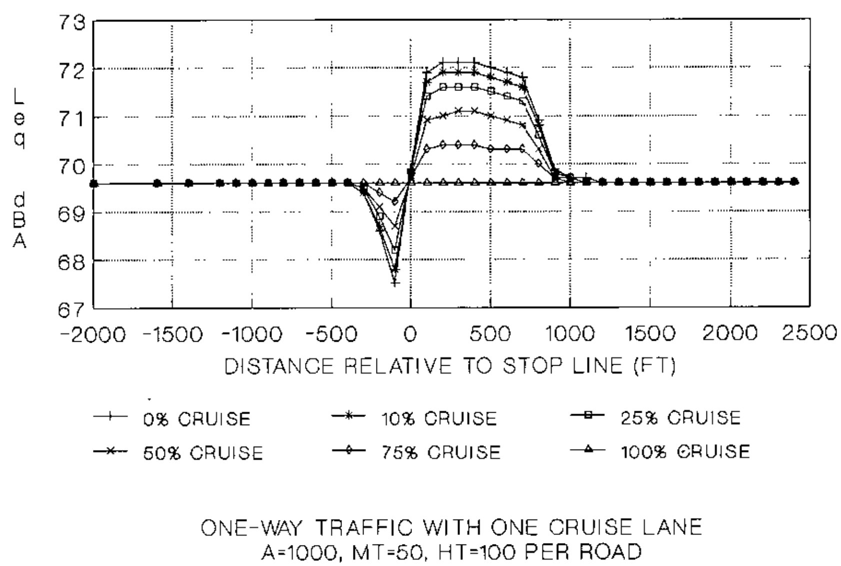

Figure 17. Sensitivity study for percent of cruise: cruise speed of 30 mph.

slightly with changes in traffic mix, the overall effect of introducing cruise-through traffic (at full cruise speed) into the predictions is to sharply diminish the predicted acceleration/deceleration effects on L_{eq}.

Effects of Two-Way Flow

Thus far, the discussion has focused on one-way traffic, which helps in understanding the effects of some of the prediction parameters, but is not typical of many of the actual situations that will be encountered. In most arterial analysis problems, for example, traffic will be bidirectional.

To examine the effects of introducing flow in the opposing direction on the predicted levels, a reverse order sequence of the same roadways was defined, based initially on an arbitrarily chosen 50-ft median width. Figure 18(a) shows the zones of influence for the assumed two-way scenario, with no cruise. Figure 18(b) shows the same scenario with cruise roadways added throughout the area of concern. For simplicity, the opposing traffic was assumed to share the same stop line, an assumption that will overstate the reduction in predicted level at the individual stop lines.

Figure 19 overlays the two-way, 100 percent interrupted flow curve on the one-way, 100 percent interrupted flow curve (same as in Figure 9) for mixed traffic based on a cruise speed of 60 mph. One first notices that the total two-way level in the pure cruise areas (e.g., beyond +2,000 ft) is predicted as being about 1 dB higher than the one-way flow. While the traffic volume has doubled, the far road is twice the distance from the receiver as the near road, decreasing its contribution to the total predicted level. One also notices that the size of the difference in levels between the cruise area and the −100-ft point has decreased by about 1 dB. This change is due to the modeling of the louder accelerating traffic in the far lanes at this point (tempered by the extra distance). Finally, the increase in levels from the stop line to +2,000 ft is more gradual than for the one-way situation,

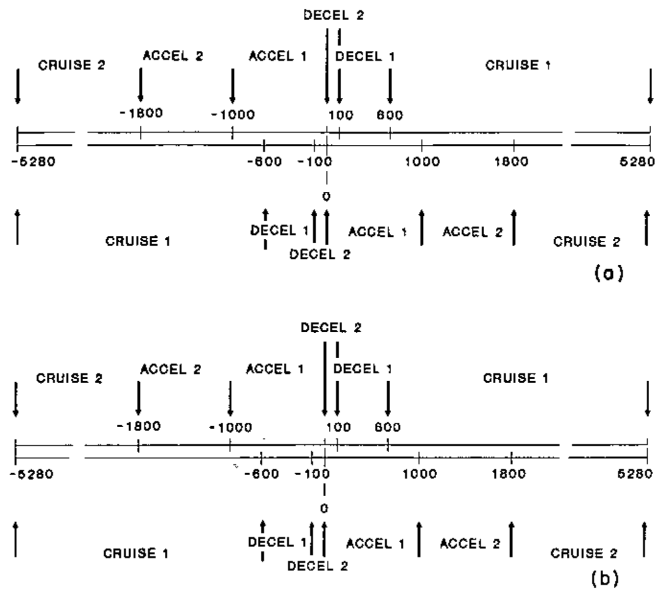

Figure 18. Sensitivity analysis scenarios for two-way flow: (a) with no cruise, and (b) with cruise.

showing the effect of the difference in modeled lengths of the opposing acceleration and deceleration sections. Figure 20 repeats the two-way 100 percent interrupted flow total level curve from Figure 19 and includes the component curves for automobiles and heavy trucks (medium trucks were included in the total calculation, but are not shown).

To contrast the effect when not all of the traffic was modeled as stopping, a 50 percent cruise, 50 percent interrupted flow scenario for each direction of travel was run. Figure 21 presents

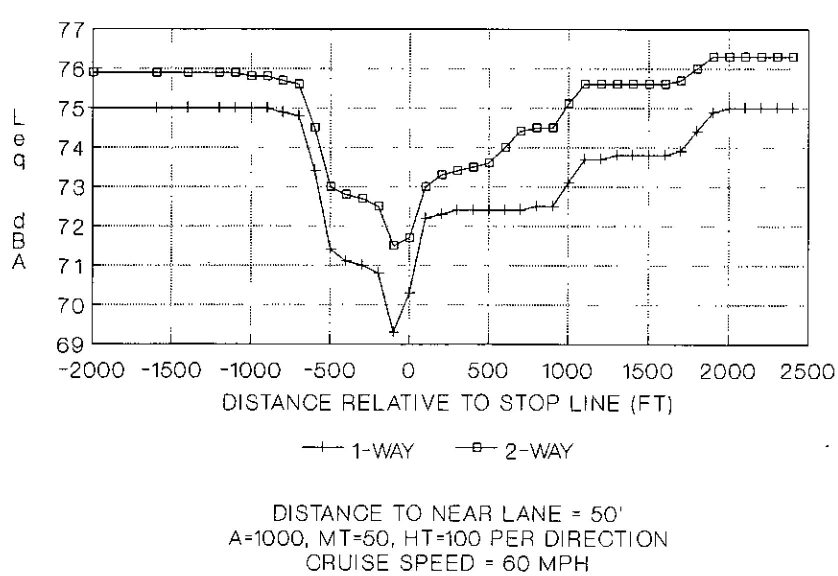

Figure 19. One-way vs. two-way traffic for 100 percent interrupted flow.

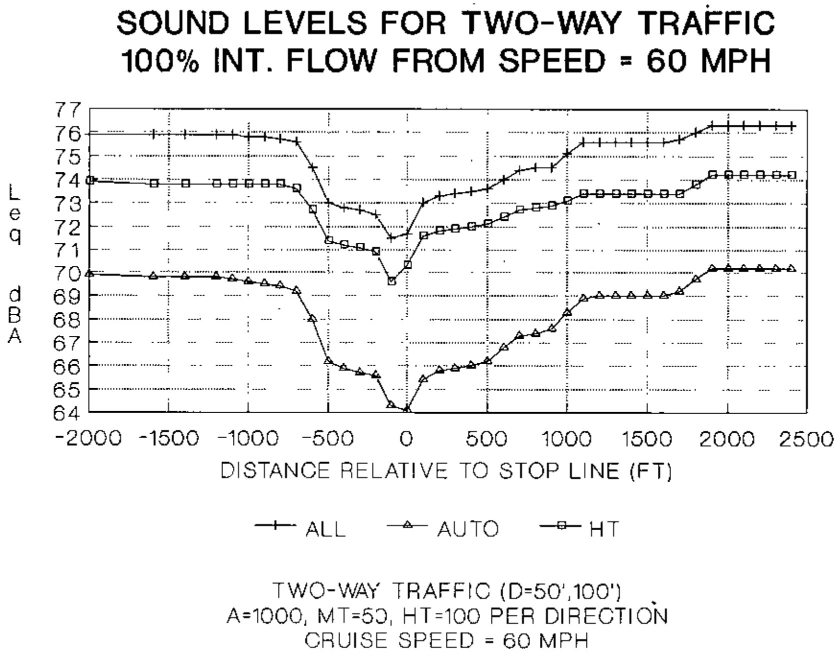

Figure 20. Sound levels for two-way traffic with 100 percent interrupted flow from speeds of 60 mph.

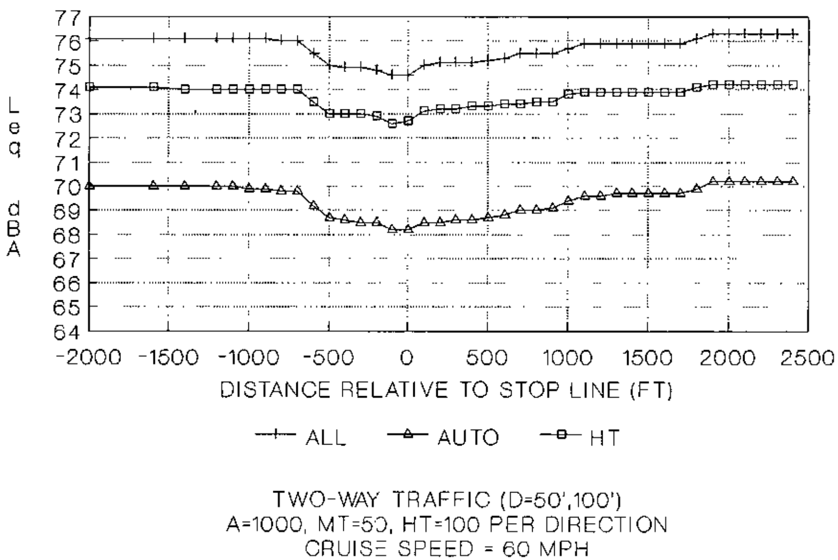

Figure 21. Sound level for two-way traffic with 50 percent cruise at speeds of 60 mph.

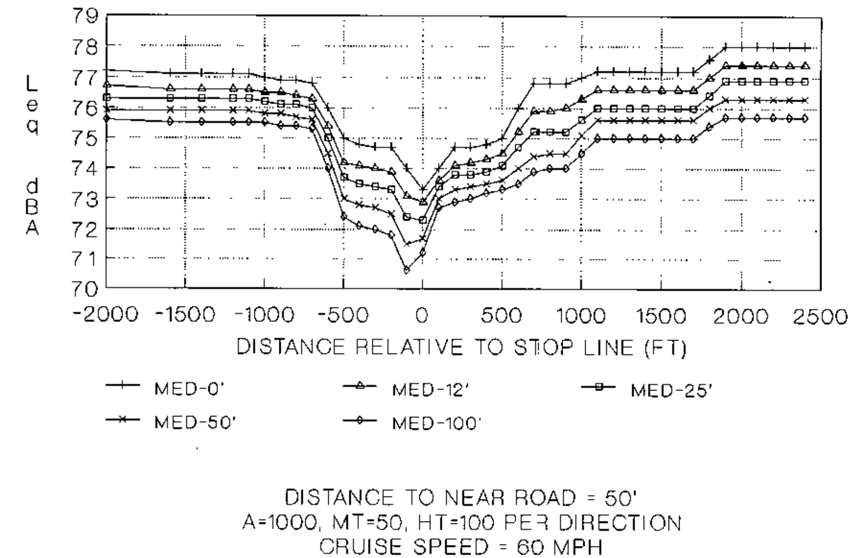

Figure 22. Sensitivity study for median width for 100 percent interrupted flow.

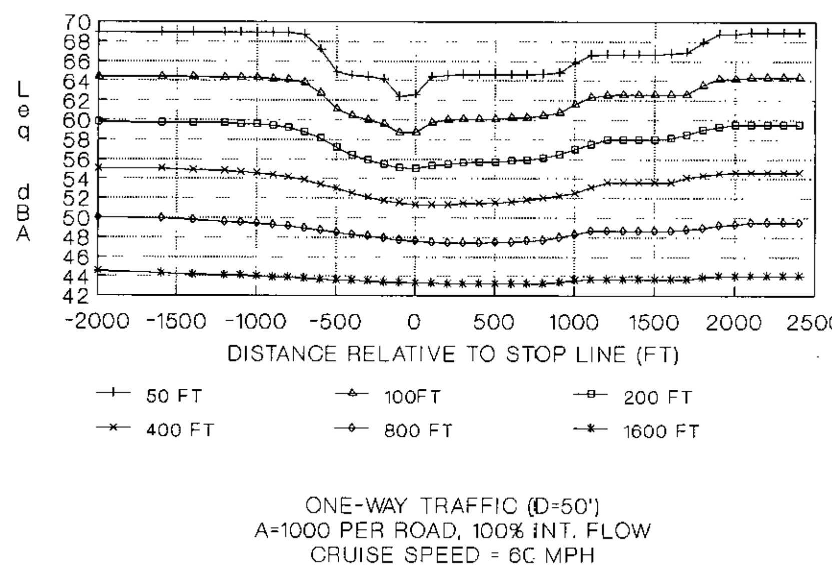

Figure 23. Sensitivity study for receiver distance: one-way traffic with all automobiles.

the results in the same format as Figure 20—total level, automobile component, and heavy truck component. The results are quite similar to what was shown earlier in Figure 16 for the one-way 50 percent cruise scenarios. The total variation in L_{eq} over the entire modeled section is less than 1.5 dB. One point should be made, however. The amount of traffic that actually cruises through an intersection without slowing may be quite small. If this volume is less than 25 percent, as shown in the sensitivity analysis (the data series with the square markers in Figure 17), the change is very small (less than 0.5 dBA) compared to the no-cruise condition (the + markers in Figure 17) and may not need to be considered.

Effect of Median Width

The two-way scenario that has been discussed was based on a 50-ft separation between the two directions of travel. Of interest and importance is how the effects vary with changing separation distance or "median width." Figure 22 shows L_{eq} curves for median widths of 12, 25, 50, and 100 ft. Also included as a lower limit reference is a 0-ft median, which illustrates the exact mirror imaging of the total predicted L_{eq} about the common stop line. As median width increases, the total predicted L_{eq} decreases because of the excess distance attenuation effect on the levels from the far lane traffic. This distance attenuation function also causes the location of the low point on the curve to shift into the mean lane deceleration zone, as the far lane acceleration zone is moved further away. The total difference at any receiver point between the two extremes of 12 ft and 100 ft is on the order of 2 dB.

Effect of Receiver Distance

All predictions thus far have been based on a 50-ft receiver offset distance from the near road. How the effects vary with receiver offset distance is of great importance in most analyses, however. Therefore, a group of scenarios was defined for offset distances of 100, 200, 400, 800, and 1,600 ft.

Figure 23 presents the results for what would be the worst case, in terms of the magnitude of differences between cruise levels and interrupted flow levels—one-way traffic of only automobiles with 100 percent interrupted flow and a cruise speed of 60 mph. The upper curve is the familiar 50-ft offset curve, showing the approximate 6.5-dB difference from cruise to near the end of the deceleration zone. As the receivers are moved back from the road, the effect flattens out and is broadened. In the calculations, the component contributions from the section of road directly in front of a receiver becomes less dominant and the total level is influenced more by adjacent sections. At the 100-ft and 200-ft offsets, the difference in levels between cruise and deceleration is about 5 dB. By 400 ft, the difference is less than 4 dB and by 800 ft, it is under 3 dB. Finally, by 1,600 ft the difference is below 2 dB. Of course, these predictions do not account for any types of shielding that would virtually always occur beyond the 200-ft point for most analysis sections where interrupted flow was a concern.

This worst-case scenario puts limits on the size of the predicted effects using the methodology; it is not a scenario likely to be encountered often in reality (STOP sign in an automobile-only zone; acceleration/deceleration ramps on an automobile-only parkway). Of more interest would be the typical situation expected near a signalized intersection: mixed two-way traffic with a certain percentage cruising through the intersection. Figure 24 shows the results of increasing receiver distance for a scenario with 50 percent cruise and 50 percent interrupted flow for the two-way, mixed traffic. Because the magnitude of the effects for the reference case was smaller than for the reference worst case, the effects of distance occur more rapidly. Figure 24 shows data only to a distance of 400 ft because by that point, the total effect is no more than 2 dB.

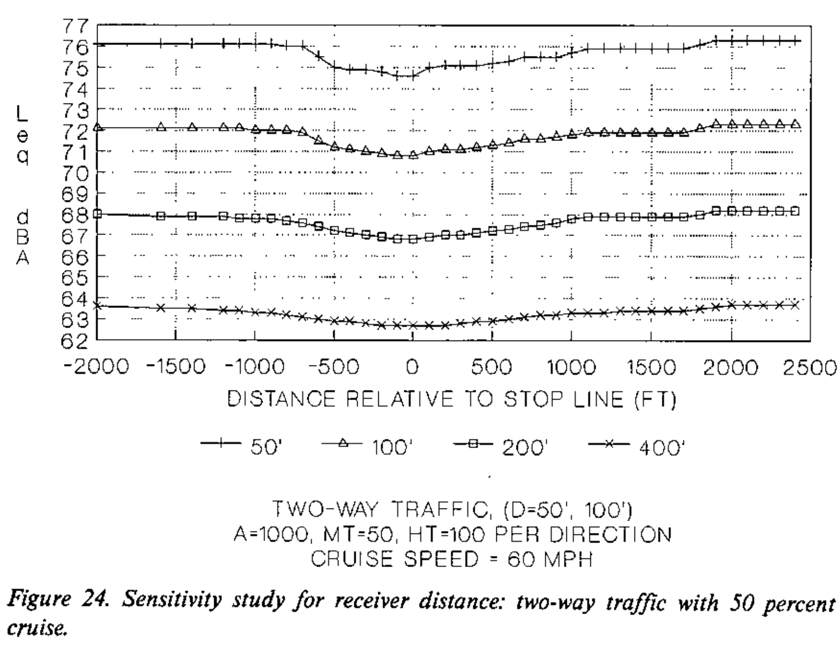

Figure 24. Sensitivity study for receiver distance: two-way traffic with 50 percent cruise.

Summary of Sensitivity Analysis

These sensitivity analyses tested the effects of a variety of traffic and site parameters on the total L_{eq} predicted by STAMINA 2.0 at a series of wayside receivers. The analyses used the initial findings of this study as the basis for the predictions, with a modification to STAMINA to allow speeds below 30 mph. The tested parameters included: (1) vehicle mix, (2) speed, (3) percent of cruise-through traffic, (4) one-way vs. two-way flow, (5) median width for two-way flow, and (6) receiver offset distance from the road.

Worst Case. The results showed that the worst case in terms of deviations in predicted L_{eq} from the full cruise mode was for 100 percent interrupted flow of automobiles traveling one-way at 60 mph for receivers located 50 ft from the road. This case is illustrated by the lower acoustical profile in Figure 9, which also shows the medium and heavy truck profiles as well as the combined profile for the entire scenario. The maximum deviation in automobile levels at the modeled receivers was 6.5 dB, although additional tests with 25-ft spacing between receivers indicated another 1.5-dB drop in levels in the last 100 ft before the stop line. The distance over which this sound level drop occurred, as well as its amplitude, was examined in more detail during testing and validation. In most actual situations, a queue of varying size would exist and would tend to broaden the area where there are differences between cruise and interrupted flow levels.

Vehicle Mix. The difference in predicted, interrupted flow levels relative to 100 percent cruise-through varied by vehicle mix. However, the maximum variation was only 2.5 dB, when comparing a 100 percent heavy truck case to 100 percent automobiles. Indeed, when the truck percentage exceeded 10 percent, the level differences (relative to cruise) were within 0.5 dB of the level difference (relative to cruise) for 100 percent trucks, indicating that in such a situation it was unnecessary to divide a scenario into more roadways solely for the sake of automobiles.

Cruise Speed. The effects of cruise speed on the predicted L_{eq} followed the patterns reported in the literature. For high speeds, there was a sharp drop in level during deceleration and an increase during acceleration, but not back up to the level of the cruising traffic. For low speeds, there is also a drop during deceleration and an increase during acceleration. However, the predicted increase during acceleration can exceed the final predicted low speed cruise level.

Percentage of Cruise-Through Traffic. There was a major effect on the total predicted level when a large portion of the traffic was modeled as passing through an intersection at the cruise speed, such as might happen at a signalized intersection with a very long green cycle or for a semiactuated signal on a lightly traveled cross street. For the situation 50 percent cruise-through and 50 percent interrupted flow based on a 60-mph cruise speed, the difference in the total predicted L_{eq} in the deceleration zone relative to the 100 percent cruise zone prior to deceleration was reduced to less than 2 dB. For a 30-mph approach speed the variation in levels in the acceleration/deceleration zone compared to full cruise was less than 1.5 dB. However, when the percentage of cruise-through traffic was set at 25 percent less, then the effect of cruise on the total predicted level in the acceleration/deceleration region was small and the intersection could be modeled with no cruise-through traffic. Because of the dominating effect on the predictions when a high percentage of cruise-through was used, the authors had to carefully consider both the cruise-through percentage and the cruise-through speed during field evaluation.

Two-Way Flow and Median Width. When roadways were defined in the opposing direction to represent two-way traffic, a slight increase in predicted levels was noted in the near direction deceleration zone because of the higher acceleration emission levels in the same region from the modeled opposing traffic. Reducing the median width tended to accentuate the effects of the opposing traffic and reduce the predicted level differences between the cruise zones and interrupted flow zones to about 3.5 dB. When traffic in both directions was modeled as a mixture of 50 percent cruise-through and 50 percent interrupted flow, the change in levels relative to the full cruise-through scenario was reduced to less than 1.5 dB (based on a 50-ft separation width).

Receiver Distance. Finally, as receiver distance from the road(s) increased, the magnitude of the maximum predicted difference between cruise and interrupted flow levels decreased, but the overall effect of interrupted flow was spread out over larger distances from the stop line. The reason for these effects is that as the receiver position was moved back from the modeled road(s), the dominance of the section directly in front of the receiver would decrease and adjacent sections would have greater effects on the total predicted level. For the worst case (all automobiles, one-way travel, 100 percent interrupted flow), the maximum level difference of 6.5 dB at a 50-ft offset is reduced to 5 dB by 200 ft—less than 4 dB at 800 ft and less than 2 dB at 1,600 ft. For mixed two-way traffic with 50 percent cruise and 50 percent interrupted flow, the maximum level difference at 200 ft was reduced to less than 1.5 dB and at 400 ft was less than 1 dB.

In summary, the sensitivity analysis results indicated that for situations where all of the vehicles stop (or start from a stopped position), such as at STOP signs, tollbooths, or the beginning and ends of certain ramp types, it was possible to model the acceleration and/or deceleration zones as separate roadways using a modified version of STAMINA 2.0 to allow input of low "equivalent" speeds. Such modeling produced effects on the L_{eq} acoustical profile that were similar to those reported in some of the literature on both field measurements and simulation models [Favre, 1978; Slutsky et al., 1983; Lewis, 1978; Lewis and James, 1980]. However, for signalized intersections, the modeling indicated that the percentage of cruise-through vehicles and the cruise-through speed greatly affected the predicted results, requiring closer examination during field evaluation.

PRELIMINARY VALIDATION

The sensitivity analysis provided a better understanding of how the methodology worked for a variety of generalized situations. The next step was to evaluate the methodology against measured time-averaged levels as an initial validation. The scope of this project did not include extensive validation, and more such evaluation is recommended.

Time-averaged levels, L_{eq}, were measured at and near the I-65 truck weigh station used for the individual truck measurements and at two signalized intersections. The purpose of the weigh station measurements was simply to examine trends in the data. The detailed methodology evaluation was done at the two signalized sites.

First Set of Weigh Station Data

Two sets of measurements were done at the weigh station. In the first, 20 simultaneous 4-min L_{eq} measurements were made along the deceleration ramp, along the acceleration ramp, and downstream at a cruise site. Figure 25 presents the 4-min L_{eq} data, which had the following mean values and standard errors:

Deceleration:	66.5 ± 1.5 dB
Acceleration:	71.9 ± 1.7 dB
Cruise:	73.9 ± 1.0 dB

Only 13 of the 20 periods were usable at the acceleration sites because of trucks pulling off the ramp close to the microphone to enter a back parking lot. A several-minute delay from when a truck would pass the deceleration site before passing the cruise site made it impossible to directly compare paired sets of readings. The mean deceleration L_{eq} represented conditions ranging from just a few high-speed decelerations to a long period with queued trucks in front of the microphone. The L_{eq} values do include contributions from other vehicle types (traffic on the main lanes when no trucks were in the vicinity) which were more important at the cruise site. Nonetheless, the 7.4-dB difference between cruise and deceleration and the 2.0-dB difference between cruise and acceleration are consistent with the differences found in the measured SEL data.

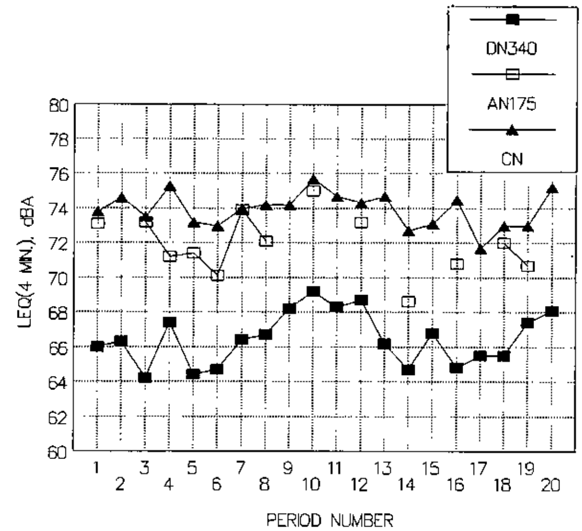

Figure 25. L_{eq} *(4 min), for deceleration, acceleration, and cruise, 6/1/88, I-65 NB weigh station.*

Second Set of Data

The second set of weigh station data provided information on how L_{eq} varied with distance from the stop line during acceleration relative to cruise levels. Eleven sets of 10-min L_{eq} were measured at three points along the acceleration ramp and at the cruise site.

Figure 26 shows the 10-min L_{eq} at each site. Several measurements had to be rejected because of unusual events at the sites (sirens, trucks stopping near a microphone). The mean L_{eq} and standard errors were as follows:

175 ft from stop line:	72.2 ± 0.7 dB
350 ft from stop line:	73.8 ± 0.7 dB
525 ft from stop line:	74.3 ± 0.6 dB
Cruise:	75.4 ± 0.3 dB

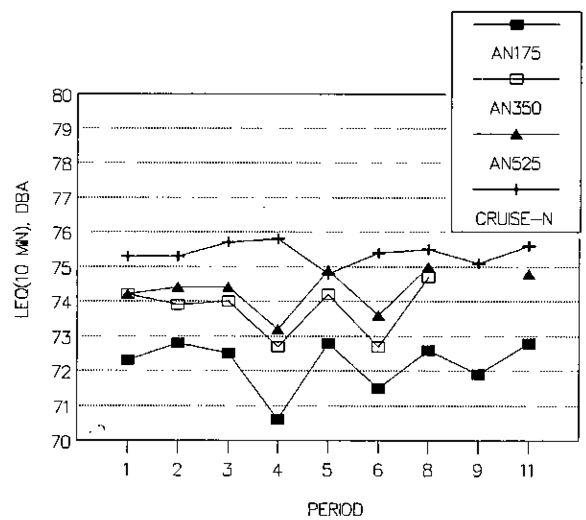

Figure 26. L_{eq} *(10 min), acceleration at 3 points and cruise, 8/23/88, I-65 NB weigh station.*

The results show that the mean L_{eq} values increase with distance from the stop line, but are still less than the cruise value. These same trends were found in the SEL measurements. The differences in acceleration mean L_{eq} compared to the cruise mean L_{eq} ranged from 1.1 dB to 3.2 dB. These differences are consistent with the mean 2.1-dB difference in sound exposure levels observed between the cruise data and the acceleration data that were aggregated for all sites.

Validation Site 1—Two-Lane Signalized Intersection

The first of the two validation sites was a signalized intersection of two well-traveled two-lane roads at the outskirts of suburban Nashville, Tennessee (Figure 27). The speed limits on the main road (Hillsboro Road) were 50 mph and 55 mph (changing at the intersection). The cross-road (Old Hickory Blvd.) speed limit was 45 mph. The signal was actuated in both directions with very short left-turn storage areas on all four legs of the intersection.

Measurements were made at a series of sites along Hillsboro Road on both sides of the intersection, at 50-ft offsets from the center of the near travel lane. On the "deceleration" side of the intersection (for the near lane traffic), sites were set at 100 ft and 250 ft from the stop line. On the acceleration side, distances from the stop line ranged from 95 ft to 445 ft. A "cruise" site was also established. The data were measured in groups of 3 to 4 sites at a time, with a common site in each group for reference.

Three different hourly periods were selected for evaluation based on consistency in the traffic data for the four periods comprising each hour. For those sites not measured in the particular hour being studied, a mean L_{eq} was estimated by nor-

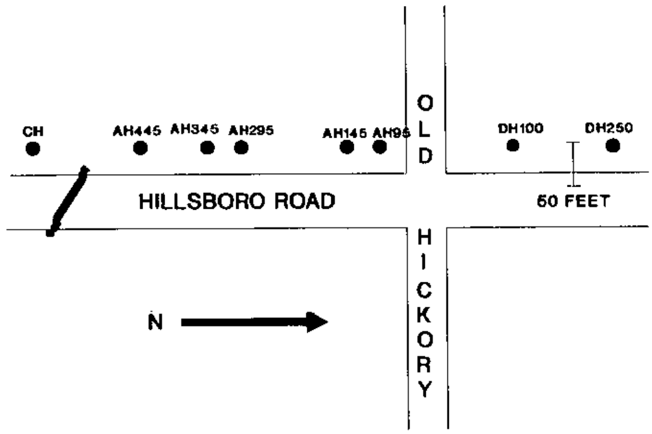

Figure 27. Time-averaged noise level measurement sites (Hillsboro Road).

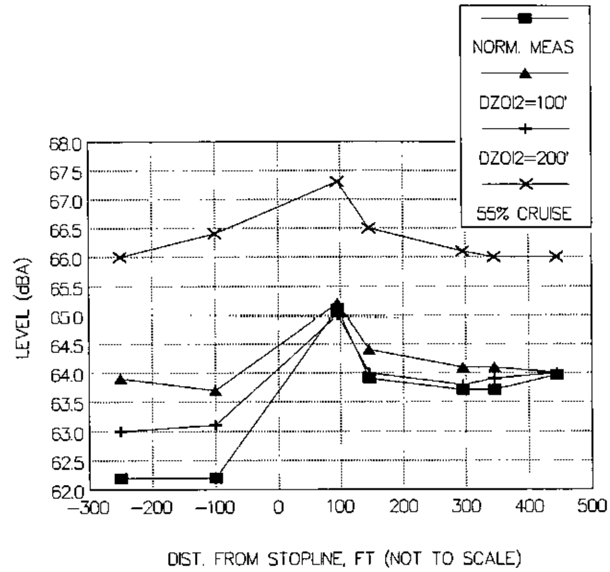

Figure 28. Validation: Hillsboro Road, measurements normalized to 10/12 data from 13:00–14:00.

malizing data from a second day during the same time period, using the common reference site as a basis for adjustment.

Figure 28 shows the mean measured L_{eq} values at each site as filled squares on the bottom curve. The other curves will be described in the following paragraphs.

Initial Modeling Efforts. For the initial modeling of the intersection, the prediction methodology was applied assuming that 55 percent of the traffic on the main road would cruise through the intersection at full speed. For this first assumption, the methodology overpredicted levels at the acceleration sites by 2 dB and at the deceleration sites by about 4 dB. The prediction was within 0.1 dB of the measured value at the cruise site of these results, as shown by the profile with the X markers in Figure 28. The results indicated that the cross-road traffic was an important contributor to the total L_{eq} close to the intersection. Subsequent field observations indicate that the "55% cruise at 55 mph" assumption was unrealistic. Only about 20 percent of the vehicles did not have to stop or slow down to near-stop because of the signal or the resultant queue. Further, most of the 20 percent that cruised through the intersection slowed down anyway and passed through the intersection at reduced speeds of 35 mph to 45 mph.

More Detailed Examination of Deceleration Levels. Because of the overprediction and the finding on the cruise-through assumption, another computer run was made, this time assuming that all of the vehicles would be modeled as stopping at the intersection. The results (the profile with the triangle markers in Figure 28) were within 0.5 dB of the measured levels at the acceleration sites, but still about 1.5 dB high at the deceleration sites. A more detailed examination was made of the way in which the deceleration ZOI were defined. The original decision to break the deceleration zone at the 20-mph point was somewhat arbitrary. That is, it was known that a large drop in levels occurred at the end of a deceleration event and the EPA data had specifically included a level for the 20-mph to 0-mph deceleration range. It was also known that the more precise method for analysis, because of the large drop, was to model the deceleration zone by several contiguous roadways instead of two. Although such a strategy would complicate the analysis in most actual situations, it was a convenient means for model evaluation.

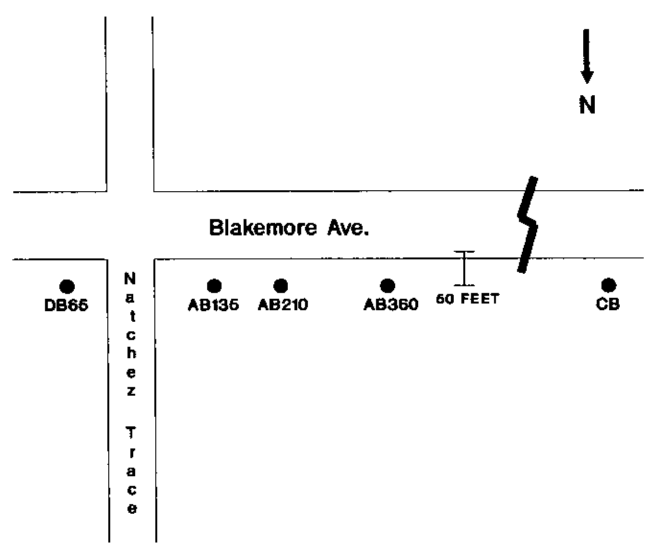

Figure 29. Time-averaged noise level measurement sites (Blakemore Avenue).

Thus, the deceleration zone was divided into five pieces, each with a constant emission level derived from the EPA data. The result was a smooth decrease in levels as the distance from the intersection decreased. However, the two-roadway approach was still desirable from a practitioner's point of view. Therefore, the lengths of the two originally defined zones were varied in a series of tests. The best results, relative to the 5-road case, were when the first DZOI was given a length of 300 ft and the second DZOI was defined as 200 ft (ending at the point of stop).

Reapplied to the validation site, the predicted L_{eq} at the deceleration site were brought to within 1 dB of the measured values (the + markers in Figure 28). The changes in the DZOI lengths also improved the results at the acceleration sites, bringing the predictions to within 0.2 dB of the measurements.

The measured data were also tested against the methodology suggested by Barry and Reagan [1978] in the FHWA model report. The levels at the deceleration sites were overpredicted by about 2 dB. At the acceleration sites, the levels were predicted within 1 dB, indicating good agreement.

Final Results at First Site. Thus, based on this first evaluation site, the following observations were made:

1. Unless there is evidence to the contrary to indicate a high percentage of high-speed traffic cruising through the intersection, all traffic should be modeled as stopping at the intersection.
2. Cross road traffic needs to be included in the modeling.
3. The modified two-zone approach works well.
4. The suggested methodology in the FHWA model report gave good results at this site for the acceleration sites, but because of its inability to model the acoustical profile overpredicted the deceleration sites.

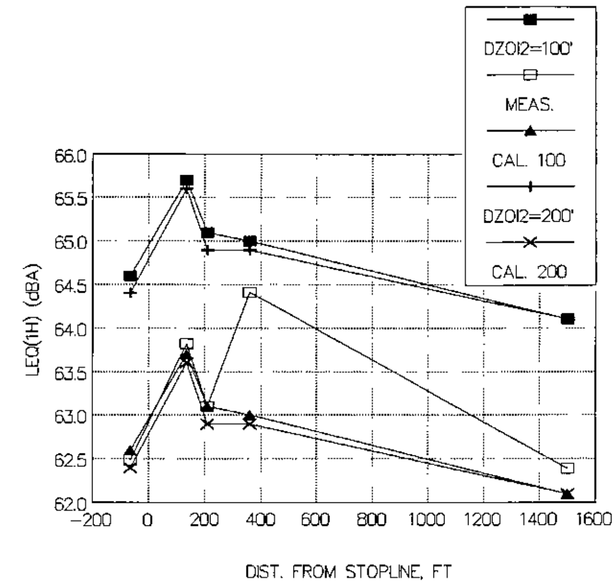

Figure 30. Validation: Blakemore Avenue, no cruise, measurements normalized to 10/14, 14:00–15:00.

Validation Site 2—Four-Lane Signalized Intersection

The second validation site (Figure 29) was in a suburban area along a four-lane arterial with a 35-mph speed limit and a center fifth turning lane. The cross road was a two-lane road with short left-turn storage areas. A series of 15-min L_{eq} were measured at one deceleration site, three acceleration sites, and a cruise site. At the cruise site, the FHWA model overpredicted levels by 2 dB. This 2-dB difference was used to calibrate the predicted levels at the other sites. The assumption of all vehicles stopping was applied to the predictions based on its successful use at the first validation location.

Initial Modeling. Figure 30 shows the mean measured levels (open square), the uncalibrated prediction (filled squares), and the calibrated predictions (triangles). The calibrated predictions all fall within 0.2 dB of the measured L_{eq} except at site AB360, where the predicted level was 1.5 dB low. A subsequent field review showed that a solid wood fence was opposite this site and is thought to have produced sound reflections that would be responsible for some or all of this difference.

Modified Modeling. The other two data series in Figure 30 represent the uncalibrated and calibrated predicted levels when the deceleration zone lengths were modified according to the findings at the first validation location results. Virtually no improvement occurred in the predictions. At this location, the low cruise speed resulted in a low emission level for the first DZOI. Thus, shifts in the break point between it and the second DZOI (also with low emission levels) changed the results little.

The methodology suggested in the FHWA model report was also tested at this location. The acceleration sites were overpredicted by 1.3 dB to 2.3 dB, and the deceleration site was overpredicted by 6 dB.

Final Results at Second Site. Thus, for the second validation site, these observations were made:

1. The prediction methodology worked very well when all vehicles were modeled as stopping (except at one measurement point where sound reflections in the field may have increased measured levels).
2. Cross-street traffic needs to be modeled.
3. The FHWA-suggested methodology overpredicts the L_{eq} significantly and does not predict the changing acoustical profile.
4. Modifying the lengths of the DZOI did not have as large an effect on the levels at the modeled points as it did for the first validation site.

Summary of Validation Results

The results of the evaluation at the two validation sites indicate that the methodology, with certain modifications, predicted levels well within 1 dB of measured values. The first modification was to model all traffic as stopping at an appropriate point of stop near the intersection, with no traffic assumed to cruise through at the posted speed limit. This modification seemed most important when the speed limit was high. The second modification was to adjust the lengths of the two deceleration zones of influence to better replicate the results of a more detailed modeling of the EPA data. With these modifications (and calibration based on the cruise site levels) the predictions were within 1 dB of the measured levels. While additional validation is certainly warranted, the results are encouraging.

USE OF THE METHODOLOGY—ASSUMPTIONS AND LIMITATIONS

Tables 6 and 7 present the definitions of the acceleration and deceleration zones of influence for use in this methodology, as modified on the basis of the validation sites.

The equivalent speeds in these tables are based on the FHWA model reference energy, mean emission level equations [Barry and Reagan, 1978]. If an agency has developed different emission levels, use of these speeds would be inappropriate. Instead,

Table 6. Combined acceleration zones of influence and corresponding equivalent speeds for three vehicle types.

Accel. Range (mph)		Length (ft)		Speed, ZOI(1) (mph)			Speed, ZOI(2) (mph)		
$S_{initial}$	S_{final}	ZOI(1)*	ZOI(2)**	Autos	MT	HT	Autos	MT	HT
0	30	500	300	38	43	43	30	43	43
0	35	600	650	39	43	43	35	43	43
0	40	1000	none	40	43	43	n/a	n/a	n/a
0	45	1000	none	42	43	43	n/a	n/a	n/a
0	50	1000	800	42	43	43	50	47	47
0	55	1000	800	42	43	43	50	49	49
0	60	1000	800	42	43	43	50	52	52
30	40	400	none	40	43	43	n/a	n/a	n/a
30	50	1000	none	42	43	43	n/a	n/a	n/a
30	60	1900	none	51	52	53	n/a	n/a	n/a
40	50	600	none	45	43	43	n/a	n/a	n/a
40	60	1500	none	50	52	53	n/a	n/a	n/a
50	60	any	none	60	60	60	n/a	n/a	n/a

* Starting from point of stop and proceeding in direction of flow
** Starting from end of ZOI(1)

the agency would have to develop its own set of equivalent speeds.

In Appendix B, a generalized expression is developed for equivalent speed, S, if the emission level equation is in the form of $a + b$ log (speed, kph):

$$S = \text{antilog}\ \{[(L_o)_{E,96\ \text{kph}} - 10\log(96\ \text{kph}) - a - \Delta_c]/(b - 10)\} \qquad (12)$$

where $(L_o)_{E,96\ \text{kph}}$ is the agency's reference emission level at 96 kph and Δ_c is the desired difference in SEL between a cruise condition of 96 kph and the acceleration and deceleration stage of interest. Tables 8 and 9 present the values for Δ_c that were developed from the analysis of the EPA data and the field data and used to derive the equivalent speeds in Tables 6 and 7. Appendix C gives a procedure for using this information to modify Tables 6 and 7.

Once the proper set of equivalent speeds is derived, the analyst would follow the step-by-step procedures in Appendix C to model a given site for STAMINA 2.0. Essentially, three types of situations are covered in the appendix: (1) signalized intersections; (2) unsignalized (STOP sign) intersections; and (3) speed change zones, such as a ramp loop.

For the first two situations, the procedure is generally the same with two important differences. The first is the location of the point from which acceleration begins. For an unsignalized intersection, this point is at the stop line. However, for the signalized intersection, this point is at a distance from the stop line equal to one-half the expected queue length. The difference is due to the nature of vehicle operation at the two traffic control devices. For a STOP sign, even if a queue exists, each vehicle will move forward to the stop line before beginning its full acceleration toward the final speed. However, for the traffic signal, the queue of vehicles will release, with some delay, as a platoon. Thus, some vehicles will be accelerating from the front of the queue, others from the middle, and some from the end. As an approximation, the average departure will be from the midpoint of the queue.

The second difference between the two cases is related to the point at which deceleration is assumed to end and the resultant length of the final deceleration ZOI. For the signalized intersection, the midpoint of the expected queue is used as the ending point for deceleration. Use of this point follows the same logic as for the start of acceleration—the first vehicle to be stopped by the signal will decelerate up to the stop line, the last vehicle will decelerate up to the end of the queue, and, on the average, the vehicles will decelerate to the midpoint of the queue.

For the unsignalized intersection, however, all vehicles will decelerate to the end of the expected queue and stop. They will then slowly move forward as each lead vehicle accelerates from

Table 7. Combined deceleration zones of influence and corresponding equivalent speeds for three vehicle types.

Decel. Range (mph)		Length (ft)		Speed, ZOI(1) (mph)			Speed, ZOI(2) (mph)		
$S_{initial}$	S_{final}	ZOI(1)*	ZOI(2)**	Autos	MT	HT	Autos	MT	HT
30	0	150	100	29	26	24	18	13	10
40	0	275	100	34	30	28	18	13	10
50	0	400	100	38	34	31	18	13	10
60	0	500	100	41	36	33	18	13	10
40	30	220	none	37	32	30	n/a	n/a	n/a
50	30	375	none	42	37	36	n/a	n/a	n/a
50	40	270	none	46	41	42	n/a	n/a	n/a
60	30	530	none	46	41	42	n/a	n/a	n/a
60	40	430	none	51	46	47	n/a	n/a	n/a

* Starting from end of ZOI(2).
** Starting from point of stop and proceeding upstream from that point.

Table 8. Change in SEL in acceleration zones of influence for three vehicle types.

Accel. Range (mph)		Change in SEL ZOI(1) (dBA)			Change in SEL ZOI(2) (dBA)		
$S_{initial}$	S_{final}	Autos	MT	HT	Autos	MT	HT
0	30	5.6	3.5	2.1	8.5	3.5	2.1
0	35	5.3	3.5	2.1	6.6	3.5	2.1
0	40	4.9	3.5	2.1	n/a	n/a	n/a
0	45	4.4	3.5	2.1	n/a	n/a	n/a
0	50	4.4	3.5	2.1	2.2	2.5	1.5
0	55	4.4	3.5	2.1	2.2	2.1	1.3
0	60	4.4	3.5	2.1	2.2	1.5	0.9
30	40	4.9	3.5	2.1	n/a	n/a	n/a
30	50	4.4	3.5	2.1	n/a	n/a	n/a
30	60	2.0	1.3	0.8	n/a	n/a	n/a
40	50	3.5	3.5	2.1	n/a	n/a	n/a
40	60	2.2	1.5	0.8	n/a	n/a	n/a
50	60	0.0	0.0	0.0	n/a	n/a	n/a

Table 9. Change in SEL in deceleration zones of influence for three vehicle types.

Decel. Range (mph)		Change in SEL ZOI(1) (dBA)			Change in SEL ZOI(2) (dBA)		
$S_{initial}$	S_{final}	Autos	MT	HT	Autos	MT	HT
30	0	8.9	8.7	5.8	14.7	15.9	11.4
40	0	6.9	7.2	4.8	14.7	15.9	11.4
50	0	5.6	5.9	4.2	14.7	15.9	11.4
60	0	4.6	5.3	3.8	14.7	15.9	11.4
40	30	5.9	6.5	4.4	n/a	n/a	n/a
50	30	4.4	5.0	3.2	n/a	n/a	n/a
50	40	3.2	4.0	2.3	n/a	n/a	n/a
60	30	3.2	4.0	2.3	n/a	n/a	n/a
60	40	2.0	2.8	1.5	n/a	n/a	n/a

the stop line. Because the levels during the last phase of deceleration were found to be similar to those when vehicles are moving forward in a queue, the last deceleration ZOI needs to be extended by the length of the queue up to the stop line.

Except for the above two differences (and the use of different formulas to determine the expected end of queue), the procedures for the signalized and unsignalized intersections are the same—determine the stopping point, determine the queue length, establish the lengths of the acceleration and deceleration ZOI based on the cruise speed, determine the coordinates for the starting and ending points of each ZOI, and create the roadway section of the STAMINA 2.0 input data file (using for speeds the values in Tables 6 and 7). "Cruise" roadways may also be defined as needed beyond the ends of the ZOI using the posted or average operating speeds beyond the ZOI.

Two additional comments need to be made on the modeling of operating modes in the vicinity of the intersection. First, the sensitivity analysis and validation results showed that modeling a large percentage of the traffic as cruising through the intersection at the initial or final cruise speed can have two consequences: (1) most of the acceleration/deceleration effects on the total L_{eq} will be masked by levels from the cruise traffic, and (2) L_{eq} will be overpredicted compared to the measurements. These effects happened both for the high approach speed location and the low approach speed site. Additional field observations showed that at these sites only a small percentage (on the order of 15 to 20 percent) of the total traffic actually cruised through the intersection and, of that percentage, most slowed down when passing through the intersection.

Because these observations are probably not universally true, each situation would require some consideration. If the analyst has reason to believe that a high percentage (e.g., 50 percent) of the vehicles will cruise through at a high speed (e.g., 50 mph or more), it may be desirable to define separate cruise-through roadways in the vicinity of the intersection. The sensitivity analysis showed that if the percent cruise-through is less than 25 percent, no cruise traffic should be modeled through the intersection. The reader is referred to the sensitivity analysis section of Appendix B for more details on the predicted effects on L_{eq} caused by modeling cruise-through traffic.

The second comment relates to the lack of explicit consideration of the idle mode in the predictions. Instinctively, one would model a stop-and-go situation as a mix of L_{eq} contributions during four modes—deceleration, idle, acceleration, and cruise. These L_{eq} values would be combined in the same manner as would the levels for different vehicle types with the exception that each mode's contribution would be weighted by percentage of time in mode.

Indeed, this was the approach originally anticipated by the authors. However, this approach is difficult to implement in STAMINA (especially for the idle mode) and would be difficult to use in practice.

The FHWA model formulation is based on the concept of integrating the changing sound level contributions from a series of point sources moving along a line at a given speed and then averaging over 1-hour time periods. During idle, speed is equal to zero and there is no vehicle flow past the receiver point, making the FHWA model formulation inapplicable. For a single idling vehicle, the level at an observer will remain constant. If the vehicle is in front of the observer, the L_{eq} will equal the L_{max}. Also, the linear relationship between L_{eq} and SEL, which was the basis for developing the methodology, will no longer apply. While the L_{eq} over an idle period would remain constant, the sound exposure level would continually increase as time increased because SEL is a representation of the total received acoustic intensity. Thus, the explicit inclusion of idle in the methodology was not possible.

However, the authors believe that idle is implicitly considered in the current methodology in two ways. First, the level for the final deceleration ZOI prior to stopping is much lower than the cruise levels and only slightly above the idle level. Thus, by assigning a length of several hundred feet to this ZOI, a region of low emission level is established behind the stop line. It is in this region where much of idle will occur. Second, there appears to be a compensating effect from excluding both cruise-through traffic with its associated high sound level and idle with its associated low level. This effect was evidenced by the good results at the validation sites when only acceleration and deceleration zones were defined near the intersection. It should be emphasized that these observations would not hold true in every case, but they appear reasonable for the typical case likely to be encountered in most situations.

Two comments should also be made about the results that were derived for automobiles and medium trucks, which were based on the EPA data. First, the cruise levels presented by EPA matched very closely with the FHWA reference energy mean emission levels. Second, the EPA data for acceleration or deceleration were presented as emission levels that represented averages over the full duration of an event for an observer moving alongside the vehicle at a 50-ft offset distance. These levels would be different from what would be observed for stationary observers, where the levels would vary as a function of the distance from the start or end of the event.

However, based on the data and on approximations of vehicle acceleration and deceleration rates from AASHTO data, these full-event averages were divided into a series of intermediate segments, each with its own average level (e.g., a 0 to 50-mph acceleration event could be broken into 0 to 20, 20 to 30, 30 to 40, and 40 to 50-mph segments). These segments were considerably shorter than the distance covered during the entire event. The assumption was then made that the average level for each segment represented a constant emission level over that segment, even though the level would generally be changing. Thus, the acceleration or deceleration event was now represented by a stepped series of constant emission levels. These stepped emission levels were then used in a second-by-second time-step simulation model to develop acoustical profiles. These profiles showed SEL at wayside receivers as a function of distance from the beginning of the event. From these acoustical profiles, decisions were made on the needed numbers and lengths of zone-of-influence roadways for STAMINA 2.0 modeling. Analysis of the field evaluation data led to a closer examination of the assumptions and revision of some of the segment lengths.

A summary of the assumptions made in the study follows:

1. The field-measured differences in SEL between cruise and acceleration or deceleration could be applied to the predicted SEL using the FHWA model cruise emission levels.

2. The assumptions used in the derivation of the FHWA model were valid.

3. Because the EPA cruise data matched the FHWA model cruise data, the EPA acceleration and deceleration data could also be compared to the FHWA model cruise data.

4. The AASHTO data on vehicle acceleration and deceleration rates were valid.

5. The EPA acceleration and deceleration emission level data, which were averaged over a full acceleration/deceleration event, could be broken into a stepped series of constant intermediate emission levels.

6. An acoustical profile could be defined in the vicinity of an intersection based on traffic and geometric considerations.

7. A single average stopping point could be used as a transition between the deceleration and acceleration modes.

APPLICABILITY OF THE RESULTS AND THE METHODOLOGY

Earlier in this chapter, the findings for each individual vehicle type were combined into a single methodology. That methodology was then evaluated through a sensitivity analysis using a modified version of STAMINA 2.0 and through comparisons to measured levels at two validation sites.

The results of this research are encouraging and should lead to better prediction of traffic noise levels in the vicinity of signalized and signed intersections, highway ramps and loops, and tollbooths.

The methodology is applicable in those situations where cruise conditions can be achieved on either end of the analysis area and where acceleration and deceleration zones of influence can be defined as being distinct from these cruise areas. For those signalized intersections with more than 25 percent of the traffic being able to cruise through at or near the posted speed, cruise roadway(s) also need to be defined crossing the intersection.

The methodology is not applicable in truly congested or unstable situations (LOS E or LOS F on interrupted flow facilities or LOS F on highways) where no cruise speeds are achieved. In such situations, the approach used by Anderson [1976] and Prahl and Miller [1975], involving specialized field measurements, seems most appropriate. The methodology also makes no account for reflections or urban canyon reverberation, a limitation inherent in the STAMINA 2.0 program.

The methodology represents an improvement over the recommendations in the FHWA model report for predicting stop-and-go levels [Barry and Reagan, 1978; p. I-1]. Specifically, use of a constant emission level over the entire zone would not correctly account for the way levels change as vehicles accelerate or decelerate. Use of a constant emission level in the FHWA model would result in a decrease in predicted L_{eq} as speed is increased, which was not borne out by this study. Instead, field measurements showed the emission level to increase with increasing speed, causing the L_{eq} to increase only slightly (or, in case of heavy trucks, to remain relatively constant) as speed increased. Additionally, the levels during deceleration were considerably different from those during acceleration. They changed much more rapidly and over much shorter distances, and need to be treated separately from the acceleration levels.

Use of the FHWA model recommendations at two validation sites gave variable results (from 0 to 6-dB overprediction), while use of the methodology developed in this research resulted in predicted levels within 1 dB of measured values.

Because the methodology is more complicated than a free-flow traffic analysis with STAMINA, potential users may wish to do an initial screening using the free-flow technique to see if the problem warrants more detailed analysis.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

This research has resulted in new data on the levels of accelerating and decelerating values and a better understanding of existing data. The research has also led to a methodology for predicting traffic noise levels in stop-and-go situations with the STAMINA 2.0 computer program, the most commonly used tool in constant speed situations.

The analysis and subsequent development of the methodology have led to a number of conclusions:

1. The use of the sound exposure level (SEL, a measure of the total acoustic intensity of an event) as a means of determining effects on the 1-hour average level, L_{eq}, is a valid way to study the effects if the averaging time is significantly longer than the event duration.

2. In general, L_{eq} tends to decrease in deceleration areas relative to cruise, regardless of the initial cruise speed. For example, for heavy trucks, the average difference in sound exposure levels between cruise at 60 mph and deceleration in the 20-mph to 30-mph range was 8 dB. Below 20 mph, the difference was about 12 dB compared to 60 mph.

3. The L_{eq} in acceleration areas will increase significantly over deceleration levels, but may be either above or below the cruise L_{eq}, depending on the final speed. For medium and heavy trucks, the L_{eq} produced in acceleration zones were equivalent to L_{eq} produced by cruise operations at a speed of about 43 mph (based on the FHWA model equation). For heavy trucks, the sound exposure level over the first 600 ft of acceleration remained relatively constant, being about 2 dB below the sound exposure level at a cruise speed of 60 mph.

4. Ideally, the most accurate way to predict stop-and-go levels would be to use a time-step simulation model that would track a vehicle's speed, distance, and resultant level over time and then integrate over time to determine SEL or L_{eq} at a given observer point.

5. The best short-term method of using STAMINA 2.0 for predicting stop-and-go levels is to use equivalent constant speeds that will produce the desired differences in SEL (and, hence, L_{eq}) relative to a known cruise situation.

6. To use these constant speeds, it is necessary to divide acceleration and deceleration regions into zones of influence. Depending on the initial or final cruise speed, the use of only one or two zones of influence per acceleration or deceleration region is sufficient to give accurate predictions.

7. Based on the field validation results, it was concluded that at signalized intersections only the acceleration and deceleration modes need to be modeled. Explicit modeling of a percentage of traffic cruising through the intersection at the posted speed caused overprediction of levels. Field observations at the validation sites showed that only a small percentage of traffic was actually able to cruise through without being impeded by the signal or by queue; further, these cruising vehicles slowed down on their own accord as they passed through the intersection. Modeling of idle levels is not easily done within the STAMINA 2.0 framework. It appears that by modeling neither idle nor cruise-through, possible effects of these two extreme cases are significantly reduced.

8. Previous FHWA recommendations for using the FHWA Traffic Noise Prediction Model for stop-and-go traffic will generally overpredict L_{eq} near intersections. The overpredictions for two field evaluation sites ranged from less than 1 dB at acceleration sites when the final speed was 55 mph to 6 dB at deceleration sites when the final speed was 35 mph.

9. The methodology developed in this research predicted levels to within 1 dB of measured levels at both evaluation sites after the cruise level predictions were calibrated to the cruise level measurements.

SUGGESTED RESEARCH

As a result of this work, areas for additional study have been identified.

First, more field validation of the methodology developed in this study is needed. The scope of work included only limited validation. This additional validation should focus on intersections controlled by STOP signs and along ramps (although mainline traffic will make the latter quite difficult to measure). Also, more validation work should be done at sites with high percentages of nonslowing traffic, such as intersections with semiactuated signals or long green cycles.

The basis for much of the methodology was that level differences between cruise and acceleration or deceleration events could be determined and could then be applied to other predicted cruise levels. To directly incorporate this idea into the STAMINA 2.0 computer program, a variable, such as distance from the defined stop point, could be used. This change would allow prediction of the acoustical profile by changing the way $(L_o)_E$ are derived in the FHWA model for acceleration and deceleration situations. The program could recognize the use of this variable by substituting a delimiter of 'A'/ (for acceleration ZOI) or 'D'/ (for deceleration ZOI) instead of the current 'L'/ in the STAMINA 2.0 input file. The acoustical profile could then be accurately predicted for each situation dependent on traffic considerations (i.e., approach speed included as the speed input) and geometric considerations (i.e., user-defined stop point). This would reduce the number of roadways that would need to be included and allow for more accurate predictions. The sound level data for implementing this change by a stepped series of constant levels is included in the detailed discussions of the EPA data in the appendixes. However, the changes to the STAMINA 2.0 computer program would require careful consideration and considerable time to implement to ensure that other sections of the code are not affected.

Finally, the field data measured by the authors supported the findings of other researchers that the FHWA reference energy mean emission levels at high speeds are higher than those observed in the field. There is a need for new high-speed cruise emission levels in the FHWA model. There is also a need for additional updated measurements of the levels from accelerating and decelerating automobiles and medium trucks.

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APPENDIX A—FINDINGS OF LITERATURE REVIEW

Findings for this project were drawn from two source categories; existing literature and measurements made by the authors specifically for this project. From these sources, data were considered in groupings. Major groupings consisted of noise levels for cars, medium trucks, and heavy trucks. These groups were further subdivided into modal noise levels related to cruise, acceleration, deceleration, idle, and mixed. The literature findings were used to guide the field measurement data collection. The data in return was used to validate literature findings and/or determine reference levels. This appendix summarizes the literature review for each of the modal groups.

Previous research has been concentrated in two areas: (1) studies dealing with emission levels and time-averaged levels, for each of the various modes associated with traffic: freely flowing (cruise), accelerating, decelerating, or idle; and (2) measurements and modeling of interrupted flow or stop-and-go traffic (mixed mode), either through adjustments to freely flowing models (along with guidelines for modeling interrupted flow segments), or through the development of separate stop-and-go models. Each of these areas was of particular importance to the goal of this research, which was to adapt the FHWA methodology used in STAMINA to predict noise from stop and go traffic. For this review, levels are reported as A-weighted sound levels in dB at 50 feet from the center of the travel lane unless specifically noted.

AUTOMOBILES

Cruise Mode

The literature overwhelmingly verifies the fact that noise emissions from automobiles in the cruise mode are a function of speed. The widely used FHWA Highway Traffic Noise Prediction Model [Barry and Reagan, 1978] predicts noise levels from free-flowing traffic between the speeds of 50 and 100 kph. The automobile "reference energy mean emission level," $(L_o)_E$, is defined as: 38.1 log (speed, kph) - 2.4 dB, and is plotted in Figure A-1. The computer programs SNAP [Rudder 1977b] and STAMINA [Rudder 1979] use the FHWA Model as the basis for their predictions. However, cruise speeds below 50 kph occur regularly near stop-and-go traffic conditions and are not specifically discussed by Barry and Reagan. Reference is made to interrupted flow conditions and will be discussed later. The automobile data for the FHWA Model came from the 1974 update to the TSC prediction model [Rudder, 1977a].

These FHWA emission levels differed from those in NCHRP Report 173 [BBN, 1976]. Barry and Reagan noted that NCHRP Report 173 reported a 4 dB "error" between measured and predicted sound levels which was subtracted from the emission levels to yield "source levels." Barry and Reagan further note that the NCHRP 173 "source levels" and the FHWA emission levels were approximately the same for automobiles and medium trucks.

One of the more valuable sources of data was collected in the mid-1970's by Plotkin [Plotkin, 1979] and adapted by Rudder [Rudder, 1979] for the USEPA National Roadway Traffic Noise Exposure Model. Rudder presented reference noise emission levels as a function of seven 2-axle, 4-tire vehicle types, operating mode, average speed, and vehicle year (projecting future levels). The data are presented in the same format as used in the FHWA Model (i.e., a mean sound level plus 0.115 times the square of the standard deviation) [Barry and Reagan, 1978]. However the EPA emission level represented an equivalent level for an observer moving alongside the vehicle at a reference distance of 50 feet, time-averaged over the entire event. As a result, if one knows the percentage of time that the vehicles are operating in each mode, a weighted energy mean emission level for that particular stop-and-go condition could be computed. Energy averages of the cruise data, weighted by reported percentage of vehicle fleet, are shown in the upper portion of Table A-1 and on Figure A-1. The EPA data supports extension of the FHWA curve to below 40 kph (25 mph) in a stepped fashion.

Work by other researchers also shows reasonable agreement with the FHWA Model during cruise conditions for automobiles. Most have extended the lower speed range. For example, Dunn and Smart recently collected data for the Florida DOT for cruise speeds ranging from 20 to 60 mph (32 to 96 kph)

TABLE A-1

EMISSION LEVELS FROM EPA NATIONAL ROADWAY TRAFFIC NOISE EXPOSURE MODEL [RUDDER, 1974]

Speed Range (mph)	Averaged Emission Level (dB) Automobiles	Medium Trucks	Heavy Trucks
		CRUISE	
below 25	60.6	74.4	80.7
25-34	63.2	74.4	80.7
35-44	67.2	76.4	82.1
45-54	70.3	79.7	84.5
above 55	72.7	82.3	86.5
		ACCELERATION	
0-20	60.9	75.1	82.6
0-30	62.8	75.7	82.8
0-40	64.1	76.5	82.8
0-50	65.9	77.5	83.0
0-60	67.4	78.7	83.2
		DECELERATION	
20-0	51.3	59.5	69.0
30-0	56.9	65.7	73.7
40-0	60.9	69.9	76.7
50-0	64.0	73.2	79.1
60-0	66.6	75.9	81.1

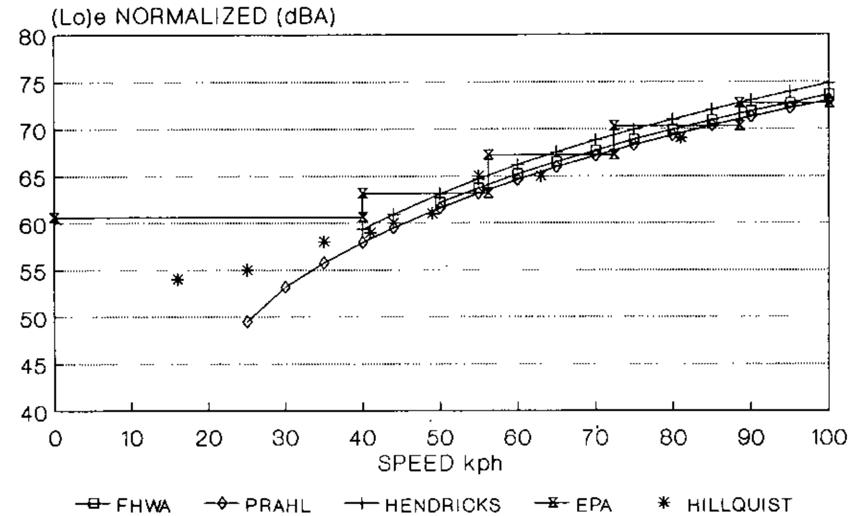


Figure A-1. Comparison of Cruise Data for Automobiles (Set 1) and analyzed them in the aggregate as well as in 5 mph speed bands for each vehicle type [Dunn and Smartt, 1986]. Their results for low speeds is essentially an extension of the FHWA Model curve, as shown in Figure A-2. However, at 55 kph the two models begin to vary with the FHWA Model showing a greater speed dependence. This extension for the FHWA Model to lower speeds was also supported by Hendriks when developing reference emission levels for Caltrans (see Figure A-1) [Hendriks, 1985].

Prahl applied a variation of the TSC model to automobiles and extended the range down to 23 kph (14 mph) [Prahl, 1975]. This application supported an extension of the FHWA curve to that speed (see Figure A-1). Hillquist presented measured data that reaffirmed the extension of the curve used by Prahl (see Figure A-1) [Hillquist, 1975]. Hillquist's data base showed that the speed dependent nature of an automobile in the cruise mode extended down to 16 kph (10 mph).

Miller [Miller, 1976] presented median peak pass-by levels of 65.6 dB at 25 mph (40 kph) and 77 dB at 55 mph (88 kph). These levels are much greater than values reported by others, including FHWA. This is due, for the 25 mph case, to contamination from acceleration (27.7% of time), which demonstrates how noise levels can be affected by modal components.

Separate from the NCHRP research was the development of the original Transportation Systems Center (TSC) model [Wesler, 1972], which included automobile emission levels based on the data reported by Olson [Olson, 1972]. The data are important since they also formed the basis for the automobile cruise levels in the FHWA Model. Olson classified vehicles into 10 mph speed ranges from 20 to 70 mph. These values, which are plotted in Figure A-1, are:

Speed Range (mph)	No. of Observations	Mean Noise Level (dB)
30-39	215	64.4
40-49	134	67.4
50-59	378	71.7
60-69	283	73.0

Olson's data showed a speed dependence of 10.5 dB per doubling of speed. Olson also presented spectral data for automobiles in these speed bands. The levels for the lower frequencies associated with propulsion noise (63-125 Hz) did not increase as much as the frequencies associated with tire noise as speeds increased.

Jung [Jung, 1978] disagreed with the low speed FHWA cruise levels when developing emission levels in Ontario. The automobile emission levels developed by Jung [19.9 log (S, kph + 33.7)], as shown in Figure A-2, did not show the same rate of decrease as speed decreased below 100 kph and were over 5 dB higher than the FHWA Model at 50 kph.

Beaton and Bourget, who addressed the problem of low speed (25-35 mph speed limits) noise levels within cities [Beaton, 1973], suggested that 7-10 decibels be subtracted from their Caltrans "chart values" for family-type automobiles. These chart values were for "worst case" noise levels from heavy trucks.

Close did not use a speed dependent function for automobiles in the cruise mode but rather a constant value of 72.5 dB below 57 kph (35 mph) [Close, 1973]. This value is considered to be high by the authors. For low speed data, Close noted that pulling a grade while maintaining a constant speed required additional power, resulting in an approximate 1.5 dB increase in sound level. However, under cruise freeway conditions, the level road conditions produced the highest sound level because of higher speeds and the increased tire noise.

Harris, based on measurements for the Georgia DOT, concluded that the FHWA emission levels may cause significant overprediction of noise levels near major highways [Harris, 1984]. Figure A-2 presents Harris' resultant emission level curve for automobiles [28.9 log (S, kph) + 2.9 dB], which shows the FHWA Model to overpredict at low speeds, while underpredicting at speeds greater than 48 mph.

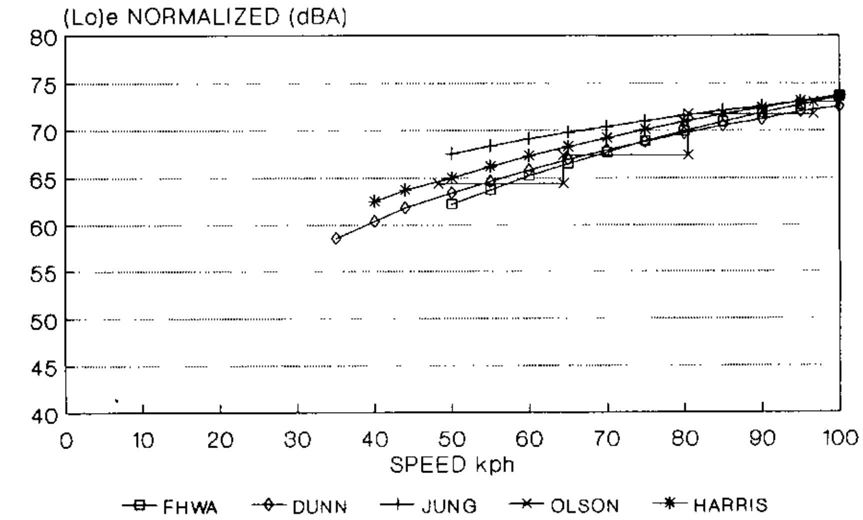


Figure A-2. Comparison of Cruise Data for Automobiles (Set 2)

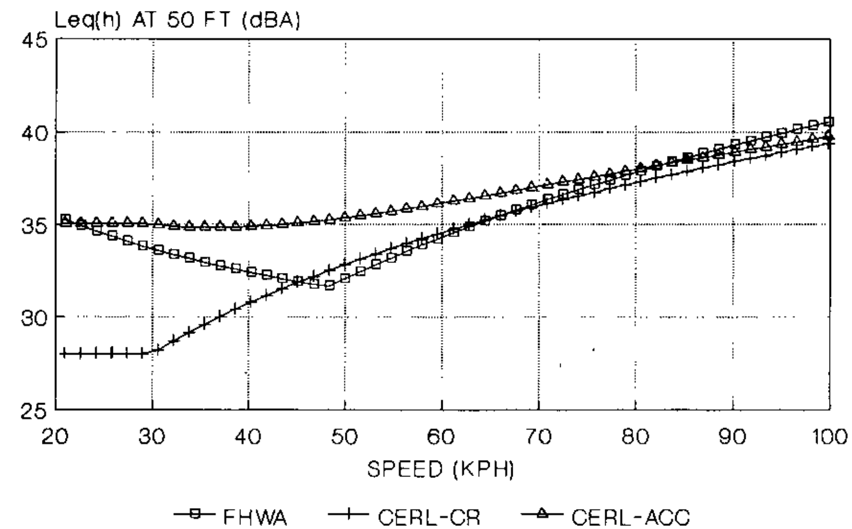


Figure A-3. Comparison of CERL and FHWA Models for Accelerating and Cruising Autos (L_{eq} for 1 veh/hr)

Also of interest, the Army Construction Engineering Research Laboratory (CERL) has developed a traffic noise prediction technique that includes low speed data for both civilian and military vehicles [Eldred, 1984]. The civilian data was developed from the data used in the EPA National Roadway Traffic Model [Rudder, 1979]. The levels were presented in terms of sound exposure (pasques) instead of the more typical maximum levels. To compare the values to the FHWA Model the data were converted to L_{eq}(1 hr) values. Figure A-3 shows the close agreement between the CERL cruise mode and the FHWA Model. Eldred reports a constant sound exposure value (and hence L_{eq}) below 30 kph. However, a constant L_{eq} does not mean a constant $(L_o)_E$ value. A constant $(L_o)_E$ when corrected for vehicle spacing would actually cause a decrease in the L_{eq} (and sound exposure) with increasing speeds.

In sum, the literature for cruising automobiles represents a good data base with the conclusions being: (1) cruise noise emission levels from autos are a function of speed to very low speeds (reported 10-15 mph); (2) the FHWA Model would seem to be valid and could be extended below the limited 50 kph lower speed range down to an idle value; and (3) the EPA database supports both the FHWA Model and its extension to lower speeds.

Acceleration Mode

Unlike the cruise mode, where it was generally agreed that the noise emission levels were speed dependent, the literature seems to reflect varying opinions for acceleration noise levels.

Also evident from the literature review was the variance in emission levels according to type of acceleration. Wide-open-throttle (WOT) acceleration produces noise levels much higher than during typical urban acceleration [Hillquist, 1975]. Hillquist's data showed average values of 67 dB (range 64-73) for typical passenger car urban acceleration, and 82 dB (range 79-85) using the Society of Automotive Engineers (SAE) WOT test procedures. This 15 dB difference would mean overprediction of urban levels if the SAE data were used. This discrepancy between urban acceleration and WOT acceleration is unfortunate, since much work has been done using the SAE procedures.

General Motors (GM) staff, unhappy with this discrepancy, developed another method to evaluate the power train related noise generation for light vehicles [Whitney, 1980]. Whitney determined representative operating modes of light vehicles utilizing a chase car technique. The results showed that 55% of the time was spent cruising and the tire/road noise dominated. Deceleration and idling levels were of less magnitude and occurred 16% and 14% of the time, respectively. The acceleration mode occurred 15% of the time, with the engine noise component being a significant factor, especially under hard acceleration conditions. Whitney's data indicated that, at least for automobiles, noise levels for idle and deceleration are less than at low cruise speeds but can significantly increase under acceleration conditions. Also of importance was that noise from accelerating automobiles was less than that of cruising automobiles at highway speeds.

While the FHWA Model does not specifically address the problem of accelerating automobiles, the NCHRP work and FHWA noise analysis training material do. The earliest NCHRP modeling work was described in NCHRP Report 78 [Galloway, 1969]. Only limited data were presented on the effects of acceleration. At 35 mph, a small group of accelerating automobiles was found to produce approximately 8 dB higher noise levels than for normal cruise conditions at the same speed.

The original FHWA traffic noise training course text suggested that the final highway speed be used to predict accelerating automobile traffic noise [Federal Highway Administration, 1973]. It also suggested that use of more than one roadway section during modeling may be needed. The training text suggested that the increase in levels due to reduced vehicle spacing would approximately compensate for the decreased emission levels of the slower speed during acceleration.

The EPA data base [Rudder, 1979] provides considerable information on automobile acceleration levels, typical of urban situations, and are particularly suited to help develop acceleration emission levels for this research. As discussed previously, the EPA data base was made up of time-averaged values at 50 feet from the vehicle for an observer assumed to travel alongside the vehicle. These time average values for acceleration were reported for cases of an initial speed of 0 mph to final speeds of 20, 30, 40, 50 and

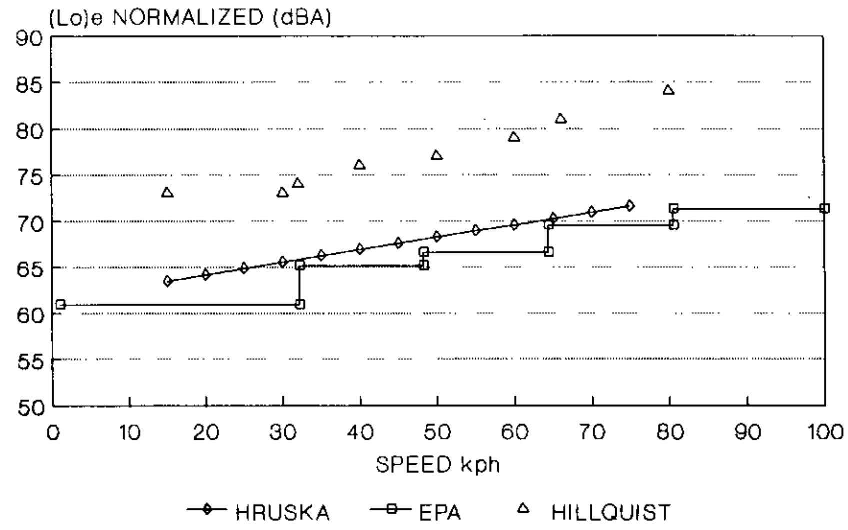


Figure A-4. Comparison of Automobile Acceleration Data

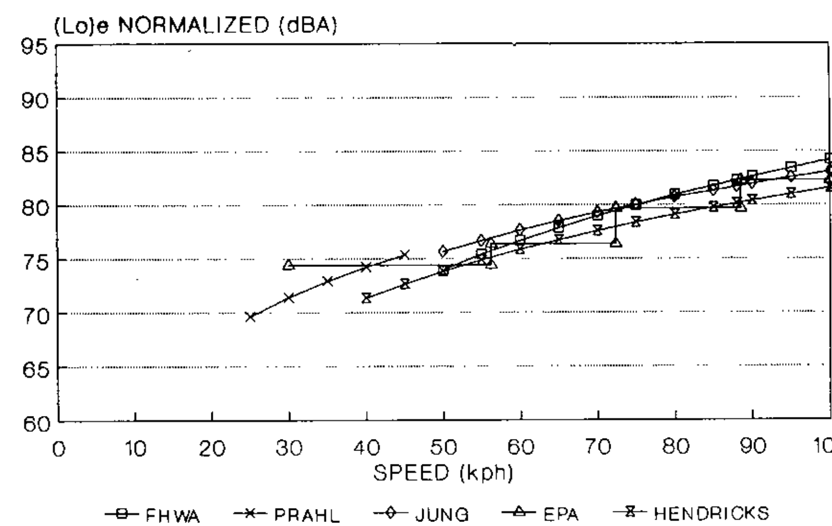


Figure A-5. Comparison of Cruise Data for Medium Trucks (Set 1)

60 mph and are shown in the middle section of Table A-1 (averaged for all passenger car types). These values can be further reduced to correspond to 10 mph speed bands (i.e., 20-30 mph) by use of the definition of L_{eq}. This is done and explained in Appendix B. The resulting 10 mph band values are shown in Figure A-4.

The CERL model [Eldred, 1984] also used the EPA database for accelerating automobiles. Figure A-3 displays the model results for a one-hour L_{eq} for one vehicle per hour at various speeds. Below 40 kph, the level experienced at the receiver is a constant, and then increases with speed. From this model, and information presented by others, it can be surmised that automobile engine noise is relatively constant during acceleration and at 40 kph, tire noise becomes an important part of the overall noise levels.

Hruska and Williams of EPA also suggested a speed dependent approach for accelerating automobiles. They assembled a database for use in vehicle noise ordinance enforcement when site conditions required measurements at close distances [Hruska and Williams, 1980]. They made measurements at a distance of 12.5 feet from the center line of traffic for 8300 light motor vehicles accelerating from rest or near rest. The longitudinal distance from point of rest of the vehicle to the microphone varied from 90 to 150 feet, being selected by judgment of where maximum sound levels would occur. That spot, which varied by site, was approximately the point where the first to second gear shift occurred. The energy average of this maximum level (adjusted to 50 feet) was 69.5 dB. This value is 7.5 dB greater than the FHWA $(L_o)_E$ at 31 mph (50 kph).

Light vehicles were divided into four classes and the data fit to a linear relation of sound level to speed <u>limit</u> (see Figure A-4). The researchers found no improvement in using a logarithmic regression with the speed limit variable compared to the linear equation. A limitation on the data is that most was obtained at speed limits of 30 or 35 mph only. Thus, while the data are grouped in a very narrow speed range and the speed data is reported by speed limit, the data do reinforce the EPA data base.

Close noted that acceleration required additional power and higher rpm at lower gear settings, which resulted in about a 1.5 dB average increase in the sound level above the low speed cruise mode [Close, 1973]. Fan and exhaust noise were considered to be roughly equivalent but because for automobiles these sources are muffled well, automobile tire noise becomes significant at a quite low speed. This would account for the low speed cruise speed dependence of automobiles. Close also suggested that after a speed where tire noise is significant, accelerating automobile noise emission levels are speed dependent. However, a review of Close's data shows the L_{50} of the peak pass-by levels to be 70 dB below a speed of 56 kph (35 mph) and 72 dB above 56 kph. This 2 dB increase does show some speed dependence, but the range is small and could well be approximated with a constant value. This is considered to be due to the engine noise levels being well above the tire noise at low speeds. Of note is that these values are greater than the FHWA Model reference emission levels until a speed of 91 kph (72 dB).

Galloway's [Galloway, 1969] earlier results are in agreement with the constant value approach for low speed automobile acceleration and the values approximate those of Close, below 50 kph.

Miller [Miller, 1976] evaluated accelerating automobiles for WOT and 1/4 g accelerations. As discussed before, WOT noise level testing is not applicable to urban acceleration cases. The 1/4 g testing, while slightly greater than typical urban acceleration (according to AASHTO), does provide comparable results. The values presented for median maximum pass-by levels are 68.6 dB ($67 + 0.115\ (3.7)^2$). This value is slightly greater than the EPA time-averaged data due to the higher acceleration rate. In a later study Miller provided data for automobile acceleration to 30 mph (68 dB) and acceleration to 40 mph (73 dB) [Miller, 1980].

Although the levels are not directly comparable because of the difference in vehicle size and design, excellent pieces of work have been done abroad and the methodologies and trends in the results are worth consideration. For example, Sakagami published a report on traffic noise emission in urban streets in Japan [Sakagami, 1975]. Sixteen classes of vehicles were defined as well as the time percentage of acceleration, deceleration, cruising and idle. This method, similar to GM's, supported the use of time averaged values. The percent of time in modes were: idle, 28; cruise, 23; acceleration, 19; and, deceleration, 20. These vary slightly from the GM values presented earlier.

In 1980, Lewis and James conducted a series of noise measurements for accelerating and decelerating traffic streams on the approach roads to traffic circles or "roundabouts" [Lewis, 1980]. This work was an extension of a 1978 study on the noise emitted by single vehicles at roundabouts [Lewis, 1978]. The results show that, in general, noise levels from the accelerating traffic streams were approximately equal to those of free-flow traffic at 50 mph on the same road. Also, the noise levels from the decelerating stream were equal to or less than the free-flow level within 150 meters of the roundabout. Accelerating levels were always greater than deceleration levels within 150 meters of the roundabout. These results correspond to the general findings by GM [Whitney, 1980]. Good agreement between predicted and measured levels was also found. The researchers recognized the difficulties in non-free-flow predictions due to the fact that the noise emitted per unit length of road is not constant, but varies as a function of the traffic flow and distance from the merging points. They decided not to attempt to develop a single model of noise for each of the traffic streams for both accelerating and decelerating traffic. Instead a relationship between noise level and the flowing composition of traffic would be determined separately for each measurement position on the approach to the circle.

To briefly sum it would appear that: (1) accelerating automobile emission levels at low speeds are greater than cruise levels at the same speed; (2) tire noise becomes significant at approximately 35-45 mph; (3) WOT values are too high to be used to predict urban acceleration noise levels; (4) a stepped series of constant L_{eq} values can be used for low speed accelerating automobiles, based on average emission levels, to yield an excellent prediction of the accelerating noise level despite the continuous changes in levels that occur during the event; and (5) the EPA data base with the time averaged values can be used to establish acceleration emission levels for automobiles.

<u>Deceleration Mode</u>

Limited data exists on deceleration emission levels of automobiles. It is generally agreed that these levels are much less than the cruise or acceleration modes. Once again, the EPA data base [Rudder, 1979] presents a full set of data. The data are presented in the lower portion of Table A-1 as constant energy time-averaged emission levels for deceleration events in various speed ranges with a final speed of 0 mph. As described in the acceleration section, a series of levels for 10 mph intermediate speed ranges was developed and is presented in Appendix B.

<u>Idle</u>

The EPA data [Rudder, 1979] indicate an energy-averaged idle emission level of 46.0 dB for automobiles and light trucks. This compares to reported "peak" values of 54 dB by Hillquist [Hillquist, 1975] and 55.5 dB by Miller [Miller, 1976]. Based on data presented by others for low speed cruise and deceleration, the values of 54-55 dB for idle appear too high for modern automobiles; the value of 46 dB seems more appropriate. The EPA data is time-averaged but since idle is non-varying, the value presented is equal to the maximum value.

<u>MEDIUM TRUCKS</u>

<u>Cruise Mode</u>

The FHWA Model [Barry and Reagan, 1978] adopted the medium and heavy truck emission levels that were collected in the TSC "four-state" study [Rickley, et al, 1978] and developed in the subsequent data analysis by Ma and Rudder. FHWA's speed dependent model is the most widely used method of determining cruise noise emissions from medium trucks (33.9 log (speed, kph) + 16.4; see Figure A-5). The lower speed boundary is 50 kph and guidance is not given for cruising medium trucks below this speed, although a procedure for interrupted flow is suggested.

Although the FHWA cruise model is widely used, a recent survey revealed that 13 of the 44 responding state DOT's indicated that they had made vehicle emission level measurements for free-flowing traffic conditions [TRB, 1985]. The medium truck results from some of these states are discussed below.

Hendriks' work for California DOT [Hendriks, 1985] suggests a speed dependence for medium trucks down to 40 kph (25 mph). Hendriks' derived equation (35.3 + 25.8 log(speed, mph) in dB) essentially is an extension of the FHWA Model to 40 kph. More recent results [Hendriks, 1987] showed that compared to the FHWA data, medium truck levels ranged from 0.5 dB less at 31 mph to 2.9 dB less at 60 mph (see Figure A-5). Unfortunately, only a limited sample of his data was taken at speeds below 45 mph.

Harris [Harris, 1984] also determined emission levels for medium trucks in Georgia (16.36 log(speed, mph) + 50.4 dB). These levels were 2 dB greater than the FHWA Model at 30 mph and 4 dB less at 60 mph, showing less speed dependence than FHWA (see Figure A-6).

Dunn [Dunn, 1986] showed a speed dependent function that extended down to 20 mph for medium trucks in Florida. A level of approximately 74 dB at 30 mph was essentially the same value as in the FHWA Model, indicating that his data (to 20 mph) simply extended the FHWA curve. However, at 60 mph, Dunn's level of 81 dB was 3 dB below that of FHWA's (see Figure A-6), showing less speed dependence than the FHWA Model for cruising medium trucks.

Olson presented limited data for cruising medium trucks [Olson, 1972]. For a range of speeds from 20-29 mph a median value of 68.5 dB was determined. For speeds from 30-39 mph a median value of 70.3 dB was given. Olson also noted that a 9 dB per doubling of speed was typical of medium trucks.

Prior to the FHWA Model development, the MOD-04 revisions to the TSC highway noise prediction program were being completed [Rudder, 1977]. The data used for these revisions came from the four state study [Rickley, 1978]. The emission levels for medium trucks were given in terms of a "log (speed)" relationship and said to be valid between 20 and 70 mph. Figure A-6 shows a comparison to the FHWA $(L_o)_E$ values.

NCHRP Report 173 [BBN, 1976] contained figures relating A-weighted sound level to vehicle speed, vehicle mode of operation, engine speed and grade. A great deal of field data on peak noise levels of individual trucks was collected. In their data analysis, the NCHRP authors divided trucks into two categories: above 50 mph and below 50 mph. They concluded that, at speeds below 50 mph, the maximum noise level was not as strongly dependent on speed as when above 50 mph. However, it should be noted that the speeds "below 50 mph" did not go below 45 mph. They suggested that the probable domination by power train sources at the lower speeds led to the relative independence of speed (a constant emitted level). Barry and Reagan [Barry and Reagan, 1978] further note that the NCHRP 173 "source levels" and the FHWA emission levels were approximately the same for medium trucks.

Miller [Miller, 1976] presented a 25 mph cruise value of 74.3 dB for medium trucks, but this value is high due to acceleration occurring during parts of the measurements. The 55 mph cruise value given (80.9 dB) was not contaminated by acceleration.

Anderson and his colleagues also presented a speed dependent equation for medium truck cruise emission levels (5.7 log (speed, mph) + 64.5 dB) used in predicting the L_{10} descriptor [Anderson, 1976] as shown in Figure A-6. Although speed dependent, Anderson's model only varies by 1.1 dB from 50 kph to the lower defined range of 32 kph (20 mph). This nearly flat slope supports the approximation by Reagan and Barry [Barry and Reagan, 1978] where the FHWA Model is assumed to be a constant emission level of 74 dB below 50 kph.

Prahl [Prahl, 1975] presented medium truck cruise noise levels as a speed dependent function (22.5 log(speed, mph) + 42.8 dB) extended to 14 mph (23 kph). Prahl's function predicted noise levels greater than the FHWA Model at lower speeds as shown in Figure A-5.

Jung [Jung, 1978] also presented a speed dependent equation (24.7 log(speed, kph) + 33.7 dB) that predicted greater noise levels than the FHWA Model at speeds less than 75 kph, and lower levels at speeds greater than 76 kph. This relationship is shown in Figure A-5. However, the values did not vary significantly from the FHWA levels.

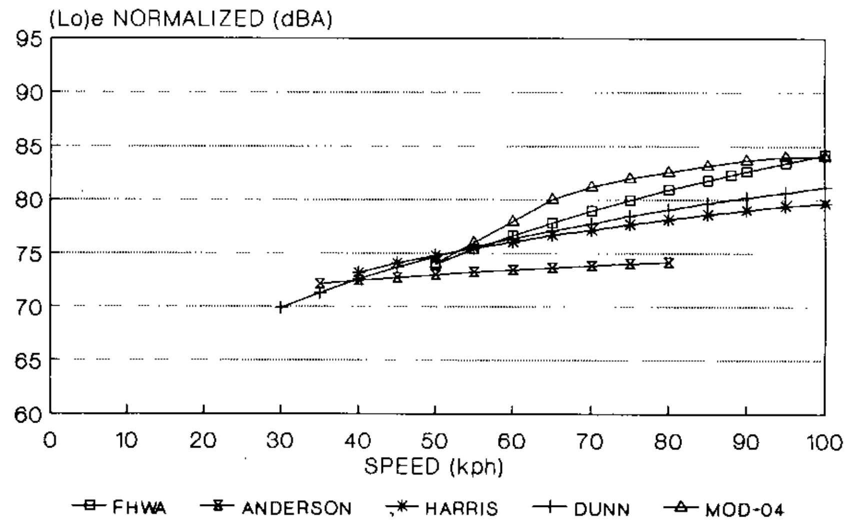


Figure A-6. Comparison of Cruise Data for Medium Trucks (Set 2)

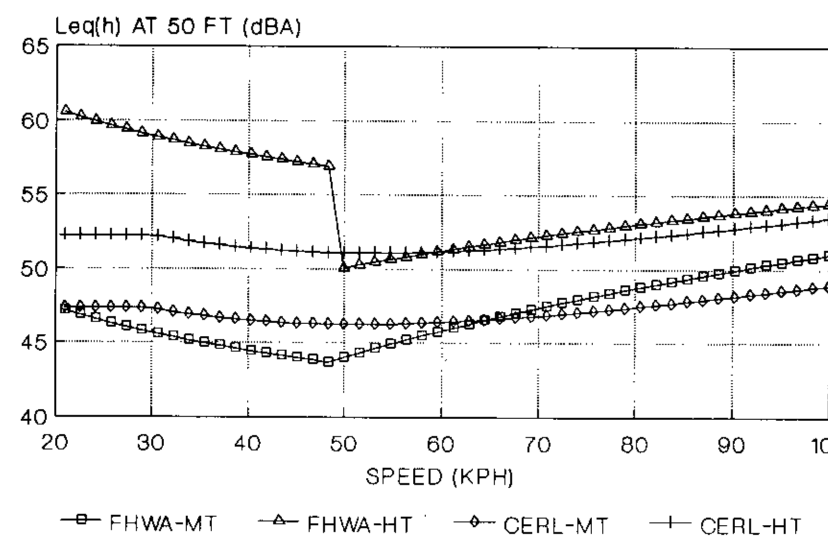


Figure A-7. Comparison of CERL and FHWA Models for Medium Trucks (MT) and Heavy Trucks (HT) (L_{eq} for 1 veh/hr)

The best medium truck cruise data base comes from EPA [Rudder, 1979] and essentially reconfirms the FHWA Model while extending the lower speed range with a constant level below 35 mph. The reported values are shown on Figure A-5 and in the upper portion of Table A-1.

Eldred [Eldred, 1984] used the EPA data to develop the cruise portion of the CERL model for medium trucks. Figure A-7 shows the receiver levels at 50 feet for a one-hour L_{eq} for a single vehicle. The trend is very similar to that of automobiles (Figure A-3), with a constant L_{eq} below 30 kph. When the CERL cruise model for medium trucks is compared to the FHWA Model (Figure A-7) a variation of as much as 2 dB is seen, although each model displays similar trends.

In summation, trends presented by the literature review for medium trucks in the cruise mode are: (1) low speed cruise levels are speed dependent; (2) although some variance may occur from state to state the FHWA Model appears valid; (3) most states report $(L_o)_E$ values as being less speed dependent than FHWA; (4) tire noise becomes significant at approximately 40 mph and above; and (5) cruise levels are dominated by power train noise at lower speeds.

Acceleration Mode

Although absolute values vary, it is generally agreed in the literature that low speed acceleration data for medium trucks can be adequately predicted by use of a constant level. This occurs because of the dominance of drive train noise at lower speeds, as discussed for low speed cruise.

While the FHWA Model does not address the issue of accelerating vehicles, several others have attempted to solve the problem. Miller [Miller, 1976] presented a median "peak pass-by level" of 77.0 dB for accelerating medium trucks. With a 3.7 dB standard deviation, this translates to an energy-averaged emission level of 78.6 dB ($77 + 0.115\ (3.7)^2$). This value would appear to be reasonable for the typical urban acceleration case.

Anderson [Anderson, 1976] also suggested the use of a constant level from 8 kph (5 mph) to 32 kph (20 mph), although at a lower value of 71.2 dB.

Prahl [Prahl, 1975] suggested a new approach for predicting L_{10}. He suggested using a reference emission level that decreased as a function of increasing speed (-4.1 log (speed, mph) + 78.7 dB), as shown in Figure A-8. This decrease in $(L_o)_E$, when combined with the speed-dependent vehicle spacing relationship causes the predicted L_{10} value to drop more quickly than for a constant emission level. Accordingly, although the $(L_o)_E$ value presented by Prahl is speed-dependent, the predicted L_{10} was higher at lower speeds for acceleration. Of interest in Prahl's report was the finding that accelerating medium trucks showed no significant correlation between maximum pass-by levels and distance from intersections.

As for automobiles, the EPA National Roadway Traffic Noise Exposure Model [Rudder, 1979] presents time averaged emission levels as a function of the final speed and a constant 50 feet from the vehicle (i.e., the microphone moves with the vehicle). These levels are shown in the middle portion of Table A-1. When converted to 10 mph speed bands as described in Appendix B, the data shows noise levels to be greater than the FHWA cruise values to 72 kph and similar from 72 kph to 100 kph (see Figure A-8).

To briefly summarize for accelerating medium trucks: (1) constant values of low speed acceleration reference emission levels seems to offer good predictive results; (2) by making the reference emission level a reducing function of speed the L_{eq} value at the receiver decreases more quickly with increasing speed due to increased vehicle spacing; and (3) the EPA data base appears very useful.

Deceleration Mode

Once again the EPA presents a good source of data for decelerating vehicles, in this case medium trucks. The time-averaged levels (for a receiver moving alongside the vehicle at 50 feet) are shown in the lower portion of Table A-1.

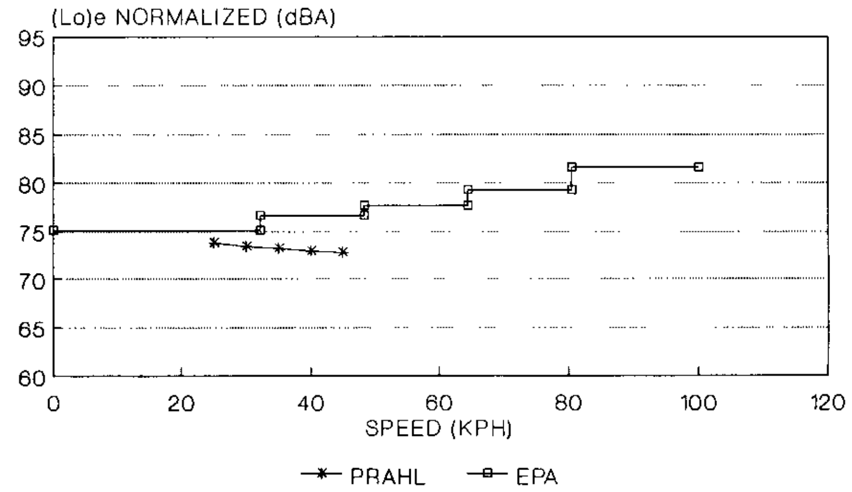


Figure A-8. Comparison of Acceleration Data for Medium Trucks

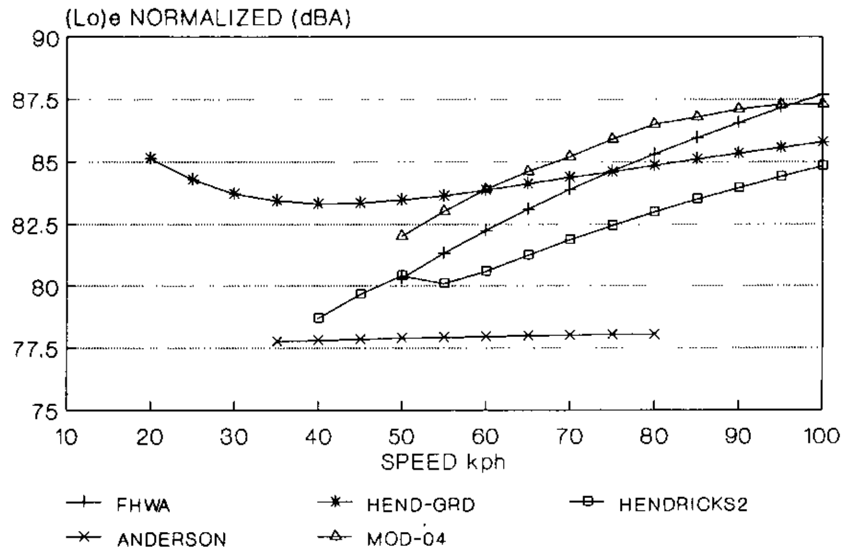


Figure A-9. Comparison of Cruise Data for Heavy Trucks

Appendix B shows how this data may be approximated as a series of intermediate 10 mph speed band levels.

Idle

Two sources have presented data for idling medium trucks. Hillquist [Hillquist, 1975] presented an L_{max} value of 56 dB, while Rudder gave a time-average value of 66 dB [Rudder, 1979]. Because Rudder's value is more consistent with reported cruise data at very low speeds for medium trucks, the value of 66 dB is considered more representative.

HEAVY TRUCKS

Cruise Mode

Again, the FHWA speed dependent model is the most widely used for cruising heavy trucks. The constraint on speed ranges (50-100 kph) is the same as for the other vehicle types. The data base for the model was derived in the four-state study [Rickley, 1978]. As for the other vehicle types, individual states have altered the reference emission levels to reflect values more closely related to their measurements. From the four-state study data, Ma and Rudder [Ma, 1978] developed regression equations in a "log (speed)" form by vehicle type and by octave band. These equations were subsequently used in the development of the STAMINA 1.0 model (although all but the overall A-weighted equation were deactivated for the STAMINA 2.0 program). The curve shown for FHWA in Figure A-9 is from this data (24.6 log(speed, kph) + 38.5 dB).

Galloway's early work [Galloway, 1969] showed heavy truck emission levels to be a constant 81 dB over a speed range of 30-70 mph. This level is similar to the FHWA Model at speeds near 30 mph but quickly deviates at higher speeds as the levels in the FHWA speed-dependent model increase.

NCHRP Report 117 [Gordon, 1971] presented a constant heavy truck emission of 82 dB for prediction of L_{50} noise levels for a range of speeds (20-70 mph) and volumes. Of interest was the hypothesis that as speeds increased, for similar volumes, the truck contribution to the overall noise level decreased. The reasoning behind this concept was that, "...truck traffic noise is a function of vehicle density only..." [Gordon, 1971; p. 10]. Accordingly, NCHRP reported speed independent noise levels for trucks as fact, backed by the work of Galloway [Galloway, 1969].

Concurrent with the NCHRP 117 model development was the development of the TSC model [Wesler, 1972], which included "highway" truck emission levels based on Olson's data [Olson, 1972] and data reported by Bolt, Beranek, and Newman, Inc. along the New Jersey Turnpike [Dietrich, 1973]. Heavy trucks, medium trucks and buses were grouped into one category. The A-weighted overall levels were about 6 dB higher than those reported by Galloway [Galloway, 1969].

Olson [Olson, 1972] presented speed-dependent, heavy truck cruise levels in 10 mph speed bands from 30 to 69 mph. These data were used in the TSC model and are slightly less than the FHWA Model levels (see Figure A-10). Olson also presented spectral data for heavy trucks that supported the ideas that engine exhaust noise is a relative constant above 40 mph and that tires are the predominant sources causing the increase in overall A-weighted noise levels above 40 mph.

Hillquist [Hillquist, 1975] confirmed Olson's findings with spectral data for all truck sources during acceleration (a maximum engine noise situation). Data was also shown indicating that the tire noise speed dependence caused an overall increase in levels above 50 mph. Some limited data was also presented for cruising heavy trucks. The median value for speeds greater than 35 mph was approximately 85 dB with a range of ± 5 dB. This 85 dB value would be predicted by the FHWA Model at a speed of approximately 48 mph. For speeds less than 35 mph, a median value of 83 dB (with a 5 dB range) was given. This corresponds to an FHWA Model $(L_o)_E$ at a speed of 40 mph. Of importance is the fact that only a 2 dB difference existed in Hillquist cruise data for the two speed ranges.

The MOD-04 revisions to the TSC model [Rudder, 1977] replaced the "highway" truck category with two categories, still used today in STAMINA: medium and heavy trucks. The source of the emission levels used was from Barry of FHWA (referenced by Rudder as a private communication with Barry, November, 1976) and so were also derived from the four-state study data. However, this speed dependent model was said to be valid from 32 kph (20 mph) to 113 kph (70 mph) [Rudder, 1977a].

NCHRP Report 173 also related heavy truck noise levels to a speed dependent function (see Figure A-10) [BBN, 1976]. Dependence on engine speed and grade were also shown. The engine noise is dominant at low speeds. From the report, an inference can be drawn that at a very low speeds noise levels would not vary in a predictive, speed-dependent manner, due to driving characteristics, and perhaps a constant value would be more appropriate. The report confirms this inference by the finding that the probable domination by power train noise at lower speeds led to a relative independence of speed.

Harris confirmed this idea during reference emission level testing for Georgia [Harris, 1984]. Based on his data, Harris recommended use of a constant energy mean emission level for heavy trucks of 81 dB at all speeds from 30 to 60 mph (48 to 96 kph). This level ranges from 0.5 to 3 dB lower than the $(L_o)_E$ values used in the FHWA Model.

NCHRP Report 173 contained considerable information on noise levels from the various components of different vehicle types [BBN, 1976]. Figures were shown relating A-weighted sound level to vehicle speed, vehicle mode of operation, engine speed and grade. Data was summarized for heavy truck levels for both SAE standard acceleration test and cruise conditions. Data on maximum noise levels of individual trucks were also collected, but mostly in the high speed range. Trucks were divided into two categories: above 50 mph and below 50 mph. The researchers concluded that, at speeds below 50 mph, the maximum noise level was not as strongly dependent on speed as when above 50 mph. They suggested that the probably domination by power train sources at the lower speeds led to the relative independence of speed. These trends are important to this research. The cruise data is similar to the FHWA values (see Figure A-10).

Prior to NCHRP 173, the USEPA had released a background document for the Interstate Motor Carrier Regulations [EPA, 1974]. For nearly 1400 trucks, the median maximum pass-by noise level was approximately 87 dB at speeds over 35 mph. No attempt was made to correlate levels with speeds. However, DOT data was displayed to show the effect of various tire treads [USDOT, 1970]. Of importance was that tire type had a significant effect on overall cruise noise levels over 30 mph.

Prahl and Miller [Prahl, 1975] measured at least 40 heavy vehicles at each of 10 different sites to study maximum pass-by levels in low speed urban conditions. The average running speeds along each city block (excluding stop time at signals) were also recorded. Valid speeds ranged between 14 and 30 mph. For heavy trucks, they found a mean maximum level of 79.7 dB (normalized to 50 feet) with a standard deviation of 4.8 dB. These values combine to give an energy mean level of approximately 82.3 dB (79.7 + 0.115 x $(4.8)^2$). They also developed an initial emission level equation for cruising heavy trucks (12.5 log (speed, mph) + 62.6 dB), which is plotted in Figure A-11. Collected in an urban environment, the noise level data included any and all contributions due to reflections off building surfaces. Also, the microphones were placed at a height of 15 feet. Despite these problems, levels from heavy trucks were only approximately 1 dB higher than the FHWA emission levels if the FHWA curve is extended to speeds below 50 kph.

Anderson [Anderson, 1976] developed a nearly constant speed dependent model for non-accelerating heavy trucks for the West Side Highway Project (approximately 78 dB from 20 to 70 mph). This is shown in Figure A-9. Because of the urban conditions for the measurements, the reported data could be affected by building reflections.

Miller also investigated heavy truck cruise noise levels [Miller, 1976], showing values of 80.9 dB at 25 mph and 88.9 dB at 55 mph. These values are slightly higher than the FHWA Model.

The EPA data presented by Rudder [Rudder, 1979] were similar to those for the FHWA Model, as shown in Figure A-11. The EPA data also showed a constant level of 80.7 dB below 35 mph (56 kph).

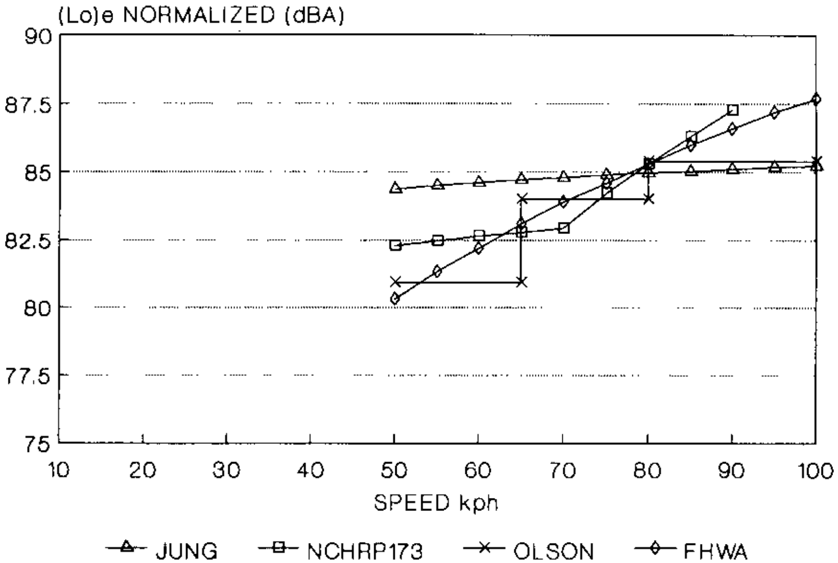


Figure A-10. Comparison of Cruise Data for Heavy Trucks (Set 1)

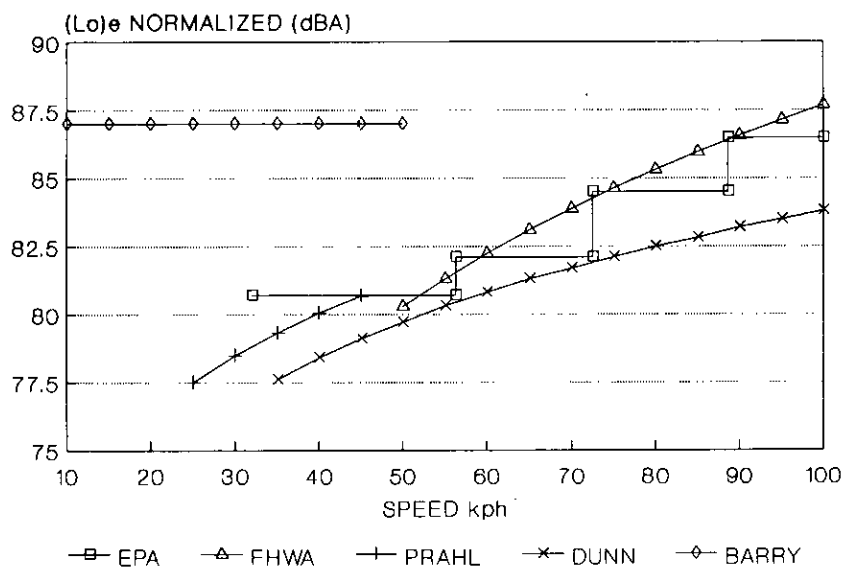


Figure A-11. Comparison of Cruise Data for Heavy Trucks (Set 2)

However, the EPA data were time-average value for a receiver moving alongside the vehicle at a constant distance of 50 feet. For heavy trucks, the EPA cruise data were as indicated in the top of Table A-1.

Beaton and Bourget [Beaton, 1973] suggested that 7 decibels be subtracted from truck levels at highway speeds to represent low speed noise levels within cities. They further noted that statements by others to the effect that diesel trucks make the same noise output regardless of speed were not borne out by their tests. This trend is consistent with the EPA data, which showed a 6 dB difference between 25 and 55 mph and with the FHWA Model (a 7.4 dB change in $(L_o)_E$, from 50 to 100 kph).

Hendriks has established California heavy truck noise emission levels at cruise and as a function of roadway grade [Hendriks, 1985] [Hendriks, 1986]. The heavy truck cruise $(L_o)_E$ values were about 0.5 dB higher than the FHWA Model $(L_o)_E$ values at 31 mph and 3 dB lower at 62 mph (see the curve with the legend HENDRIKS2 in Figure A-9). Close agreement is shown at the low end of the defined range but Hendriks shows less speed dependence. Hendriks' $(L_o)_E$ values are also defined for a greater speed range than FHWA (25 to 65 mph). Hendriks had limited data to support extension of the cruise equation to a speed of 25 mph (40 kph). Previous to this, California had used the FHWA curve for cruising heavy trucks, but transitioned from a value of 80 dB at 50 kph to a constant 87 dB below 40 kph [Hatano, 1980].

For the testing on grade, six sites were chosen to allow heavy trucks to decelerate from free-flowing speeds of 55-60 mph to sustained crawl speeds. The results showed no direct grade dependency at any observed speed. Dependency on truck loading were significant however. If traffic noise levels are not grade dependent then stop-and-go conditions would not become more complicated in these instances. Only the zone-of-influence length would change. However, Hendriks notes that this apparent grade independence could be masked by other events such as truck type and loading. These results are interesting since NCHRP 117 suggested a correction factor from 2 to 5 dB depending on grade.

Speed dependency was concluded to be significant by Hendriks. He developed a combined speed-dependent curve for use as default heavy truck emission levels on grades ranging from +3 to +7%. These values show first a decrease with speed before increasing (see Figure A-9, curve HEND-GRD) and are based on a second degree polynomial equation rather than a simple log relationship.

Dunn also extended the lower range of the FHWA Model to 32 kph [Dunn, 1986], although his value is approximately 4 dB higher at 100 kph (see Figure A-11).

Jung and Blaney of Ontario [Jung, 1978] found results which support a speed-independent energy mean emission level. Although a function was presented (2.82 log (speed, kph) + 79.6 dB), as shown in Figure A-10, for all practical purposes a level of 84 or 85 dB may be used. As a result, Jung and Blaney show greater levels at speeds below 80 kph than does the FHWA Model.

Eldred also determined a cruise emission mathematical model for heavy trucks (as discussed previously). The data source for the reference emission values were from Plotkin. The units of the reference emission values used by Eldred are pasques to represent sound exposure. To permit a comparison to the FHWA Model, both Eldred's and FHWA's reference values were converted to L_{eq}(1 hr) for a single vehicle. Figure A-7 shows the L_{eq} curve comparison. Because SEL(1 hr) equals L_{eq}(1 hr) plus a constant (by definition), the same shape of curve, corrected for a time constant would be plotted for SEL. The curve approximate the FHWA curve within one dB from 50-100 kph.

Also of note in Figure A-7 is the decrease in L_{eq} values from 30 kph to approximately 60 kph. This decrease is caused by holding the $(L_o)_E$ value constant while the vehicle spacing factor decreases. This effect is important. For example, if Barry's [Barry and Reagan, 1978] recommendations are used and $(L_o)_E$ values increase to a constant 87 dB for speeds less than 50 kph, then the predicted L_{eq} values will decrease as speed increases to 50 kph. At 50 kph the $(L_o)_E$ begin to increase again and so does the L_{eq} (although at a lesser rate than $(L_o)_E$ due to the effect of the vehicle spacing adjustment at greater speeds).

From the previous discussion, it can be concluded that: (1) at low speeds, and possibly through the mid-speed ranges, cruise levels are very speed independent, dominated by engine noise, and a constant value could approximate emission levels well; (2) operational changes are extremely important considerations for trucks at low speeds; (3) tire noise would not seem to become significant until speeds greater than 40 mph; (4) the effect of grades would seem only to change the length of the zones-of-influence (ZOI) and not the emission levels in these zones; and (5) Rudder's interpretation of Plotkin's data base provide good emission values below 25 mph.

Acceleration Mode

The EPA background document for the heavy truck noise emission regulations [EPA, 1974] presents a great deal of data collected using the SAE J366 test procedure. Unfortunately, the test procedure involves full acceleration of the truck from two-thirds of maximum rated or governed engine speed, which is uncharacteristic of urban acceleration. However, data on the propulsion system and engine noise showed that at a very low speed (less than 10 mph) engine noise dominated and remains constant to over 50 mph (except for irregularities due to gear changes). Tire noise, according to tire type, was not a factor until speeds greater than 30-40 mph. Tire noise was primarily responsible for increases in the noise level above 40 mph. This implies that for low speed wide open throttle acceleration (per SAE) a constant value for $(L_o)_E$ may be used. Also of note, if new rib tires are used, a constant value could be used for the entire acceleration event, 0 to 50 mph.

The background document also notes the results of another survey of truck noise emissions [Sharp, 1972] where median levels of 76 and 84 dB were reported in speed zones below 35 mph for trucks with two and five axles, respectively. That study resulted in a great deal of measurement data on the directivity characteristics of vehicle noise levels. Cruise and acceleration levels were measured for a variety of test vehicles, including automobiles, pick-up trucks, diesel trucks and busses. Since the thrust was to examine noise directivity, no conclusions were drawn comparing levels from the different operating conditions.

Sharp also reported that operations on grades, where traffic typically slowed, resulted in lower sound levels [Sharp, 1972]; the lowest sound levels were recorded for the freeway on-ramp acceleration case. The California Highway Patrol, which was the original source of this data [CHP, 1971], reported possible problems with the acceleration sound level data. The trend, however, indicated that the higher speed operations produced the highest sound levels, whereas lower speed freeway operations represented by the at-grade or on-ramp acceleration cases produced lower sound levels. These results indicate that the acceleration mode dominated in the low speed situations.

The original FHWA noise fundamentals training text noted that Olson's data indicated that an average noise level of 81.9 dB during acceleration [FHWA, 1973]. Of particular interest to this research is that this finding shows that the sound level for accelerating heavy trucks was equivalent to the noise emitted at cruising between 40-49 mph. Accordingly, a constant reference emission level could be specified for accelerating vehicles by determination of a "reference" equivalent speed.

The New York State DOT incorporated Olson's results in its HUSH computer program because of underpredictions of the L_{10}(1 hr) levels for truck speeds below 40 mph [NYSDOT, 1975]. Use of an equivalent truck speed of 40 mph when the actual truck speed was under 40 mph produced more realistic results, as long as the actual truck operating speed was used for the traffic flow adjustment calculation. Coupled with the deletion of the NCHRP Report 117 interrupted flow adjustment, NYSDOT reduced the discrepancy that often appeared between comparable noise level measurements and predictions. The HUSH program was later modified (HUSH 003) for the prediction of equivalent sound levels [NYSDOT, 1979], and did not contain an interrupted flow adjustment based on findings in NCHRP 174 and in [Agent, 1980].

The original FHWA noise training text contained guidelines which shows the recommended volumes, speeds and sound level adjustment for automobiles and trucks for the NCHRP 117 and TSC models. The text also stated when speed varied, such as acceleration on a ramp, that one could assume that each vehicle accelerated according to a constant power relationship. Thus, the average speed over the length of the acceleration roadway would be two-thirds the final speed where the ramp entrance speed was zero. That average speed would result in reduced vehicle spacing, which would increase the truck noise level by two dB. The training text then suggested using the final highway speed for the prediction

(NCHRP 117 or TSC) but adding two decibels to the truck levels on the ramp, and applying this adjustment to a mile long stretch downstream from the ramp entrance to the expressway. Remember that in the TSC model, the truck emission level was assumed independent of speed (speed independent). For the NCHRP 117 method, 5 dB more must be added to allow for increased noise levels from accelerating trucks. Accordingly, for the NCHRP 117 method, it was suggested that 7 dB be added to the predicted truck level based on final highway speed. Of note is the assumed one mile zone-of-influence (ZOI).

Prahl [Prahl, 1975] also developed a model for accelerating heavy trucks, expressed as: $(L_o)_E$ = -8.2 log (speed, mph) + 91.1 dB. This model is valid from 14 to 30 mph. Of interest is that the $(L_o)_E$ values decrease with increasing speed. This model predicts that acceleration noise had the greatest amplitude during early stages of the acceleration and diminished with speed until speeds of approximately 30 mph.

Miller also evaluated accelerating heavy trucks at low speeds [Miller, 1976], and reported a value of 85 dB (which, with a 3.7 dB standard error, which corresponds to an 86.6 dB $(L_o)_E$).

Once again, EPA [Rudder, 1979] provides an excellent data base. For accelerating heavy trucks, these data showed very little change in the time averaged values (only a 0.6 dB increase between the 0-20 mph and 0-60 mph cases), as indicated in the middle portion of Table A-1. This data would seem to indicate that during acceleration, changes are small in the emission levels for heavy trucks.

In summary, the findings for heavy trucks in the accelerating mode are: (1) long zones-of-influence would seem to occur for accelerating heavy trucks; (2) accelerating trucks emission levels change very little from low speeds to high speeds (and so are nearly speed independent); (3) acceleration noise from trucks is louder than low speed cruise but less than cruise noise levels at highway speeds; (4) the SAE standard procedure wide-open throttle tests do not provide data comparable with urban acceleration; (5) care must be taken when using a constant $(L_o)_E$ value since vehicle spacing effects could cause predicted results at the receivers to vary in unintended ways; and (6) EPA offers an excellent data base.

Deceleration Mode

Again, EPA [Rudder, 1979] offers a good source of data, in this case for decelerating heavy trucks. The data values presented are shown by Figure A-12 and in the lower portion of Table A-1. Of note is the large change from low speeds to high speeds. This change is much more than for cruise and for acceleration, which was nearly speed-independent.

Idle Mode

Rudder [Rudder, 1979] presents idle data for heavy trucks in the EPA report. The 1974 measured reference emission value of 66 dB compares very favorably with measurements by Hillquist [Hillquist, 1975] which showed a value of 67 dB (L_{max}). Also, these values match very well with measurements done by the authors for this study (65-67 dB, L_{max}). Accordingly, the value of 66 dB is thought to be quite good for use for idling heavy trucks.

INTERRUPTED FLOW (MIXED MODE)

Much of the literature has reported on combined overall levels for all vehicle types and modes, typical of urban stop-and-go situations. While this data could not be used to predict emission levels from individual modes or establish reference emission levels for vehicle types, it does allow comparison of the models to real traffic situations.

A study in England by Gilbert presents a prediction method for L_{10} traffic noise levels [Gilbert, 1977]. Some 300 sites were surveyed and permitted many different traffic situations to be analyzed. This study found the pattern of arrival at intersections to be important, and included an "index of dispersion" parameter into the prediction equation along with flow rates, heavy vehicles and mean speed. The method produced reasonable results with a standard error of 2.7 dB and 95% confidence limits of ±5.4 dB. The vehicle emissions vary significantly from that of U.S. vehicles, but the methodology is sound.

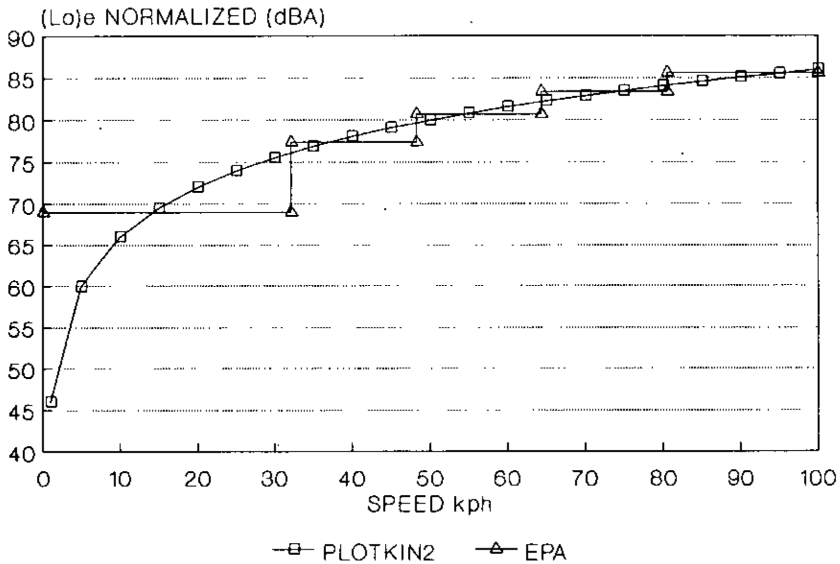


Figure A-12. Comparison of Deceleration Data for Heavy Trucks

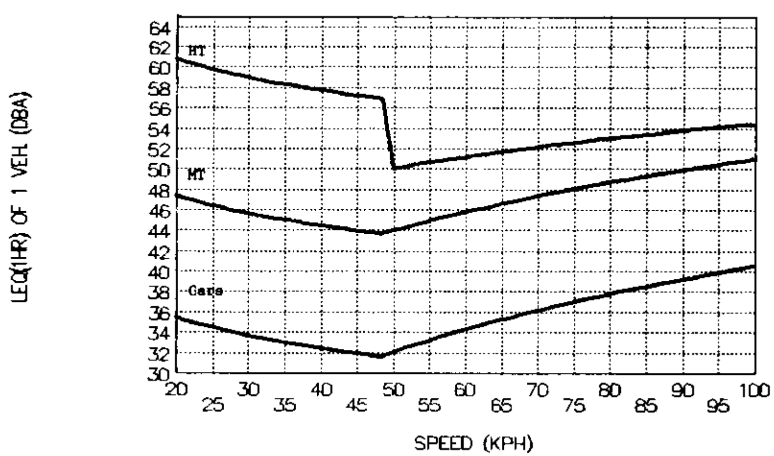


Figure A-13. L_{eq} (1 hr) for One HT, One MT and One Auto for FHWA Model Assumptions Below 30 mph

Gilbert suggested an independence of speed for interrupted flow conditions. In his discussion comparing free-flow to interrupted flow, he stated, "For free flow noise predictions, speed is an important explanatory variable but for interrupted flow it is likely that noise levels are largely independent of speed in the range 25-45 km/h. Attempts to include speed as an explanatory variable for all 134 sites by estimating speeds from . . . speed-flow relationships did not prove at all satisfactory." [Gilbert, 1977; p. 176]. Attempts to correlate the noise levels with other variables was also unsuccessful. However, Gilbert suggested in his conclusions that the index of dispersion for traffic and a level of service index could prove very useful in future attempts to model interrupted flow.

Appendix I of the FHWA Model documentation suggests levels in this mixed mode are independent of speed, and that a constant level could be used. The appendix notes that such a technique "has not been verified in the field but seems reasonable" [Barry and Reagan, 1978; p. I-1]. In that method a reference emission level of 87 dB for heavy trucks, which corresponds to the emission level of trucks at 100 kph (60 mph) is used. For automobiles and medium trucks, the reference level at 50 kph was suggested. For each vehicle type, the values were assumed independent of speed. However, the traffic flow adjustment factor should be computed using the mean speed of the vehicles, taking into account the traffic stops, rather than using a constant speed.

The suggestion of using the 87 dB level for heavy trucks has caused much concern about overprediction among noise analysts. If arbitrarily applied, the suggestion would cause the heavy trucks' equivalent sound level to suddenly increase to 87 dB as the speed dropped below 50 kph. Another problem also occurs. If the $(L_o)_E$ value is held constant then the predicted L_{eq}(1 hr) will decrease with increasing speed as shown by Figure A-13 and discussed previously.

Hatano used the same methodology to overcome effects of mode change during interrupted flow and extended the FHWA curve as a constant value below 50 kph for automobiles and medium trucks [Hatano, 1980]. For heavy trucks, he transitioned the level from 80 dB at 50 kph to 87 dB at 40 kph with a constant value of 87 dB below 40 kph. This methodology was included in the 1980 Caltrans noise manual [Hatano, 1980]. The problem of decreasing noise levels with speed would still be a problem.

In terms of explicit recognition of possible effects of stop-and-go traffic on noise levels, NCHRP Report 117 recommended interrupted flow adjustments of +2 dB for autos and +4 dB for trucks for the L_{10} descriptor within 1000 feet of a traffic signal [Gordon, 1971]. No adjustments were reported required for L_{50} values. The report's authors speculated that the noise characteristics of interrupted traffic flow would be different compared to the same traffic in a free-flowing condition. The report suggested that one approach to the problem might be to relate the noise output of a vehicle to the mechanical power expended in this mode of operation with a variable stop-and-start speed. With vehicle power being primarily expended on the changing of vehicle speed, noise output might be tied to the variance of the velocity or of the acceleration, both of which could be derived using a floating-car technique. These conclusions tend to confirm the use of speed independent values since changes in mechanical power occur at different points for various vehicles (i.e., changing of gears) and tend to "smooth" the final noise emission levels.

However, the actual recommended adjustments in NCHRP Report 117 were based on two sets of measurements made with two microphone positions each -- one near an intersection and one 1.5 mi. from the intersection. The recordings were not made simultaneously, but 45 min. apart. Hourly flow rates were close to 4,000 veh/hr and speeds estimated at about 50 mph. The truck percentage was 2% on the first day and not recorded on the second day. However, the +2 dB or +4 dB adjustments recommended by Gordon, et al, were not exactly apparent in looking at their data, and as a result, practitioners have not made extensive use of this adjustment factor.

In fact, Agent and Zegeer, in their study of the effect of interrupted flow on traffic noise, noted that the NCHRP Report 117 adjustment was not considered to be valid and was not generally used [Agent, 1980]. They also noted that subsequent NCHRP studies did not include an adjustment for interrupted flow (NCHRP Report 174). Agent and Zegeer collected data at 15 intersections with traffic control. Typically, three microphones were set up at at time in 100 foot intervals along the main road at an offset of 50 feet from the center of the near lane, out to a total distance of between 1,000 and 4,000 feet from the intersection. Their work was intended to define trends to indicate that the interrupted flow influenced the noise levels, both for L_{10} and L_{eq}. Figures A-14 to A-16 display Agent and Zegeer's data.

In Figure A-14, their data at four intersections for the same roadway has been plotted. When each is normalized for distance and volumes the absolute levels become quite similar. Although some intersections show changes with distance, no trends are apparent. Figure A-15 was plotted to compare intersections with small truck volumes. When normalized, as before, absolute values were similar but no trends were apparent. Figure A-16 shows a plot of the Agent-Zegeer data for low total volume intersections. No identifiable trends could be determined once again.

So, although it appears that some sites vary significantly from others in Agent and Zegeer's report, after normalization for truck percentages, distance, and speed, the data show similar values. When averaged over the 10 intersections, the range of L_{eq} at the various measurement positions was only 1.2 dB. They recommended that no adjustment factor be used in Kentucky DOT noise studies and that the traffic speed used in the prediction be the freely flowing vehicle speed (speed limit).

Agent and Zegeer concluded that there was no effect near intersections. However, this is misleading because Agent and Zegeer were implying no change in noise levels. As such, the data show no speed dependence. So, in reality, the speed-dependent cruise mode occurring near intersections was not present due to some effect, increasing the noise levels. As seen from other researchers reports, this occurs because of the dominant engine noise at low speeds. Accordingly, acceleration effects are shown by the data, resulting in near constant levels at the receivers distributed various distances from the intersection.

In another report, researchers for the Michigan DOT have suggested that an interrupted flow adjustment of +3 dB be added to the L_{eq} values whenever the site in question is within 300 feet of a controlled intersection [Harwood, 1981].

Also, Hajek [Hajek, 1975] of Ontario initially recommended that predicted L_{10} interrupted flow levels be increased by 2 or 3 dB if the traffic flow contained at least 60 heavy trucks per hour. However, Hajek and Jung later reversed this finding [Hajek, 1982]. They noted that the latest data indicated that an adjustment for interrupted flow was not necessary. They recommended that average operating speeds during the green cycle should be used to calculate sound levels.

The U.S. Department of Housing and Urban Development (HUD) also suggested a correction factor for interrupted flow [Schultz, 1971]. For traffic within 800 feet of a stop sign, Schultz suggested that heavy trucks be multiplied by a factor of 5. This would be equivalent to adding up to 7 dB as an adjustment depending on the percent of truck traffic. However, in the latest HUD handbook [USDHUD, 1985] slightly different multipliers are used, the distance requirement is less, and automobiles are also considered. The methodology is based on a 55 mph speed and adjustments are given for speed as well as near stop signs. For automobiles, receivers within 600 feet of a stop sign are adjusted according to the distance from the stop sign. This multiplier varies from 0.1 at the stop sign to 1.0 at 600 feet from the stop sign. These adjustments would define an acoustic profile for automobile traffic that decreased as the vehicle approached the stop sign (by up to 10 dB at the stop sign) and increase as the automobile left the stop sign. The length of the zone of influence would be 1200 feet (600 feet either side of the stop sign). The multipliers for heavy trucks (over the same 1200 foot zone of influence) vary according to the daily truck traffic volume; from 1.8 if the daily truck volume is less than 1200 to 4.5 for daily truck traffic greater than 19,200. These adjustments would cause the noise levels for heavy trucks to vary from +2.5 to +6.5 dB in the zone of influence. This methodology would indicate noise levels decrease for automobiles near stop signs and increase for heavy trucks. The combination, according to the number of each vehicle type could then decrease or increase near stop signs. No reference is given for these adjustments and no explanation is presented.

One of the more interesting studies on noise level by stop-and-go traffic was by Favre of the French Institute for Transportation Research [Favre, 1978]. He modelled the noise on the approaches to a set of traffic signals in terms of a single line of vehicles whose flow is pulsed by action of the signals. Because of the shown speed independence, Favre tried to correlate interrupted flow noise levels with engine speed by allowing for gear changes. He used a microscopic traffic simulation program with certain

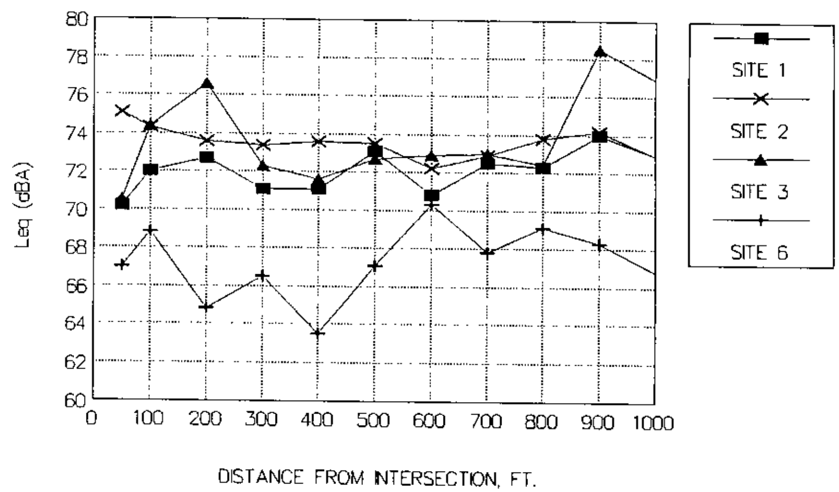


Figure A-14. L_{eq} at Signalized Intersections from Agent and Zegeer (1980): 1, 2, 3 and 6; All on Nicholasville

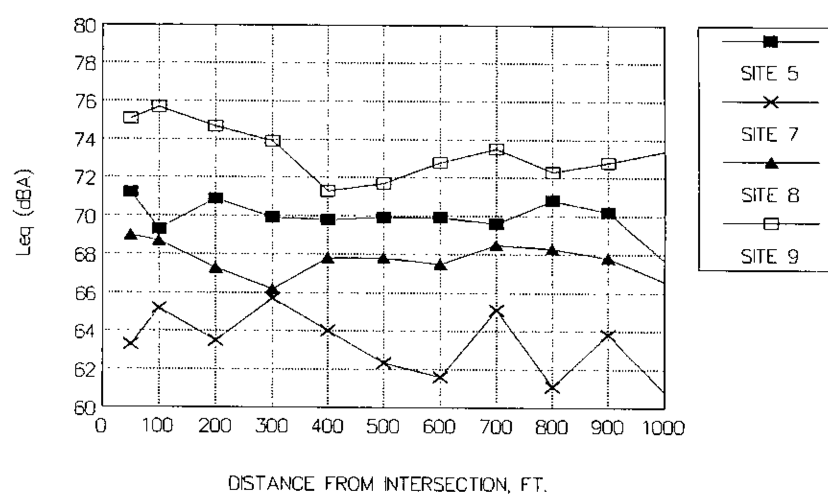


Figure A-15. L_{eq} at Signalized Intersections from Agent and Zegeer (1980): Sites 5, 7, 8, 9; All Truck % Greater than 4.3%

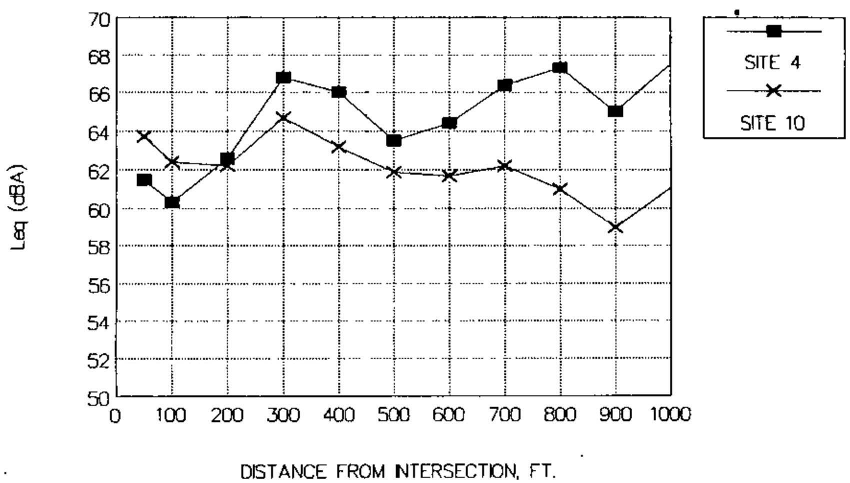


Figure A-16. L_{eq} at STOP sign intersections from Agent and Zegeer (1980): Sites 4 and 10: Low Volumes

simplifications such as not allowing turning movements. Assumptions were also made on the acoustic performance of an individual vehicle in different traffic situations, to produce "acoustic signatures" of the traffic at specific locations along the road. The acoustic signatures were the sound level profiles at varying distances (and hence time) from the traffic signal. Good agreement with field measurements was demonstrated. His work showed that there are non-linear "traffic lights effects" on the length of the zone of influence (which he defined as approximately 200 m from the signal) and on the maximum change in values (up to 8-10 dB, depending on traffic parameters and signal cycles). The derived model, verified by some measurement data, displayed variations that decreased just upstream of the traffic light and then suddenly increased just downstream. Figure A-17 displays the L_{eq} profile for three traffic conditions.

Recently, Slutsky, et al, have studied stop-and-go urban intersection noise [Slutsky, 1983]. The researchers also departed from using speed as a variable and instead used distance. This approach permitted the emission level to vary, much the same as Favre's simulation model. They developed a computer program for FHWA which takes into account the speeds of 15, 30 and 45 mph, vehicle decelerations (from 45 mph) under mild, normal and severe decelerations, and vehicle accelerations from rest to 30 mph to establish a relationship for each combination of vehicle class and operating mode. With four modes of operation and seven vehicle types, a total of 28 distinct categories needed to be studied. Unfortunately, data were presented as scattergrams or as individual pass-bys and not shown in the aggregate. Accordingly, this information was not in a form useable for this project.

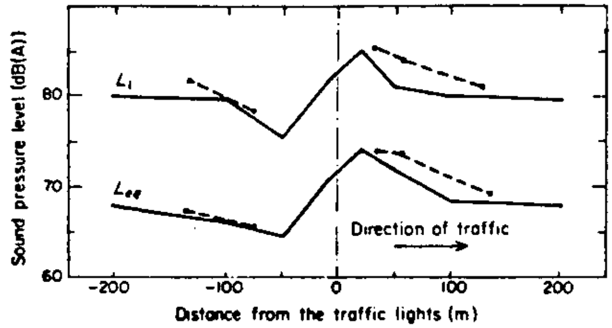
Functions were developed for the pass-by mode (cruise) by vehicle type, and as expected are functions of the logarithm of the speed. Expressions were also presented for the acceleration mode, but not as a function of speed, but of the logarithm of distance. The data were collected at various "lateral" distances.. The relationships for deceleration were also in terms of the maximum pass-by level as a function of the logarithm of the lateral distance. Slutsky, et al, conclude that the emission level for a constant speed pass-by is speed-dependent, but the other operating modes are speed-independent and rely on other variables for prediction. Slutsky presents all of these derived relationships in a series of tables in his final report. The reader is referred to this work for further details [Slutsky, 1984].

Anderson, et al, present an example of how to use field measured data to adjust a model to specific site conditions for the West Side Highway Project [Anderson et al, 1976]. Through vehicle emission level measurements along Manhattan streets, they developed noise emission equations to modify the TSC model for predicting L_{10}. These equations were presented previously in this appendix for each vehicle type. They sorted sites based on several criteria. They pointed out that to predict future noise levels, traffic engineers could not project which vehicles would or would not be accelerating on a vehicle by vehicle basis. Nor could they project percentage of vehicles accelerating near a given traffic signal since the percentage depended on a complex interrelation of many traffic parameters.

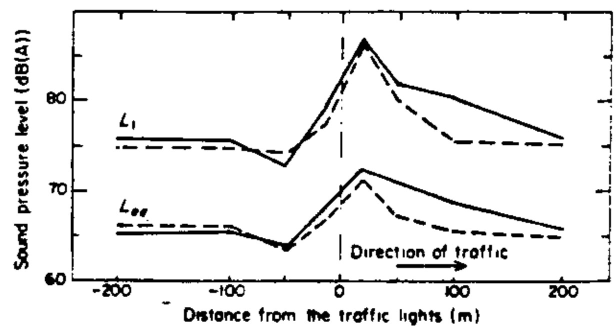
They therefore decided to designate all measurement sites within 100 feet of a traffic signal as "acceleration sites." The measured emission levels of vehicles at the site had to incorporate both accelerating and non-accelerating trucks. The noise emission equations for non-accelerating vehicles were dependent upon vehicle speed, whereas they were speed independent for accelerating vehicles. Gaussian approximations were made for each distribution.

(The use of the Gaussian distribution was questioned by Canner of Minnesota DOT [Canner, 1976]. Canner made measurements near a traffic signal on a city arterial street with an average running speed of approximately 30 mph. The traffic flow of 750 veh/hr (with 7.5% trucks) was highly queued with lulls between each of the signals. Data analysis showed that the traffic flow was non-Gaussian and better described by Poisson distribution. He found that by assuming the Poisson distribution, his predictions were within 0-2 dB of the measured values after adjustment for distance and vehicle emissions.)

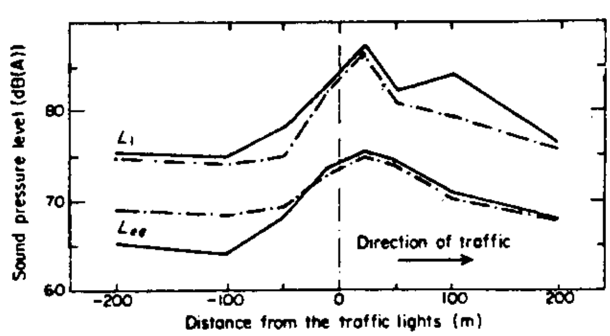
For the West Side Highway model, for non-accelerating vehicles, average speeds from intersection to intersection were approximated as twice the length of the applicable street link divided by the time required to drive that link. A factor of two corrected for red signal time, assuming that on the average each signal was red for 50% of the time. A comparison of these with the non-accelerating vehicle levels indicated very little difference in measured emission levels of single vehicles. However, a particular



(a) Traffic Flow: Approximately 700 vehicles/h, 5% Heavy Vehicles. Traffic Speed: 50 to 70 km/h. Traffic Light Cycle: 50 s Green, 5 s Amber, 45 s Red. Lateral Location: 75 m from the Traffic Lane Axis. ____, · Results of Simulation; -----, Results of Measurement.



(b) Traffic Flow and Traffic Light Cycle Constant, Speed Limit Varied; Flow: 250 Vehicles h, 0% Heavy Vehicles: Cycle: 30 s Green, 5 s Amber, 56 Red. -----, V = 40 to 60 km/h; ____, V = 60 to 80 km/h.



(c) Traffic Flow and Speed Limit Constant, Traffic Light Cycle Varied. Flow: 700 Vehicles h, 0% Heavy Vehicles. Speed: 60 to 80 km/h. Traffic Light Cycles: ____, 30 s Green, 5 s Amber, 65 s Red; -----, 70 s Green, 5 s Amber, 25 s Red.

Figure A-17. Variations in the Simulated and Measured Values of L_1 and L_{eq} with Distances from the Traffic Lights for a Single Line of One Way Traffic (from Favre, 1978).

problem with applying their data more generally was that all of the emission levels had the effects of either increased levels from reflections off building walls or from cobbled pavement at certain sites.

Although the emission level data from the West Side Highway study were site specific because of the influence from building reflections and cobbled pavements, the approach agrees with others such as Favre in the use of specified modal areas. The researchers offered three possibilities in their report to account for the small difference in the levels for various traffic modes. First, near any signalized intersection, not all trucks were stopped by a red signal. Second, under high volume conditions, even those trucks that were stopped did not accelerate with full throttle away from the intersection and it was possible that vehicles were also accelerating at the mid-block sections. Finally, accelerating trucks were balanced by trucks that were coasted toward the red signal, and by the periods when virtually no traffic moved past the microphone.

As a result of these observations, the West Side Highway noise model, in the end, did not distinguish between acceleration and non-acceleration sites; the non-acceleration equations and adjustments were used. For the predictions, the researchers used an average traffic speed which included stop time at traffic control devices, and an adjustment to convert it to an average running speed. A multiplier was also used that depended upon the type of traffic control devices. Also, while volumes and speeds varied by block along the local streets and by link along the highway, the traffic parameters were averaged over all segments used in the noise calculations.

In a recent paper, Anderson discussed problems in doing traffic noise studies [Anderson, 1985]. He noted that the national average emission levels were inaccurate, and could result in overestimates of the noise level in four situations: (1) off-ramps; (2) accelerating to mainline speed after leaving on-ramps; (3) anywhere near traffic signals; and (4) full-throttle in anticipation of an up-grade or just after cresting a hill. He further noted that if speeds are below 30 mph, one should insert realistic vehicle emissions, which he recommends are best measured specific to each project.

A special case of interrupted flow traffic that has received little attention is at toll booths. This case, similar to a one-way stop sign situation, can provide insight to the relative levels. The Texas State Department of Highways and Public Transportation has done some limited sampling for this situation [Moe, 1988]. The site-specific results indicate a near constant value upon approach followed by a large increase in noise levels just downstream (due to acceleration). Of interest is that acceleration levels at the toll booth are below the 55 mph cruise levels, which supports other researchers opinion that maximum noise levels occur at high speed cruise conditions.

Nelson of the British Transport and Road Research Laboratory has reported on an interrupted flow program, called URBANN [Nelson, 1976]. URBANN was specifically designed to predict traffic noise at positions close to a roadway (less than 20 m) where average vehicle speeds fall below the free-flow region and are in the 20-50 kph range. Vehicles are divided into three types: light, medium-heavy, and heavy. Speed is specified in terms of an average speed of all vehicles in a given lane. As Nelson reported in a later study [Nelson, 1977; p. 5], "...the evidence so far obtained supports the adoption of the approximation that in non-free flow urban traffic average vehicle noise does not vary with speed."

Separate from the work of Favre, other French researchers [C.E.T.U.R., 1980] have taken a very interesting approach to predicting stop-and-go traffic noise levels. Traffic acceleration and deceleration speed profiles are defined on the approach and departure legs of the intersection. If speed were plotted as a function of distance, these profiles would combine for a "V" shape where the bottom of the "V" is the stop line at an intersection. Figure A-18 illustrates this "V" shape. Noise profiles are then "fitted" to these speeds distribution and a noise level function is defined based on the speed profile. A typical resulting acoustical profile is shown by Figure A-19. These curves are then combined for acceleration, cruise and deceleration to form an overall weighted function, which is used to predict the final noise level.

Nelson and Piner examined low-speed vehicle noise level data collected on shopping streets in urban areas in England [Nelson and Piner, 1977]. They found that under non-freeflow conditions there was a greater range between the average levels of the noisiest and quietest vehicle categories than that expected for freeflow conditions. They divided the vehicles operating at low speeds and non-freeflow

conditions into six acoustically separate vehicle categories. At low speeds (below 30 kph) it was stated that noise levels are independent of vehicle speed. Above 50 kph vehicles showed a 6-12 dB increase with doubling of speed.

Lewis and James [Lewis, 1978] measured noise levels from traffic entering and exiting "roundabouts" in England. Their early work generally showed noise levels to decrease as vehicles decelerated to the roundabout. Also, as vehicles accelerated from the roundabout, noise levels were generally higher than the corresponding levels that would be expected for cruise conditions (see Figure A-20). In a later article, they found the same trends for accelerating and decelerating traffic streams and developed a model for L_{10} prediction [Lewis, 1980]. They extended the noise effect from the decelerating traffic stream to 130-150 meters upstream from the roundabout. The accelerating traffic showed a constant level that was equivalent to downstream cruise levels at much greater speeds.

Samuels of the Australian Road Research Board has also developed a model to predict L_{10} values from interrupted flow [Samuels, 1988]. His model and measurements also show decelerating traffic noise levels to be less than cruise conditions and accelerating traffic to be equal or greater than cruise conditions. Interrupted flow noise levels were shown to be much greater than cruise conditions for the same speeds (up to 13 dB). The model also pays particular attention to the platoon effect of traffic flow. He felt this to be an important consideration when modelling traffic near signalized intersections.

Summing for interrupted flow, the following findings can be surmised: (1) levels in the mixed mode are nearly speed independent due to changes in engine speed, mode mix and acceleration rates; (2) a constant $(L_o)_E$ will result in a decreasing L_{eq} value at the receiver as speed increases when vehicle spacing with speed is considered; (3) using other variables such as distance from the intersection, than speed, show promise for modelling interrupted flow noise levels; (4) decelerating traffic generally shows lower noise levels than cruise at the same speed; (5) decelerating traffic show strong speed dependence (engine noise is low and tire noise decreases with speed); (6) acoustical profiles of interrupted flow are possible to determine and model; (7) the acoustical profile length changes with various approach and departure speeds; (8) zones-of-influence can be determined for traffic conditions where a single mode dominates (i.e., intersections); (9) simulation models allow the $(L_o)_E$ values to change with conditions, but could not easily be adapted for use with STAMINA; and (10) traffic dispersion can be an important consideration for predicting noise levels near intersections.

CONCLUSIONS

All vehicle types display speed dependent relationships (increasing noise levels with increasing speed) in the cruise mode. Data support the extension of the FHWA Model to lower speeds. During cruise, tire noise is the primary contributor to noise levels at speeds above approximately 30 mph for automobiles and 40 mph for trucks. Engine noise dominates at the lower speeds.

Acceleration noise, particularly at the lower speeds, is dominated by engine exhaust and drive train noise. This domination, along with wide variability, has led to the use of constant levels to predict acceleration noise.

Deceleration noise is highly speed dependent and decreases with speed. Deceleration levels are less than either the cruise or acceleration mode at the same speed. Idle noise levels represent the lower band.

Interrupted flow depends on roadway geometry and is a mixture of all four modes (idle, acceleration, deceleration, and cruise). STAMINA is a constant speed computer model which predicts well for cruise but not for the other modes. Simulation models have been used to try and overcome this problem but could not be easily and to adopt STAMINA. A methodology that seems promising to adapt STAMINA 2.0 is the use of equivalent speeds and defined roadways for the various zones-of-influence in a stepped manner. In this way acoustical profiles can be estimated. Future enhancements to STAMINA could be to allow a different independent variable to be used for accelerating and decelerating roadways (such as distance from the point-of-stop). In this way, the acoustical profile would be established for $(L_o)_E$ values based on position at the intersection.

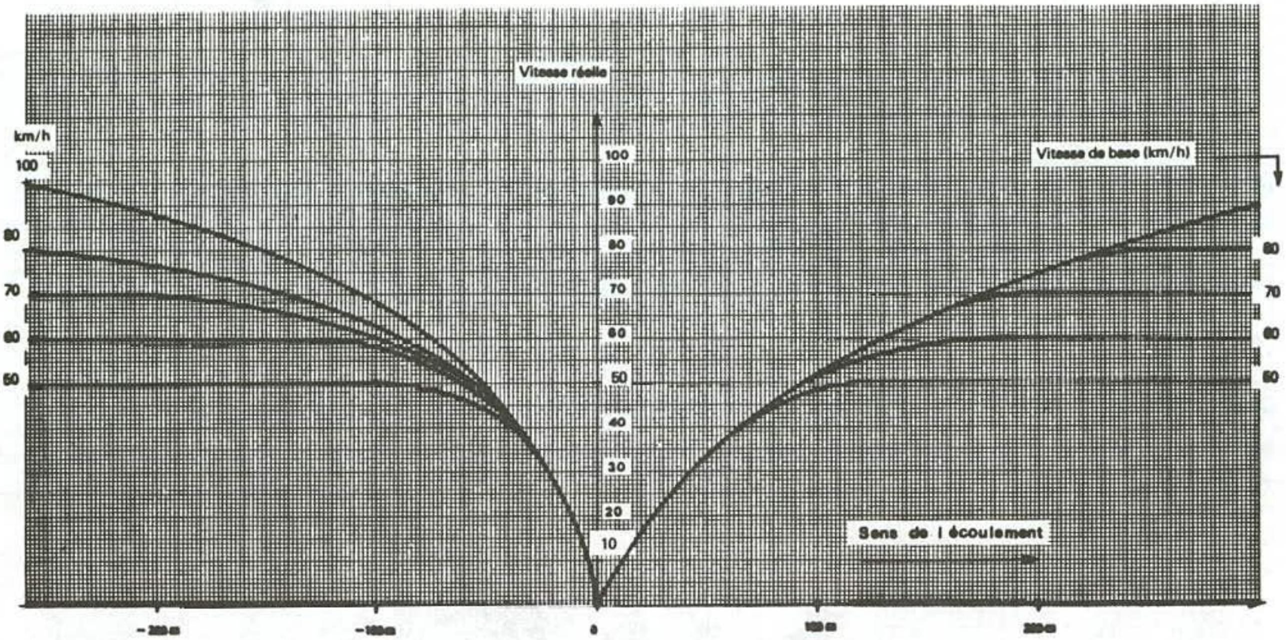


Figure A-18. Traffic Speed Profiles Presented by C.E.T.U.R. (1980)

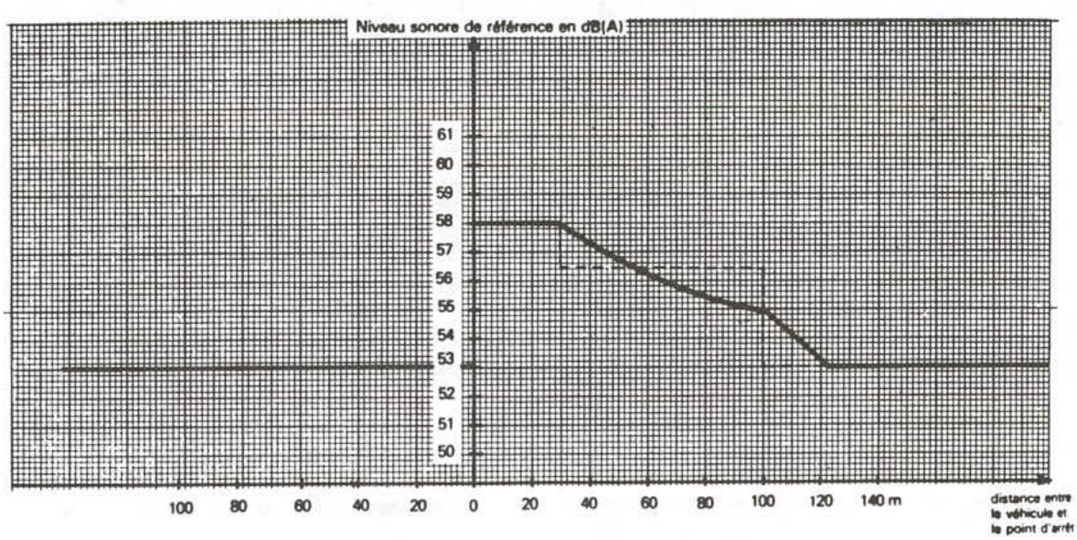
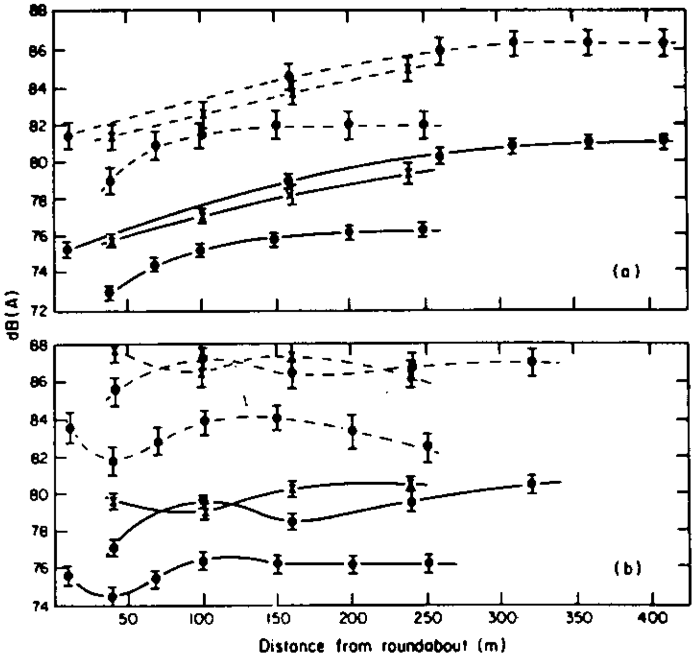


Figure A-19. Acoustical Profile Predicted by C.E.T.U.R. (1980)



_____ Light Vehicles
------ Heavy Vehicles

ɸ standard error of means

Figure A-20. Vehicle Noise at Three Roundabout Sites for (a) Decelerating Vehicles and (b) Accelerating Vehicles (from Lewis and James, 1978)

APPENDIX B—ANALYSIS OF DATA AND METHODOLOGY DEVELOPMENT

INTRODUCTION

This Appendix presents a detailed discussion of the basis for a methodology to predict stop-and-go traffic noise levels. It builds on the results of the literature review, with special emphasis on the data presented by Rudder for the EPA [Rudder, 1979]. The discussion also includes a detailed examination of the emission level measurement data collected in this study.

The discussion first describes the rationale behind the choice of the measurement parameters. Then, the automobile data is examined, followed by the data for medium trucks and heavy trucks. Finally, the results for the three vehicle types are combined into a single methodology.

Emission level data collection focused on heavy trucks, defined as vehicles with three or more axles, because of their high levels and important contribution to the total traffic noise levels. A limited amount of automobile (2-axle, 4-tire) and medium truck (2-axle, 6-tire) data was collected.

Details on the site selection, measurement equipment and procedures, the tabulated measurement data and additional measurements used in the evaluation of the methodology are available from NCHRP in a supplemental report.

RELEVANT NOISE DESCRIPTORS

Data were collected to obtain a better understanding of the phenomenon, to aid in understanding existing field data, to add to the existing database, and to perform an initial validation of the results. In order to accomplish the goals, two types of data were collected: levels of individual vehicles and time-averaged levels from streams of traffic.

For the individual vehicles, two main descriptors were measured:

1. the maximum A-weighted level (fast response) of the pass-by event: L_{AFmax} or, as used here, L_{max}
2. the A-weighted Sound Exposure Level (SEL) of the event: L_{AE} (in this report, the more familiar abbreviation, SEL, will be used in both the text and the equations)

The time-averaged level is referred to in most traffic noise literature as the equivalent sound level, L_{eq}, and will be discussed in detail in the next section.

Sound Exposure Level and its Relationship to L_{eq}

SEL may be defined as:

$$SEL = 10 \log \int_{t_1}^{t_2} [p(t)^2/p_o^2]dt \qquad \text{(B-1)}$$

where p(t) is the instantaneous sound pressure at time t and p_o is the reference sound pressure of 20 micropascals.

SEL represents the level of the total sound exposure of the event (relative to a reference exposure) integrated over the event's duration. SEL is directly related to the time-averaged sound level (L_{eq}). L_{eq} represents the level of the total sound exposure of the event averaged over some duration. The duration could be the time when the level of the event is within 10 dB of its maximum value; or, the duration could be the time typically used in traffic noise predictions (one hour). L_{eq} is defined mathematically as:

$$L_{eq} = 10 \log \{[1/(t_2 - t_1)] \int_{t_1}^{t_2} [p(t)^2/p_o^2]dt\} \qquad \text{(B-2)}$$

Rearranging terms and using the principle that log(ab) = log(a) + log(b),

$$L_{eq} = 10 \log \int_{t_1}^{t_2} [p(t)^2/p_o^2]dt + 10 \log [1/(t_2 - t_1)] \qquad \text{(B-3)}$$

or,

$$L_{eq} = SEL + 10 \log [1/(t_2 - t_1)] \qquad \text{(B-4)}$$

More precisely, the L_{eq} term should be written as $L_{eq}(t_2\text{-}t_1)$ to indicate that its value is directly dependent on the time over which it is computed.

For example, if $(t_2\text{-}t_1)$ is one hour, or 3600 seconds, then $L_{eq}(1\ hr)$ will be equal to:

$$L_{eq}(1\ hr) = SEL + 10 \log (1/3600) = SEL - 35.6\ dB \qquad \text{(B-5)}$$

But, for example, if $(t_2 - t_1)$ is four seconds, the typical duration of a high speed passby, then L_{eq}(pass-by) = SEL + 10 log (1/4) = SEL - 6 dB. Two observations may be made on the relationship between SEL and L_{eq} that are relevant to this study. First, for a typical vehicle passby, as the averaging time increases, the L_{eq} decreases. However, the SEL for all practical purposes will remain constant once the energy within the 10 dB rise-and-fall window is captured, no matter how long the measurement's duration. (Each 10 dB decrease in level represents a ten-fold decrease in intensity.) This type of situaton will occur for cruising, accelerating or decelerating vehicles so long as the level rises and falls at least 10 dB during the event.

Now consider the case of the idling vehicle in front of the observer. The level remains constant over time, causing the L_{eq} to remain constant also. However, because SEL represents the total intensity of the event, SEL will continue to increase as the duration increases.

The relationship of L_{eq} to SEL as described by the above two situations will be important in the modeling of stop-and-go traffic.

Maximum Passby Level

The first data collection parameter that was mentioned was the maximum level, or L_{max}. Its importance to the modelling process stems from the fact that most models of traffic noise use some function of L_{max} as the basis for the emission levels in the model. For example, the FHWA Traffic Noise Prediction Model [Barry, 1978] is specified in terms of an emission level and a series of adjustments, specifically,

$L_{eq}(h)_i = [(L_o)_E]_i$	reference energy mean emission level	(B-6)
$+ 10 \log [(N_i \pi D_o)/S_i T]$	traffic flow adjustment	
$+ 10 \log (D_o/D)^{1+\alpha}$	distance adjustment	
$+ 10 \log [(\phi_1, \phi_2)/\pi]$	finite roadway adjustment	
$+ \Delta_s$	shielding adjustment	

where

$L_{eq}(h)$ is the hourly equivalent sound level of the ith class of vehicles.

$[(L_o)_E]_i$	is the reference energy mean emission level of the ith class of vehicles.
N_i	is the number of vehicles in the ith class passing a specified point during some specified time period (1 hour).
D	is the perpendicular distance, in meters, from the centerline of the traffic lane to the observer.
D_o	is the reference distance at which the emission levels are measured (15 meters).
S_i	is the average speed of the ith class of vehicles and is measured in kph
T	is the time period over which the equivalent sound level is computed (1 hour).
α	is a site parameter whose values depend upon site conditions.
	is a symbol representing a function used for segment adjustments, i.e., an adjustment for finite length roadways.
Δ_s	is the attenuation, in dB, provided by some type of shielding such as barriers, rows of houses, densely wooded areas, etc.

The $(L_o)_E$ term represents the energy average of the maximum levels of a series of individual pass-by events:

$$(L_o)_E = 10 \log [(1/n)\sum_{i=1}^{n} 10^{(0.1\, L_{max,i})}] \qquad \text{(B-7)}$$

where n is the number of events and $L_{max,i}$ is the maximum level of the event. If the distribution of the maximum levels is normal (or "Gaussian"), an approximation may be derived [Barry and Reagan, 1978]:

$$(L_o)_E = L_o + 0.115s^2 \qquad \text{(B-8)}$$

where (L_o) is the arithmetic average of the maximum levels of the n events and s is the standard error of the measured maxima.

The emission level is thus independent of time. Yet it is used to predict the 1-hour L_{eq}. The averaging of the passby level over the hour is imbedded within the traffic flow adjustment and the distance adjustment in Eq. B-6. The reader is referred to Appendix A of [Barry and Reagan, 1978] for a full derivation of the FHWA Model equation which is based initially on the integration over time of the pass-by level of a single vehicle. That derivation also shows how the terms of the equation are rearranged into what was felt to be the easier-to-understand series of adjustments in Eq. B-6).

<u>Relationship between SEL and L_{max} for Constant Speed</u>

What is of importance in this study is the relationship between SEL and L_{max}, especially as they relate to the prediction of a time-averaged level. Eldred et al recently presented a traffic noise prediction method based in part on the FHWA Model [Eldred, 1984]. However, instead of using the same methodology as the FHWA Model, they choose to use as the basis for prediction the quantity SEL, or more specifically, the sound exposure SE of individual pass-by events. SE is defined as the "time integral of the squared frequency-weighted instantaneous sound pressure" [ASA, 1988; p. 3]:

$$E = \int_0^T p_A^2(t)dt \qquad \text{(B-9)}$$

The unit is the pasque or the pascal-squared second (Pa^2s). SEL is defined in terms of sound exposure as:

$$SEL = 10 \log (E/E_o) \qquad \text{(B-10)}$$

where E_o is the reference sound exposure equal to $(p_o)^2 t_o$ with: p_o being the reference sound pressure of $2x10^{-5}$ Pa and t_o being 1 second. Thus, E_o is $4x10^{-10}$ Pa^2s or $4x10^{-10}$ pasques.

Recalling Eq. B-5 and substituting the expression in Eq. B-10 yields the L_{eq}(1 hr) for a single vehicle at a reference distance:

$$L_{eq}(1\ hr) = 10 \log (E/E_o) + 10 \log (1/3600) = 10 \log [E/(3600E_o)] \qquad \text{(B-11)}$$

The same quantity is computed in the FHWA Model by the first two terms of Eq. B-6, assuming the finite roadway and shielding adjustments to be zero:

$$L_{eq}(1\ hr) = (L_o)_E + 10 \log [(\pi D_o)/(ST)] \qquad \text{(B-12)}$$

To allow for mixed units of D_o in meters and S in kilometers/hour, it is necessary to introduce a units conversion term of 1 km = 1000 m into the equation:

$$L_{eq}(1\ hr) = (L_o)_E + 10 \log [(\pi D_o)/(1000\ ST)] \qquad \text{(B-13)}$$

Eqs. B-11) and (B-12) may be equated:

$$10 \log [E/(3600E_o)] = (L_o)_E + 10 \log [(\pi D_o)/(1000\ ST)] \qquad \text{(B-14)}$$

or

$$(L_o)_E = 10 \log [E/(3600E_o)] - 10 \log [(\pi D_o)/(1000\ ST)]$$

$$= 10 \log (E/E_o) + 10 \log [1000ST/(3600\pi D_o)]$$

$$= SEL + 10 \log(S) + 10 \log [(1000T)/(3600\pi D_o)]$$

$$(L_o)_E = SEL + 10 \log(S) - 22.4\ dB \qquad \text{(B-15)}$$

This relationship is at a reference distance of 15.2 m (50 ft) only. For example, if S = 100 k/h, $(L_o)_E$ = SEL - 2.4 dB.

Because the FHWA Model equation is based on a constant speed relationship, Eq. B-15 is valid for constant speeds only. This poses a problem for accelerating or decelerating vehicles, where, by definition, speed changes with time, or during idling, where speed equals zero.

Indeed, Eq. B-12 is valid only for constant speeds. A different approach is required for acceleration or deceleration. That approach is suggested by Eq. B-11. Specifically, the integration over time of the sound energy of a pass-by may be able to be done without having to depend on a 10 log (1/S) factor.

Thus, the measurement program was designed to look at how both the SEL and L_{max} behaved in the acceleration and deceleration conditions in an attempt to solve the problem of the reality of a time-varying speed in a constant speed model.

NOISE LEVELS FOR ACCELERATING AUTOMOBILES

To gain a better understanding of the potential effects of changing speed on changing levels, it is instructive, initially, to examine one set of data in the literature and to compare that data with the FHWA Model recommendations. This initial examination will be done for automobiles.

The EPA Data Base

The best source of data on levels from accelerating autos is that of Plotkin [Plotkin 1979], as presented by Rudder in the EPA National Roadway Traffic Noise Exposure Model [Rudder, 1979]. This data is described in detail in Appendix A. Rudder presented emission levels by vehicle type for five speed ranges. There were seven vehicle types for 2-axle 4-tire vehicles. Given the relative percentages of each vehicle type for the year in which the noise levels were collected (1974), as reported by Rudder, combined weighted energy-averages of the different vehicle type levels for each speed range were computed as shown in Table B-1.

The Moving Observer. The levels in Table B-1 represent the time-averaged level of the acceleration noise as the vehicle goes from 0 mph to the final speed. However, the observer position is assumed by Rudder to be moving along with the vehicle at a reference distance of 50 feet. Thus, these levels are not the same that a stationary wayside receiver would observe. Rudder chose this moving observer concept because in his model he assumed that all receiver points along a road at a given offset distance would have equal likelihood of having an accelerating vehicle passing them at any point in the acceleration cycle. This generalized view of acceleration was deemed sufficient for a national exposure model where site-specific levels were not being predicted. However, for the purposes of this study, and the projected use of these results, that approach is inadequate. The level at the beginning of acceleration at a 50-foot offset distance will be in the high-50 to low-60 dB range. At the end of the acceleration when the car is at 60 mph, its reference level would be the same as the cruise level of about 74 dB, where tire noise dominates. Thus, a total change of over 10 dB is possible from one end of the acceleration zone to the other. The emission level presented by Rudder is simply the time-averaged level over the full acceleration cycle, which disguises this speed/distance/time relationship.

Variation of SEL With Distance From Start Based on FHWA Model Assumptions

However, the EPA data is still very useful. The relationship between longitudinal distance from the start of acceleration and emitted level implies that the only totally accurate way to compute the level at a receiver is to do a time-step simulation of the received level as the vehicle proceeds along the acceleration path. Thus for each incremental time t, of the acceleration event, one would determine:

1. the speed;
2. the resultant emission level alongside the vehicle;
3. the longitudinal distance from the stopline;
4. the distance from the receiver to the vehicle;
5. the distance propagation loss; and finally,
6. the resultant received level.

One could then integrate these received levels over the duration of the event to determine an SEL, at the receiver. This SEL would change with receiver position along the acceleration zone. The closer to the start point, the lower the SEL; the closer to the end point, the nearer the SEL will be to the cruise SEL.

Analysis Based on a Two-Step Acceleration Rate. Figures B-1 through B-5 illustrate this concept for the following situation, and will be discussed in detail to give a better picture of the problem:

1. speed range: 0-60 mph
2. automobile emission level above 30 mph equal to the FHWA Model equation [Barry and Reagan, 1978; p. I-1]: 38.1 log(speed) - 2.4 dB

TABLE B-1 -- WEIGHTED TIME-AVERAGED LEVELS FOR ACCELERATION BASED ON SEVEN TYPES OF "PASSENGER CARS" (EPA DATA FROM RUDDER, 1979)

Speed Range (mph)	Time-Averaged Levels (dB)
0-20	60.9
0-30	62.8
0-40	64.1
0-50	65.9
0-60	67.4

TABLE B-2 -- DISTANCES AND TIMES FOR 10-MPH SPEED CHANGES FOR TWO-STEP ACCELERATION RATES (0.083 G TO 30 MPH; 0.05 G TO 60 MPH)

Speed (mph)	Distance (ft)	Time (sec)
0	0	0.0
10	40	5.5
20	161	11.0
30	362	16.5
40	796	25.0
50	1459	35.0
60	2186	44.0

3. emission level equal to 62 dB below 30 mph (per FHWA recommendations [Barry and Reagan, 1978; p. I-1])
4. receiver offset distance of 50 feet from the center of the lane
5. acceleration rate of 0.083 g from 0-30 mph and 0.05 g from 30-60 mph (1 g = 32.2 ft/sec/sec or 22 mph/sec)

These acceleration rates approximate the acceleration curve in the AASHTO Green Book based on an initial speed of zero [AASHTO, 1984; p. 784]. Thus, use of a 2-stage acceleration profile seems appropriate over the full speed range.

Returning to Figures B-1 to B-5, each figure shows a 40-second window of the time history of the noise level for the acceleration event at a particular longitudinal distance from the stopline. The five longitudinal distances are 100, 200, 400, 800 and 1600 feet. These time histories are superimposed onto a 40-second window of a time-history for a 60-mph passby. The time axis should be read separately for each curve. For the cruise event, time t = 0 is assumed to be the exact moment the vehicle passes the observer. The graph displays how the level varies from t = -20 to t = +20. For the acceleration event, the event is assumed to begin at time t = -20, and the graph displays what happens to the level at the receiver for the next 40 seconds.

Receiver at 100 Feet From Stopline, 50 Feet From Center of Lane. In Figure B-1, the receiver is 100 feet from the stopline. As shown, it takes about 9 seconds (to t = -11) for the accelerating car to pass by the receiver, at which point the maximum level of 62 dBA is shown (based on assumption 3, above, where the speed at this point is computed to be 16 mph). The level of 55 dBA at the receiver at t = -20 (the beginning of the acceleration) represents the assumed 62 dBA emission level (at 50 feet), with a 6-dB attenuation per distance doubling over a distance of 112 feet (the diagonal distance computed from a longitudinal distance of 100 feet and offset distance of 50 feet). Beyond t = -20, but not shown, the level is assumed to be for an idle condition and on the order of 46 dB [Rudder, 1979].

The shape of the acceleration curve is more rounded than the 60 mph curve, because the vehicle is moving in a low speed range during that portion of its acceleration. Displayed on the left side of the figure are the overall SEL of the acceleration and cruise events of 70 and 76 dB, respectively. The slope of the acceleration curve is steeper after the vehicle passes the receiver because the speed is increasing while the emission level is assumed to remains constant until the speed exceeds 30 mph. The final speed of 60 mph is computed to be reached at t = +24, which is past the end of the graph. Beyond this point, the speed, and hence, the emitted level is assumed to remain constant: the resultant decrease in level beyond this point at the observer is due solely to distance spreading (and not increased emission level with increased speed). The 6 dB difference between the acceleration and cruise SEL would represent the error that would occur in the prediction of the level at this 100-foot receiver if the final speed of 60 mph was used for this acceleration roadway.

Receiver at 200 Feet From Stopline, 50 Feet From Center of Lane. Figure B-2 locates the receiver at a longitudinal distance of 200 feet from the stopline. Now, at the start of the acceleration event, the received level is reduced to 50 dB due to the extra distance attenuation. It takes 12 seconds (from t = -20 to t = -8) for the vehicle to reach the 200 foot point. The speed at this point (not shown, but computed as 22 mph) is still below 30 mph, as evidenced by the 62 dB maximum level (see assumption 3 above).

The difference in the SEL for this receiver compared to the 60-mph cruise is 7 dB, one dB more than for the 100-foot receiver. The reason for the SEL at the 200 feet passby point being less than the SEL at the 100-foot passby point is that the increased speed (22 mph versus 16 mph) is shortening the time in front of the receiver at a faster rate than at 100 feet while the emission level is assumed to remain the same at 62 dB.

Receiver at 400 Feet From Stopline, 50 Feet From Center of Lane. By the time the vehicle reaches the 400 foot passby point (Figure B-3), the speed has been computed to be above 30 mph (actually, 31 mph). This fact is evidenced by the fact that the maximum passby level at the 50 foot offset distance is just beginning to increase above 62 dB. The shape of the curve looks more like the 60-mph

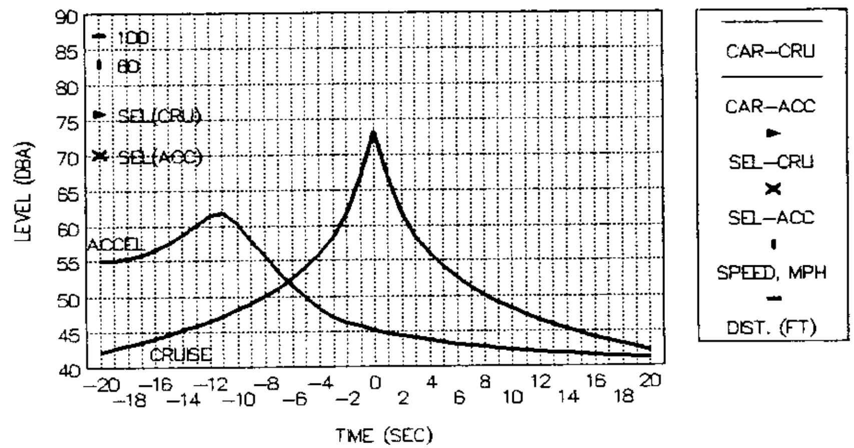


Figure B-1. Time History of Car Cruise and Acceleration
(Speed = 60 mph; Distance = 200 ft)

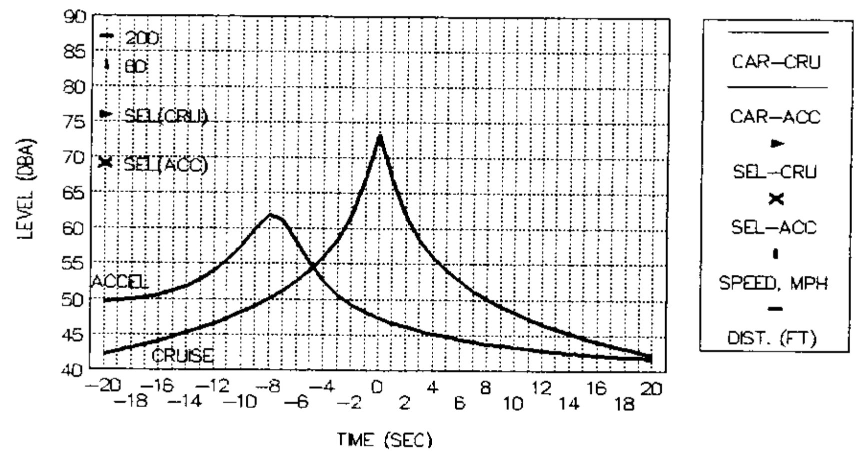


Figure B-2. Time History of Car Cruise and Acceleration
(Speed = 60 mph; Distance = 200 ft)

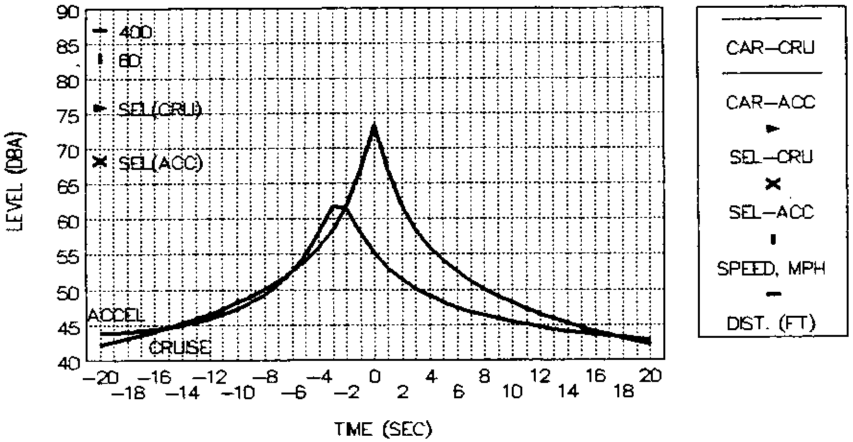


Figure B-3. Time History of Car Cruise and Acceleration
(Speed = 60 mph; Distance = 400 ft)

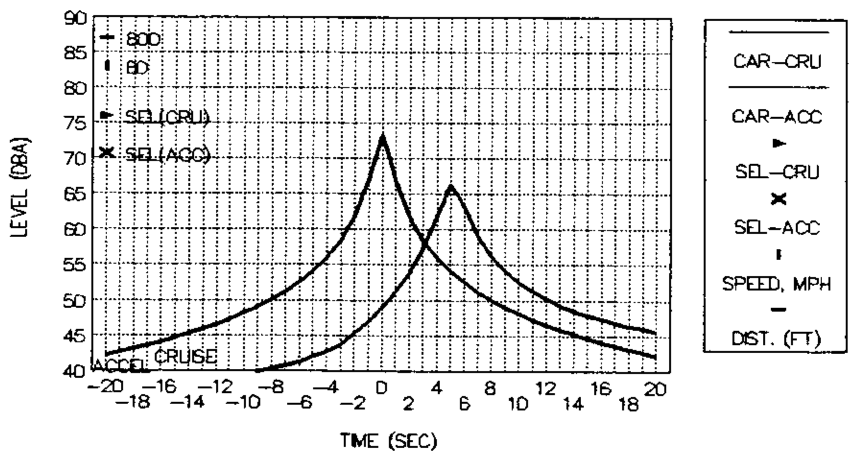


Figure B-4. Time History of Car Cruise and Acceleration
(Speed = 60 mph; Distance = 800 ft)

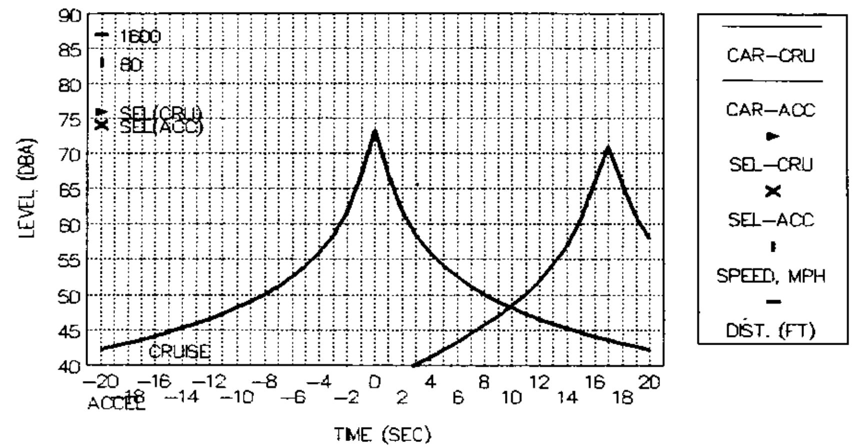


Figure B-5. Time History of Car Cruise and Acceleration
(Speed = 60 mph; Distance = 1600 ft)

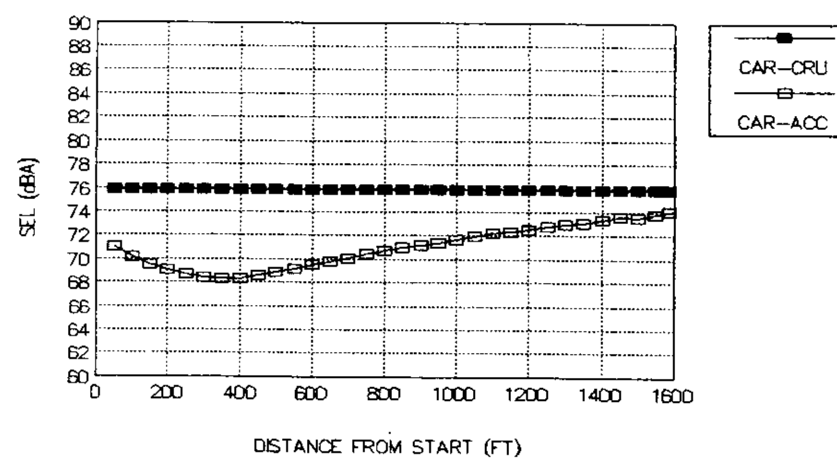


Figure B-6. SEL at Vvarious Distances from Start: Car Cruise
at 60 mph and Acceleration at Constant 62 dBA

curve than at the previous points. The SEL is slightly lower than at the 200-foot point, reflecting the effect of the increased speed without a large enough increase in emission level. As an approximation of the AASHTO passenger car acceleration curve, the acceleration rate above 30 mph is lowered to 0.05 g.

Receiver at 800 Feet From Stopline, 50 Feet From Center of Lane. At the 800-foot passby point (Figure B-4), the emission level has now increased to about 66 dBA (the speed is computed at about 40 mph), and the shape of the curve continues to approach that of the 60-mph curve. The difference in SEL for the two events is now only about 5 dB, reflecting the strong speed dependence on emission level caused by increasing tire noise.

Receiver at 1600 Feet From Stopline, 50 Feet From Center of Lane. Finally, as shown in Figure B-5, 1600 feet from the start of acceleration, the acceleration curve continues to approach the 60 mph cruise curve because of the continued increase in speed at the passby point (computed to be 53 mph).

Summary of Effects Based on 2-Step Acceleration and FHWA Model Assumptions. The above example was based around the assumptions stated at its beginning. Key among those were the 2-step rate of acceleration (changing at 30 mph) and the constant emission level of 62 dB below 30 mph. Changing these values would change the shape of the acceleration sound level curve, and the resultant SEL. However, barring radical differences the trend remains the same--the SEL of an automobile acceleration event will be less than that of a 60 mph passby at any longitudinal passby distance and, the magnitude of that SEL difference will vary as well, as discussed in the next paragraph. Using the final speed will thus overpredict the L_{eq} for the acceleration roadway.

Figure B-6 summarizes these effects. The open squares define an acoustical profile that shows how the SEL would vary with the longitudinal passby distance from the start of the acceleration event for a series of receivers offset at 50 feet from the center of the travel lane. Superimposed on the curve is the constant SEL for the 60 mph-passby event. To bracket the effect, the SEL of a constant 34 mph cruise event (not shown) would equal the low point of the acceleration SEL curve. Recalling the direct relationship between SEL and L_{eq}(1 hr), one can state that for this example, L_{eq}(1 hr) depends on the longitudinal distance and that use of the constant final speed would lead to prediction errors of as much as 7 dB.

The implication for more accurate STAMINA predictions is clear: either the acceleration road must be broken into a series of shorter length roads, each with its own emission level, or a receiver (or distance) dependent sound level adjustment must be developed. Neither alternative is attractive, the first from the user's perspective and the second from the programmer's perspective. However, if the number of shorter roads can be minimized, the first approach is the easiest to implement in the near term. This approach will be developed in more detail below.

Consideration of a Reduced-Length Roadway Approach

Currently STAMINA requires that road data be divided into "roadways" with traffic volumes and speeds that are constant throughout the length. A roadway may consist of 1 to 14 serial segments. The speeds define the vehicle emission levels, according to the FHWA Model equations and directly affect the traffic flow density adjustment. As was shown above, the SEL and hence L_{eq} depends on the speed of the vehicle when it passes the receiver. Thus, both descriptors depend on the receiver distance from the start of acceleration. Rudder presented data from Plotkin on the time-averaged emission levels averaged over the duration of the acceleration event, but for an observer moving along the vehicle; the data were shown earlier in Table B-1. A starting point in deciding how to break an acceleration road into smaller roadways is to examine this data in more detail. This will be done first assuming a constant rate of acceleration from 0-60 mph, and then for the 2-stage acceleration approximating the AASHTO curves.

The concept of a series of acceleration (or deceleration) roadways will be used throughout much of this Appendix. These roadways define an area where the emission levels are influenced by the acceleration or deceleration. The term zone of influence (ZOI) is used to define this region. More specifically, for the purposes of this study, this zone will be designated as an acceleration ZOI (AZOI) or

a deceleration ZOI (DZOI). Also, as each zone is broken into reduced-length segments, the segments will be described by an index number, such as AZOI(1), which would be the first "roadway" in an area where acceleration was modelled as having an effect on levels. Figure B-7 illustrates these various zones in a general sense.

Assuming Constant Acceleration from 0-60 mph.

Dividing into Two Segments Based on Speed Midpoint. If the rate of acceleration is constant, then speed increases linearly with time. Thus, the time to accelerate from 0-60 mph will be twice that to go from 0 to 30 mph. One may then ask if the time-averaged level for the period from 0-30 mph is 62.8 dB (the weighted average value in Table B-1 from the EPA data) and the time-averaged level for the period from 0-60 mph is 67.4 dB, what would be time-averaged level have to be for that portion of the time when the vehicle goes from 30 to 60 mph. Recall Eq. B-7 for energy-averaging the levels of n equal events (or equal time periods):

$$L(\text{total}) = 10 \log \left[\sum_{i=i}^{n}(1/n)\ 10^{0.1\,L(i)}\right] \qquad \text{(B-16)}$$

One needs to solve for L(30-60 mph) in the following expression:

$$L(\text{0-60 mph}) = 10 \log\left[(1/2)\{10^{[0.1L(\text{0-30 mph})]}+10^{[0.1\,L(\text{30-60mph})]}\}\right] \qquad \text{(B-17)}$$

or,

$$L(\text{30-60 mph}) = 10 \log\ \{2\text{x}10^{[0.1L(\text{0-60})]} - 10^{[0.1\,L(\text{0-30})]}\} \qquad \text{(B-18)}$$

$$L(\text{30-60 mph}) = 10 \log\ (2\text{x}10^{6.74} - 10^{6.28}) \qquad \text{(B-19)}$$

$$L(\text{30-60 mph}) = 69.6\ \text{dBA.} \qquad \text{(B-20)}$$

Thus, if the L_{eq} for the second half of a time period was 69.6 dB and the L_{eq} for the first half was 62.8 dB, the total L_{eq} would be 67.4 dB. It should again be pointed out that this L_{eq} is only for the duration of the event (i.e., the time to go from 0 to 60 mph) and for a receiver moving alongside the vehicle at a 50 foot offset.

Resulting Roadway Lengths. Therefore, one possibility in analyzing an acceleration lane is to divide it into two "roadways", assigning the first an emission level of 62.8 dB and second an emission level of 69.6 dB. It would be assumed that those levels would apply over the entire length of each roadway, and inherent in each would be a speed-dependent error at each end. The upper portion of Table B-2 illustrates, for an acceleration rate of 0.1 g, the distances a car would travel from a stopped position, and the resultant time to do so.

Thus, using the two roadway scheme in the way described above, the first roadway would be 300 feet in length and the second would be 900 feet long (1200 minus 300).

FHWA Model Speeds to Produce These Emission Levels. An appropriate average speed would have to be chosen for each segment to produce the 62.8 dB and 69.6 dB $(L_o)_E$ values. Using the FHWA Model equation for cars, those speeds would be 32 mph and 48 mph (51 and 77 kph).

Speeds Based on SEL and FHWA Model Assumptions. Using another approach, the needed speeds may be determined based on the SEL computed using a time-step simulation of the acceleration event illustrated in Figure B-7. Figure B-7 presents a series of these acceleration SEL and is similar to Figure B-6 except that the SEL are based on a constant 0.1 g acceleration rate. In Figure B-8, for passby distances of 50-300 feet, the computed SEL at a 50-foot distance offset are shown to range from 71 dB down to 68.5 dB. The equivalent constant speeds for passbys that would produce the same SEL may

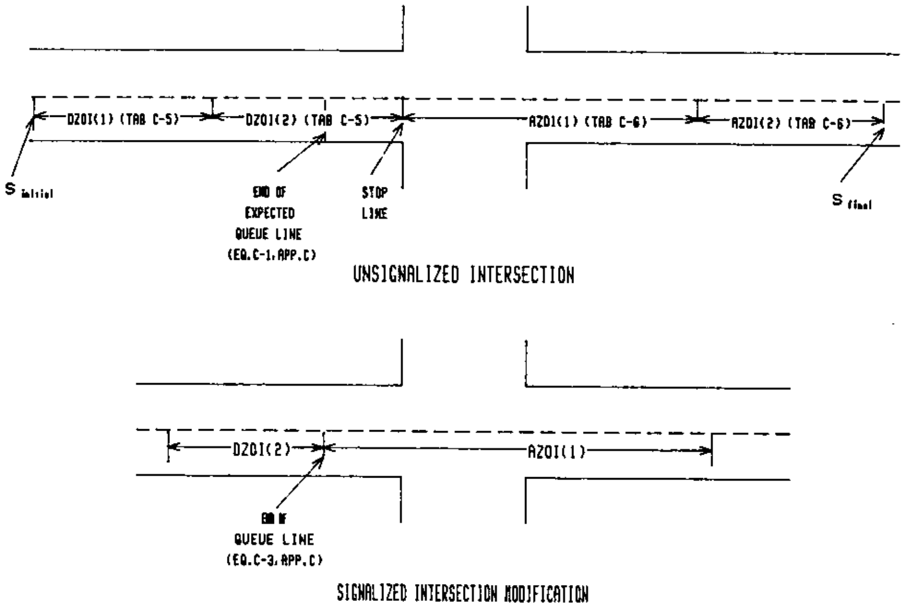


Figure B-7. Definitions of Zones of Influence for Unsignalized (Top) and Signalized (Bottom) Intersections

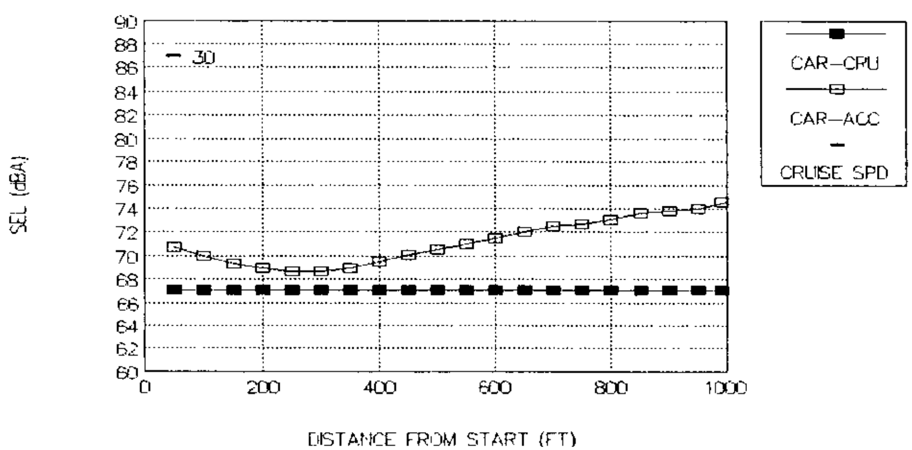


Figure B-8. SEL at Various Distances From Start: Car Cruise at 30 mph and Acceleration of 0.1 g at 62 dBA

be computed to range between 33 and 40 mph (55-65 kph). The expression for computing these speeds is developed below:

$$SEL = L_{eq}(1h) + 10 \log (3600 \text{ sec})$$

$$= a + b \log (S) + 10 \log [(\pi D_o^2)(3600 \text{ sec/hr})]/[(1000 \text{ m/km})(S)] \quad \text{(B-21)}$$

If $D_o = D = 15.2$ m, the expression becomes:

$$SEL = a + (b\text{-}10) \log (S) + 22.4 \text{ dB} \quad \text{(B-22)}$$

Letting a = -2.4 and b = 38.1 for automobiles yields

$$SEL = 28.1 \log (S) + 20.0 \text{ dB} \quad \text{(B-23)}$$

where S is in kph.

Based on Table B-2, it was noted that for the 30-60 mph range, the vehicle travels from a point 300 feet from start of acceleration to a point 1200 feet from start. The corresponding SEL in Figure B-8 range from 68.5 to 76 dB. Unfortunately, a 7.5 dB range from one end of a segment to another is too large to be modelled as a constant value. This indicates that either the second roadway needs to be divided into more roadways or the division point between the two roadways needs to be shifted further down the road.

Using FHWA Model Assumptions and SEL to Shift Break Point. Figure B-8 indicates that the predicted SEL at a 50-foot offset distance will range between 68.5 and 71.5 dB over distances of 50-600 feet, centered on values of 70 dB at 100 feet and again at 450 feet. Thus, the use of an SEL of 70 dB over this distance range of 50-600 feet would limit the error on either end of the roadway to ±1.5 dB. The equivalent constant speed that would produce an automobile SEL of 70 dB at 50 feet offset may be computed to be 38 mph (61 kph).

Then, for the second segment, running from 600 feet to 1200 feet, the acceleration SEL would range between 71.5 and 76 dB, with a mean of 73.8 dB. The equivalent constant speed for a 73.8 dB SEL may be computed as 51 mph (82 kph). Use of this constant speed for the 600-1200 foot roadway would give an error of ±2.3 dB at each end of the roadway. The acceptability of such an error depends on the importance of the acceleration ramp or lane relative to the rest of the study area. A lightly travelled ramp would produce a much lower $L_{eq}(1 \text{ hr})$ compared to a heavily travelled main road, to the point of the level from the ramp having no effect on the total level at a receiver. Likewise, once the percentage of trucks on the ramp increases to over 5 or 6%, a 2.3 dB error in the automobile emission level would make little difference in the predicted L_{eq} at 50 feet from the ramp.

Checking the Break Point with the EPA Data. The above analysis of splitting the acceleration road into two roads at the 600-foot point can be checked against the EPA data. Note first in Table B-2 that at a rate of 0.1 g a speed of 40 mph is reached at 548 feet, just short of the 600-foot point. It is therefore useful to consider the EPA time-averaged level for a 0-40 mph acceleration cycle, which is 64.1 dB. Again using the logic of Eqs. B-16 through B-20, one can compute the needed time-averaged level for the second roadway (the 40-60 mph portion of the acceleration cycle) that would lead to a total 0-60 mph time-averaged level of 67.4 dB.

Specifically, one can use the 18-second time to go from 0-40 mph and the 27-second time to go from 0-60 mph that are shown in Table B-2:

$$L(0\text{-}60 \text{ mph}) = 10 \log [(1/27) \{18 \times 10^{[0.1 L(0\text{-}40 \text{ mph})]} + 9 \times 10^{[0.1 L(40\text{-}60)]}\}] \quad \text{(B-24)}$$

Rearranging and solving for L(40-60 mph) yields:

$$L(40\text{-}60 \text{ mph}) = 10 \log [(1/9)(27 \times 10^{6.74} - 18 \times 10^{6.41}] = 70.5 \text{ dB} \quad \text{(B-25)}$$

Constant Speeds to Produce the EPA Emissions Levels. A 70.5 dB emission level, using the FHWA Model equation, would be produced by a car travelling at 51 mph (82 kph). This speed is identical to that computed from the 73.8 dB SEL in Figure B-8 for the 600-1200 foot segment. The SEL in Figure B-8 were based on an acceleration model where the emission level at any speed during acceleration followed the FHWA Model equation.

The 64.1 dB level for the 0-40 mph roadway would be produced using a speed of 35 mph (56 kph) in the constant speed FHWA Model emission level equation. The speed computed using the acceleration SEL calculation method was 38 mph (61 kph). The average of these two speeds is 36.5 mph (59 kph).

The authors believe that this two-roadway approach will give acceptably accurate results in most cases of normal traffic situations.

Summary of the Constant Acceleration Approach. To summarize, if using a constant automobile acceleration rate of 0.1 g from 0-60 mph:

1. break the acceleration zone into two equal length roadways;
2. use a constant speed of 36.5 mph for the first half;
3. use a constant speed of 51 mph for the second half;
4. the possible error from using a constant speed for receivers near the first "roadway" at an offset of 50 feet will be on the order of ±1.5 dB, being a function of receiver distance along the ramp from the start line;
5. the possible error for receivers offset 50 feet from the second "roadway" will be on the order of ±2.3 dB, with overprediction toward the beginning of the roadway and underprediction toward the end of the roadway. In an actual modelling situation, the total error will be less because of the smoothing effects on the received level caused by other roadways that are included in the scenario.

If one felt the need for more accuracy in an acceleration zone, the zone could be divided into more roadways, using the EPA data. That data may be used to determine the time-averaged level for each 10 mph band during a constant 0.1 g acceleration from 0-60 mph. The results of such calculations are shown in the upper half of Table B-3.

The distances and durations used in the above analysis were based on the authors' use of a 0.1 g acceleration rate. The methodology may be used with other rates as deemed appropriate by the reader. The use of other rates is illustrated in the next section.

Use of a Two-Step Acceleration Rate Based on Time-Averaged EPA Emission Levels. The previous discussion on breaking an acceleration road into two segments was based on a constant acceleration rate of 0.1 g. This rate is higher than that in the AASHTO curve.

Use of different acceleration rates will directly affect the time to reach a given speed, as well as the distance travelled, thus affecting decisions on where to split a roadway for noise modelling purposes. To illustrate this, the discussion of the previous section will be modified based on an acceleration rate of 0.083 g from 0 to 30 mph and 0.05 g from 30-60 mph. These values may be approximated by examining the AASHTO curve [AASHTO, 1984; p. 784].

Break Point at Midpoint of Speed Range. Recall first that Table B-1 showed a weighted average L_{eq} of 62.8 dB for an observer moving alongside a car accelerating from 0-30 mph, and an L_{eq} of 67.4 during a 0-60 mph acceleration event. However, in the case of varying acceleration rates, speed will not increase linearly from 0-60 mph. For the mixed case of 0.083 g and 0.05 g rates, an automobile would travel different distances in different times for each 10 mph increase in speed. These values are shown in the lower half of Table B-2.

TABLE B-3 -- TIME-AVERAGED AUTOMOBILE EMISSION LEVELS FOR INTERMEDIATE ACCELERATION ZONES FOR TWO-STEP ACCELERATION RATES (COMPUTED FROM EPA DATA, ASSUMING 0.083 G TO 30 MPH; 0.05 G TO 60 MPH)

Speed Range (mph)	Time-Averaged Level (dB)	Duration in This Range (sec)	Distance Travelled in This Speed Range (ft)
0-20	60.9	11.0	161
20-30	65.1	5.5	201
30-40	65.9	9.0	434
40-50	68.6	9.0	663
50-60	70.7	9.0	727

TABLE B-4 -- COMPUTED ACCELERATION SEL AT VARIOUS DISTANCES BASED ON THE EPA DATA

Longitudinal Distance (ft)	Speed at That Distance (mph)	Computed Acceleration SEL (dB)	Delta-SEL re Predicted Cruise SEL*
50	11.0	70.3	-1.0
160	20.0	70.1	-1.2
360	30.0	70.9	-0.4
740	38.0	70.8	-0.5
800	40.0	71.2	-0.1
1000	43.5	72.3	+1.0

* Cruise speed of 42 mph

TABLE B-5 -- AUTOMOBILE ACCELERATION ZONES OF INFLUENCE

Speed Range mph	L_{max} at Cruise (dB)	SEL at Cruise (dB)	First Acceleration Zone Length (ft)	First Acceleration Zone Speed (mph)	First Acceleration Zone SEL (dB)	Second Acceleration Zone Length (ft)	Second Acceleration Zone Speed (mph)	Second Acceleration Zone SEL (dB)
0-30	61.7	67.1	500	38	70.0	none	n/a	n/a
0-35	64.3	69.0	600	39	70.4	none	n/a	n/a
0-40	66.5	70.7	800	40	70.7	none	n/a	n/a
0-45	68.5	72.2	1000	42	71.3	none	n/a	n/a
0-50	60.2	73.5	1000	42	71.3	1400	48	73.0
0-55	71.8	74.7	1000	42	71.3	1800	50	73.5
0-60	73.1	75.9	1000	42	71.3	2200	53	74.2

One can compute the time-averaged level between 30 and 60 mph as:

$$L(30\text{-}60 \text{ mph}) = 10 \log \{[1/(44-16.5)][44 \times 10^{(67.4/10)} - 16.5 \times 10^{(62.8/10)}]\} \quad \text{(B-24)}$$

$$L(30\text{-}60 \text{ mph}) = 68.8 \text{ dB} \quad \text{(B-25)}$$

Thus, a time-averaged level of 62.8 dB from 0-30 mph and a time-averaged level of 68.8 dB from 30-60 mph would result in a time-averaged level of 67.4 dB from 0-60 mph. The average constant speeds to produce emission levels of 62.8 and 68.8 dB may be computed as 32 mph and 46 mph (51 and 74 kph).

Thus, one possibility is to split the roadway at the 362-foot point and use constant speeds of 32 mph in the first half and 46 mph on the second half. However, the 6 dB difference in the two time-averaged emission levels may be too large for accurate modelling.

Break Point Based on SEL Computed With FHWA Model Assumptions. It is therefore useful to re-examine Figure B-6, which was based on the 2-step acceleration rate. One may observe that over a distance range of 50-1000 feet, the calculated SEL ranged from 71 dB down to 68.3 dB and back up to 71.6 dB, centered on 70 dB. Thus, use of a constant 70 dB emission level over this distance would result in maximum errors of ± 1.7 dB. The needed constant speed to produce a 70 dB SEL using the FHWA Model equations is 38 mph.

While not shown on the figure, the SEL from the accelerating auto would equal that of the cruise auto (76 dB) when the accelerating auto reached a speed of 60 mph, which would occur at a distance of 2186 feet. Thus, the SEL would range from 71.6 dB at 1000 feet to 76.0 dB at 2186 feet, for a mean value of 73.8 dB (at 1550 feet). An equivalent speed to produce a 73.8 dB SEL is 51 mph (82 kph). As with the previous discussion on a constant acceleration rate, the acceptability of a ± 2.2 dB error at either end of the section due to the use of the 73.8 dB value depends on the situation.

The authors believe that such an error will typically be quite acceptable because of the generally larger contributions that will reach an observer from heavy trucks or higher speed traffic on other roadways.

Summary of Two-Step Acceleration Rate Approach Based On EPA Time-Averaged Levels. To summarize, for a 2-step acceleration rate of 0.083 g from 0-30 mph and 0.05 g from 30-60 mph:

1. break the roadway into two roadways, the first being 1000 feet long;
2. use an approximate speed of 35 mph for the first roadway;
3. use an approximate speed of 50 mph for the second roadway.

For intermediate speed changes, the time-averaged levels in the lower portion of Table B-3, computed from the EPA data, may be used. Again, by the EPA definition, these emission levels are for an observer moving alongside the vehicle at a 50-foot offset distance. As such, they could be used to approximate the maximum energy-averaged level for a pass-by of a stationary observer at 50 feet, and could be assumed to apply for the full length of the segment.

Use of a Two-Step Acceleration Rate Based on SEL Computed From the EPA Data. The above discussions for both the constant acceleration rate and the 2-step acceleration rate were based on only considering the EPA data as time-averaged emission levels, without examining what those levels would produce in terms of SEL. The discussion that was presented on SEL was based on the FHWA Model report assumptions:

1. $(L_o)_E = 38.1 \log (S, \text{kph}) - 2.4$ dB for S greater than 50 kph
2. $(L_o)_E = 62$ dB for S less than or equal to 50 kph (31 mph)

However, the EPA data in the lower portion of Table B-3 does not support the second assumption when broken into intermediate speed bands. The time-averaged level from 20-30 mph was computed as 65.1 dB for a 0.083 g acceleration rate, which was 3.1 dB above the 62 dB FHWA assumption.

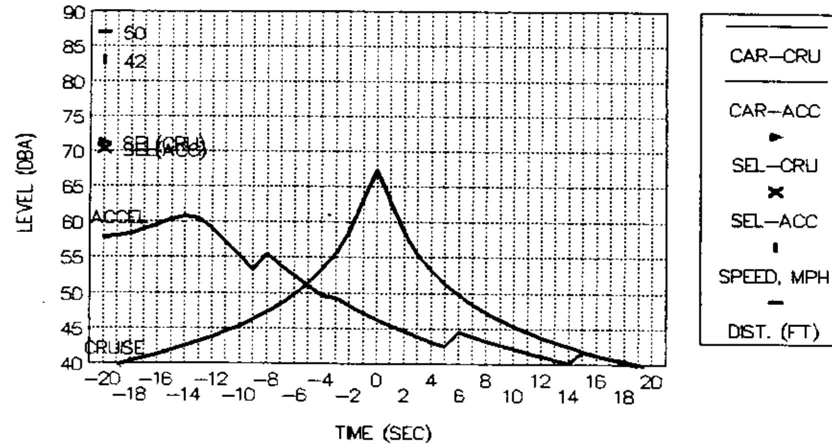


Figure B-9. Time History of Car Cruise and Acceleration (Speed at 42 mph; Distance = 50 ft)

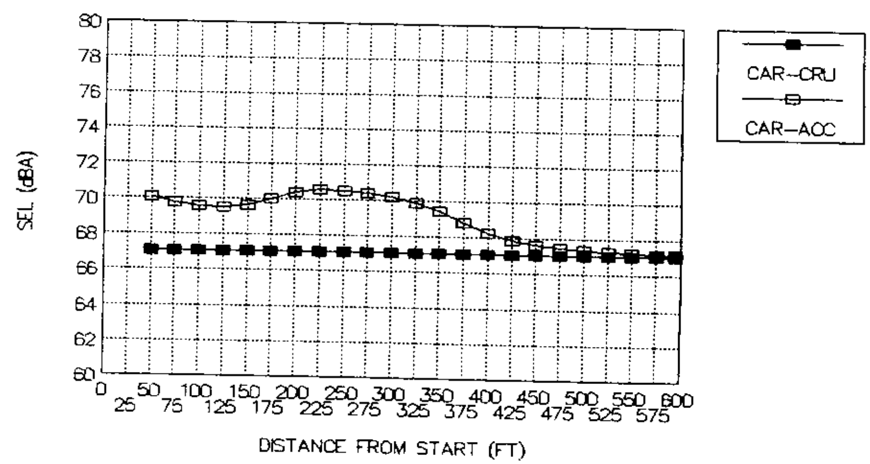


Figure B-10. SEL at Various Distances From Start: Car Cruise at 30 mph and Acceleration per EPA Levels

Computation of SEL. To try to better simulate the production of an SEL at any distance from start so that the best roadway split point could be determined, the time-step model that was used to generate Figures B-1 to B-5 was modified as follow. At each second of the event, a speed and a distance from start were computed. If the speed was between 0 and 20 mph, the EPA emission level of 60.9 dB (from Table B-3) was assigned to the vehicle at that distance. If the speed was between 20 and 30 mph, the level of 65.1 dB was assigned. Likewise, the other data in the lower portion of Table B-3 were applied, as appropriate, up to the final speed of 60 mph.

Then, based on the distance from start for each second of the event, and the corresponding emission level at that distance, an SEL could be computed at any distance from start for an offset distance of 50 feet. The resulting SEL could be examined to determine an appropriate equivalent constant speed that would produce a similar SEL.

The Resultant Constant Speed. Calculations were made for a variety of constant speeds, starting with the 38 mph value from the previous section. However, this speed underpredicted the acceleration SEL based on the EPA date by 0.1 to 2.3 dB over longitudinal distances of up to 1000 feet. A speed of 42 mph was found to give the best results, i.e., an SEL of 71.3 dB at a 50 foot offset.

Figure B-9 overlays the time history of a constant 42 mph event on an accelerating event at a distance of 50 feet from the start. The secondary peaks in the acceleration curve simply result from use of a stepped emission level. They do not imply phenomenon such as gear shift changes, and would not show up in real life. The SEL for 42 mph cruise event is shown as 71.3 dB; the acceleration SEL at the 50-foot longitudinal distance is 70.3 dB. The speed of the accelerating car is 11 mph at the passby point.

The same acceleration event was examined at other longitudinal distances from start, specifically at those distances where the speed was 20, 30, 40 and 42 mph, and at 1000 feet, the recommended roadway break point from the previous section. The results are shown in Table B-4. Use of a speed of 42 mph to represent the SEL on a 0-1000 foot range would result in errors of -1.2 dB to +1.0 dB.

Roadway Break Points for 0-60 mph Event. This discussion has been for a 0-60 mph acceleration event with a roadway break point at 1000 ft. A constant equivalent speed for the first roadway of 42 mph would simulate the level predicted by the stepped EPA emission level data to an accuracy of about ±1 dB.

Beyond the 1000 foot point, a second acceleration roadway needs to be defined. The car would reach the final speed of 60 mph, at about 2200 feet according to the AASHTO curve. An appropriate equivalent speed must be chosen for the second roadway. Choice of a speed depends on the final speed. Using the time-step simulation model, the SEL were computed using the FHWA emission level equation for cruise and the EPA stepped data for acceleration. Examination of that data for the 1000-to-2200 foot roadway indicates the constant equivalent speed should be chosen as 50 mph. This speed will result in an SEL of 73.5 dB, roughly halfway between the 71.3 dB SEL at 42 mph and a 75.9 dB SEL at 60 mph, yielding a -2.2, +2.4 dB error.

Other Speed Situations. In cases where the final speed is less than 60 mph, other rules will apply in defining zones of influence. For a final speed of 30 mph, the EPA data in Table B-3 gives acceleration emission levels of 60.9 dB between 0 and 20 mph, and 65.1 dB between 20 and 30 mph. These emission levels will result in a calculated SEL on the order of 70-71 dB. If the final cruise speed is 30 mph, the FHWA Model equation predicts an emission level of 61.7 dB, which is 3.4 dB below the EPA acceleration level from 20-30 mph. While such a sudden decrease from 65.1 to 61.7 dB will not happen in reality as the vehicle crosses the 30 mph speed point, the differences reflect the influence of increased engine noise during acceleration below 30 mph. The effects of the various emission levels on SEL are shown in Figure B-10. This figure plots SEL for a 30 mph cruise event overlaid on the SEL of a 0-30 mph acceleration event as a function of distance from the stopline (offset distance of 50 feet). From this figure, a reasonable judgment can be made that the first roadway should be 0-500 feet long. Beyond 500 feet, a cruise speed of 30 mph should be used. The constant equivalent speed for the 0-500 foot roadway should still be 42 mph to achieve the desired acceleration SEL of 70-71 dB.

In a similar manner, other final speeds between 30 and 60 mph were examined. Table B-5 shows the resulting rules for determining zone of influence break points and equivalent speeds. The errors from the use of the constant speeds compared to the stepped EPA data are about 1 dB or less for the first roadways. For the second roadways, the errors will be under ±2 dB.

Summary of Predictive Analysis. Three examinations were made of ways to divide an automobile acceleration zone into two pieces, based on a mean SEL for each that would minimize errors at each end of each piece. To allow use of the FHWA Model for predicting accelerating automobile noise levels, equivalent constant speeds that would produce the same SEL were computed.

The three approaches showed that for a 0-60 mph acceleration zone, the use of two roadways will give acceptable results if the breakpoint for the two roadways is between 600 and 1000 feet from start. The greater the length of the first roadway, the less the potential error will be at the endpoints of the second roadway.

The use of the 2-step acceleration rate was more in line with the AASHTO acceleration curve, but the authors believe that curve shows lower acceleration rates than might be expected, especially on acceleration ramps to highways.

Use of a 1000 foot break point with a constant equivalent speed of 42 mph will give SEL, and hence L_{eq}(1 hr), within ±1 dB at either end of the segment. This error is greater than would be observed at any given observer when the contributions from any other roadways are included in the total calculated level at the observer.

For the second roadway, choice of an ending distance depends on the final speed. For a speed of 60 mph, that point would be about 2200 feet from the start of acceleration. For final speeds under 40 mph, only one roadway need be defined. Use of a 40 mph speed will produce SEL comparable to those computed for the accelerating vehicles.

It should be pointed out that this discussion has been limited for automobiles. When the other sources are also considered, it will be shown that it is desirable to shift speeds and midpoints to minimize the number of roadways being defined.

Measured Accelerating Automobile Noise Levels

The major thrust of the data collection was aimed at heavy trucks because they are the loudest vehicle type. Nonetheless, a limited amount of automobile emission level data was collected during this study. A convention was established for naming measurement points. Essentially, each point is called a "site." It is given a label that describes the mode of operation, the direction of travel and the distance from the stopline. For example, a site named AE110 is in an Acceleration zone, with the traffic in the near lane heading Eastbound at 110 feet from the stopline. The distance designator is excluded from the cruise site labels.

On 10/7/88, a sample of approximately thirty accelerating automobiles was measured at three sites downstream from a stop sign at Post Road and Davidson Road in Nashville (see Figure 3 in main text). Additionally, approximately 40 automobile cruise sound levels were measured on 10/5/88 at 0.5 miles downstream from these sites on Post Road. Speed data were collected separately at each location. The sound level data are summarized in Figure B-11 as mean levels plus/minus one standard error.

In addition to the approximately 30 individual samples at each acceleration site, the data were paired up where possible to compare the same vehicle's levels from point to point. From 24 to 27 comparisons could be made between both the SEL and L_{max} at each combination of two of the three acceleration sites. The statistical analyses of those comparisons, as well as of the comparisons of the unpaired data means at each site are discussed below.

The mean SEL at three acceleration sites ranged from 66 dB at site AE110 to 68 dB at site AE170 to 67.8 dB at AE270, compared to a mean SEL of 70.4 dB at the cruise site. The mean SEL

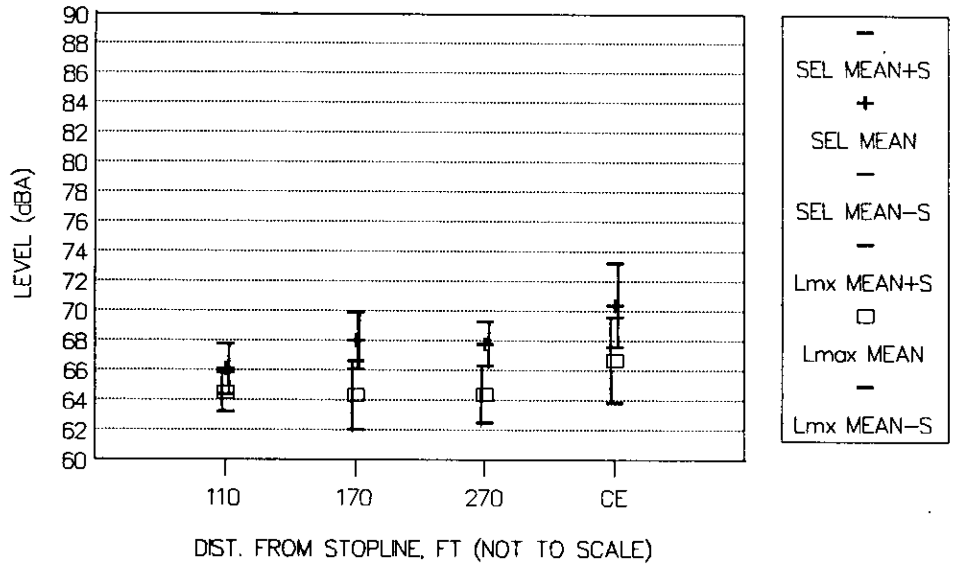


Figure B-11. Mean and Standard Error of Automobile Data: SEL and L_{max}, 10/07/88, Post Road (eastbound)

TABLE B-6 -- AUTOMOBILE ENERGY MEAN EMISSION LEVELS COMPUTED FROM MEASURED L_{MAX}

Site	L_{max} Mean (dB)	L_{max} S.E. (dB)	$(L_o)_E$ (dB)	Speed Mean (mph)	Speed S.E. (mph)
AE110	64.5	1.3	64.7	20	1.9
AE170	64.3	2.3	64.9	25	2.3
AE270	64.4	1.9	64.8	29	2.4
CE	66.7	2.9	67.7	42	4.4

differences between AE110 and AE170, and between AE110 and AE270 are significant at the 5% level of significance. The mean difference between AE170 and AE270 is not statistically significant. The lower mean SEL at site AE110 may be in part due to measurement difficulties at site AE110. Interference from traffic on the cross street made it very difficult to obtain valid SEL measurements for vehicles on Post Road. Examination of the data shows the sampled event durations to be consistently 1-2 seconds shorter than the other sites, which would all else being equal, result in a lower SEL. In reality, the duration of the event should be slightly longer, because of the somewhat slower speed at AE110. The comparisons to the SEL at the site should thus be viewed with caution, and any differences regarded as worst case upper limits.

This observation is borne out in the comparisons of the L_{max} means and in the tests of the means of the L_{max} paired differences. In all cases, the means were not different at the 5% level of significance and the mean paired differences were not significantly different from zero.

If one were to make, for the moment, an assumption of constant speed, reference energy mean emission levels could be computed from the mean L_{max} by:

$$(L_o)_E = L_{max} + 0.115s^2 \quad \text{(B-26)}$$

The results are in Table B-6. At the cruise site, an average speed of 42 mph yields an $(L_o)_E$ of 67.3 dB according to the FHWA Model automobile emission level equation. This compares very well with the measured $(L_o)_E$ of 67.7 dB, supporting use of the FHWA Model at cruise speeds in the 40 mph range. At speeds below 30 mph, the FHWA Model report recommends use of a 62 dB emission level [Barry and Reagan, 1978; p. I-1]. That value appears to be about 3 dB lower than this study's sample for accelerating automobiles. However, as shown earlier in Table B-1, the EPA combined automobile time-averaged levels from Rudder (weighted by fleet mix) were 60.9 dB for a 0-20 mph acceleration event and 62.8 dB for a 0-30 mph event. From the lower portion of Table B-3, the time-averaged level for acceleration from 20 to 30 mph computed from the EPA 0-20 mph and 0-30 mph data is 65.1 dB. This matches extremely well with the measured $(L_o)_E$ of 64.9 dB at site AE170 where the mean speed was 25 mph (midway within the 20-30 mph range). Thus, support for use of the Table B-3 values is gained. At point AE110, the measured $(L_o)_E$ of 64.7 dB is 3.8 dB higher than Rudder's value for a 0-20 mph event; however, the speed at point AE110 was 20 mph, and would thus be at the high end of this range, with a corresponding higher level than the average.

The mean measured SEL at sites AE170 and AE270 were both about 68 dB. The distances from the stopline at these two sites were 170 and 270 feet. Returning to Figure B-10, which plotted a SEL versus distance from stopline for a two-step acceleration rate using the EPA time-averaged levels in each speed range, one notes an SEL at these distances of about 70 dBA. The 2 dB difference may be attributed in part to traffic conditions that caused the sample durations to be shorter than desired. Thus, the sample of measured automobile acceleration levels offers some support of the use of the EPA data at low speeds and the FHWA Model equation for cruise.

DECELERATING AUTOMOBILES

EPA Data and Intermediate Values

The EPA study presents a useful set of automobile deceleration levels [Rudder, 1979; p. 3-14 to 3-16 and p. A-83 to A-88]. As with acceleration, the data are time-averaged over a full deceleration event for an observer moving alongside the vehicle. The deceleration events range from 20-0 mph to 60-0 mph. Time-averaged levels for intermediate speed ranges may be computed from that data if a deceleration rate is assumed. The AASHTO Green Book [AASHTO, 1984; p. 36] provides automobile deceleration distances as a function of initial and final speeds based on "comfortable" deceleration rates (as well as minimum braking distances for wet and dry pavement). These data support use of a constant deceleration rate of about -0.18 g. Table B-7 shows the EPA data and the intermediate speed range time-averaged levels based on that deceleration rate.

The 60-0 mph Case as an Example

Consider the deceleration event for a speed of 60 mph. The FHWA Model cruise level for 60 mph would be 73.1 dB. From Table B-7 the time-averaged deceleration levels for the intermediate range speeds fall 1.4 to 21.8 dB below this level. (As a lower limit, the EPA data showed an idle level of 46 dB, about 25 dB below the 60 mph level). Clearly the difference is speed-dependent (being strongly dependent on tire noise). Ideally, the adjustment for deceleration levels should be defined as a function of speed (or distance from start of deceleration). Such an adjustment would require fundamental changes in the STAMINA code.

Use of Equivalent Speeds. A possible alternative is to examine the data and select constant equivalent speeds that best approximate the deceleration event. The data suggests that for a 60-0 mph event, it would be ideal to break the road into five deceleration roadways (at the 10 mph points). While this would limit the change in levels from one roadway to the next, it is totally impractical, especially given that the AASHTO data show full deceleration from 60 mph to a stop will occur in only about 470 feet. Such a procedure is not recommended unless a particular analysis problem demanded such attention.

Defining a Break Point for Roadways. Examination of the data suggests that the greatest change in level occurs in the last stages of deceleration. The level drops 12 dB from 60 mph to the 30-20 mph band, but then drops an additional 9.5 dB from that band to the 20-0 mph band (with a further 3 dB drop to the idle level). These decreases suggest that, if one wishes to minimize deceleration roadways, then a possible split is at the 20 mph speed point. The AASHTO curves show that deceleration from 20-0 mph will occur in a distance of about 80 ft. Thus, for the 60 mph case, the first automobile deceleration roadway would begin at 470 feet from the stopline and end at 80 feet from stop. The second deceleration roadway would run from 80 feet down to the stopline.

To further define these roadways, a series of calculations was made. First, it was noted that the difference in emission levels between cruise at 60 mph and the 30-20 mph band was 12.3 dB (73.1 - 60.8 dB). An equivalent speed was computed that would split this difference to minimize errors at either end. That speed was 41 mph, and would result in an L_{eq} about 4 dB below the 60 mph L_{eq}. The second roadway, representing a speed change of 20 to 0 mph (from 80 feet out to the stopline), had a time-averaged emission level of 21.8 dB below the 60 mph emission level. A constant speed of 18 mph would produce an emission level about 20 dB down from the 60 mph level, with a resultant L_{eq} about 15 dB below the L_{eq} at 60 mph. Thus, a first approximation for a flow of automobiles decelerating from 60 to 0 mph is:

1. first deceleration roadway from 470 feet to 80 feet, with an equivalent speed of 41 mph;
2. second deceleration roadway from 80 feet to the stopline, with an equivalent speed of 18 mph.

Other Deceleration Ranges

Examination of the data for deceleration events with initial speeds below 60 mph supports the splitting of the deceleration road at the 20 mph point (80 feet from stopline) with the equivalent speed of 18 mph for the 20-0 mph section. Table B-8 presents how the deceleration road would be broken into these two deceleration zones of influence. The lengths for the first roadway were determined by examining the AASHTO passenger car deceleration curves [AASHTO, 1984; p. 36].

After discussions of medium and heavy trucks, this Appendix will address how these zones of influence may be modified in consideration of the other vehicle types and contributions of adjacent roadways.

MEDIUM TRUCKS

During the course of the heavy truck measurements, a limited amount of medium truck data was also collected. In general, most attempts to measure clean medium truck passbys were ruined by noise from heavy trucks at the weigh station or vehicles in the main lanes (see site sketch as Figure 5 in main text). The focus of the medium truck analysis, however, was on the data presented by Rudder in the EPA

TABLE B-7-- TIME-AVERAGED LEVELS FOR AUTOMOBILE DECELERATION BASED ON EPA DATA (ASSUMING CONSTANT DECELERATION)

Speed Range (mph)	Time-Averaged Level (dB)*
60-0	66.6
50-0	64.0
40-0	60.9
30-0	56.9
20-0	51.3
60-50	71.7
50-40	68.8
40-30	65.4
30-20	60.8

*Weighted by % of fleet for seven vehicle types (see [Rudder, 1979] for details)

TABLE B-8 AUTOMOBILE DECELERATION ZONES OF INFLUENCE

Speed Range mph	L_{max} at Cruise (dB)	SEL at Cruise (dB)	First Deceleration Zone Length (ft)	First Deceleration Zone Speed (mph)	First Deceleration Zone SEL (dB)	Second Deceleration Zone Length (ft)	Second Deceleration Zone Speed (mph)	Second Deceleration Zone SEL (dB)
60-0	73.1	75.9	370	41	71.0	80	18	60.8
50-0	70.2	73.5	260	38	70.0	80	18	60.8
40-0	66.5	70.7	150	34	68.6	80	18	60.8
30-0	61.7	67.1	90	29	66.7	80	18	60.8
20-0	51.3	62.1	80	18	60.8	--	--	--

National Exposure Model. Both the field measurement results and the EPA data are discussed in the next sections.

Medium Truck Cruise Levels

Eleven medium trucks were sampled at the cruise sites. The range in SEL was 80.7-89.0 dB. The mean SEL was 84.8 dB, with a standard error of 2.5 dB, for a 95% confidence limit on the mean of 1.5 dB. The energy-averaged SEL was 85.5 dB. The mean L_{max} was 83.5 ± 2.7 dB with a 1.6 dB 95% confidence limit on the mean. The range was 79-87.9 dB, and the energy average of the L_{max} values was 84.3 dB. These data are summarized in the top portion of Table B-10.

The measured L_{max} energy average may be compared to the FHWA Model energy mean emission level, where the equation for medium trucks is:

$$(L_o)_E = 33.9 \log (\text{speed, kph}) + 16.4 \text{ dB} \quad \text{(B-27)}$$

For a sampled average speed of 96 kph for all trucks, this equation gives an $(L_o)_E$ of 83.6 dB, about 0.7 dB below the sampled value.

Medium Truck Accelerating Noise Levels

Measured Data. During the heavy truck sampling on 7/11, fifteen SEL were measured at the three sites for nine medium trucks (five of the trucks were measured at both sites AS175 and AS365, one was measured at all three sites). Twelve L_{max} were also obtained. On 10/18, four more medium trucks were sampled at site AN75. The SEL ranged from 78.2 to 88.4 dB; the L_{max} ranged between 70.6 and 84.9 dB. The center portion of Table B-9 summarizes the acceleration data, which are shown in Figure B-12.

Combining the 19 SEL yields a mean SEL of 81.8 ±2.9 dB (1.3 dB 95% confidence limit), with an energy averaged SEL of 82.8 dB. Combining the 16 L_{max} gives a mean L_{max} of 75.9 dB with a standard error of 3.9 dB (95% confidence limit of 1.9 dB). The energy-averaged L_{max} is 77.9 dB (which would be equivalent to that of a medium truck cruising at about 40 mph (65 kph), according to the FHWA emission level equation).

The measured energy averaged combined acceleration SEL of 82.8 dB for medium trucks was 2.7 dB below the measured combined cruise SEL of 85.7 dB. This 2.7 dB difference is consistent with a 2.1 dB difference observed for the large sample of combined heavy truck SEL data that will be discussed later in this Appendix.

EPA Data and Intermediate Values. The previously-discussed EPA study again provides a good data base for use in this work [Rudder, 1979]. Rudder presents time-averaged levels, based on Plotkin's measurements for acceleration zones of 0-20 mph up to 0-60 mph for an observer moving along with the vehicle. Using the method described for automobiles, the time-averaged levels for intermediate speed ranges may be computed. Table B-10 presents the EPA levels and the intermediate range levels.

If one assumes that the intermediate range levels are good approximations of the energy-averaged passby level for a stationary observer at any point along the roadway defined by that intermediate speed range, then passby SEL may be computed. Figure B-13 presents the results of one such set of calculations (the data series with the vertical line markers), showing SEL of an accelerating medium truck computed for a 50-foot offset receiver as a function of distance from the stopline. Overlaid on the curve is the constant SEL of 82.7 dB from a constant speed of 43 mph (open square markers), computed from the FHWA Model equation for medium trucks. The constancy of the calculated acceleration SEL is remarkable: use of the 43 mph FHWA Model cruise speed models the acceleration SEL to within 1 dB from 100 to 1600 feet from the stopline. Thus, for a final cruise speed of about 45 mph, only one acceleration roadway needs to be defined. For greater final speeds, a break point needs to be defined. The AASHTO acceleration curves for cars and heavy trucks indicate that those vehicle types reach 45 mph at about 1050 and 3000 feet, respectively [AASHTO, 1984; p. 784]. Other AASHTO data indicate that "single unit" truck acceleration rates are slightly higher than the average of those for "passenger cars" and

TABLE B-9 -- SUMMARY OF MEASURED MEDIUM TRUCK NOISE DATA

Site	SEL Mean (dB)	SEL S.E. (dB)	SEL No. of Samples	L_{max} Mean (dB)	L_{max} S.E. (dB)	L_{max} No. of Samples
			CRUISE DATA			
CS	84.8	2.5	11	83.5	2.7	11
			ACCELERATION DATA, 7/11/88, 10/10/88			
AN75	79.3	2.7	4	72.4	2.0	4
AS175	81.5	2.2	7	75.5	3.3	6
AS365	82.9	2.0	6	77.6	1.9	4
AS610	84.9	3.5	2	80.6	4.3	2
			DECELERATION DATA, 7/15/88, 9/6/88			
DS475	77.3	2.7	4	71.9	3.3	4
DS435	76.1	1.4	5	71.9	2.0	5
DS375	75.1	6.0*	4	71.0	6.8**	4
DS255	75.1	1.8	4	--	--	-
DS175	76.0	--	1	70.0	--	1

*Range of 67 to 82 dB for 4 events.
**Range of 64 to 82 dB for 4 events.

TABLE B-10 -- TIME-AVERAGED LEVELS FOR MEDIUM TRUCK DECELERATION BASED ON EPA DATA (ASSUMING CONSTANT DECELERATION)

Speed Range (mph)	Time-Averaged Level (dB)
60-0	75.9
50-0	73.2
40-0	69.9
30-0	65.7
20-0	59.5
60-50	81.1
50-40	78.2
40-30	74.5
30-20	69.7

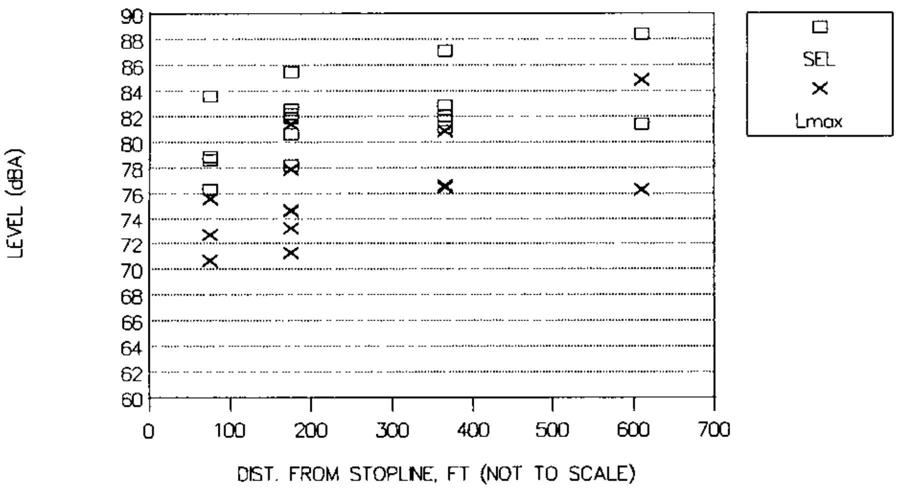


Figure B-12. SEL and L_{max} vs. Distance: Medium Truck Acceleration, 75 ft - 610 ft from Stopline

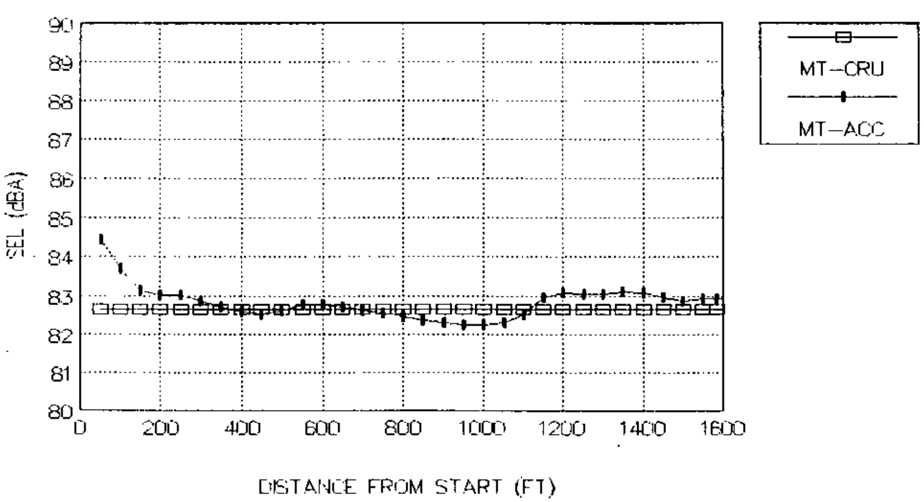


Figure B-13. SEL at Various Distances from Start: Medium Truck Cruise = 43 mph; Acceleration per EPA Data, 0.07 g

"WB-50" tractor trailers [AASHTO, 1984; p. 783]. Thus, if one only considered medium trucks, a break point of just over 2000 feet is suggested. Combining the results for all three vehicle types will be discussed later in this appendix.

Medium Truck Deceleration Levels

Measured Data. Several medium trucks were also measured during the heavy truck deceleration measurements on 7/15 and 9/6. Figure B-14 shows the SEL and L_{max} deceleration data as a function of distance from the stopline. The four events at the 475 and 375-foot sites (DS475 and DS375) represented paired readings for four medium trucks; one of the same trucks was also measured at DS175. Four of the five events at DS435 on 9/6 were paired with the four SEL measured at DS255.

Even with this small sample, the scatter in the data is large, which is consistent with previous researchers' findings. This scatter is especially evident when looking at paired differences. For the four trucks measured on 7/15 at DS475 and DS375, the SEL at DS475 ranged from 2.1 dB below to 9.5 dB above the level at DS375 (the L_{max} range was- 4.4 dB to 7.7 dB). Likewise, the 9/6 paired differences from DS435 to DS235 showed a range of -0.6 dB to 3.0 dB. The one medium truck that was measured at the cruise site as well as DS435 and DS255 showed an SEL that was 6.2 dB above the SEL at DS435 and 9.2 dB above the SEL at DS255.

Combining the SEL data at all of the deceleration points gave a mean SEL of 75.9 ± 3.4 dB. The combined L_{max} was 71.7 dB ± 4.3 dB. Recall that the mean SEL for medium truck cruise was 84.8 ± 2.5 dB and the mean L_{max} was 83.5 dB. Thus, the SEL was 8.9 dB lower than the cruise SEL and the L_{max} was 11.8 dB below the cruise L_{max}. The 8.9 dB difference in SEL compares well with an 8.6 dB difference found for heavy trucks to be discussed later in this appendix.

EPA Data and Intermediate Values. As with accelerating medium trucks, the EPA data base proves useful. Table B-10 presents the EPA data for deceleration events from 60-0 mph down to 20-0 mph in 10 mph increments. Also shown are the intermediate speed range values (i.e., when the final speed was not 0 mph) calculated from this data and based on the assumption of a constant deceleration rate (and hence, equal time in each 10 mph band).

The large range in the levels is consistent with that found for automobiles, especially the large drop in the final 20-0 mph stage of deceleration. It is therefore useful to consider two deceleration segments -- from the cruise speed down to 20 mph, and from 20 mph down to 0 mph. A series of equivalent speeds may then be computed to minimize the errors at either end of these deceleration segments. Table B-11 presents these data. Deceleration ramp design length data from AASHTO are used to define zone lengths [AASHTO, 1984; p. 1044].

Integration of the medium truck data with the other vehicle types is discussed later in this appendix.

HEAVY TRUCKS

The main focus of the data collection effort was on heavy trucks due to their usually substantial contribution to the total noise levels at wayside observer points.

Measured Heavy Truck Cruise Levels

As indicated in Table B-12, cruise single event heavy truck data were collected on 6/1, 7/11, 8/25 and 9/6. Histograms for the combined SEL and L_{max} data are shown in Figure B-15. Noting the relatively good fit to normal distribution (except for a few very loud outliers), one may compute an energy averaged emission level according to Eq. B-8. This $(L_o)_E$ for the measured heavy truck data is computed as 85.8 dB.

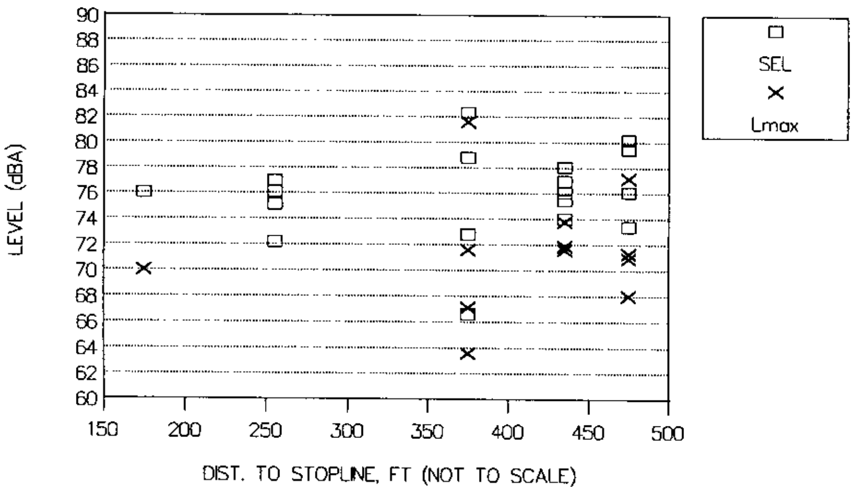


Figure B-14. SEL and L_{max} vs. Distance: Medium Truck Deceleration, 175 ft - 475 ft to Stopline

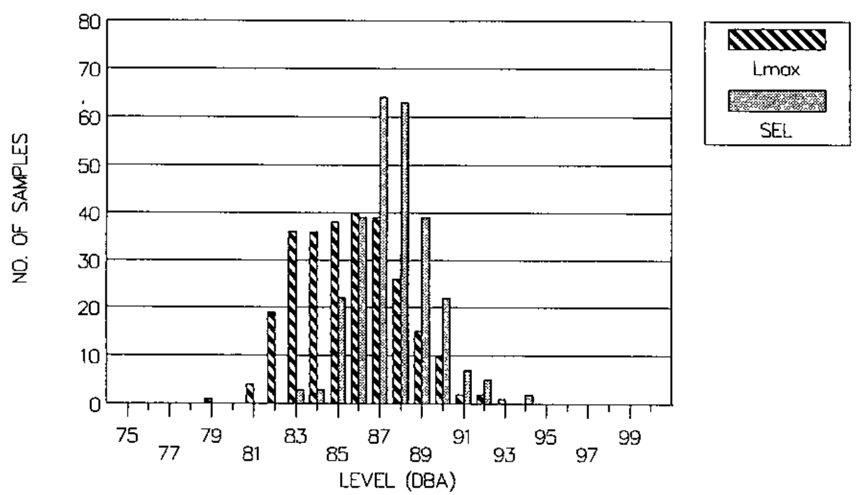


Figure B-15. Distribution of Sampled Data: Heavy Truck Cruise at 55-65 mph

TABLE B-11 -- MEDIUM TRUCK DECELERATION ZONES OF INFLUENCE

Speed Range mph	L_{max} at Cruise (dB)	SEL at Cruise (dB)	First Deceleration Zone Length (ft)	Speed (mph)	SEL (dB)	Second Deceleration Zone Length (ft)	Speed (mph)	SEL (dB)
60-0	83.7	86.3	550	36	80.7	100	13	70.0
50-0	81.0	84.3	400	34	80.1	100	13	70.0
40-0	77.7	81.9	275	30	79.2	100	13	70.0
30-0	73.5	78.8	150	26	77.7	100	13	70.0
20-0	67.5	74.5	100	13	70.0	--	--	--

TABLE B-12 -- HEAVY TRUCK CRUISE NOISE LEVEL DATA SUMMARY

Date	#Events	Cruise SEL Mean (dB)	Cruise SEL S.E.(dB)	Cruise L_{max} Mean (dB)	Cruise L_{max} S.E. (dB)
6/1	37	86.0	1.5	83.8	1.9
7/11	54	86.6	1.6	85.3	1.7
8/25	75	87.1	1.6	83.5	1.9
9/6	103	88.0	1.7	86.7	2.0
ALL DATA COMBINED:	269	87.2	1.8	85.1	2.4

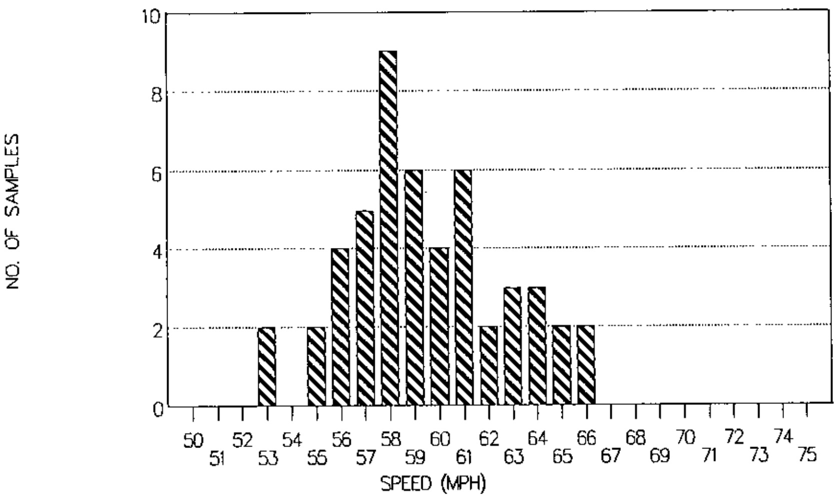


Figure B-16. Distribution of Sampled Heavy Truck Cruise Speeds

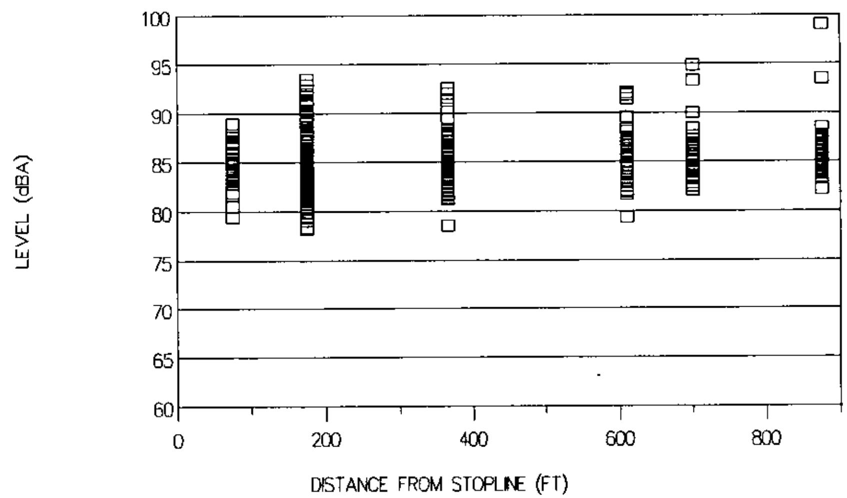


Figure B-17. SEL vs. Distance, Heavy Truck Acceleration, 75 ft-875 ft from Stopline

Speed data were collected at the cruise site on 7/11, and are shown in Figure B-16. The mean speed was 59.5 ± 3.2 mph (50 events, 95% confidence limits of ± 0.9 mph on the mean). Applying the FHWA Model heavy truck emission level equation $[(L_o)_{E,HT} = 38.5 + 24.6 \log(\text{speed, kph})]$ to the speed range yields an $(L_o)_{E,HT}$ of 87.2± 0.6 dB, compared to the above value of 85.8 dB computed from the measurements in this study. As was discussed in the literature review, it is typical to see recently measured levels being lower than those in the FHWA Model.

The mean SEL of all of the measured cruise data was 87.2 dB with a standard error of 1.8 dB (269 samples, 95% confidence limits of ±0.2 dB); the energy-averaged SEL was 87.6 dB.

Heavy Truck Acceleration Noise Levels

Measured Data and Statistical Summaries. Heavy truck acceleration emission level data were measured on 6/1, 7/11, 8/25, and 10/18. During all but the 10/18 measurements, attempts were made to measure a sample of the same vehicles at the cruise site downstream, allowing paired differences in levels to be studied. Table B-13 presents the mean SEL and L_{max} data for each day. Figures B-17 and B-18 present all of the SEL and L_{max} acceleration data as a function of distance from the stopline.

Comparing Results Between Sites.

Differences in Means. In all cases where the mean of the SEL data at an acceleration site was compared to the mean of the cruise SEL, the difference in the means was statistically significant at the 5% level of significance. The same was true for the mean L_{max} values. Figure B-19 illustrates these means with error range bars. Also, in most cases where the acceleration means were compared for each other, the differences were statistically significant, both for the SEL and the L_{max}. The only cases where the differences were not significant were the SEL at 700 feet and 875 feet on 8/25, and the L_{max} at 365 feet and 610 feet on 7/11.

However, whether or not a statistically significant difference is important in the real world is a separate issue. The differences in mean SEL between acceleration and cruise were on the order of 1.3 to 3.6 dB (cruise being higher). On 6/1, the mean acceleration SEL was actually 0.7 dB higher than the mean cruise SEL. When comparing the mean acceleration SEL between any two acceleration sites, the differences ranged from 0.1 to 3.2 dB. The largest difference of 3.2 dB was actually at the same site, AN175, on two different days.

The differences were much larger for the mean L_{max} than for SEL, especially between the cruise and acceleration sites (with mean cruise L_{max} being 3.8 to 7.4 dB higher). The differences in the mean L_{max} values between the acceleration sites ranged from 0.3 to 4.0 dB.

Mean Differences. A better statistical comparison than using the difference of two means is to examine the mean of paired differences between the two sample sets and test if the difference itself is statistically significant compared to no difference. Table B-14 summarizes the comparisons from the previous tables, grouping the pairs as either cruise vs. acceleration or acceleration vs. acceleration. In general, the data sets of paired differences were smaller than the data sets of the actual SEL and L_{max}. It was not always possible for each team member to make a clear measurement of the same vehicle.

At the 5% level of significance, virtually all of the mean paired differences were different from zero. This was true for both SEL and L_{max}, and for comparisons of acceleration sites to cruise sites as well as comparisons of acceleration site to acceleration sites. The only exception was the SEL comparison between CN (cruise) and AN875 on 8/25 which showed no significant difference.

Again, it is important to examine the magnitude of the mean differences. The data in Table B-14 indicate that the mean differences between acceleration sites within 610 feet of the start are less than 1 dB. However, the mean differences between the cruise and acceleration SEL within 610 feet of the start range between 1.1 and 3.1 dB.

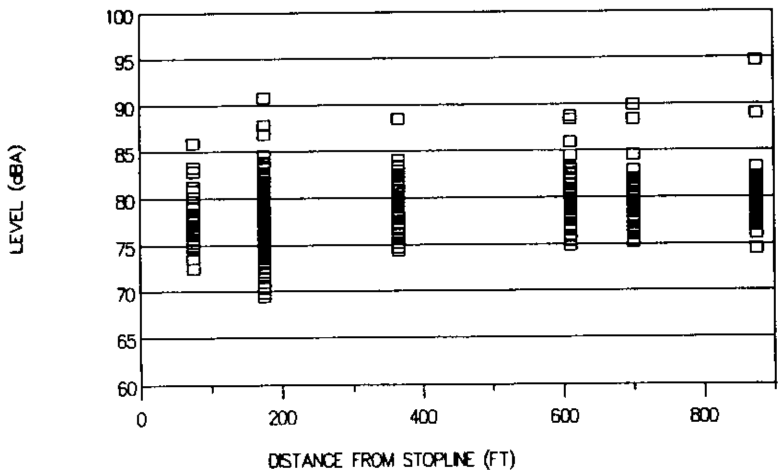


Figure B-18. L_{max} vs. Distance, Heavy Truck Acceleration, 75 ft-875 ft from Stopline

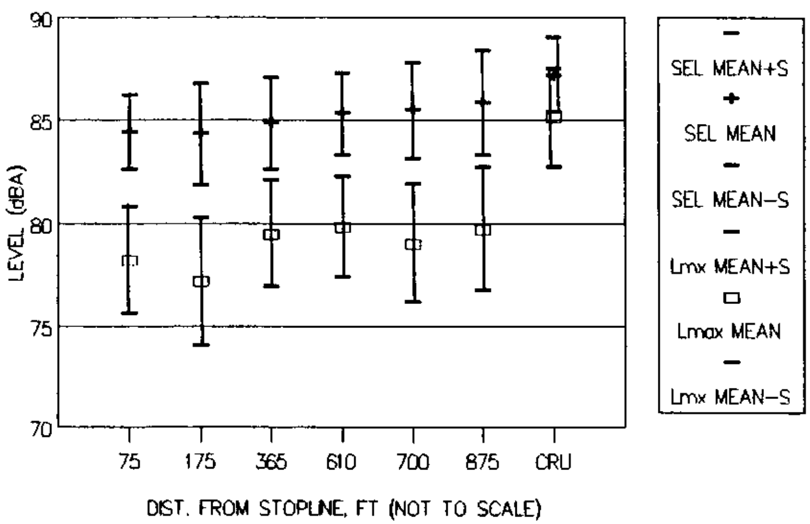


Figure B-19. Mean and Standard Error of Data: Heavy Truck, SEL and L_{max}, 75 ft - Cruise

TABLE B-13 -- SUMMARY OF ACCELERATING HEAVY TRUCK SITES AND RESULTS

Site	Distance from Stopline (ft)	Date	Accel SEL Mean (dB)	Accel SEL S.E. (dB)	Accel # of SEL Samples	Accel L_{max} Mean (dB)	Accel L_{max} S.E. (dB)	Accel # of L_{max} Samples
AN75	75	10/18	84.4	1.8	46	78.2	2.6	46
AN175	175	6/01	86.7	2.7	30	--	--	--
AN175	175	8/25	83.5	2.6	83	75.7	3.2	83
AN175	175	7/11	84.3	2.1	167	77.9	2.8	166
AS365	365	7/11	84.8	2.2	154	79.5	2.6	64
AS610	610	7/11	85.3	2.0	91	79.8	2.4	91
AN700	700	8/25	85.5	2.3	52	79.0	2.9	52
AN875	875	8/25	85.8	2.5	54	79.7	3.0	54

TABLE B-14 -- SUMMARY OF PAIRED DIFFERENCES FOR HEAVY TRUCK CRUISE AND ACCELERATION SEL DATA

Sites	Mean Difference (dB)	# of Samples	Signif. at 5%
COMPARISONS OF CRUISE TO ACCELERATION			
CN-AN175 (6/1)	1.1	10	Y
CN-AN175 (7/11	3.1	22	Y
CS-AS175	2.1	17	Y
CS-AS365	1.5	15	Y
CN-AN700	1.2	15	Y
CN-AN875	0.6	17	N
COMPARISONS BETWEEN PAIRED ACCELERATION SITES			
AS175-AS365	0.6	148	Y
AS175-AS610	0.9	87	Y
AS365-AS610	0.4	84	Y
AN175-AN700	1.7	52	Y
AN700-AN875	0.4	45	Y

Combined Data. The difference between heavy truck cruise and acceleration levels can be seen more graphically when all of the cruise data from all days are combined (as shown earlier in Figure B-15) and are then compared to all of the combined acceleration SEL data. The combined acceleration case includes the data from 10/18, where vehicles were only measured at 75 feet from the stop line. The results of this combination of acceleration data are shown in the distributions in Figure B-20 for SEL and L_{max}. The mean combined SEL for cruise and for acceleration are as follows:

Case	Mean SEL(dB)	Std.Err.(dB)	Energy-Averaged SEL (dB)	No. of Samples
Acceleration	84.8	2.4	85.5	633
Cruise	87.2	1.8	87.6	269

The 95% confidence limits for each case were ± 0.2 dB. These results are important mainly because the SEL are directly comparable to L_{eq} when the averaging time (1 hour) is much greater than the average duration of the event (typically 3-20 seconds). The means are different, even at the 1% level of significance. Also, the standard errors are comparable to those for cruise conditions in the FHWA Model, implying that the trends of the larger population have been similarly represented. The relatively small standard error of 2.4 dB for all of the SEL data is especially encouraging when considering that the range in distances from the stop line is 75 feet to 875 feet. One problem in trying to adjust STAMINA for acceleration conditions is that the equations are based on a constant cruise speed. Because speed changes with distance during acceleration, the FHWA Model equations would require dividing the road in a number of constant-level segments where the change in level from one end to the other is not too large.

Given that the standard error of the mean acceleration SEL is comparable to the standard errors for the cruise data in the FHWA Model, it is concluded that a constant SEL of 84.8 ± 2.4 dB (or an energy-averaged SEL of 85.5 dB) may be used to characterize the SEL at all of the acceleration measurement sites in this study. This directly implies that the variation in the $L_{eq}(1\ hr)$ of a stream of accelerating heavy trucks would be of the same order of magnitude.

Further, the difference between the mean energy-averaged cruise SEL and the mean energy averaged acceleration SEL, which is 2.1 dB, describes the difference in $L_{eq}(1\ hr)$ that may be expected at those same measurement points. In other words, the $L_{eq}(1\ hr)$ from a stream of accelerating heavy trucks should be 2.1 dB less than the $L_{eq}(1\ hr)$ of the same trucks at the measured mean cruise speed of 59.5 mph. Within the error indicated by the 2.4 dB standard error, this relationship should hold true for any point along the acceleration lane.

While the individual site data, especially the paired SEL differences, seem to indicate a distance-from-stopline effect on SEL, linear regression of SEL as a function of log (distance) only had a correlation coefficient of 0.21 (r^2 of 0.046). It is thus felt that the difference is small enough to be totally outweighed by the ability to develop a relative simple adjustment for predictions based on the FHWA Model theory and using the STAMINA 2.0 computer code.

The next question is how to incorporate this finding into the FHWA Model in an easily used manner. Two methods will be considered: use of equivalent constant speeds that produce the same SEL as the acceleration event, and use of a level adjustment that would be applied to a final cruise speed prediction. The latter method offers some advantage for first-cut analyses and will be discussed first.

Developing an Acceleration Level Adjustment. Recalling Eq. B-6 and its development in [Barry and Reagan, 1978], one can show that the $L_{eq}(1\ hr)$ at any distance from an infinitely long acoustically hard site reduces to:

$$L_{eq}(1\ hr) - (L_o)_E + 10 \log [(N\pi D_o^2)/(STD)] \qquad \text{(B-28)}$$

Given that $(L_o)_E = a + b \log (S)$, (B-29)

then, $$L_{eq}(1\ hr) = a + (b-10) \log (S) + 10 \log (N\pi D_o^2/TD) \qquad \text{(B-30)}$$

It is necessary to specify a constant speed to use this equation, which in the case of cruise, would be the cruise speed. In acceleration, however, the speed is constantly changing and some other speed must be used in the model. One approach is to let this speed be the final speed at the end of acceleration, which would correspond to the cruise speed of the main roadway. However, an adjustment must be made to the predicted Leq(1hr) to account for the fact that this higher than actual speed will change both the emission level and the traffic flow adjustment, as expressed by the (b-10) log(speed) expression in Eq. B-30.

Procedure to be Used. The following procedure was used to determine this acceleration adjustment:

1. Predict the $L_{eq}(1\ hr)$ for a speed of 59.5 mph (96 kph), (which was the mean speed at the cruise sites corresponding to the mean SEL of 87.2 dB).
2. Subtract the 2.1 dB SEL difference from this value to get an acceleration $L_{eq}(1\ hr)$.
3. Predict the $L_{eq}(1\ hr)$ for a range of speeds between 10 and 60 mph.
4. Subtract the acceleration $L_{eq}(1\ hr)$ from the $L_{eq}(1\ hr)$ in step 3 to get the needed acceleration adjustment based on that speed.
5. Develop an equation for the acceleration adjustment based on the results of step 4. For this equation, it is useful to express the adjustment as a linear function of log(speed) or,

$$\Delta_{acc} = a_{acc} + b_{acc} \log (S_{final}) \qquad \text{(B-31)}$$

Mathematical Development. This adjustment is developed mathematically below. As shown earlier,

$$L_{eq}(1\ hr) = a + b \log(S) + 10 \log (N\pi D_o^2/STD) \qquad \text{(B-32)}$$

or

$$L_{eq}(1\ hr) = a + (b-10)\log(S) + \text{constant} \qquad \text{(B-33)}$$

For the general case of predicting an adjustment based on a cruise SEL at a reference speed S_{ref}:

$$L_{eq}(1\ hr)_{Sref} = a + (b-10)\log(S_{ref}) + \text{constant} \qquad \text{(B-34)}$$

Based on the relationship between SEL and $L_{eq}(1\ hr)$, one defines

$$L_{eq}(1\ hr)_{acc} = L_{eq}(1\ hr)_{Sref} - (SEL_{Sref} - SEL_{acc}) \qquad \text{(B-35)}$$

Substituting from Eq. B-34,

$$L_{eq}(1\ hr)_{acc} = a + (b-10)\log(S_{ref}) - (SEL_{Sref} - SEL_{acc}) + \text{constant} \qquad \text{(B-36)}$$

However, the acceleration $L_{eq}(1\ hr)$ is to be given in terms of the final speed and an acceleration adjustment.

$$L_{eq}(1\ hr)_{acc} = a + (b-10)\log(S_{final}) + \Delta_{acc} + \text{constant} \qquad \text{(B-37)}$$

Substituting from Eq. B-31

$$L_{eq}(1\ hr)_{acc} = a + (b-10)\log(S_{final}) + [a_{acc} + b_{acc}\log(S_{final})] + \text{constant} \qquad \text{(B-38)}$$

Equating the expressions in Eqs. B-36 and B-38

$$(b-10)\log(S_{ref}) - (SEL_{Sref} - SEL_{acc}) = (b-10)\log(S_{final}) + a_{acc} + (b_{acc})\log(S_{final}) \qquad \text{(B-39)}$$

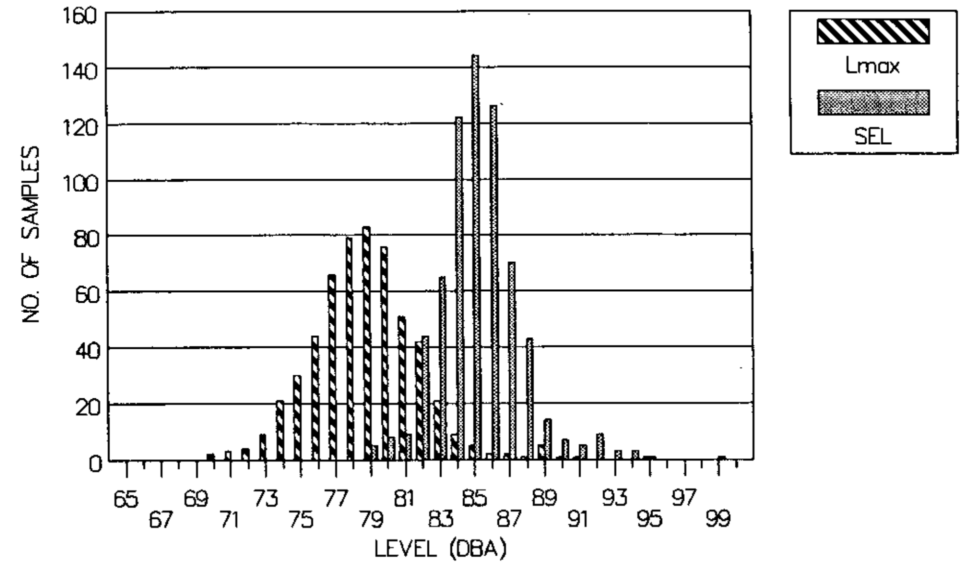


Figure B-20. Distribution of Sampled Data:
Heavy Truck, Acceleration from Stopline

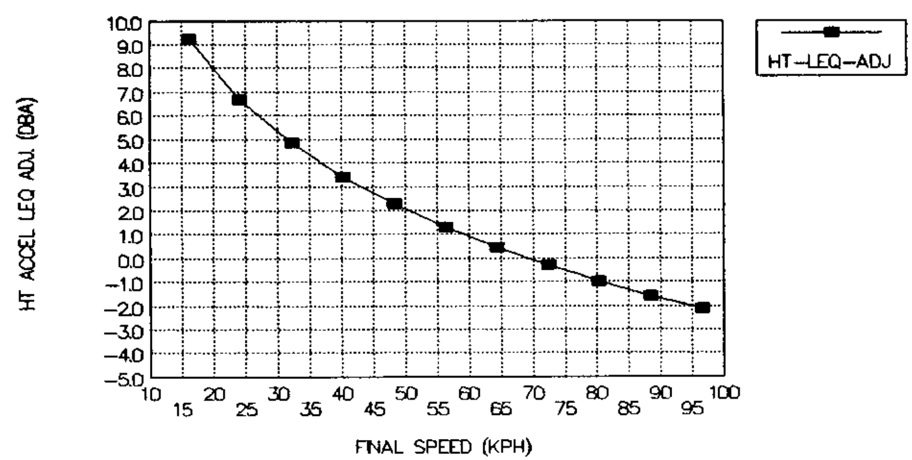


Figure B-21. Heavy Truck Acceleration L_{eq} Adjustment Based on Final Speed for an L_{eq} of 2.1 dB Below the L_{eq} at 96 KPH using the Model

Rearranging terms

$$a_{acc} + b_{acc}\log(S_{final}) = (b\text{-}10)\log(S_{ref}) - (SEL_{Sref} - SEL_{acc}) - (b\text{-}10)\log(S_{final}) \quad \text{(B-40)}$$

Thus

$$a_{acc} = (b\text{-}10)\log(S_{ref}) - (SEL_{Sref} - SEL_{acc}) - (b\text{-}10)\log(S_{final}) \quad \text{(B-41)}$$

$$b_{acc} = (b\text{-}10) \quad \text{(B-42)}$$

Final Acceleration Adjustment Expression for Heavy Trucks when Using the FHWA Model Equation. For heavy trucks in the FHWA Model, b = 24.6; also S_{ref} was measured to be 59.5 mph or (96 kph), SEL_{Sref} was 87.6 dB and SEL_{acc} was 85.5 dB. Thus,

$$\Delta_{acc,HT} = (24.6\text{-}10)\log(96) - (87.6\text{-}85.5) - (24.6\text{-}10)\log(S_{final}) \quad \text{(B-43)}$$

$$\Delta_{acc,HT} = 26.8 - 14.6\ \log(S_{final}) \quad \text{(B-44)}$$

Figure B-21 presents this adjustment in terms of the final speed. The adjustment should be subtracted from the heavy truck L_{eq}(1 hr) to get the accelerating heavy truck L_{eq}(1 hr).

Generalized Final Expression. For the more general case, where a transportation agency might have different values for a and b in the heavy truck emission level equation, the acceleration adjustment may be expressed as

$$\Delta_{acc,HT} = (b\text{-}10)\log(96) - 2.1 - (b\text{-}10)\log(S_{final}) \quad \text{(B-45)}$$

$$\Delta_{acc,HT} = 1.978(b\text{-}10) - 2.1 - (b\text{-}10)\log(S_{final}) \quad \text{(B-46)}$$

Ideally, this adjustment factor needs to be coded into STAMINA to be useful. STAMINA currently does not display the heavy truck L_{eq} separate from the total L_{eq}.

Lacking coding changes, the user would have to run STAMINA separately for heavy trucks, manually add in the adjustment and then manually combine the adjusted L_{eq} with the L_{eq} of automobiles and medium trucks to get the total L_{eq}. It is unreasonable and inefficient to expect a user to do that.

Developing an Equivalent Speed to Adjust Levels for Acceleration. Thus, an alternative is needed until the STAMINA code is actually changed. The field data shows that the SEL remains relatively constant (84.8 dB ± 2.4 dB) from 75 to 875 feet from the start of acceleration and that the actual energy-averaged level is 2.1 dB below the cruise energy-averaged SEL of 87.6 dB at 59.5 mph (96 kph). Thus, an interim method is to determine the constant speed that would produce an SEL 2.1 dB below the SEL at 59.5 mph.

Computation of the Speed. Recall the general relationship between $(L_o)_E$, SEL and speed developed in Eq. B-15,

$$(L_o)_E = SEL + 10\ \log(S,\ kph) - 22.4\ dB \quad \text{(B-47)}$$

and the FHWA Model emission level equation for heavy trucks,

$$(L_o)_E = a + b\ \log\ (S,\ kph) \quad \text{(B-48)}$$

where a = 38.5 and b = 24.6. Solving for SEL, the expression for heavy trucks becomes

$$SEL_{HT} = 38.5 + 14.6\ \log\ (S,\ kph) + 22.4\ dB \quad \text{(B-49)}$$

$$SEL_{HT} = 60.9 + 14.6\ \log\ (S,\ kph) \quad \text{(B-50)}$$

For the cruise speed of 59.5 mph (96 kph)

$$SEL_{HT,96\ kph} = 60.9 + 14.6\ \log\ (96) = 89.8\ dB \quad \text{(B-51)}$$

This value is 2.2 dB above the measured energy-averaged cruise SEL of 87.6 dB. Thus,

$$SEL_{HT,acc} = SEL_{HT,\ 96\ kph} - 2.1 = 89.8 - 2.1 = 87.7\ dB \quad \text{(B-52)}$$

Substituting this value of 87.7 dB into Eq. B-50 for SEL_{HT} and solving for S yields a speed of 68.4 kph or 43 mph.

Thus, use of a constant equivalent speed of 43 mph along the acceleration roadway will produce the desired effect--an SEL (and hence an L_{eq}) that is 2.1 dB below the value at 59.5 mph.

Roadway Length. The distances over which the field data were collected were 75 to 875 feet. A sampling of speeds were made at the sites, as summarized in Table B-15. By 875 feet, the mean speed was 31.8 mph. This matches very well with the AASHTO curve for accelerating heavy trucks on level grade [AASHTO, 1984; p. 784], which shows a speed of 32 mph at about 900 feet. In the region beyond these distances the speeds and the corresponding levels should both show an increase until the truck reaches cruise speed.

According to the AASHTO curve, trucks will not reach the 43 mph speed until about 2500 feet from start. Thus, one might consider choosing a roadway break point at the 2500-foot distance and use an equivalent speed of 43 mph on that roadway to achieve the 2.1 dB difference between acceleration and cruise at 59.5 mph. However, that adjustment was based on measured levels averaged over points between 75 and 875 feet from the stopline. At the 875 foot point, the mean acceleration SEL was 85.8 dB, only 1.4 dB below the mean cruise SEL of 87.2 dB. Further, the mean difference of the paired data at the two sites was only 0.6 dB (for 17 events with 95% confidence limits of ±1.0 dB). The difference was not statistically significant at the 5% level of significance. Thus, it is not entirely correct to apply the broad 2.1 dB heavy truck acceleration adjustment to the roadway from 0-2500 feet. Instead, the road should be broken at the 800-1000 feet region. The equivalent speed of 43 mph should be used for that roadway.

Need to Consider Grade. The actual distance for a heavy truck to reach any given speed is affected by grade. AASHTO provides data that can be used to correct the lengths of the ZOI's to account for grade [AASHTO, 1984]. Table X-5 from AASHTO (p. 1043) gives multipliers for ramp length as a function of grade. Table IX-8, also from AASHTO (p. 796), gives multipliers for acceleration times at intersections for vehicles as a function of vehicle type and grade. These multipliers are consistent with ramp length multipliers given in AASHTO Table X-5. Using these tables it is possible to determine multipliers for the ZOI to allow for the change in length due to grade. The derived multipliers are shown in Tables C-3 and C-4 of Appendix C.

However, AASHTO Figures III-26A and III-26B [AASHTO, 1984; p. 254 and 255] shows the effect of grade on distance travelled and final truck speed. At some point on positive grades, a truck will no longer be able to increase its speed and will reach a crawl speed. Hendricks gives curves for California truck emission levels in this situation, although for a given grade, trucks will reach different crawl speeds at different distances, as a function of the truck and its loading [Hendricks, 1986]. To overcome this problem, the use of a cruise roadway following the acceleration zones of influence is not recommended if an up-grade of greater than 2 per cent is present. This still allows approximately one-half mile to be modeled upstream of the stop point.

Summary of Equivalent Speed Procedure for Accelerating Heavy Trucks. Thus, an alternative procedure for accounting for accelerating heavy trucks is:

1. determine the final desired speed
2. if this speed is less than 43 mph:
   a. determine the distance to reach that speed including grade effects;
   b. establish that point as an end-of-roadway point for STAMINA; and

TABLE B-15. SUMMARY OF HEAVY TRUCK SPEED DATA AT ACCELERATION SITES

Site	Mean Speed (mph)	S.E. (mph)	No. of Samples
AN175	12.8	1.9	63
AS175	13.1	1.5	60
AS365	20.1	2.6	60
AS610	24.5	2.9	60
AS700	26.8	3.1	102
AN875	31.8	3.7	102

TABLE B-16. SUMMARY OF HEAVY TRUCK DECELERATION SITES AND RESULTS

Site	Distance From Stop-line (ft)	Date Measured	Decel SEL Mean (dB)	Decel SEL S.E. (dB)	Decel # of SEL Samples	Decel L_{max} Mean (dB)	Decel L_{max} S.E. (dB)	Decel # of L_{max} Samples
DS175	175	7/15	75.3	2.2	24	70.0	2.8	24
DS255	255	9/6	78.5	2.5	48	--	--	--
DN340	340	6/1	79.9	1.6	10	71.8	3.0	10
DS375	375	7/15	78.6	2.0	53	73.9	3.3	52
DS435	435	9/6	78.3	2.1	52	73.8	2.8	52
DS475	475	7/15	80.3	2.2	52	76.5	3.7	52

c. assign an equivalent speed of 43 mph to that roadway

3. if the final speed is over 43 mph:
   a. determine the distance from start to reach 43 mph including grade effects;
   b. break the road into a new STAMINA roadway at this point, using an equivalent speed of 43 mph;
   c. determine the distance to reach the final speed;
   d. establish that point as a STAMINA roadway endpoint;
   e. assign a speed to this roadway as the average of 43 mph and the final speed.

It needs to be emphasized that this procedure in its current form only deals with heavy trucks. Because a given analysis problem will typically have a mix of automobiles, medium trucks and heavy trucks, any final procedure needs to be viewed in the context of the requirements for all vehicle types. Combining the results for each vehicle type will be done after a discussion of heavy truck deceleration levels.

Heavy Truck Deceleration Noise Levels

Measured Data and Statistical Summaries. Heavy truck deceleration emission level data were measured on 6/1, 7/15, and 9/6. On 6/1 and 9/6 attempts were made to measure a sample of the same vehicles at the cruise site downstream, allowing paired differences in levels to be studied.

At the truck weigh stations, the heavy trucks began their deceleration at various distances along or before the exit ramp; where they began deceleration depending largely on the size of the queue, if any, at the station. As an example, during the measurements in the deceleration zone on 6/1, conditions ranged from zero trucks in the queue to over 15, all within the span of 10-15 minutes. Trucks tended to arrive in groups at the weigh station. As a result, the speed profile of trucks on deceleration ramps will vary quite a bit. This queuing posed problems in trying to get valid pass-by measurements that had an adequate rise and fall of the level during the event. As a result, most of the events had to be sampled when the queue was small or nonexistent, tending to bias the data toward the higher speed approaches with faster decelerations. Also, the distances from the stopline at which measurements could be done were restricted by the terrain, by joints in the pavement that caused banging noises and by interference from noise from the traffic and the main lanes. Nonetheless, meaningful samples were collected.

Figures B-22 and B-23 show all of the SEL and L_{max} data as a function of distance, while Figure B-24 shows the means and error bars for all of the sites, along with the cruise values.

Table B-16 indicates the various distances at which measurements were made, and summarizes the individual site statistics. These analyses compare the mean of the parameter measured at each site against each other site measured that day to see if the differences are statistically significant.

Comparing Results Between Sites. T-tests comparing mean levels on the same day showed the differences in SEL at all three sites on 7/15 to be statistically significant at the 5% level of significance. The same was true for L_{max} at these sites. On 9/6, the difference in mean SEL at DS255 and DS435 was zero dB.

Paired difference tests were also able to be made on a smaller sample of the same vehicles on each day, with the same basic results as the comparisons of the differences in the means. Table B-17 summarizes the paired data results. As with the acceleration case, the size of the differences needs to be examined. The mean SEL differences for the paired cruise/deceleration data range from 5.2 dB (for only two pairs) to 9.4 dB (for 24 pairs). However for the paired data between deceleration sites, the range is much smaller, from 0 dB between 46 pairs at DS435 and DS255 to 4.2 dB for 20 pairs between DS475 and DS175. Thus the differences in SEL between cruise and deceleration are much higher than between cruise and acceleration.

Effects of Speed on Roadway Lengths. To better understand the differences, it is useful to look at the speed data collected at the sites. A small sampling of speeds was made on 7/15, with a larger sample on 9/6. The results are in Table B-18. As shown, over a distance range of 175 to 475 feet, the mean speed ranged between approximately 13-23 mph (over this range, the mean SEL varied by 4.6 dB).

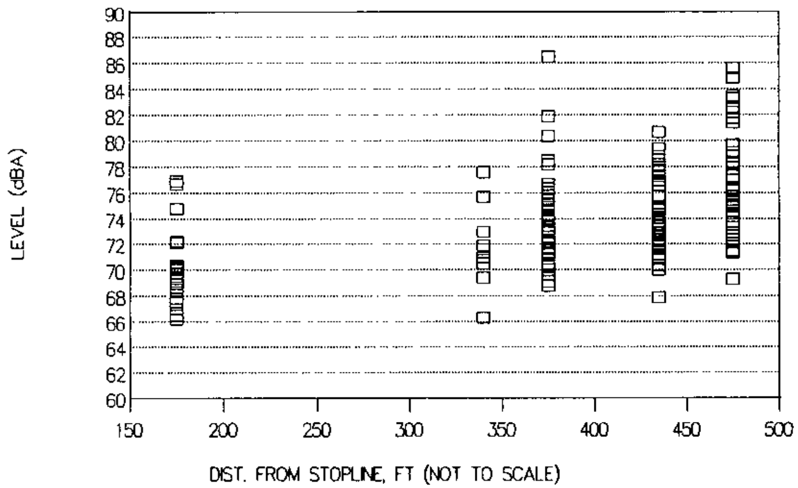


Figure B-22 -- L_{max} vs. Distance, Heavy Truck, Deceleration 175 ft-475 ft

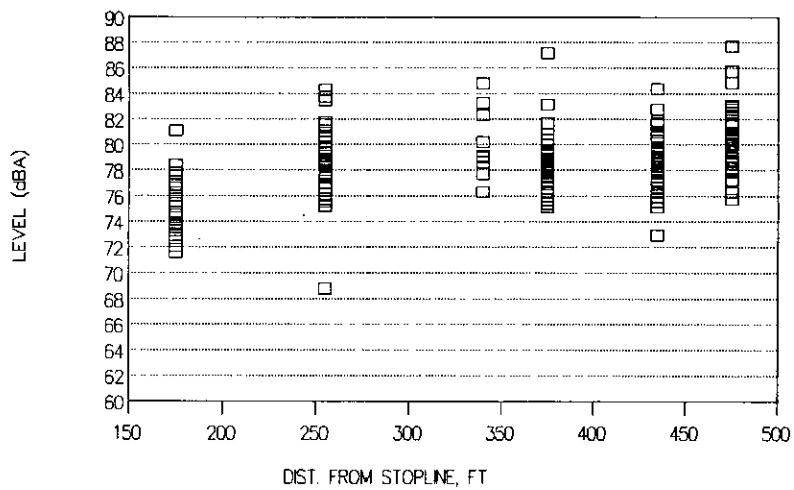


Figure B-23 -- SEL vs. Distance, Heavy Truck, Deceleration 175 ft-475 ft

TABLE B-17 -- SUMMARY OF PAIRED DIFFERENCES FOR CRUISE AND DECELERATION SEL DATA

Sites	Mean Difference (dB)	# of Samples	Signif. at 5%
COMPARISONS OF CRUISE TO DECELERATION			
CN-DN340	5.2	2	N
CN-DS435	9.4	24	Y
CN-DS255	9.0	23	Y
COMPARISONS BETWEEN DECELERATION SITES			
DS475-DS375	1.5	44	Y
DS375-DS175	3.0	20	Y
DS475-DS175	4.2	20	Y
DS435-DS255	0.0	46	N

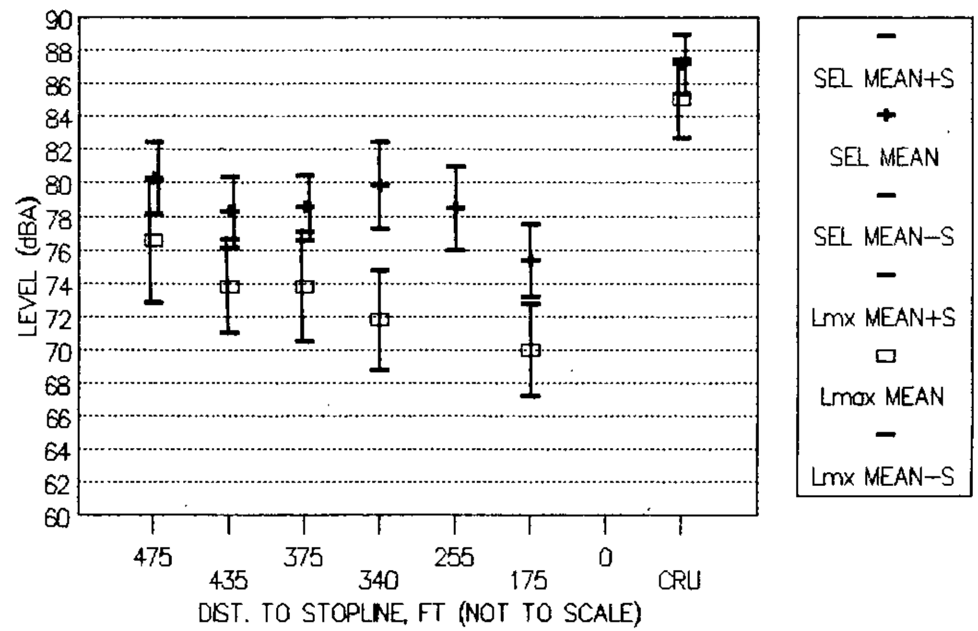


Figure B-24 -- Mean and Standard Error of Data: Heavy Truck, Deceleration SEL and L_{max}

TABLE B-18 -- SUMMARY OF SPEED DATA FOR DECELERATING HEAVY TRUCKS

Site	Date	Mean Speed (mph)	S.E. (mph)	# of Samples	95% Confidence Limit (mph)	Speed Range mph
DS175	7/15	12.7	2.2	10	1.4	9-16
DS255	9/06	17.8	5.5	58	1.4	8-28
DS375	7/15	18.0	2.2	10	1.4	15-22
DS435	9/06	22.3	7.6	59	1.9	10-36
DS475	7/15	19.5	2.1	10	1.3	18-23

TABLE B-19 -- EPA DECELERATING HEAVY TRUCK TIME-AVERAGED LEVELS

Deceleration Speed Range (mph)	Heavy Truck Time-Averaged Emission Level(dB)
EPA DATA	
60-0	81.1
50-0	79.1
40-0	76.7
30-0	73.7
20-0	69.0
INTERMEDIATE SPEED RANGES	
60-50	85.6
50-40	83.4
40-30	80.7
30-20	77.4
20-0	69.0

These speeds seem exceedingly low at these distances from the stopline if compared with the AASHTO design chart for the lengths of deceleration ramps [AASHTO, 1984; p. 1044]. For example, the recommended ramp length for deceleration from an operating speed of 53 mph to a complete stop is only 615 feet. Further, the length is 550 feet for deceleration from 58 to 22 mph. Taken together, the two design guidelines imply that the final deceleration from 22 to 0 mph only takes the difference in the two distances, or 65 feet. Yet the speed data collected in this study (Table B-18) shows a speed on the order of 20 mph at about 450 feet from stop, a much greater distance than the design charts would indicate.

It is speculated that the difference in the deceleration rates between field data and the design charts is due to the nature of the field site being a specialized facility for trucks. The deceleration ramp was very long because of the need for it to function as a storage bay for queues of as many as 20 trucks. That length might induce drivers to begin their deceleration earlier than if the ramp design was based on the normal AASHTO guidelines. Additionally, the presence of a few trucks in the queue would require drivers to begin deceleration earlier than otherwise. Finally, the presence of law enforcement personnel at the station might cause more conservative behavior by the drivers.

Thus, Table B-18 is important not so much because of the distances at which the speeds occurred, but because the speeds can be correlated to the corresponding sound levels in Table B-16. In other words, the measured mean speed range of 12.7-22.3 mph in Table B-18 corresponds to a mean SEL range of 75.3 to 80.3 dB (Table B-16) and a mean L_{max} range of 70.0 to 76.5 dB (also Table B-16). This information, when combined with the 60 mph cruise speed levels, gives useful guidance on the effect of speed on level. Then, using the AASHTO ramp design chart, one may relate level back to distance along a typical deceleration ramp.

Combined Heavy Truck Data. The large differences in the paired cruise and deceleration data suggest the possibility of aggregating the deceleration data for all of the sites . When done, the following results are obtained:

1. SEL = 78.6 ± 2.6 dB (n = 239, energy-averaged SEL = 79.4)
2. L_{max} = 74.0 ± 3.8 dB (n = 191, energy-averaged L_{max} = 75.7)

The 95% confidence limits on these two means are 0.3 dB and 0.5 dB, respectively. Figure B-25 shows histograms for the combined data.

The aggregated cruise data levels over all measurement days, as reported earlier, were:

1. SEL = 87.2 ± 1.8 dB (n = 269, energy-averaged SEL of 87.6 dB)
2. L_{max} = 85.1 ± 2.4 dB (n = 229, energy-averaged L_{max} of 86.7 dB)

As with the case of the acceleration data, the 2.6 dB standard error on the mean SEL for the combined deceleration data is similar to the standard error on the cruise emission levels in the FHWA Model. Thus, as a first approximation, one may say that the energy-averaged SEL, and hence, L_{eq}(1 hr) of decelerating trucks at a range of 175-475 feet from the stopline is 8.2 dB (87.6 minus 79.4) below the cruise level for heavy trucks.

The tradeoff in such an approximation in terms of accuracy at either end of the section should be viewed in the context of the larger scenario where traffic on other lanes or roads would tend to dominate the total received levels. Indeed, this very fact made it difficult to obtain valid pass-by measurements of the decelerating trucks, even though the mainline traffic consisted almost entirely of cars (as virtually all of the trucks had exited into the weigh station).

Developing a Heavy Truck Deceleration Adjustment Equation. To build this finding into an easily used adjustment for STAMINA, one must choose a constant speed to keep within the formulation of the algorithms. One approach is similar to that used for accelerating trucks: use the initial speed at the beginning of deceleration and develop an adjustment based on the 8.2 dB difference between the cruise and

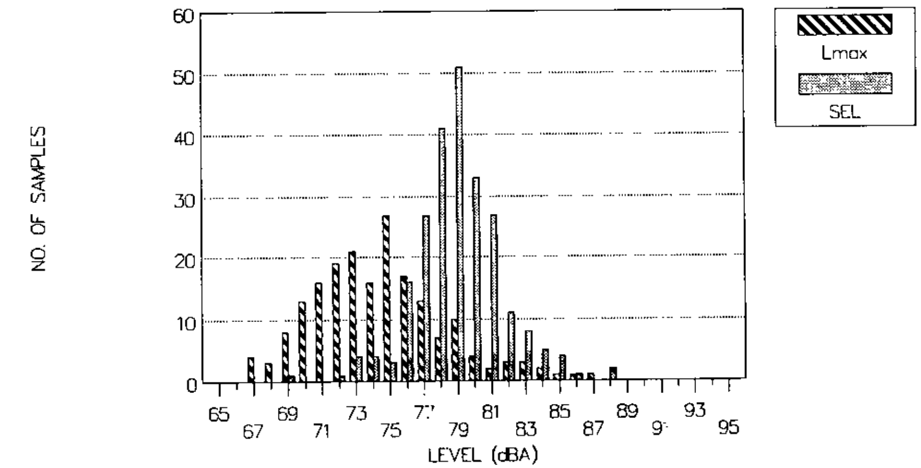


Figure B-25 -- Distribution of Sampled Data, Heavy Truck, Deceleration 175 ft-475 ft

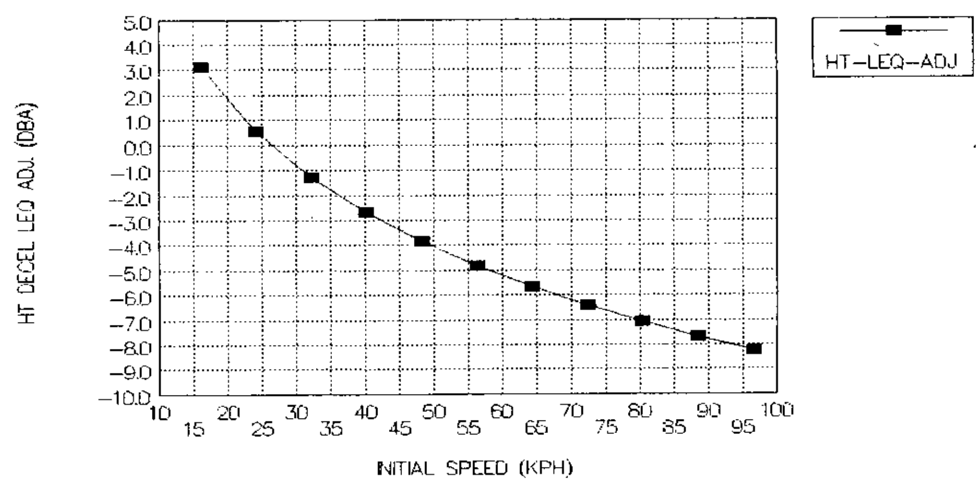


Figure B-26 -- Heavy Truck Deceleration L_{eq} Adjustment Based on Initial Speed For an L_{eq} of 8.2 dB Less than the L_{eq} at 96 kph using the FHWA Model deceleration SEL. Following the same steps as for the acceleration case, a deceleration adjustment may be computed to be in the form of:

$$\Delta_{dec} = a_{dec} + b_{dec}\log(S_{initial}) \quad \text{(B-53)}$$

where $a_{dec} = (b-10)\log(S_{ref}) - (SEL_{cruise} - SEL_{dec}) - (b-10)\log(S_{initial})$, (B-54)

and $b_{dec} = (b-10)$ (B-55)

With b = 24.6 in the FHWA Model and $S_{initial}$ = 96 kph, the adjustment becomes

$$\Delta_{dec} = 20.7 - 14.6\log(S_{initial}) \quad \text{(B-56)}$$

This adjustment, when used with any initial speed at the beginning of a roadway, will result in an L_{eq} that will be 8.2 dB below the L_{eq} at 59.5 mph (96 kph). Figure B-26 presents the adjustment as a function of the initial speed.

Developing an Equivalent Speed to Model Deceleration Levels. As an alternative method to the use of this adjustment, an equivalent constant speed could be computed that would result in an SEL 8.2 dB below the SEL at 59.5 mph (96 kph). Recalling Eq. B-50, which was derived from the FHWA Model equation for heavy trucks:

$$SEL_{HT} = 60.9 + 14.6 \log (S, kph) \quad \text{(B-57)}$$

Also, the mean cruise $SEL_{HT,96\ kph}$ was 89.8 dB, resulting in:

$$SEL_{HT,dec} = SEL_{HT,96\ kph} - 8.2 = 89.8 - 8.2 = 81.6 \text{ dB} \quad \text{(B-58)}$$

This level can be substituted into Eq. B-57,

$$SEL_{HT,dec} = 60.9 + 14.6 \log (S, kph) = 81.6 \text{ dB}, \quad \text{(B-59)}$$

and solved for S:

$$S = 26.2 \text{ kph (16.2 mph)}. \quad \text{(B-60)}$$

Thus, use of a constant equivalent speed of 26.2 kph (16.2 mph) would produce an L_{eq}(1 hr) that was 8.2 dB below the L_{eq}(1 hr) at 96 kph (59.5 mph). Use of such a speed requires modification to the STAMINA code, which currently has a lower limit for speed of 30 mph.

Speed Range for a Level Adjustment Based on EPA Data. The next question deals with the range of initial speeds over which the deceleration adjustment or the equivalent speed is valid. The data were measured out to a distance of only 475 feet from the stopline, where most of the sampled speeds were already reduced to less than 30 mph. Most literature indicates the dominance of tire noise at the higher speeds, and thus, a strong speed dependence for emission level. This would be even more true during a deceleration event, when the engine load is reduced and, with the exception of the use of an engine brake, the level is totally dictated by tire noise. A strong case can thus be made for using the cruise emission levels during the initial phases of deceleration.

However, as was described for other situations, the EPA deceleration data [Rudder, 1979] is very useful. Rudder presented time-averaged levels over various deceleration speed ranges for a reference microphone that, in effect, moved alongside the vehicle at an offset distance of 50 feet. The upper portion of Table B-19 presents those levels for heavy trucks for speed ranges varying from 60-0 mph down to 20-0 mph. These levels are averaged over the time to go from the initial speed down to a speed of zero. Using the methodology presented earlier for automobiles, the time-averaged levels for the various intermediate speed ranges may be determined, as listed in the lower half of Table B-19. Again, these levels represent constant equivalent levels for an observer moving along with the vehicle. For a wayside observer,

they would represent an average of the maximum level that could be expected to be received during the pass-by. Given a maximum level and a rate of deceleration, one could compute a time history profile of the level at stationary wayside observer, and from that, the SEL of the event or the L_{eq} of the event over a time period such as one hour.

The Low Speed Range. The low speed range values need to be examined in more detail. From 20-0 mph, Rudder presents a level of 69.0 dB; from 30-0 mph, the level is 73.7 dB; assuming a constant deceleration rate, a level from 30-20 mph was computed as 77.4 dB. Noted earlier, the mean L_{max} for the combined deceleration data was 74.0 ± 3.8 dB. Using the relation, $(L_o)_E = L_{max} + 0.115s^2$, one computes:

$$(L_o)_E = 74.0 + (0.115)(3.8)^2 = 75.7 \text{ dB} \quad \text{(B-61)}$$

This level was measured over a range of mean speeds of about 13-23 mph. It is 1.7 dB below the 77.4 dB value computed from the EPA data for the higher speed range of 30-20 mph, and is thus consistent with the EPA values.

However, given that the EPA time-averaged level for the 20-0 mph range was 69 dB, it is apparent that the deceleration level must drop off very rapidly in the final stages of deceleration, and that aggregation of all data disguises that effect. This premise is supported by closer examination of the DS175 data. At DS175, the mean speed was 12.7 mph and the mean L_{max} was 70.0 ± 2.8 dB for an $(L_o)_E$ of 70.9 dB. This $(L_o)_E$ is totally consistent with the EPA level of 69 dB, which is averaged over a speed ranging down to zero mph. Also, the DS175 $(L_o)_E$ is nearly 5 dB lower than the aggregate measured deceleration L_{max} of 75.7 dB.

Effect on SEL. This analysis supports the speed dependence of L_{max} during deceleration. A similar, but lesser, effect is seen in the SEL data where the mean SEL for DS175 is 75.3 dB, which is 2.3 dB below the aggregate mean deceleration SEL of 78.6 dB. It is the effect on SEL that will appear in any L_{eq}(1 hr) calculations, indicating a potential 2.3 dB error at 175 feet from the stopline, and probable higher errors at lesser distances, from use of the aggregate value.

The importance of the error depends entirely on the context of the problem and whether or not the levels for the last 175 feet of deceleration are high enough to affect the combined L_{eq} from all roadways. If this last section of road was felt to be important, then it could be modelled as a separate roadway, with an emission level of 69 dB.

Comparing Deceleration Data to Predicted Cruise Levels. As a final comparison, it is interesting to check the measured SEL against the equation derived from the FHWA Model emission level equation, assuming for the moment validity at low speeds. The predicted $SEL_{HT,pred}$ would be:

$$SEL_{HT,pred} = 60.9 + 14.6 \log (S, kph) \quad \text{(B-62)}$$

For the high speed cruise case, the measured mean SEL was 87.6 dB; the predicted value at the mean measured speed of 59.5 mph (96 kph) would be 89.8 dB, a 2.2 dB overprediction. This 2.2 dB overprediction was used as a calibration factor to adjust the predictions at the deceleration sites. Table B-20 summarizes the predicted/measured comparisons. The results show that even with the 2.2 dB adjustment, the extrapolation of FHWA Model equation in the low speed range generally still overpredicts the deceleration SEL.

Additional Field Observations on Deceleration Levels. More insight into levels at the low end of the deceleration events may be gained from some additional data collected at the DN340 site on 6/1 (separate from the previously presented single event comparisons with AN175 and CN). During a series of 4-minute L_{eq} measurements, a number of observations were made of maximum levels as trucks passed the DN340 site; no SEL were measured. The events included "fast" passbys with rapid deceleration (when no queue existed), "slow" passby decelerations when a queue existed, unspecified decelerations, idling noise when several trucks were in queue in front of the microphone, and a combination of short periods of acceleration,

TABLE B-20 -- COMPARISON OF MEASURED HEAVY TRUCK DELELERATION SEL AND PREDICTED LOW SPEED SEL USING AN EXTENSION OF THE FHWA MODEL EQUATION

Site	Mean Speed (mph)	SEL_{pred}(dB)*	Calibrated SEL_{pred}(dB)**	SEL_{meas}(dB)	Delta Pred.-Meas (dB)
DS175	12.7	80.0	77.8	75.3	2.5
DS255	17.8	82.2	80.0	78.5	1.5
DS375	18.0	82.4	80.2	78.6	1.6
DS435	22.3	83.6	81.4	78.3	3.1
DS475	19.5	82.8	80.6	80.3	0.3

*Assuming emission level equation applied at low speeds

**Based on a 2.2 dB difference obtained by comparing the measured mean SEL for high-speed cruise with a predicted SEL at 59.5 mph (the mean measured cruise speed).

TABLE B-21 -- SUMMARY OF L_{MAX} OBSERVATIONS DURING VARIOUS TYPES OF DECELERATION, HEAVY TRUCKS 6/1/88

Type of Event	Mean L_{max} (dB)	S.E. (dB)	No. of Samples
Fast pass-by, rapid deceleration	70.8	2.6	29
Slow pass-by, slow deceleration	68.3	1.9	5
Unspecified pass-by & deceleration	69.1	2.4	26
Idle of several trucks in queue	68.0	2.3	27
Accleration/Deceleration/Idle of Trucks Moving up in Queue	71.1	2.3	15

deceleration and idle as trucks moved up in the queue. The fast, slow and unspecified decelerations were clean events (at least a 6 dB rise and fall); the other events were influenced by other trucks in the queues.

These additional events are summarized in Table B-21. Of interest is that all of the means are in the 68 to 71 dB range, within which would fall the EPA time-averaged level over the 20-0 mph deceleration event of 69 dB. The means also compare well with the mean L_{max} of 70.0 measured at DS175 and are just below the 71.8 dB mean L_{max} measured later on 6/1 at site DN340. "Fast" deceleration levels were about 2.5 dB higher than "slow" deceleration levels.

The idle level of 68 dB included the combined effect of several trucks and was actually the maximum level, which occurred when one of the tractor cabs was directly in front of the microphone. The idle level of a single truck may be approximated as about 64 dB, as computed below, by assuming all of the trucks to have equal idle levels and that the spacing between cabs was 50 feet. Using point source propagation it can be shown that the levels of the truck cabs directly in front of and behind the center truck would be down 3 dB. The level for the next two trucks on either side of center would be down 7 dB; the third set would each be down 10 dB. Then, if the level of one truck is L,

$$L_{total} = 10 \log [10^{L/10} + 2x10^{(L-3)/10} + 2x10^{(L-7)/10} + 2x10^{(L-10)/10}] \quad \text{(B-63)}$$

If L_{total} is 68 dB, then

$$10^{68/10} = 10^{L/10}[1 + 2x10^{-0.3} + 2x10^{-0.7} + 2x10^{-1.0}] \quad \text{(B-64)}$$

Rearranging and solving for L:

$$L = 10 \log [10^{6.8}/(1 + 2x10^{-0.3} + 2x10^{-0.7} + 2x10^{-1.0})] = 63.9 \text{ dB} \quad \text{(B-65)}$$

Rudder reported a similar idle level of 65 dB [Rudder, 1979]. Also, several other idling trucks were measured during this study, with an average level of 65 dBA.

These extra data collected on 6/1 indicates that in true stop-and-go situations the L_{eq} at 50 feet from a stream heavy trucks will be in the 68-71 dB range. This type of information is very useful, albeit awkward to try to program into a model like STAMINA.

Summary for Decelerating Heavy Trucks. To summarize the heavy truck deceleration data:

1. The energy-averaged SEL at a 50 foot offset for distances of 175 to 475 feet from the stopline was 79.4 dB, which was 8.2 dB below the SEL for cruise at 59.5 mph. The mean pass-by speeds at these distances ranged from 22.3 to 12.7 mph.
2. Within 175 feet, and for conditions of slowed deceleration, mixed with idling and slow acceleration, the L_{max} were on the order of 68-71 dB.
3. At speeds above 30 mph, it is anticipated that the levels may be modelled according to the FHWA Model equation for cruise.
4. Levels for deceleration zones where the final speed is not zero have been computed from Rudder's EPA data and appear to give good results.

COMBINING THE RESULTS FOR DIFFERENT VEHICLE TYPES

The previous sections presented discussions for individual vehicle types based on the field work and the EPA data. Little attempt was made to look for commonalities in the results toward developing a realistic, useable approach for a prediction methodology. This section will blend the individual results together.

Having to model a road or ramp separately for each vehicle type is undesirable, especially when the road may need to be divided into several STAMINA roadways separately for each vehicle type. In STAMINA, roadways are defined as having constant speeds, in accordance with the FHWA Model. To model a changing speed scenario with STAMINA, therefore, a series of constant speed roadways would need to be defined. The user needs to examine each problem and look for roadway break points that may be applied in common to all of the vehicle types to minimize the total number of roadways to be defined.

One must realize that modelling has inherent statistical errors, being based on real-world distributions of vehicle characteristics. Depending on the receiver location relative to the stopline, shifts in the starting or ending point of a roadway may or may not cause significant changes in predicted levels. In the larger context, each STAMINA roadway is typically just a part of a series of STAMINA roadways and the received level at any point is a blend of levels from all roadways. Further, given the logarithmic nature of the combination of levels, one needs to keep in mind that if the level from a particular roadway (or vehicle type) is 10 dB or more below that of other roadways (or vehicle types), the total level will not change no matter how finely that roadway is divided or in how much detail it is modelled. The following sections discuss the blending together of the vehicle type dependent results first for acceleration and then for deceleration.

Acceleration

Before combining the results, the individual findings are summarized.

Summarizing Automobile Results. For automobiles, a series of roadway break points and equivalent constant cruise speeds were developed for different speed change ranges. The idea was to maintain consistency with the approach of the FHWA Model as embodied in STAMINA 2.0. Table B-5, discussed earlier, summarized the results.

Essentially, it was found that for final speeds of 45 mph or less, the acceleration zone could be approximated by a single roadway. The length of the roadway depended on the final speed, ranging from 500 feet for 30 mph to 1000 feet for 45 mph. For final speeds above 45 mph, use of at least two roadways was needed (two were sufficient to keep errors reasonable, although more could be defined). The first roadway needed to be 1000 feet long, based on achieving a speed of 45 mph per AASHTO. The length of the second depended on the final cruise speed, ranging from 400 feet beyond the 1000-foot point for 50 mph to 1200 feet beyond for 60 mph.

The equivalent speed to be used for cars on the first roadway was dependent on the speed at the end of the segment. For example, for a 30 mph final speed, the first roadway would end at 500 feet from start. A speed of 38 mph would produce an SEL of 70.0 dB, comparable to the SEL for accelerating cars computed using the EPA data. When the first roadway is 1000 feet in length, use of a 42 mph equivalent speed would produce SEL of 71.3 dB, equivalent to those for accelerating vehicles. When a second acceleration roadway needs to be defined, an average of the actual speed at 1000 feet (computed from AASHTO data) and the final speed should be used. These constant speed assumptions would keep errors at either end of either roadway to about 1 dB when compared to an SEL generated by a time-step acceleration model using the intermediate speed range data computed from the EPA data.

Summarizing Medium Truck Results. The analysis of the EPA data and subsequent calculations of levels for intermediate speed ranges led to the finding that medium truck acceleration SEL showed virtually no speed dependence. The SEL was equivalent (within 0.5 dB) to that of a 43 mph cruise event over a range of distances from the stopline from 100 feet to at least 1600 feet. The limited amount of field data collected in this study supported the idea that a medium truck acceleration event SEL was about 2.7 dB below a cruise event at 59.5 mph. The field measured L_{max} data supported use of an equivalent cruise speed of 40 mph, although there appeared to be a dependence on distance from stopline.

Summarizing Heavy Truck Results. For heavy trucks, the findings were generally similar to the other types, although the roadway lengths and speeds differed. For example, the field data showed that up to a speed of 32 mph, the acceleration SEL could be characterized as being 2.1 dB below the 59.5 mph cruise SEL. Use of a 43 mph equivalent constant speed in the FHWA Model would produce that lower SEL. Accelerating to 32 mph would take about 800 feet. Use of the 43 mph speed would result in an error of about +1 dB at the beginning of the segment and -1 dB at the end. Beyond the 32 mph point, the difference in acceleration SEL relative to cruise at 59.5 mph is 1 dB or less. Thus for final speeds above

45 mph, a roadway break point should be put near the 800 foot position, and the final speed should be used for that roadway.

Addressing Speed Change Ranges. In blending the results together for the three vehicle types, the various possible speed change ranges need to be addressed. This will be done first in 5 mph increments for the case of acceleration from a stopped position. Then, the speed changes from a non-zero initial speed (such as might happen on the end of a loop ramp where the vehicles accelerate to merge onto the intersecting road) will be considered in 10 mph increments.

The 0-30 mph Case as an Example. First, consider the 0-30 mph case. Cars will reach 30 mph by 500 feet from start. However, an equivalent speed of 38 mph is needed to produce the needed effect on SEL. Beyond 500 feet, the 30 mph cruise speed may be used. Heavy trucks, on the other hand, will not reach 30 mph until about 800 feet. Use of the 43 mph equivalent truck speed will result in the 2.1 dB field-measured difference between acceleration SEL and 60 mph cruise SEL. Beyond 800 feet, the cruise speed of 30 mph should be used. For medium trucks, an equivalent speed of 43 mph should be used to represent the acceleration from 0-30 mph. The medium truck will reach 30 mph at about 700 feet. A conservative approach is to extend that point to the 800 foot mark used for the heavy trucks.

Thus, the 0-30 mph case could be modelled by two zone-of-influence roadways:

1. 0-500 feet: cars at 38 mph, trucks at 43 mph
2. 500-800 feet: cars at 30 mph, trucks at 43 mph
3. 800 feet and beyond: cars at 30 feet, trucks at 30 mph.

At 500 feet, a heavy truck speed of 25 mph would be obtained from the AASHTO curves [AASHTO, 1984; p. 784]. The measured mean SEL at site AS610, where the mean speed was 24.5 mph (Table B-15), was only 1.3 dB below the 60 mph cruise SEL. As a result, the user could consider moving the heavy truck break point to 500 feet to coincide with the car point; the result, would be one less roadway to model in STAMINA, with a small change in accuracy.

The Other Speed Ranges. In a similar manner, the speed ranges from 0-35 mph to 0-60 mph were addressed. Also, the cases of non-zero initial speeds were examined. Of particular interest is the fact that for acceleration from 0-40 mph, no special modelling of the roadway would be required for all of the vehicle types.

For each breakpoint, the distance from the stopline, the actual speed reached at that point (per the AASHTO curves), the equivalent speed recommended for modelling, and the corresponding SEL were determined. The SEL were derived from the FHWA Model equations based on the field data findings and/or on the EPA time-averaged reference levels after conversion to intermediate range values. For the higher final speed cases, two acceleration ZOI roadways needed to be defined. The speed and corresponding SEL for the second ZOI may be approximated quite well by the average of the speeds at the beginning and end of the segment.

Table B-22 presents the results of combining the individual vehicle type breakpoints where possible to minimize both data input for a STAMINA run and the potential sound level errors from shifting points.

Deceleration

The EPA data was analyzed in detail for all three vehicle types, supplemented by a good deal of heavy truck measurements. Computations of intermediate speed band levels were made from the EPA data. The analysis for each vehicle type showed the emission levels to be strongly speed dependent. About half of the drop in level for a 60-0 mph event occurred in the final stage of deceleration (from 20 to 0 mph).

Also, the distance over which the deceleration event occurs was quite shorter than for acceleration. For example, the AASHTO curves showed automobiles to decelerate from 60 mph to 0 mph at a "comfortable" rate in 470 feet. The AASHTO guidelines for deceleration ramps, which must

TABLE B-22 -- COMBINED ACCELERATION ZONES OF INFLUENCE AND CORRESPONDING EQUIVALENT SPEEDS FOR THREE VEHICLE TYPES

Accel. Range (mph)		Length (ft)		Speed, ZOI(1) (mph)			Speed, ZOI(2) (mph)		
$S_{initial}$	S_{final}	ZOI(1)*	ZOI(2)**	Autos	MT	HT	Autos	MT	HT
0	30	500	300	38	43	43	30	43	43
0	35	600	650	39	43	43	35	43	43
0	40	1000	none	40	43	43	n/a	n/a	n/a
0	45	1000	none	42	43	43	n/a	n/a	n/a
0	50	1000	800	42	43	43	50	47	47
0	55	1000	800	42	43	43	50	49	49
0	60	1000	800	42	43	43	50	52	52
30	40	400	none	40	43	43	n/a	n/a	n/a
30	50	1000	none	42	43	43	n/a	n/a	n/a
30	60	1900	none	51	52	53	n/a	n/a	n/a
40	50	600	none	45	43	43	n/a	n/a	n/a
40	60	1500	none	50	52	53	n/a	n/a	n/a
50	60	any	none	60	60	60	n/a	n/a	n/a

* Starting from point of stop and proceeding in direction of flow
** Starting from end of ZOI(1)

TABLE B-23 -- COMBINED DECELERATION ZONES OF INFLUENCE AND CORRESPONDING EQUIVALENT SPEEDS FOR THREE VEHICLE TYPES

Decel. Range (mph)		Length (ft)		Speed, ZOI(1) (mph)			Speed, ZOI(2) (mph)		
$S_{initial}$	S_{final}	ZOI(1)*	ZOI(2)**	Autos	MT	HT	Autos	MT	HT
30	0	150	100	29	26	24	18	13	10
40	0	275	100	34	30	28	18	13	10
50	0	400	100	38	34	31	18	13	10
60	0	500	100	41	36	33	18	13	10
40	30	220	none	37	32	30	n/a	n/a	n/a
50	30	375	none	42	37	36	n/a	n/a	n/a
50	40	270	none	46	41	42	n/a	n/a	n/a
60	30	530	none	46	41	42	n/a	n/a	n/a
60	40	430	none	51	46	47	n/a	n/a	n/a

* Starting from end of ZOI(2).
** Starting from point of stop and proceeding upstream from that point.

accommodate trucks, showed a length of only 615 feet for deceleration from 58 mph to 0 mph. A 20-0 mph deceleration occurred in 80 feet. Thus, while the changes in level were great, a large part of the changes were confined to within about 100 feet from stop. Use of a 100 foot length for this last deceleration section appeared reasonable as a first assumption, pending model evaluation.

Thus, for all three vehicle types, the 20 mph point appeared to be a reasonable break point. For the initial phase of deceleration down to 20 mph, equivalent cruise speeds were computed based on the FHWA Model cruise emission level at the initial speed and the EPA time-averaged level for the 30-20 mph range. These speeds were chosen to split the difference between these two levels. The difference could be quite large (e.g., -12.3 dB for automobiles starting at 60 mph) but would occur over a relatively short distance (compared to acceleration) of several hundred feet. The analysis could be improved by further sub-dividing the upper roadway into shorter roadways, but would cause more roadways to be modelled in STAMINA, increasing the level of effort for a small gain in accuracy.

<u>The 60-0 mph Case as an Example</u>. The following example for deceleration from 60-0 mph will illustrate the modelling process. For automobiles, the FHWA cruise emission level is 73.1 dB. For the 30-20 mph range, the EPA time-averaged level is 60.8 dB, or 12.3 dB lower than the cruise level.

The objective is to choose a constant speed that would produce an emission level of one-half of 12.3 dB (or approximately 6.2 dB) below the cruise emission level. Use of the FHWA Model results in a speed of 41 mph for this condition. The difference in SEL for receivers at the 60 and 41 mph passby points was only 4.8 dB.

For the second deceleration roadway representing the 20-0 mph condition, the EPA time-averaged level of 51.3 dB is 21.8 dB below the FHWA cruise emission level (the EPA idle level of 46 dBA is only an additional 5 dB below the 20-0 mph range level.) Using a conservative- 20 dB value for a guide, an equivalent constant speed of 18 mph may be computed.

For medium trucks, the cruise $(L_o)_E$ is 83.7 dB, and the 30-20 mph range level is 69.7 dB (or 14 dB down relative to cruise). An equivalent speed of 36 mph results in an emission level that is half that difference (7 dB) below the cruise level. The time-averaged level in the 20-0 mph range is 59.5 dB, or 24.2 dB below 60 mph cruise. An equivalent constant speed of 13 mph would produce a 59.5 dB emission level.

For heavy trucks, the field data in this study showed the deceleration SEL at passby speeds of 18-23 mph to be about 8 dB below cruise at 59.5 mph. A speed of 33 mph may be computed for the first deceleration roadway to produce a level half of that difference below the cruise level. For the second stage of deceleration, the EPA data was 20 dB below the FHWA cruise level. An equivalent speed of 10 mph is needed to achieve this "20-dB down" level.

In all three cases, the break points could be adequately modelled as running from 600 feet to 100 feet and from 100 feet to the stopline.

<u>Other Speed Ranges</u>. Table B-23 summarizes the results for other initial and final speeds with the levels computed in the same manner as above. Again, the 100 foot break point for the 20 mph transition point should apply to most situations. When the final speed is equal to or above 20 mph, only one deceleration roadway needs to be defined.

<u>A Note About Lengths of Defined Roadways</u>. The preceding sections have shown how the individual vehicle type results could be combined into single sets of recommendations for acceleration and deceleration. The combinations were done in an attempt to define no more than two STAMINA zone of influence roadways for any given acceleration or deceleration scenario.

The equivalent speeds (or adjustments) derived from the previous discussion must be allocated over defined roadways (zones of influence). As a starting point, the lengths may be defined by the vehicle characteristics alone, using the AASHTO curves. For example, for a 60-0 mph deceleration for trucks, the first deceleration zone of influence (DZOI(1)) would be 535 feet long and would represent the distance needed to slow down from 60 to 20 mph (per AASHTO guidelines). The second deceleration zone of influence (DZOI(2)) would be 80 feet long and represent the distance needed to decelerate from 20 to 0 mph. The total length of the two DZOIs is then 615 feet.

However, if modeled in this way, the end effects of the contiguous roadways could result in errors. For example, the 80 foot DZOI(2) roadway would be bounded upstream by DZOI(1) with a constant emission level over 8 dB greater than that for DZOI(2) and would be bounded downstream by an accelerating roadway (AZOI(1)) approximately 10 dB higher. Accordingly, the L_{eq} contributions from DZOI(2) would tend to be masked or dominated by those from these adjacent roadways. Therefore, the lengths of the DZOIs were first established from reported AASHTO vehicle characteristics and then modified based on a sensitivity analysis traffic considerations (i.e., signalized or unsignalized intersection) and field validation (see Chapter Three).

Generalized Method for Determining Equivalent Speeds

The discussion so far has been based on using the FHWA Model emission level equations for the different vehicle types. The equivalent speeds for the acceleration or deceleration ZOI were computed using these equations and level differences relative to the 60 mph cruise case. Not all agencies use the FHWA Model equations. Therefore, use of the equivalent speeds in Tables B-22 and B-23 in those situations would not produce the desired level differences.

However, a generalized expression for computing equivalent speed may be derived if the emission level equation is in the form of:

$$(L_o)_E = a + b \log(S, \text{kph}) \qquad \text{(B-66)}$$

Recall Eq. B-15), which expressed $(L_o)_E$ in terms of SEL:

$$(L_o)_E = SEL + 10 \log(S, \text{kph}) - 22.4 \text{ dB} \qquad \text{(B-67)}$$

Equating the above two expressions and solving for SEL yields:

$$SEL = a + (b-10) \log(S, \text{kph}) + 22.4 \text{ dB} \qquad \text{(B-68)}$$

The basis for the equivalent speed calculation was the difference in SEL between the 60 mph (96 mph) cruise case and the averaged SEL for the acceleration or deceleration ZOI of concern. This difference may be written as:

$$\Delta_c = SEL_{96\ kph} - SEL_{ZOI} \qquad \text{(B-69)}$$

Or,

$$SEL_{ZOI} = SEL_{96\ kph} - \Delta_c \qquad \text{(B-70)}$$

The SEL at 96 kph may be related to the $(L_o)_E$ at 96 kph by rearranging and substituting into Eq. B-67:

$$SEL_{96\ kph} = (L_o)_{E,96\ kph} - 10 \log(96) + 22.4 \text{ dB} \qquad \text{(B-71)}$$

Substituting Eq. B-71 into Eq. B-70 and then substituting SEL_{ZOI} for SEL in Eq. B-68 yields:

$$(L_o)_{E,96\ kph} - 10 \log(96) + 22.4 - \Delta_c = a + (b-10) \log(S, \text{kph}) + 22.4 \text{ dB} \qquad \text{(B-72)}$$

Solving for S (in kph):

$$S = \text{antilog}\ [(L_o)_{E,96\ kph} - 10 \log(96) - a - \Delta_c]/(b-10) \qquad \text{(B-73)}$$

In words, use of this equivalent speed S will produce an SEL that is Δ_c dB below the SEL produced at a cruise speed of 96 kph for a model using an emission level expression of the form a + b log (S, kph).

The assumption is that the level differences determined through the analysis of the EPA data base, the FHWA Model and the measurements made in this study will apply to other cruise emission level models. Only detailed data collection in each individual case can verify this assumption.

SUMMARY

This appendix has presented a detailed examination of acceleration and deceleration noise levels for the three vehicle types--automobiles, medium trucks and heavy trucks--used in the FHWA Highway Traffic Noise Prediction Model [Barry and Reagan, 1978]. The sources of the data were the EPA National Traffic Noise Exposure Model [Rudder, 1979] and field measurements made during this research.

From this analysis, a methodology was developed for each vehicle type for predicting the L_{eq}(1 hr) for "interrupted flow" with the STAMINA 2.0 computer program, which is based on the FHWA Model. Because the FHWA Model is built around the concept of use of a constant speed, some means of accomodating changing speeds needed to be developed. The most successful way of doing this was to divide an acceleration or deceleration event into several pieces and determine approximate constant emission levels for each piece. Then, appropriate constant speeds could be calculated for each piece that, when used in the FHWA Model, would produce the desired effect on the L_{eq}. The "pieces" were called "zones of influence" and defined as areas where the levels would be affected by accelerating or decelerating traffic.

The basis for developing the methodology was the linear relationship between the sound exposure level of individual vehicle events and the average level of the events over the one-hour analysis period.

After separate examination of each vehicle type, the results were combined into one overall methodology, adjusting the lengths of the zones of influence and the equivalent speeds to be used on them. A goal was to be able to characterize an accerlation or deceleration region by a maximum of two separate zones.

APPENDIX C—DESIGN GUIDE FOR PREDICTING STOP-AND-GO TRAFFIC NOISE LEVELS

INTRODUCTION

Appendix B described, in detail, the development of a methodology to predict stop-and-go traffic noise levels, using the STAMINA 2.0 computer program, within the defined scope of this study. The methodology was based on an analysis of the existing literature and emission level data collected for this study. Chapter Three of the main text presents documentation of the evaluation of the prescribed methodology at real-world sites and recommended modifications. This Appendix presents the revised methodology as a step-by-step design guide. Included are examples to illustrate use of the procedures.

To begin, it is helpful to consider how traffic is characterized for this methodology. Stop conditions or reduced speed conditions may occur within zones-of-influence where repeated modal activity occurs. These conditions generally correspond to an intersection or to a ramp, and each is predicted differently by the methodology. For example, at a STOP sign, vehicles always accelerate from the same location, the stop line. If a queue line forms, vehicles must "idle" forward to wait their turn in the queue. Accordingly, the deceleration zone of influence (DZOI) must be offset upstream from the end of queue and also account for the area of the queue line. For a signalized intersection, vehicles accelerate from the location of their stop. Therefore, in order to designate zones of influence (acceleration/deceleration) an average stop point must be determined. This average stop point location would correspond to one-half of the queue length. These differences cause signalized and unsignalized intersections to be analyzed differently. Of course, many ramps do not include a stop and are treated differently from intersections.

The various prediction scenarios that are defined by the methodology are discussed below. Intersections are characterized for this project as: (1) unsignalized intersections which include stop signs, flashing red signals or tollbooths (where all vehicles decelerate from cruise to a stop and then accelerate from a single stopped position back to cruise); (2) signalized intersections.

Highway ramps are characterized as: (1) deceleration to a stop for all vehicles with acceleration from a defined location (if a stop occurs for all vehicles because of a traffic control device or sign, the methodology treats this as a ramp and then as an intersection); (2) acceleration and deceleration sections with speed changes from non-zero final and initial speeds (e.g., a slip ramp); and (3) deceleration or acceleration where only a portion of the vehicles stop or start from a stopped position as when a traffic signal is at end of a ramp (essentially a combination ramp and intersection scenario as described earlier).

Highway loop ramps are a special case and can experience either an initial acceleration or deceleration, followed by a section of relatively constant speed (cruise), followed by another section of acceleration or deceleration. This scenario is treated as a combination of two ramps and a cruise roadway.

This design guide does not separate the cruise-through traffic from the interrupted flow traffic. However, users of these procedures could modify them, if it were necessary to separate traffic into cruise and interrupted flow through the intersection. This would only be required if a large percentage (over 25 percent) of vehicles cruised through the intersection under analysis without slowing.

Use of the methodology for the different scenarios will be described in the remainder of this appendix. In all cases, the procedures represent some variation on the following steps:

1. Determine initial and final speeds.

2. Determine the transition point where vehicle deceleration is assumed to end, or acceleration to begin (this point will be referred to as a "point of stop" (P.S.) for intersection evaluations).

3. Determine the length(s) of the roadway(s) to be modelled.

4. Apply those lengths as roadways to the study site using the transition point as an endpoint (note that in the STAMINA 2.0 program the word endpoint is used generically to represent a starting point or an ending point of a roadway segment).

5. Assign appropriate equivalent speeds for the traffic on each roadway (or assign a cruise speed and determine speed level adjustments relative to cruise for the various acceleration or deceleration segments if the FHWA $(L_o)_E$ emisson levels are not used).

6. Create and run a STAMINA 2.0 file (making sound level adjustments if the latter option in step 5 is used).

To better understand the procedures in the next section, data requirements for each scenario are first discussed. Then, the specific analysis steps are outlined in an easy-to-follow format.

DATA REQUIREMENTS

All four of the vehicle operating scenarios -- unsignalized intersections, signalized intersections, loops, and ramps -- will require certain similar data items as well as having their own unique requirements. The items common to all will be described first.

Universal Data

A geometric layout or scaled plans for the roadway being studied will provide the analyst with needed geometric data (i.e., number of lanes, turning radii, location of receivers) for the location to be modeled.

Profile or elevation data will also be required. If the roadways traversed by vehicles are level, no grade or gradient adjustments are necessary. Adjustments, as described later, will be necessary if non-level gradients are present.

Another universal data requirement is traffic information. The percentage of vehicles by vehicle type (i.e., automobile, medium truck or heavy truck) is needed, because each of these vehicle types has different operating characteristics and each emits differing noise levels. Accordingly, the vehicle mix or traffic composition is an important consideration that must be known or be reasonably estimated.

Vehicle hourly volumes for the desired time of analysis are also required. Through traffic and turning traffic volumes for each road are fundamental data that are required, where appropriate.

Operating cruise speed(s) (constant, representative speed(s) for uninterrupted vehicle flow(s)) are needed where appropriate. These operating cruise speeds will occur on roadway segments before or after acceleration or deceleration conditions.

After determining these data the analyst must determine specific data that are required for the geometric layout to be studied. The following sections describe these specific data needs in detail.

Intersections

Intersections must be analyzed in terms of: (1) number of approaches, and (2) type of traffic control (i.e., signalized or unsignalized). In addition, vehicle volumes (demand), intersection capacity as it relates to geometric design features, gradients, approach speeds, and vehicle mix are also factors that affect the operational characteristics of an intersection.

In order to accurately replicate the typical traffic conditions at an existing intersection, there is no substitute for a careful field study of actual conditions. When this is not possible or the intersection is only in the design stage, other procedures must be followed.

For an existing intersection, the analyst must obtain the total hourly volume (i.e., throughput) for each approach during the time of interest (usually the peak hour conditions). An important phenomenon to observe or estimate for each approach is the "end of the queue" (E.Q.) location. This is the point or location where, on the average, the approach queue ends under typical operating conditions, during the defined time period. Locating the E.Q. is important because it influences approaching vehicles that must transition their speeds, and so defines where the deceleration zone of influence (DZOI) will occur.

Manual or mechanical observations to obtain actual traffic count data are the best. These data can provide valuable information for the traffic engineer and noise analyst, pertaining to answering such questions as where the end of queue is located. However, surrogate means of determining the E.Q. for each approach must be used if field data are not available. The E.Q. point can be determined from the approach volume by use of queueing theory for both unsignalized and signalized intersections.

The following sections describe the appropriate queueing theory for signalized and unsignalized intersections.

Unsignalized Intersections

The point where the first vehicle will stop will be adjacent to the location of the STOP or YIELD sign (or stop line if one exists); this point will be referred to as the stop-line point. The end of queue (E.Q.) can then be defined some distance upstream of the stop-line point. Behind the stop line is a zone (length of roadway) where the transition from stopped vehicles to approaching vehicles will likely occur. The E.Q. will influence the length of this zone. This is called the deceleration zone of influence (DZOI). Figure C-1 depicts these points.

Various queueing equations allow determination of the expected number of vehicles in the queue per approach. The equation best suited for unsignalized intersections, in this application, to estimate the average or expected number of vehicles in the system is as follows:

$$E(n) = A/(S-A) \qquad \text{(C-1)}$$

where E(n) = average number of vehicles in system per approach; A = arrival rate or directional design hourly volume, DDHV; S = 1500 pcplph service rate (pcplph = passenger car per lane per hour). (It is noted that the AASHTO "Green Book" states on page 81 that, "The rate at which vehicles can depart from a standing queue is estimated by various authorities as being within the range of 1,500 to 1,800 pcplph." Thus, 1,500 passenger cars per lane per hour, pcplph, was selected as a reasonable discharge flow rate to assure that an optimum queue length per approach would be considered [AASHTO, 1984].)

Once E(n) has been determined, the appropriate proportion of passenger cars can be converted to single unit and heavy trucks if they exist in sufficient numbers in the vehicle stream. Because of the typically small E(n) and the use of the conservative 1,500 pcplph, other vehicle types can usually be ignored except in extreme situations.

Once the expected number of waiting vehicles or queue per approach is determined, standard linear distances per vehicle type can be used to obtain an average queue length. Standard distance must include vehicle length with some additional distance or gap for "between vehicle" spacing considerations. The length of the queue line is included in the deceleration zone of influence for unsignalized intersections, and is discussed in more detail in the section on detailed procedures.

Signalized Intersection Analysis

Signalized intersection analyses are similar in many ways to unsignalized intersection analyses, and build upon the earlier unsignalized analysis techniques. The concepts of cycle length, C, "green time" to cycle length ratio, G/C, and capacity service volume or saturation flow rate, S, for each approach per hour

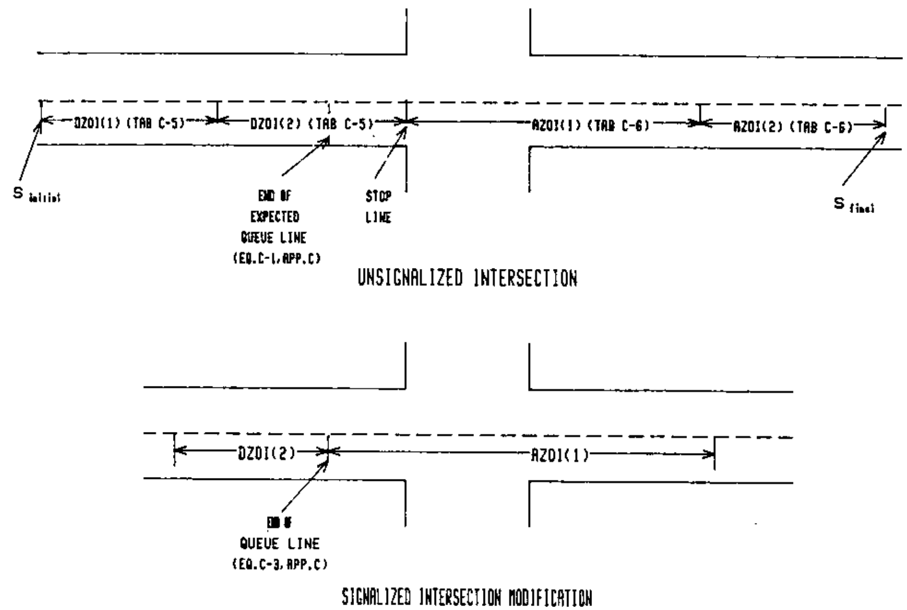


Figure C-1 -- Definition of Zones of Influence for Unsignalized (top) and Signalized (bottom) Intersections of effective green time are additional important parameters at signalized intersections. These data are reported in vehicles per hour of green (vphg).

The E.Q. is equivalent to the point described for unsignalized operations but is derived differently for a signalized analysis. The significance in signalized operations is equally as important as for the unsignalized case. To obtain the E.Q., signal cycle split or percent "green time" per signal cycle must be determined. For existing operations this requires merely determining the percent "green time" for each approach as a proportion of the total signal cycle length. If the signal does not exist yet, "green time" per approach must be approximated. This is done by examining approach volume per phase. The percent "green time" per phase is roughly equivalent to the cycle length multiplied by the ratio of largest directional volume per phase to the sum of the largest volumes for all phases.

Using this ratio, G/C, with the intersection capacity and demand, the proportion of vehicles that will have to stop for a signal may be determined using an equation originally developed by Webster [1958] as presented in the EPA "Volume 9" air quality guidelines [U.S. Environmental Protection Agency, 1978; p. 19]:

$$P = [1 - (G/C)]/[1 - (V/S)] \quad (C\text{-}2)$$

where P = proportion of vehicles that must stop at signal; G = effective green-phase time, in seconds; C = length of signal cycle, in seconds; V = one-hour traffic demand for an approach, in vph; and S = capacity service volume or saturation flow rate, in vphg.

Note that if P is greater than 1.0, congested or saturated flow will result (Level of Service (LOS) = E or F) and these guidelines are not appropriate for determining traffic flow (and, hence, noise emission levels) at this intersection. The user is referred to the NCHRP Report 133 (1972) or the Highway Capacity Manual (HCM) (1985) for possible alternative methods of predicting delay at an over-capacity or saturated intersection to determine the number of vehicles that must stop.

Once P is known, all required data are available to calculate the number of vehicles per cycle per approach that would be subject to queueing delay [U.S. Environmental Protection Agency, 1978; p. 20]:

$$N_i = (P_i V_i C/3600) + [V_i/(CAP_i - V_i)] \quad (C\text{-}3)$$

where N_i = number of vehicles on approach i delayed per cycle; P_i = proportion of vehicles for approach i that must stop at signal; V_i = one-hour traffic demand for approach i, in vph; C= length of signal cycle, in seconds; and CAP_i = actual capacity per hour resulting from capacity service volume, S_i, multiplied by "green time"/cycle length ratio, in vph ($CAP_i = S_i \times G/C$).

From the number of approach vehicles delayed per cycle, the distance or queue length to the E.Q., referenced from the stop line, can be located. This average vehicle queue length is then divided in half to establish the average distance for the point of stop (P.S.) upstream from the mandatory stop line. Table C-1 gives the space (i.e., vehicle length plus gap) allocated to each vehicle type. N_i may be rounded to the nearest whole number.

Ramps and Loops

Ramps may be treated as subcases of the signalized or full-stop intersection scenarios with the additional feature being that deceleration or acceleration zones are generally designed in accordance with AASHTO guidelines. Acceleration or deceleration would occur over the length of the ramp. In some cases queues may build at the end of an exit ramp at a traffic control device, thereby influencing when exiting vehicles begin their deceleration. Similarly for entrance ramps, traffic control devices and turning movement geometrics may create a condition of acceleration from an approximate stop for most or all vehicles.

In other cases, ramps serve as transition zones from one cruise speed to another without vehicle stops. One example is a slip ramp from a highway to a collector road. A second example is a loop where, generally, there will be an initial zone of deceleration or acceleration depending on the approach speed, followed by a zone of constant speed defined by the ramp geometry, followed by a zone of acceleration to the final cruise speed.

Thus, additional data are required to analyze noise levels from ramps and loops. Specifically, the following ramp data are also required: (1) initial speed on ramp; (2) cruise or constant speed on ramp, if applicable; (3) final speed on ramp; (4) point where first vehicle will stop, P.S, (if applicable); (5) posted ramp speed; (6) design ramp speed; and (7) ramp gradient.

If the values are not known for ramp speeds, speeds may be estimated if either the radius of the loop or the degree of curvature for the loop is known. Table C-2 (derived from AASHTO 1984, pg. 177) shows the corresponding speeds for various radii and degree of curvatures.

GRADIENT ADJUSTMENTS

If the grade is not level, the length of the ZOI will change. Noise emissions will be the same but over greater distances for upgrades and lesser distances for downgrades. Tables C-3 and C-4 provide multipliers for deceleration and acceleration zones of influence. These multipliers are used to obtain the adjusted distances, which is the product of the multiplier and the length of the ZOI. The lengths of the ZOI are discussed in detail in the next section.

DETAILED PROCEDURES

1. Unsignalized Intersections

1.1 Scenarios including this condition:

1.1.1 STOP sign or flashing red at intersection or ramp (special case, but treated in a like manner: tollbooths).

1.2 Deceleration zones:

1.2.1 Determine initial cruise speed, $S_{initial}$, to nearest 10 mph. This step is necessary to obtain the length of the deceleration zone of influence (DZOI) and to allow a proper approximation of the emission level. The initial cruise speed is the speed before deceleration begins. In the absence of other available speed data, the posted speed limit for the roadway segment may be used.

1.2.2 Determine the design hourly volume (or traffic for hour of interest) and vehicle mix (percent automobiles, percent medium trucks, percent heavy trucks) for the approach road or ramp.

1.2.3 Determine the expected number of vehicles in the queue, E(n), behind the stop line, using Eq. C-1. Round E(n) to the nearest whole number and multiply by the appropriate spacing from Table C-1 to determine the length of the queue line and E.Q. For unsignalized intersections the distance is added to the DZOI and the stop line is used as the beginning of the acceleration zone of influence (AZOI).

1.2.4 Based on the initial cruise speed and the final speed of 0 mph, determine the length(s) of the DZOI(s) from Table C-6. The first deceleration zone of influence, DZOI(1), represents deceleration from the initial cruise speed to a 20-mph transition speed; the second zone, DZOI(2), represents the final stage of deceleration from the transition speed to the P.S. DZOI(2) is increased for unsignalized intersections by the length of the queue line:

$$DZOI(2) = E.Q. + (\text{value from Table C-5}) \quad (C\text{-}4)$$

TABLE C-1 -- SPACE ALLOCATION IN A QUEUE

Vehicle Type	Space
Automobile A	25 feet
Medium Truck, MT	35 feet
Heavy Truck, HT	60 feet

TABLE C-2 -- SPEED VALUES FOR LOOP RAMPS (FROM AASHTO, 1984, PG. 177 AND 1044)

Design Speed (mph)	Running Speed (mph)	Maximum Degree of Curvature	Minimum Radius (ft)
20	20	45.0 - 58.0	99 - 127
25	24	24.8 - 44.9	128 - 230
30	28	19.0 - 24.75	231 - 302
35	32	13.3 - 18.9	303 - 431
40	36	10.0 - 13.25	432 - 573
45	40	8.3 - 9.9	574 - 693
50	44	6.0 - 8.25	694 - 955
55	48	5.3 - 5.9	956 -1090
60	52	3.75 - 5.25	1091 -1528

TABLE C-3 -- MULTIPLIERS FOR DECELERATION ZONES OF INFLUENCE (DZOI) TO ACCOUNT FOR GRADE - ALL SPEEDS (FROM AASHTO, 1984, PG. 1043)

Grade (percent)	Upgrade DZOI Multiplier	Downgrade DZOI Multiplier
0-2	1.0	1.0
3-4	0.9	1.2
5-6	0.8	1.35

TABLE C-4 -- MULTIPLIERS FOR ACCELERATION ZONES OF INFLUENCE (AZOI) TO ACCOUNT FOR GRADE (FROM AASHTO, 1984, PG. 254, 255 AND PG. 1043)

Highway Design Speed (mph)	Upgrade* (percent)	Upgrade AZOI	Downgrade (percent)	Downgrade AZOI Multiplier
20	0-2	1.0	0-2	1.0
	3-4	1.3	3-4	0.9
	5-6	1.5	5-6	0.8
30	0-2	1.0	0-2	1.0
	3-4	1.3	3-4	0.8
	5-6	1.5	5-6	0.7
40	0-2	1.0	0-2	1.0
	3-4	1.4	3-4	0.7
	5-6	1.7	5-6	0.6
50	0-2	1.0	0-2	1.0
	3-4	1.6	3-4	0.65
	5-6	2.0	5-6	0.55

* When upgrades exceed two percent, cruise roadways should not be used after the acceleration zones of influence. The truck will reach a substained crawl speed at high engine power, producing a noise level equivalent to the acceleration condition.

Determine the total length of DZOI(2) and subtract upstream from the stop line. DZOI(1) begins at this point and extends upstream the length given in Table C-5. The upstream endpoint of the DZOI(1) roadway would represent the ending point for a cruise roadway that could be defined as occurring before the deceleration zone.

1.2.5 Also from Table C-5, determine the equivalent speeds to be used for each vehicle type based on the initial speed and a final speed of 0 mph. These speeds may be directly encoded in the STAMINA input data file for the two DZOI roadways (STAMINA 2.0 must be modified to allow speeds of less than 30 mph to be input. The required changes to accomplish this are discussed at the end of this appendix).

1.3 Acceleration zones:

1.3.1 Determine final cruise speed, S_{final}, to nearest 5 mph. This speed is the cruise speed after acceleration has been completed. It is typically the posted speed limit for the road.

1.3.2 Determine the design hourly volume (or hour of interest) and vehicle mix (percent automobiles, percent medium trucks, percent heavy trucks) for the departure leg from an intersection or for the ramp (note that all turning movements on to this departure leg are also included).

1.3.3 Based on the final cruise speed and an initial speed of 0 mph determine the length(s) of the acceleration zones of influence, AZOI, from Table C-6. Add these lengths downstream from the P.S. to determine the endpoints of these AZOI roadways for input into STAMINA. The AZOI(1) represents acceleration from stop to a transition speed, and AZOI(2) represents acceleration from the transition speed to the final speed. The final endpoint of the AZOI(2) would also be the initial point of a full cruise roadway if one were to be defined beyond the end of the acceleration zones.

1.3.4 Also from Table C-6, determine the equivalent speeds for input into STAMINA for each vehicle type for each zone based on an initial speed of 0 mph and the final cruise speed.

1.4 Example for stop sign:

1.4.1 Given approach and departure speeds of 60 mph and design hourly volumes of 1,150 vph, for a hypothetical one-lane, one-way road consisting of 87 percent automobiles, 4 percent medium trucks and 9 percent heavy trucks, define the needed roadway input data for a STAMINA file. Ignore the cross-street for this example. To solve, first compute E(n), E.Q., and P.S., look up the DZOI lengths and equivalent speeds, and compile the results in the needed format for STAMINA.

1.4.2 Expected queue length:

E(n) = A/(S-A) = 1,150/(1,500-1,150) = 3.3 vehicles (use 3 vehicles)

1.4.3 End of queue and point of stop:

E.Q. = 3 x 25 ft = 75 ft back from stop line (four percent MT & nine percent HT are considered negligible for E.Q. calculations for this example)

P.S. = stop line (unsignalized intersection)

1.4.3 Deceleration zones of influence and equivalent speeds (using Table C-5):

DZOI(1) = 300 ft
$S_{A,DZOI(1)}$ = 41 mph
$S_{MT,DZOI(1)}$ = 36 mph
$S_{HT,DZOI(1)}$ = 33 mph

DZOI(2) = 200 ft + E.Q. = 275 ft
$S_{A,DZOI(2)}$ = 18 mph
$S_{MT,DZOI(2)}$ = 13 mph
$S_{HT,DZOI(2)}$ = 10 mph

TABLE C-5 -- COMBINED DECELERATION ZONES OF INFLUENCE AND CORRESPONDING EQUIVALENT SPEEDS FOR THREE VEHICLE TYPES

Decel. Range (mph)		Length(ft)		Speed, ZOI(1)(mph)			Speed, ZOI(2)(mph)		
$S_{initial}$	S_{final}	ZOI(1)*	ZOI(2)**	Autos	MT	HT	Autos	MT	HT
30	0	150	100	29	26	24	18	13	10
40	0	250	100	34	30	28	18	13	10
50	0	200	200	38	34	31	18	13	10
60	0	300	200	41	36	33	18	13	10
40	30	220	none	37	32	30	n/a	n/a	n/a
50	30	375	none	42	37	36	n/a	n/a	n/a
50	40	270	none	46	41	42	n/a	n/a	n/a
60	30	530	none	46	41	42	n/a	n/a	n/a
60	40	430	none	51	46	47	n/a	n/a	n/a

* Starting from end of ZOI(2) (see Figure B-7).
** Starting from point of stop and proceeding upstream from that point (see Figure B-7).

TABLE C-6 -- COMBINED ACCELERATION ZONES OF INFLUENCE AND CORRESPONDING EQUIVALENT SPEEDS FOR THREE VEHICLE TYPES

Accel. Range (mph)		Length(ft)		Speed, ZOI(1)(mph)			Speed, ZOI(2)(mph)		
$S_{initial}$	S_{final}	ZOI(1)*	ZOI(2)**	Autos	MT	HT	Autos	MT	HT
0	30	500	300	38	43	43	30	43	43
0	35	600	650	39	43	43	35	43	43
0	40	1000	none	40	43	43	n/a	n/a	n/a
0	45	1000	none	42	43	43	n/a	n/a	n/a
0	50	1000	800	42	43	43	50	47	47
0	55	1000	800	42	43	43	50	40	49
0	60	1000	800	42	43	43	50	52	52
30	40	400	none	40	43	43	n/a	n/a	n/a
30	50	1000	none	42	43	43	n/a	n/a	n/a
30	60	1900	none	51	52	53	n/a	n/a	n/a
40	50	600	none	45	43	43	n/a	n/a	n/a
40	60	1500	none	50	52	53	n/a	n/a	n/a
50	60	any	none	60	60	60	n/a	n/a	n/a

* Starting from point of stop and proceeding in direction of flow (see Figure B-7).
** Starting from end of ZOI(1) (see Figure B-7).

1.4.4 Acceleration zones of influence and equivalent speeds (using Table C-6):

AZOI(1) = 1,000 ft	AZOI(2) = 800 ft
$S_{A,AZOI(1)}$ = 42 mph	$S_{A,AZOI(2)}$ = 50 mph
$S_{MT,AZOI(1)}$ = 43 mph	$S_{MT,AZOI(2)}$ = 52 mph
$S_{HT,AZOI(1)}$ = 43 mph	$S_{HT,AZOI(2)}$ = 52 mph

The roadway portion of the STAMINA file can then be developed as shown in Figure C-2. It is assumed that cruise roadways of 2,000-ft. length are defined prior to DZOI(1) and after AZOI(2). It is also assumed that the origin is centered on the center of the intersection and the x-axis is parallel to the road.

2. Signalized Intersections

2.1 Deceleration zone:

2.1.1 Determine the initial approach cruise speed. This speed is typically the average operating speed exclusive of any stop time or the posted speed limit.

2.1.2 Determine the design hourly volume (or hour of interest) and vehicle mix (percent automobiles, percent medium trucks, percent heavy trucks) for the approach road (or ramp).

2.1.3 Determine the percentage of vehicles that can be expected to have to stop for the signal, using Eq. C-2. The following data are required:

G = effective green-phase time (seconds)
C = length of signal cycle (seconds)
V = one-hour traffic demand (vph, from step 2.1.2)
S = capacity service volume or saturation flow rate (vphg)

G may be approximated by multiplying C by the ratio of the largest volume per phase on the roadway of interest to the sum of the largest volumes for each roadway for all phases. An example calculation follows: assume C = 120 seconds, with a 3-phase signal to allow one phase for simultaneous left turns. The largest volumes for each phase are 200 vph eastbound turns, 450 westbound through and 550 northbound through. Then the percent green per phase would be 200/1,200 or 16.7 percent of the 120 seconds for the left turn phase, 450/1,200 or 37.5 percent for the east-west movements and 550/1,200 or 45.8 percent for the north-south movements. These percents would then represent 20, 45, and 55 seconds, respectively, for the various phases.)

2.1.4 Determine the number of vehicles per cycle subject to queueing delay using Eq. C-3, where P_i was computed in step 2.1.3 and V_i is the total approach traffic on the roadway of interest. Round N_i to the nearest whole number, multiply by the spacing from Table C-1, and subtract the result to get the distance from the stop line location to determine the location of the E.Q. Divide this distance in half to locate the average P.S.

2.1.5 Based on the initial cruise speed and the stop speed of 0 mph, determine the length(s) of the deceleration ZOI(s) from Table C-5. Subtract these lengths upstream from the P.S. point to determine the end points for the DZOI roadways for entry into the STAMINA 2.0 program input file. DZOI(1) represents deceleration from the initial cruise speed to a 20-mph transition speed; DZOI(2) represents the final stage of deceleration from the transition speed to the E.Q. The far upstream end point of the DZOI(1) roadway would represent the ending point for a cruise roadway that could be defined as occurring before the deceleration zone.


```
*NNNNY
 SIMPLE ACCEL/DECEL CASE; STOP SIGN
1 3
2 6
 CRUISE ONE
'CARS'  1000 60
'MT'    50   60
'HT'    100  60
'L'/
'CR1-1' -2575 0  0 0
'CR1-2' -575  0 0  0
'L'/
 DECEL ONE
'CARS'  1000 41
'MT'    50   36
'HT'    100  33
'L'/
'DC1-1' -575 0 0 0
'DC1-2' -275 0 0 0
'L'/
 DECEL TWO
'CARS'  1000 18
'MT'    50   13
'HT'    100  10
'L'/
'DC2-1'  -275 0 0 0
'DC2-2'   0   0 0 0
'L'/
 ACCEL ONE
'CARS'  1000 42
'MT'    50   43
'HT'    100  43
'L'/
'AC1-1'  0 0 0 0
'AC1-2'  1000 0 0 0
'L'/
 ACCEL TWO
'CARS'  1000 50
'MT'    50   52
'HT'    100  52
'L'/
'AC2-1'  1000 0 0 0
'AC2-2' 1800 0 0 0
'L'/
 CRUISE TWO
'CARS'  1000 60
'MT'    50   60
'HT'    100  60
'L'/
'CR2-1' 1800 0 0 0
'CR2-2' 3800 0 0 0
'L'/
```

Figure C-2 -- STAMINA Input File Example
Unsignalized Intersection (STOP sign)

2.1.6 Also from Table C-5, determine the equivalent speeds to be used for each vehicle type, using the initial speed and a final speed of 0 mph. These speeds may be directly encoded in the STAMINA 2.0 input data file for the two deceleration ZOI roadways (note: the STAMINA program must be corrected as shown at the end of this appendix).

2.1.7 As needed, beyond the far end point of DZOI(1), an all-cruise roadway that contains the total traffic volumes with the posted or operating speeds may be defined.

2.2 Acceleration zones:

2.2.1 Determine the final cruise speed, which will typically be the posted roadway speed.

2.2.2 To obtain the volumes of accelerating vehicles on the departure leg, take the total volume of vehicles on the approach leg, and subtract its turning movement traffic onto the other legs. Then, add the turning movements from each cross-street leg onto the departure leg. Multiply this sum by the vehicle mix percentages to get the hourly volumes of accelerating traffic for each vehicle type. Assume all of this traffic will accelerate from the average P.S. on the approach leg.

2.2.3 Based on the final cruise speed and an initial speed of 0 mph determine the length(s) of the acceleration zones of influences (AZOI(s)) from Table C-6. Add these lengths downstream to the P.S. point to determine the end points for these AZOI roadways for input into STAMINA. AZOI(1) represents acceleration from stop to a transition speed, and AZOI(2) represents acceleration from the transition speed to the final speed. The final end point of AZOI(2) would also be the initial point of a full cruise roadway if one were to be defined downstream of the acceleration zones.

2.2.4 Also from Table C-6, determine the equivalent speeds for input into STAMINA for each vehicle type for each AZOI based on an initial speed of 0 mph and the final cruise speed.

2.2.5 As needed, an all-cruise roadway can be defined downstream of AZOI(2).

2.3 Example for signalized intersection:

2.3.1 Given a hypothetical north-south, two-lane roadway which intersects with a two-way, four-lane road (as shown in Figure C-3) develop the portion of the input file for STAMINA 2.0 for acceleration, deceleration, and cruise roadways for the northbound direction of the two-lane road only. Assume a 50-mph posted speed limit, and a vehicle mix of 80 percent automobiles, 10 percent medium trucks and 10 percent heavy trucks. Assume a 90-sec cycle for a 2-phase signal and assume the turning movements are as shown in Figure C-3. Define a 2,000 ft long cruise section beyond the end of the interrupted flow zone. To solve, compute P, N_i, E.Q., P.S. and the appropriate volumes for each vehicle type. Use Tables C-5 and C-6 to determine the ZOI and equivalent speeds.

2.3.1 Proportion of stopping vehicles:

G/C (for NB/SB phase) = 500/(500 + 900) = 0.357
$P_i = [1 - (G/C)]/[1 - (V/S)]$
$P_i = [1 - 0.357]/[1 - (500/2{,}000)] = 0.857$

2.3.2 Number of vehicles developed per cycle:

$N_i = (P_i V_i C/3{,}600) + V_i/(CAP_i - V_i)$
$N_i = (0.857)(400)(90)/3{,}600 + 400/(2{,}000\text{-}400)$
N_i = 8.82 vehicles delayed per cycle (use 9 vehicles)

2.3.3 End of queue and point of stop:

E.Q. = 9 vehicles x 25 ft = 225 ft
P.S. = (0.5)(225) = 113 ft

2.3.4 Approach and departure volumes (from traffic diagram and turning movements):

$V_{NB,approach}$ = 300 + 20 + 80 = 400 vph
$V_{NB,departure}$ = (400 - 20 - 80) + (25 + 60) = 385 vph

2.3.5 Deceleration zones of influence and equivalent speeds (from Table C-5):

DZOI(1) = 200 ft	DZOI(2) = 200 ft
$S_{A,\,DZOI(1)}$ = 38 mph	$S_{A,\,DZOI(2)}$ = 18 mph
$S_{MT,\,DZOI(1)}$ = 34 mph	$S_{MT,\,DZOI(2)}$ = 13 mph
$S_{HT,\,DZOI(1)}$ = 31 mph	$S_{HT,\,DZOI(2)}$ = 10 mph

2.3.6 Acceleration zones of influence and equivalent speeds (from Table C-6):

AZOI(1) = 1000 ft	AZOI(2) = 800 ft
$S_{A,\,AZOI(1)}$ = 47 mph	$S_{A,\,AZOI(2)}$ = 50 mph
$S_{MT,\,AZOI(1)}$ = 43 mph	$S_{MT,\,AZOI(2)}$ = 43 mph
$S_{HT,\,AZOI(1)}$ = 43 mph	$S_{HT,\,AZOI(2)}$ = 43 mph

The resultant section of the STAMINA file for the northbound roadways is shown in Figure C-4.

3. Slip Ramps, Loop Ramps, Channelized Ramps

3.1 Speeds:

3.1.1 Determine the posted speeds or operating speeds for the exited roadway, the final speed of the entered roadway, and any critical sections of the ramp (a critical section being where the ramp geometrics call for a reduced operating speed). The subsequent analysis may simply involve a cruise-acceleration-cruise or cruise-deceleration-cruise series of roadways if ramp geometries do not require an intermediate low speed section. However, as in the case of a loop from one highway to another, there will probably be the following sequence of operations: (1) cruising on initial (exiting) highway; (2) deceleration (or acceleration) on first portion of loop; (3) cruising on center portion of loop; (4) acceleration (or deceleration) on last portion of loop; and, (5) cruising on final (entered) highway. This latter 5-sequence situation can be analyzed as two connecting cases of the simpler scenarios.

3.2 Deceleration:

3.2.1 Determine the point that approximates where deceleration ends or begins. AASHTO design curves present the lengths of ramp sections as functions of initial and final speed. Deceleration is assumed to begin when the vehicle leaves the main roadway and to end when the vehicle reaches the ramp curve at an operating speed based on the ramp design speed. Thus, the beginning of curve point is an appropriate point for assuming the deceleration has ended. If curve geometries are confusing, the starting point of deceleration (when the vehicle leaves the main lanes) may be used.

3.2.2 Determine the length of the deceleration ZOI using Table C-5, which is based on the AASHTO design chart, with the appropriate initial and final speeds.

3.2.3 The point chosen in step 3.2.1 will serve as the ending or starting point of the DZOI roadway for input into STAMINA. From that point move back (or forward) for the required DZOI length determined in step 3.2.2 to establish the DZOI roadway for input into STAMINA.

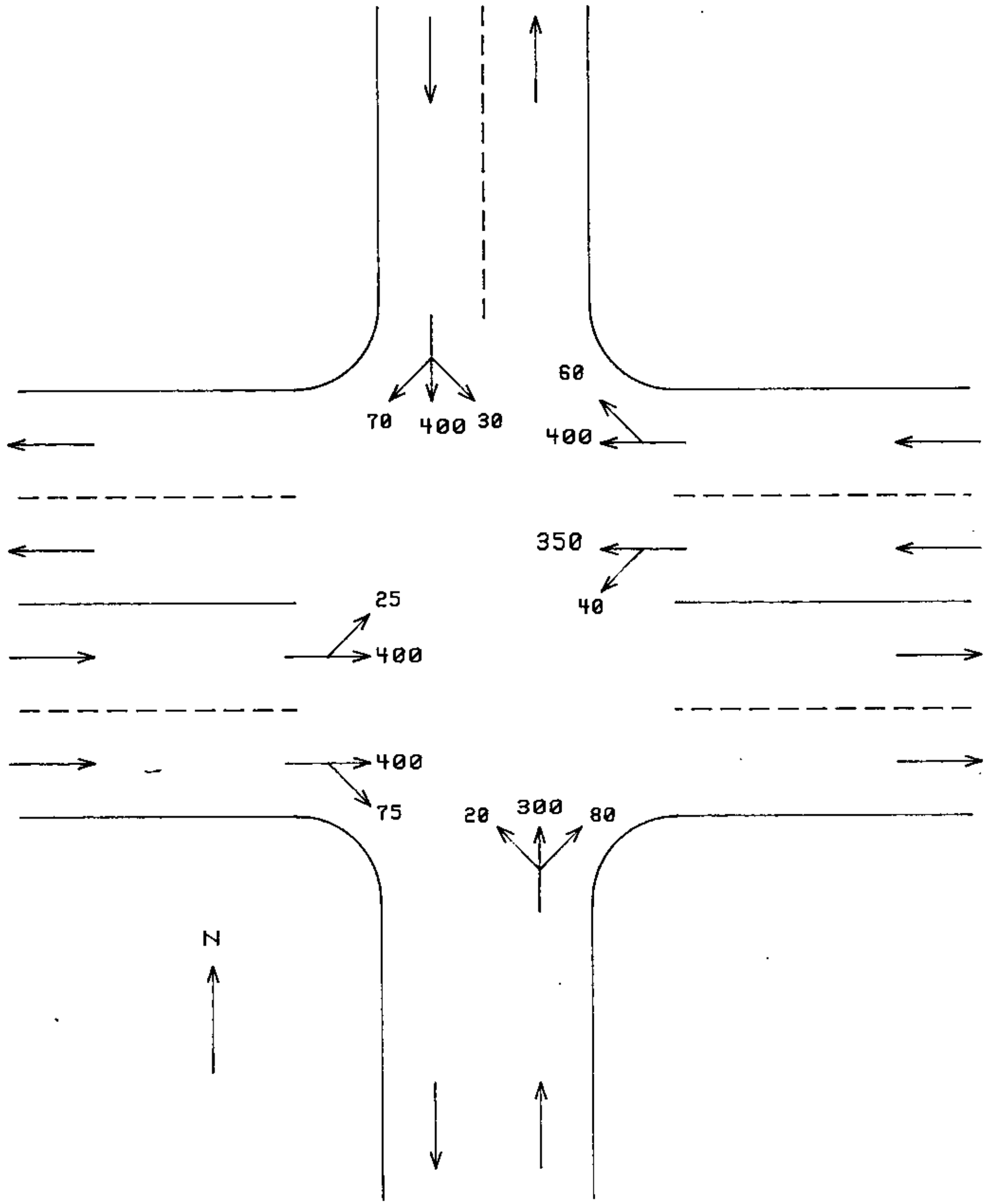


Figure C-3 -- Plan View of Signalized Intersection (Numbers Indicate Total Traffic Flow)


```
*NNNNY
 SIGNALIZED INTERSECTION; NORTHBOUND TRAFFIC
1 3
2 6
 CRUISE ONE
'CARS'  320 60
'MT'    40   60
'HT'    40  60
'L'/
'CR1-1' -2513 0  0 0
'CR1-2' -513  0 0  0
'L'/
 DECEL ONE
'CARS'  320 41
'MT'    40   36
'HT'    40  33
'L'/
'DC1-1' -513 0 0 0
'DC1-2' -313 0 0 0
'L'/
 DECEL TWO
'CARS'  320 18
'MT'    40   13
'HT'    40  10
'L'/
'DC2-1'  -313 0 0 0
'DC2-2'  -113 0 0 0
'L'/
 ACCEL ONE
'CARS'  308 42
'MT'    38   43
'HT'    39  43
'L'/
'AC1-1'  -113  0 0 0
'AC1-2'  887 0 0 0
'L'/
 ACCEL TWO
'CARS'  308 50
'MT'    38   52
'HT'    39  52
'L'/
'AC2-1'  887 0 0 0
'AC2-2' 1687 0 0 0
'L'/
 CRUISE TWO
'CARS'  308 60
'MT'    38   60
'HT'    39  60
'L'/
'CR2-1' 1687 0 0 0
'CR2-2' 2687 0 0 0
'L'/
```

Figure C-4 -- STAMINA Input File Example
Signalized Intersection

3.2.4 Determine the equivalent speeds to be used for each vehicle type on the DZOI roadway from Table C-5 based on the appropriate initial and final speeds.

3.3 Acceleration:

3.3.1 Determine the point along the roadway at which acceleration begins. As with deceleration, the AASHTO Green Book presents acceleration lengths for entrance ramps based on initial and final speeds for the segment of ramp of concern. The point on the ramp that corresponds to the initial speed is the transition point from the ramp curve to the spiral or tangent point.

3.3.2 Determine the length of the acceleration ZOI from Table C-6 (which is based on the AASHTO design chart) using the appropriate initial and final speeds. The initial speed would be the operating speed on the ramp curve, which is a function of the curve design speed. The final speed would be the operating speed of the entered roadway.

3.3.3 The point chosen in step 3.3.1 will serve as the beginning point of the acceleration ZOI. Move forward from that pont the AZOI length determined in step 3.3.2 to establish the end point of the AZOI for input into STAMINA.

3.3.4 Using the initial and final speeds, determine the equivalent speeds for each vehicle type on the AZOI from Table C-6. These speeds should be included in the STAMINA input file.

3.4 Connecting cruise section:

3.4.1 If the ramp is a loop ramp, there will be a center section of fixed degree of curvature that controls the ramp design speed. The beginning and ending points of that fixed speed zone were used to define the deceleration and acceleration ZOI in section 3.3. The curve itself may be defined as a separate roadway in STAMINA. The traffic may be assigned a constant speed (cruise) equal to the operating speed, which in turn is based on the ramp curve design speed. This "roadway" may be broken into smaller straight-line segments in the same manner as roadways are currently defined for STAMINA.

3.5 Example for a loop ramp:

3.5.1 Given a loop ramp with a design speed of 35 mph connecting two highways with 60-mph operating speeds, define the STAMINA roadways representing the DZOI, the AZOI, and the constant speed connector. Traffic in the area of concern is 1,000 automobiles, 50 medium trucks, and 100 heavy trucks. Figure C-5 shows the scenario with a coordinate system labeled on it and also includes the modeled roadways. Note that in this example, an approximate two percent grade occurs in the cruise roadway on the ramp and, therefore, no adjustment is required to the ZOI.

To solve the problem, one needs to know the operating speed on the ramp corresponding to a design speed of 35 mph. Table X-4 of the AASHTO Green Book [AASHTO, 1984; p. 1039] gives that speed as 30 mph. Then, Tables C-5 and C-6 may be consulted to determine the ZOI lengths and speeds.

3.5.2 Deceleration:

Given $S_{initial}$ = 60 mph and S_{final} = 30 mph, then DZOI(1) = 530 ft, and $S_{A, DZOI(1)}$ = 46 mph, $S_{MT, DZOI(1)}$ = 41 mph, and $S_{HT, DZOI(1)}$ = 42 mph.

3.5.3 Acceleration:

Given $S_{initial}$ = 30 mph and S_{final} = 60 mph, then AZOI(1) = 1900 ft, and $S_{A, AZOI(1)}$ = 51 mph, $S_{MT, AZOI(1)}$ = 52 mph, and $S_{HT, AZOI(1)}$ = 53 mph.

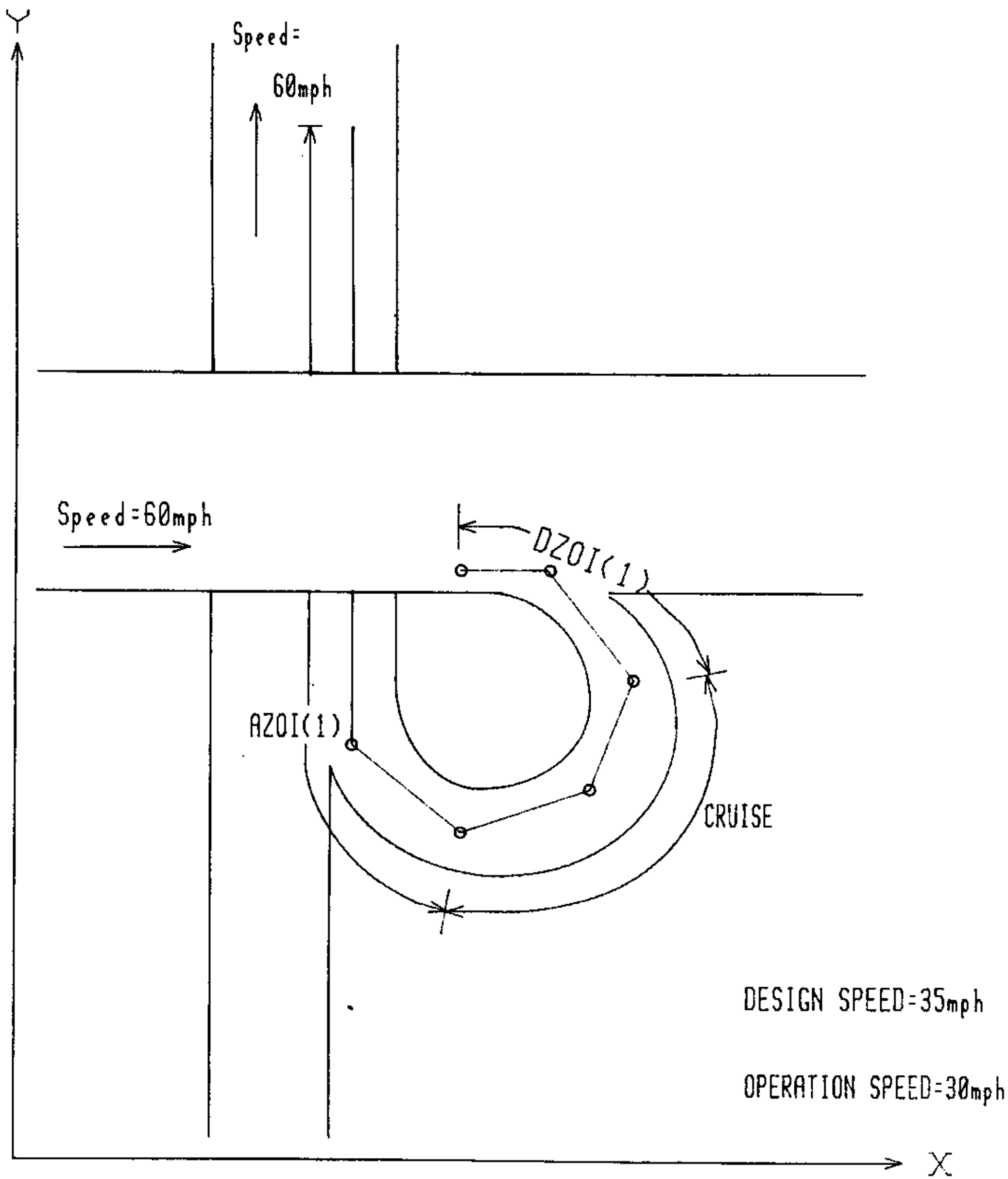


Figure C-5 -- Plan View on Loop Ramp Example
(STAMINA Modeled Roadways Shown)


```
*NNNNY
 SIMPLE ACCEL/DECEL CASE; LOOP RAMP
1 3
2 5
 CRUISE ONE
'CARS'   1000 60
'MT'     50   60
'HT'     100  60
'L'/
'CR1-1'     0  1400 20 0
'CR1-2'  1360  1440 20 0
'L'/
 DZOI
'CARS'   1000 46
'MT'     50   41
'HT'     100  42
'L'/
'DZ-1'   1360  1440 20 0
'DZ-2'   1570  1440 20 0
'DZ-3'   1840  1232 20 0
'L'/
 CRUISE TWO
'CARS'   1000 30
'MT'     50   30
'HT'     100  30
'L'/
'CR2-1'  1840  1232 20 0
'CR2-2'  1680  880  10 0
'CR2-3'  1240  840   0 0
'L'/
 AZOI
'CARS'   1000 51
'MT'     50   52
'HT'     100  53
'L'/
'AZ-1'   1240   840  0 0
'AZ-2'   960   1180  0 0
'AZ-3'   960   3080  0 0
'L'/
 CRUISE THREE
'CARS'   1000 60
'MT'     50   60
'HT'     100  60
'L'/
'CR3-1'  960   3080  0 0
'CR3-2'  960   3200  0 0
'L'/
```

Figure C-6 -- STAMINA Input File Example; Loop Ramp

The portion of roadway between the deceleration and acceleration ZOI would be defined as a cruise roadway with the cruise speed used. The portion of the STAMINA 2.0 file containing the roadway data for this ramp is shown as Figure C-6.

4. <u>Adapting STAMINA 2.0</u>

STAMINA 2.0, in its current form, does not allow computations with speeds less than 30 mph. A slower speed will be interpreted as 30 mph. To overcome this limitation, it is suggested that one line of FORTRAN coding be added and two lines commented out of the program (or deleted). Figure C-7 shows the changes needed. Search routines may be used to easily locate and change these specific program lines.

METHODOLOGIES IF FHWA $(L_o)_E$ VALUES ARE NOT USED

As reported in the literature review (Appendix A) several states have developed reference emission levels, $(L_o)_E$, that vary from the reported FHWA values. If FHWA $(L_o)_E$ values are not used, the equivalent speeds given in Tables C-5 and C-6 will be applicable, although the basic methodology remains unchanged. In this situation, the user is required to apply adjustments to the predicted L_{eq} values for each vehicle type. This can be accomplished by one of two alternative methodologies: (1) alter the L_{eq} values after prediction for each vehicle type; or, (2) develop equivalent speeds for each vehicle type.

The first methodology may be accomplished in either one of two ways:

1. <u>Multiple STAMINA 2.0 runs</u>: The easiest way is to execute STAMINA 2.0 separately for each vehicle type, and apply the adjustments as given in Tables C-7 and C-8, for each defined ZOI and vehicle type. This will require multiple computer runs and, thus, will be time consuming and costly.

2. <u>Restructuring STAMINA 2.0</u>: Another way is to restructure the STAMINA 2.0-program to allow the L_{eq} contribution for each vehicle type to be printed out instead of the current output, which is only the total of all vehicles. Then, the adjustments given Tables C-7 and C-8 can be applied and the adjusted values summed. This approach, also, will be inconvenient.

The second methodology of developing equivalent speeds is very similar to the approach taken by the authors in developing Tables C-5 and C-6, except the individual state $(L_o)_E$ values will be used. It is assumed that $(L_o)_E$ is given in the same form as the FHWA equation where $(L_o)_E = a + b \log (S, kph)$. The derivation of the equivalent speed equation was developed in Appendix B. The derived equation is:

$$S_{equiv} = \text{antilog } [(L_o)_{E,96kph} - 19.82 - a - \Delta_C]/(b-10) \qquad \text{(C-5)}$$

where S_{equiv} = equivalent speed, in kph; $(L_o)_{E,96kph}$ = state $(L_o)_E$ value at 96 kph; a = Y-intercept from state $(L_o)_E$ equation; Δ_C = change in SEL value (from Tables C-7 and C-8); and b = slope from state $(L_o)_E$ equation.

To use this equation and methodology, the following procedure will be required:

1. Select the ZOI and vehicle type to be considered.
2. Determine the value for $(L_o)_{E,96kph}$ from individual State equation for specific vehicle type.
3. Also from individual state equation, list the Y-intercept, a, and the slope, b.
4. Determine Δ_C for specific vehicle type and ZOI from Table C-7 or Table C-8.
5. Solve for S_{equiv} by substituting values into Eq. C-4 and solving.
6. Repeat steps 1 through 5 until new tables have been developed to replace Tables C-5 and C-6.
7. Proceed, as outlined earlier in this appendix, with the new tables.

Once this procedure has been completed and the two new tables have been formed, the user may proceed as before with the new tables replacing Tables C-5 and C-6.

TABLE C-7 -- CHANGE IN SEL IN ACCELERATION ZONES OF INFLUENCE FOR THREE VEHICLE TYPES

Accel. Range (mph)		Change in SEL ZOI(1) (dBA)			Change in SEL ZOI(2) (dBA)		
$S_{initial}$	S_{final}	Autos	MT	HT	Autos	MT	HT
0	30	5.6	3.5	2.1	8.5	3.5	2.1
0	35	5.3	3.5	2.1	6.6	3.5	2.1
0	40	4.9	3.5	2.1	n/a	n/a	n/a
0	45	4.4	3.5	2.1	n/a	n/a	n/a
0	50	4.4	3.5	2.1	2.2	2.5	1.5
0	55	4.4	3.5	2.1	2.2	2.1	1.3
0	60	4.4	3.5	2.1	2.2	1.5	0.9
30	40	4.9	3.5	2.1	n/a	n/a	n/a
30	50	4.4	3.5	2.1	n/a	n/a	n/a
30	60	2.0	1.3	0.8	n/a	n/a	n/a
40	50	3.5	3.5	2.1	n/a	n/a	n/a
40	60	2.2	1.5	0.8	n/a	n/a	n/a
50	60	0.0	0.0	0.0	n/a	n/a	n/a

TABLE C-8 -- CHANGE IN SEL IN DECELERATION ZONES OF INFLUENCE FOR THREE VEHICLE TYPES

Decel. Range (mph)		Change in SEL ZOI(1) (dBA)			Change in SEL ZOI(2) (dBA)		
$S_{initial}$	S_{final}	Autos	MT	HT	Autos	MT	HT
30	0	8.9	8.7	5.8	14.7	15.9	11.4
40	0	6.9	7.2	4.8	14.7	15.9	11.4
50	0	5.6	5.9	4.2	14.7	15.9	11.4
60	0	4.6	5.3	3.8	14.7	15.9	11.4
40	30	5.9	6.5	4.4	n/a	n/a	n/a
50	30	4.4	5.0	3.2	n/a	n/a	n/a
50	40	3.2	4.0	2.3	n/a	n/a	n/a
60	30	3.2	4.0	2.3	n/a	n/a	n/a
60	40	2.0	2.8	1.5	n/a	n/a	n/a

```
      IF(IDUN.EQ.IVEH(5))ITY=5
      IF(IDUN.EQ.IVEH(6))ITY=6
      IF(IDUN.EQ.IVEH(7)) ITY=7
      IF(IDUN.EQ.IVEH(8)) ITY=8
      IF(ITY.EQ.0)60 TO 805
      IF(METIN.EQ.1) GO TO 217
C FOR SPEED LOWER THAN 30*****CHANGE TO BE MADE****
      IF(XMH.GT.0.) GO TO 216
C     IF(XMH.GE.30.) GO TO 216
C     XMH=30
      WRITE(IOUT ,2038) J
      GO TO 219
216   IF(XMH.LE.65.) GO TO 219
      XMH=65.
      WRITE(IOUT ,2039) J
      GO TO 219
217   IF(XMH.GE.50.) GO TO 218
      XMH=50.
      WRITE(IOUT,2040) J
      GO TO 219
218   IF(XMH.LE.105.) GO TO 219
      XMH=105.
```

Figure C-7 -- Change to STAMINA 2.0 Code (Subroutine "INPUT")

APPENDIXES D, E, F

SUPPLEMENT TO NCHRP REPORT 311

Appendixes D, E, and F are not published in this report but are contained in a separate volume entitled "Predicting Stop-And-Go Traffic Noise Levels—Supplement to NCHRP Report 311." The table of contents and a listing of the tables and figures, together with page numbers, from the Supplement are reproduced here for the convenience of those interested in the subject area. Copies of the Supplement are available for purchase, at a cost of $3.00, upon written request to the NCHRP, Transportation Research Board, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

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