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HIGHWAY TRAFFIC NOISE PREDICTION METHODS

Proceedings of a workshop sponsored by the Transportation Research Board's Committee on Transportation-Related Noise, held September 23-24, 1975, in Washington, D.C.

subject area
52 road user characteristics

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INTRODUCTION

John E. Wesler, U.S. Department of Transportation

This workshop grew out of discussions at the 54th Annual Meeting of the Transportation Research Board. These discussions indicated that difficulties in predicting highway traffic noise seemed to head the list of noise-related problems among transportation people. Existing noise predictions procedures give different answers for identical situations, do not provide valid predictions for low-volume traffic situations, and apparently do not agree well with field measurements. Therefore, as a first step in attempting to remedy this problem, this workshop was set up to:

1. Bring together knowledgeable and experienced workers in the area of highway traffic noise prediction, in order to compare experiences and mutual problems, and to enhance future communications;
2. Provide a forum for the exchange of ideas and the sharing of past experience in applying noise prediction procedures; and
3. Disseminate information regarding the effectiveness of the older prediction procedures and the details of the newest procedures.

This workshop consisted of 4 half-day sessions. The first session was intended to provide the basic foundation for our discussions, through a brief description of how we got to where we are now in predicting highway traffic noise, why a practical prediction procedure is necessary, and a current program to provide valid comparisons of the three major prediction procedures. The second session was devoted to the new procedure recommended to the Transportation Research Board through NCHRP Project 3-7/3. At the third session, there were presentations from three major users of highway traffic noise prediction procedures who have valid field experience in their applications. Finally, at the fourth session, several other recent approaches to this same problem were presented.

All sessions were both informal and informative. Through these sessions, we hoped to reach our main objectives set for this workshop:

1. To identify and priorize major problem areas and deficiencies (if indeed there are any) relating to highway traffic noise prediction;
2. To explore and possibly outline future projects for resolving those problems or eliminating those deficiencies; and
3. To lay the foundation for a single, universally accepted highway traffic noise prediction procedure (perhaps, a rather idealistic objective).

WORKSHOP SUMMARY

In overall summary, the participants at this workshop reached general agreement on several pertinent factors related to the prediction of highway noise levels.

1. A single, accepted prediction procedure is needed, capable of uniform use by all those involved in highway noise design and control. Ideally, this single procedure should include reasonable flexibility of use, especially in instances involving low traffic volume and low traffic speeds, and should include a manual (noncomputer) approximate procedure. Above all, however, the single procedure must provide reliable simulations so that users may have confidence in the accuracy of those results and their acceptance by the public and the courts.

2. There is no clear advantage between the use of L_{10} or L_{eq} for highway traffic noise prediction and highway design. The ten-percentile level (L_{10}) allows easier field measurement with unsophisticated procedures and is easier to explain and justify to the nontechnical public. The equivalent sound level (L_{eq}) permits better prediction accuracy with less mathematical complications and is more compatible with other noise sources (for example, industrial and construction sites) for determining overall community noise levels. It was generally concluded that the FHWA should retain both descriptors in federal highway noise design standards, and allow state transportation authorities the option of using either one.

3. A prediction procedure for urban street traffic noise levels is feasible and should be developed.

4. Noise engineering prediction procedures need to be coordinated better with other engineering disciplines involved in highway design (specifically, traffic engineering, civil engineering, and air quality) so that the basic parameters used in describing the highway locations and traffic flows are compatible and interchangeable.

5. Noise barrier effectiveness prediction procedures are good, except for wide berms, especially those with rounded tops and significant vegetation. More attention and possibly education need to be devoted to the effect of barrier length, since end effects can reduce the barrier's attenuation.

SESSION I: SUMMARY

John E. Wesler, U.S. Department of Transportation

The first session established the basic framework for the overall discussions by outlining the general history of the development of highway traffic noise prediction procedures, by describing the importance and need for reliable prediction procedures, and by presenting early results of a current analysis designed to evaluate the most widely used prediction procedures.

Highway traffic noise prediction is a relatively recent development, associated with the rising concern with noise as an environmental pollutant. The first known traffic noise model was published in 1952, representing overall noise levels as a function of traffic volume and density. Subsequent workers have refined the mathematical relationships, adding the effects of additional factors as their importance was realized. In common with most simulations of real-world phenomena, each successive mathematical refinement proved adequate to compare relative traffic noise conditions resulting from alternative design evaluation. Inevitably, however, absolute criteria were necessary to assure environmental acceptability, so that absolute prediction accuracy became important. The real world involves complex situations, which are not easily simulated in detail. Thus, the simple traffic noise prediction models have proven inadequate for many required applications.

Two prediction procedures are presently accepted for highway noise design use. NCHRP Report 117, as modified by NCHRP Report 144, provides a procedure intended originally for manual use. Separate sets of curves are presented to determine the fifty-percentile noise levels (L_{50}) of light vehicle traffic streams and heavy vehicle traffic streams. Graphs are provided to include the effects of barriers and depressed or elevated roadways, to convert L_{50} values to ten-percentile noise levels (L_{10}), and to sum the two noise levels to represent the total traffic stream. These manual procedures have been programmed for time-shared computer operation by the Michigan Department of State Highways and Transportation.

The TSC procedure is essentially an analytical approach, derived from basic physical principles, and was developed expressly for computer application. This procedure also assumes separate light vehicle and heavy vehicle traffic characteristics and combines these with statistical relationships to provide mean-energy noise levels (L_{eq}), L_{50}, and L_{10} values. The TSC user's guide for this procedure also includes a simple nomograph for first-approximation manual predictions.

Typically, if two prediction procedures are available for traffic noise levels, they will provide two different answers. Such is the case with the NCHRP 117/144 and TSC procedures. Experience in the use of both has shown that the TSC results are consistently higher than those from the NCHRP 117/144 procedure and higher than the limited valid field measurements that are available. Further, both procedures appear to break down for low traffic volume situations. Thus, the current state of knowledge in traffic noise prediction is unsatisfactory.

Reliable noise models are extremely important in highway work. They are essential to environmentally acceptable highway designs, both to ensure that highway impacts do not exceed established criteria and to assure that the most cost-effective design is adopted. Noise models also provide the basis for compatible land use planning near highways, and inaccurate noise predictions can result in undue economic expenditures to overprotect adjacent land areas or after-the-fact remedies to correct underprotected neighbors.

The stakes in the applications of noise models are high. In FY 1974, about \$13 billion was spent on highway improvements, with commensurate funding levels for succeeding years. It is estimated that \$32.5 million will be spent each year for noise barriers alone for new or improved construction on the federal-aid system where such barriers can be built. To solve the remaining noise impacts by buying impacted residences, the annual cost is estimated at \$3 billion. Inaccuracies in identifying noise-impacted zones, due to prediction errors, could easily double or halve this estimate, depending on the direction of the errors.

The essential ingredients of a noise prediction model are several. The model(s) must be versatile and comprehensive to cover the diverse situations in which highways are found. The models must be easy to use by a wide range of users, from small general engineering county highway staffs to the more expert consultants. The models must be accurate, reliable, and mutually consistent so that they may be used and applied with the confidence of the highway designer, the general public, and the courts.

The FHWA/DOT have under way an extensive measurement and analysis program to evaluate the performance of the NCHRP 117/144, TSC, and new NCHRP Project 3-7/3 noise prediction procedures. Field measurements are being made at four different sites in each of four states. These measurements have been completed in North Carolina and Florida and are scheduled in Colorado and Washington. Statistical hourly noise levels are being recorded as well as individual vehicle noise characteristics. From this program, valid appraisals of the three prediction procedures are expected, and subsequent improvements in their accuracy will follow.

SESSION II: SUMMARY

Grant S. Anderson, Bolt Beranek and Newman, Inc.

The discussion was devoted to the results of the new NCHRP Project 3-7/3, which recently resulted in the publication of a Revised Design Guide for Prediction of Expressway Traffic Noise. This guide is a composite product of NCHRP Reports 117/144 and the Transportation Systems Center (TSC) methods, supplemented by additional data taken as part of the NCHRP project and as part of an additional FHWA project on noise barrier effectiveness. In addition, the two authorized methods were supplemented by additional mathematical structuring, derived from physical reasoning, with the hopes of extending the guide to low-volume traffic situations.

In brief, the guide structure consists of an L_{10} nomograph (similar to the TSC nomograph but with revised source data and revised distance dependence), a barrier nomograph (similar to the FHWA barrier nomograph but with revised distance dependence and revised estimates of the noise flanking around the barrier ends), and a series of worksheets—all leading to a hand-method calculation for simple geometrics. As a partner to the hand method, the guide includes a computer program (similar to the TSC program but with revised source levels, variable propagation drop-off, revised low-volume statistics, segment adjustments and many other factors) for the detailed prediction of expressway noise levels, both for complex roadway geometrics and for detailed barrier design. In addition, this computer program has been supplemented by a diagnosis capability that pinpoints hot spots along the roadway and enables the user to balance any barrier design up and down the roadway to avoid under- or over-design of expensive roadway barriers. This afternoon session was devoted mostly to the presentation of the guide, rather than to discussion.

The experimental verification of the changes incorporated in the guide and the conceptual differences betweeen the guide and the two FHWA authorized methods (117/144 and TSC) were presented.

The verification was based on data taken as part of the developmental NCHRP project (which also contributed to NCHRP Report 144), as well as data taken most recently on an FHWA-sponsored barrier measurement program. Discussed first was the verification at distances close to the tested roadways, verification of the propagation away from the roadways, and the barrier attenuation verification. Data were obtained at 13 sites across the United States (in all, 500 data points) sampled under a full variety of weather conditions. The tested range of parameters was (a) distance between 50 and 1600 ft (15.24 and 487.68 m), (b) total volume between 200 and 15,000 vehicles per hour, and (c) speed between 50 and 75 mph (80 and 120 km/h). The geometry at each test site was uniform and unvarying up and down the roadway.

Close in to the test roadways [approximately 50 to 100 ft (15.24 to 30.48 m)], a zero average discrepancy across all 13 sites, and no correlation between the discrepancy as plotted against the following variables was found: speed, truck percentage, and total vehicle volume. The scatter about the zero-slope discrepancy lines in each plot was approximately 2.5 dBA, representing perhaps an irreducible minimum of scatter (without introducing intractable variables, such as wind and thermal gradients and detailed ground topography). It is important to note that this lack of correlation and this zero average discrepancy was obtained using the FHWA data also, which was separate from the NCHRP data on which the model was based. In effect, the model was thus tested against independent data.

The only trends detected in this comparison of predictions with measurements was a so-called "site bias" of up to 3 dBA. It was conjectured that this site bias might be best ascribed to site anomolies in the detailed topography and/or variations in vehicle strength. If so, then increased time-duration measurements would not wash out these site differences, as such increased measurements would if the discrepancies were due to particular meteorological conditions at the times of measurements or to particular biases in the truck population passing during the measurements. It was also conjectured that the apparent site biases might be due to the "instability" of the L_{10} descriptor, although the experimental agreement was only marginally better using the L_{eq} descriptor.

The propagation drop-off between these close-in measurements and measurements made out to 1600 ft (487.68 m) from the roadway were discussed next. The NCHRP 3-7/3 data, which support a 10 log D and also a 15 log D dependence, as a function of the ground cover, was summarized.

Finally, data on the performance of roadside noise barriers were presented. Again the plots related the measured barrier attenuation to that predicted by the guide. The agreement was good—generally the discrepancies ranged randomly between ±2 dBA for barriers consisting of free-standing walls and of walls on top of earth berms. For berm barriers, there was a significant underprediction of the barrier attenuation by some 2 to 5 dBA. Calculated (Revised Design Guide) attenuations are based on the Maekawa point-source data, modified to line source by the mathematics of U. Kurze (J. Sound. Biv.), with the berm modeled as a single thin screen. It was concluded that berms provide more attenuation than this thin-screen approximation implies.

In summary, country-wide supporting data, over many sites and weather conditions, that support the guide method were presented. Only two trends away from the method were detected: (a) a moderate site bias (maximum 3 dBA) and (b) an underprediction of barrier attenuation for berms.

Next, the conceptual differences between the guide and the two FHWA-authorized methods, 117/144 and TSC, were discussed. The three prediction methods were assembled into a single conceptual framework — emissions, L_{eq} at 50 ft (15.24 m), propagation, and conversion to L_{10} — to better understand their interelationships. Next, the conceptual differences that become obvious within this framework were summarized and delineated where these differences would produce 5 dBA, or 10 dBA, or even 15 dBA differences in the predictions. The discussion concentrated on the resulting reductions in noise prediction at low traffic volumes, on the resulting reduction in noise predictions for significant "medium-truck" populations, and on the increased flexibility in the propagation constant, which can result in decreased noise predictions at large distances.

The conceptual framework common to all three prediction methods first consists of vehicle emission levels as a function of speed for automobiles, medium trucks, and heavy trucks — differently for the three methods. There is extreme overprediction when all trucks must be classified as "heavy trucks" in the two authorized methods. The emission levels extend downward to some 10 mph (16 km/h), although their data base stops at 50 mph (80 km/h). Heavy truck emissions remain independent of speed.

The second link in the framework consists of the conversion equation from emission levels to L_{eq} at 50 ft (15.24 m). Although this equation differs somewhat among methods (range = 4 dBA), these differences tend to wash out the differences in emission levels for a net balancing among methods — except for medium trucks.

The third link, switchable from 10 log D to 15 log D in the guide, is the propagation constant from 50 ft (15.24 m) to other distances. At large distances of say, 1000 ft (304.8 m) the use of the inapplicable constant (as is often forced on the user in the two authorized methods) can lead to discrepancies up to approximately 5 dBA. The guide allows variable propagation, depending on ground cover and the observer height.

A method was presented that allows conversion from L_{eq} to L_{10} (and also to L_{50}) for each of the three methods, including both the computer mathematics and the nomograph mathematics separately. At low volumes, strictly at low VD/S of below 100 ft/mile (30.48 m/km), the improved statistics of the guide result in significantly lower noise predictions, by as much as 5 to 10 dBA.

Finally, an ad hoc adjustment is required for the 117/144 method, to account for a particular hang-up of that method at 100 ft (30.48 m), its base-line distance.

In summary of this conceptual framework, the 3 graphs, one equation, and one ad hoc adjustment serve to quantitatively duplicate the calculations of the three prediction methods, all in one framework, within 1 dBA of the legitimate predictions (i.e., using the legitimate methods instead of this unified approach).

Finally, the differences among the three methods for the gradient adjustment, barrier attenuation (including the differing limits on the maximum attenuation possible), row-of-buildings attenuation, vegetation attenuation, road surface adjustment, and interrupted flow adjustment were indicated.

This session emphasized the situations in which the guide will predict significantly different noise levels than will the 117/144 and the TSC methods. It is hoped that the predicted differences at low traffic volumes, which follow from mathematical modeling of the L_{10} statistics, will be tested experimentally. In addition, it was emphasized that because the guide is built on a physical structure that separately considers emissions, propagation, barriers, etc., it will be relatively simple to modify as new data—perhaps site specific—are obtained.

SESSION III: SUMMARY

Stanley E. Dunn, Florida Atlantic University

The intended purpose of the third session was to develop a picture of the position currently occupied by state highway agencies with respect to the actual application of the existing, approved highway noise prediction methods. Specifically it was considered necessary to know the degree to which states had been successful in using either the NCHRP 117/144 or the TSC predictive models to handle highway noise impact assessment problems, to catalog any modifications to the existing methods that the user states had deemed necessary, to examine any unresolved problems that the states were experiencing, and to elicit any suggestions from the states for further improvements of the predictive models. The goals of this session were achieved, and this summary presents the results of the committee's efforts.

Three states, California, North Carolina and Minnesota, were chosen to discuss their particular experiences with the existing predictive methods. Based on the differences in the selected states' sizes, geographic locations, departmental organizational structures, and preferred predictive models used, it was felt that they would provide a good overview of the country's experience as a whole. The first presentation was given on the experiences of the state of California. California's reliance on the 117/144 method was presented with additional comments that state regulations on specific occasions required the analysis of peak traffic noise levels under a portion of the California procedure as well as the requirement under state law that requires the California Department of Transportation to provide noise contours for major roads to local governments for planning purposes.

North Carolina presented its experiences in using the TSC Computer Prediction Program. Emphasis was placed on the rural and small-city character of the state and the manner in which North Carolina's centralized noise analysis organization responded to the task of assessing the state highway noise problems. Of major importance to North Corolina, in their opinion, was the simplification of the TSC imput-output format, which was necessary to fully realize the comprehensive geometrics capabilities of the model in handling complex, multiroad element problems.

Minnesota presented its experiences in using the 117/144 predictive model as adopted for desk calculators. In addition, the use of the 117/144 barrier design technology was presented with specific reference being made to the analysis and design of the barrier on I-35W in Minneapolis. The selection of two states to speak on the use of the 117/144 model reflected the preference that the majority of states have exhibited for this model.

On the subject of the accuracy of the models it was the opinion of all of the states that, when properly applied, the existing predictive models were satisfactory for use in high-volume, free-flowing situations such as freeways. North Carolina added that, under many circumstances, optimum accuracies were achieved through the use of the TSC model while employing an 82 dBA truck and a drop-off rate of 4½ dB per doubling of distance. However this was somewhat sight dependent. Further, the accuracies of either model became unpredictably poor when applied to low-volume or stop-and-go traffic situations. Errors as high as 7 dB were not uncommon in these cases. On the subject of the accuracy of the prediction capabilities of the barrier design techniques, little conclusive data were available for presentation.

On the subject of the causes of the errors arising from the use of the existing predictive programs, there was agreement that the instability of the L_{10} indicator was a cause of the errors, especially at the lower volume flows. Also, errors in the selection of values to model spreading losses or vehicle source strengths constituted a major cause of inaccuracy of the models. In addition, the apparent site-to-site dependence of the influence of these model variables was stressed.

With regard to the improvement of the accuracy of the existing models or the development of any new model during this session, the state representatives stressed the need, based on their past experience, for a method well founded on rigorous scientific principles but that, when put into the user format, would be easily used by the highway engineer without sacrificing accuracy. Compatibility of the method with other well-established and allied highway engineering design methodologies was deemed desirable. The use of the L_{eq} as the basic descriptor was favored for its inherent stability in prediction as well as its capability to be used in multimodal transportation noise problem analyses. Improvements in modeling low-volume or stop-and-to urban traffic situations were given a high priority by all of the participants. It is in this area that currently existing models now offer the least assistance. Further, any improved model should be structured in such a way as to allow the highway engineer to specify input variables such as vehicle source strengths or propagation spreading loss factors in order to accurately model given situations. Finally, the need for barrier design capabilities with defined accuracy capabilities was stressed.

The need of the state highway agencies to have available highway noise predictive models of known accuracy characteristics was a central theme throughout the presentation. With the levels of environmental concern on the increase, highway agencies will be required to provide accurate assessments of the potential for impact associated with proposed projects. Because of the associated high costs involved, the recommendations for noise abatement, which may result again, must be made with as much accuracy as possible. In addition, state governments increasingly are requiring that highway agencies become involved in providing land planning information with regard to noise, that existing noisy highway sections be retrofitted with sound barriers, and that state environmental noise codes be complied with. This increasing number of environmental noise-related constraints on highway designs and operations will demand that highway agencies be capable of assessing traffic noise problems to the limits of accuracy that technology can realistically afford to provide.

SESSION IV: SUMMARY

Louis F. Cohn, New York State Department of Transportation

This concluding session of the workshop was designed to examine the possible future directions that should be taken relative to highway noise prediction. Six topics, or presentations, were discussed covering areas such as new noise prediction methods, field evaluation of some of the methods, modifications to one of the methods (NCHRP 117), roadway surface type adjustments, a new comprehensive study involving a proliferation of traffic and meteorological data, and the effects of changes in legislation and enforcement of vehicle emission levels on highway noise prediction. The session concluded with a brief discussion concerning possible areas for further work.

Jerry J. Hajek of the Ontario Ministry of Transportation and Communications opened the session with a presentation of the Ontario Highway Noise Prediction Method, an emperical model based on 133 sound level measurements taken at 120 locations near rural and urban freeways, highways, and residential streets. The Ontario method was compared to the NCHRP 117 and Delany methods. The Delany method was found to be somewhat more accurate for nonfreeway situations than NCHRP 117, which was designed for freeway use. The standard error of estimate using the Ontario method for L_{10} was found to be 2.2 dBA.

Hajek said that about 50 percent of his department's ongoing work in noise is concerning barriers, and he would like to see a special workshop set for the purpose of studying barriers.

The next speaker, the writer, is performing a noise measurement study of the NCHRP 117, Ontario, and Revised Design Guide (RDG) methods. Up to this point approximately 60 sites have been measured using a variety of measurement procedures. The measurements have been taken mostly at 50, 100, and 200 ft (15.24 m, 30.48 m and 60.96 m) from the roadway, and for a wide range of traffic and truck volumes.

The results of the study thus far indicate that NCHRP 117 consistently over-predicts L_{10} levels by 3 to 4 dBA, with a standard deviation slightly less than 3. The Ontario method underpredicted actual conditions by less than one dBA but with a standard deviation slightly larger than 3. For low-volume conditions, the standard deviation was 4.0. The RDG overpredicted the L_{10} by less than one dBA, and the L_{eq} by 2 to 3 dBA, both with standard deviations less than 3. These preliminary results indicate that the (L_{10}-L_{eq}) equations in the RDG may need further verification, and that the L_{10} descriptor may be unreliable for low volumes of traffic.

Jerry Reagan of FHWA presented a study by a consultant in California that produced a method to predict noise levels for city streets, based on an equation in the so-called "Levels Document" of the U.S. Environmental Protection Agency. The method has a heavy reliance on existing noise levels and is, therefore, limited to those situations where geometry changes are not pronounced.

An externally applied modification nomograph for NCHRP 117 was briefly discussed by Ken Agent of the Kentucky Department of Transportation. The nomograph combines the effects of distance, truck volume, and automobile speeds to reduce the NCHRP 117 over-prediction from 4.8 dBA to 1.9 dBA for 270 measurements. He also discussed a new report by his department on roadway surface noise. This report concluded that sand-asphalt surfaces are quieter than grooved concrete by 7 dBA, and that open-graded mixes are quiet when first laid, but get noisier as they are worn.

William McColl of the New York State Department of Transportation made a presentation on the upcoming Long Island Expressway Air Quality Model Validation Study and the proposed noise research that could be generated. Components of the study will include extensive micrometeorological data gathering, and lane-by-lane classification of traffic parameters such as vehicle speed, type, and volume. The Long Island Expressway is a 6-lane, 120,000 vehicle per day freeway east of New York City. He suggested that answers may be generated for questions concerning distance drop-off rate, atmospheric attenuation, excess ground attentuation, and others. He welcomed any suggestions or recommendations for data gathering and analysis.

The final presentation for the session was made by Don Whitney of the General Motors Corporation, concerning the effects of legislative and enforcement changes on vehicle emission levels and, therefore, on highway noise prediction. The conclusion was drawn that, because the new interstate emission standards promulgated by the U.S. Environmental Protection Agency regulate only power plant noise, tire noise will totally dominate future truck emissions, and thus tires needed regulation. Therefore, truck emission levels will become increasingly speed dependent.

During the discussion that followed the presentation, a list of recommendations of items for further consideration was developed. The primary conclusion was that a comprehensive model for predicting noise in urban and suburban situations is sorely needed. Also, barrier prediction needs more work because of the potential implications of retro-fitting existing highways with barriers. It is also important for the Revised Design Guide to be field validated in various states across the nation. Other conclusions were that the L_{eq} descriptor has many advantages and should be included, at least as an option, in the highway noise standards; that reliable manual prediction methods need to be available; and that excess environmental and ground attenuation characteristics be identified and quantified.

INTRODUCTION AND HISTORY OF HIGHWAY
NOISE PREDICTION METHODS

John E. Wesler, U.S. Department of Transportation

As concern with the quality of our environment has grown throughout the world, so too has the need for design tools to evaluate the impact of man's activities on the environment. Of man's many activities, his transportation systems seem to cause the greatest adverse impact, especially due to noise, an undesirable by-product of most moving vehicles. Thus, the growing interest and concern with highway traffic noise. In general, simple simulation models of highway noise levels sufficed for a number of years to compare the relative results of different highway designs, so that relative numbers were sufficient for design evaluation purposes. But, inevitably, absolute numbers must be attached to the results of these simulation calculations, either because of imposed regulations or because of the acceptance of criterion limits intended to maintain the noise levels below reasonable values. As a result, the comparison becomes the real world, and absolute accuracy becomes important to the estimating or simulation procedure.

Highway traffic noise prediction entails the usual basic components of sound generation and propagation—the basic noise source (the vehicle); the interaction of a stream of such sources; the propagation of that sound through the atmosphere; and the effects of obstacles in the propagation path, whether those obstacles are there intentionally to reduce the noise or accidentally as the result of natural topography. Any practical prediction procedure must represent accurately each of these basic components.

Prediction procedures must also consider two other important factors—the noise unit or statistic necessary to represent the impact of the noise on the receiver (the public or highway neighbor), and the mechanics of the procedure itself (manual tabularized computations, nomograph, or computer). These two factors are not so much the subject of this workshop. Even those intimately involved in researching the effect of transportation noise on people cannot agree on the relative merits of L_{10}, L_{eq}, L_{dn}, NPL, TNI, and nauseam. So, we need not waste our time arguing these relative merits ourselves. Similarly, the mechanical format of the procedure is largely irrelevant. If the basic acoustical and mathematical relationships are accepted, these can be arrayed in any number of convenient formats, to the liking of the user.

The purpose of this paper is to examine the basic components of those procedures that are in use, in order to understand their similarities and their differences. Ideally, there should be one simple, universally accepted procedure that provides accurate answers for all practical real-life situations. Recognizing the absurdity of that dream, however, we must instead look to what is available, where these may be deficient, and how they may be improved, if improvement is needed.

The first attempt to represent traffic noise, which I was able to find in the literature, was presented in the 1952 Wright Air Development Center Handbook of Acoustic Noise Control (1). The time-averaged overall sound pressure level was represented by

$$L_{50} = 68 + 8.5 \log (V) - 20 \log (D) \quad \text{dB}$$

where

V = traffic volume in vehicles/hour (vph)
D = distance from traffic lane, in feet.

This relation was indicated for use for average speeds of 35-45 mph (56-72 km/h) and distances greater than 20 ft (6.096 m).

At the Fifth International Congress on Acoustics in 1965, Nickson(2) suggested that traffic noise level could be represented by

$$L_{50} = 50 + 10 \log (V/D) \quad \text{dBA}$$

for vehicles traveling at a mean speed of 40 mph (65 km/h) and a 10 percent commercial vehicle composition. At the same Congress, Lamure(3) proposed an equation corresponding to

$$L_{50} = 52 + 10 \log (V/D) \quad \text{dBA}$$

for traffic volumes in the range of 1200 to 5000 vph containing not more than 15 percent heavy vehicles.

In 1968, Johnson and Saunders(4) developed a more complex relation based on series of traffic noise measurements made in England during 1963 to 1965:

$$L_{50} = 3.5 + 10 \log (VS^3/D) \quad \text{dBA}$$

where S represents the mean vehicle speed in miles per hour (mph). Based on the measured cases, this relation was assumed valid for a traffic mix of 20 percent heavy vehicles, although their data indicated agreement within $\pm$ 1 dB over the range of 0 to 40 percent mix of heavy vehicles. The authors also recognized the effects of excess attenuation due to ground cover, and of roadway gradients, and included correction factors for these effects.

In 1968, NCHRP Report 78(5) published the results of Galloway's Monte Carlo simulation of traffic noise levels. Galloway's model simulated a static array of vehicles distributed randomly along a roadway and summed their noise levels at specified points off the roadway. By repeating different static arrays but maintaining vehicle density, he generated statistically time-weighted noise levels, which he approximated by the relation:

$$L_{50} = 20 + 10 \log (VS^2/D) + 0.4\, T \quad \text{dBA}$$

where T represents the percentage of total vehicular flow composed of heavy trucks.

In 1971, NCHRP 117(6) contained the most widely used traffic noise prediction method, representing light-vehicle and heavy-vehicle contributions separately:

$$\text{(cars)} \quad L_{50} = 29 + 10 \log (VS^2) - 15 \log (D) + 10 \log [(\tanh (.00119\, VD/S)] \quad \text{dBA}$$

$$\text{(trucks)} \quad L_{50} = 95 + 10 \log (V/S) - 15 \log (D) + 10 \log [(\tanh (.00119\, VD/S)] \quad \text{dBA}$$

The noise levels from the two streams of traffic are added (on an energy basis) to obtain the total traffic noise level. An additive factor is also included for calculating L_{10} values from the total L_{50} level. Two new concepts were included in these relations. First, the sound levels fall off with distance at the rate of 4.5 dB per double-distance (15 log D), rather than the usual 3 dB per double-distance (10 log D) characteristic of a line sound source (the traffic stream). Second, truck noise is essentially independent of truck speed and only depends on truck density (vehicles per mile). The NCHRP 117 procedure was subsequently programmed for a time-shared computer by the Michigan Department of State Highways and Transportation.

In 1972, the so-called TSC method was published(7) to provide a computerized highway noise prediction method. Similarly with the NCHRP 117 method, the TSC method calculates light-vehicle and heavy-vehicle noise levels separately and sums them to obtain the total noise. The TSC method also includes a third class of vehicles, for which the octaveband spectrum can be specified and the resultant noise added to the levels calculated for light vehicles and heavy vehicles. The basic relation in the TSC procedure is

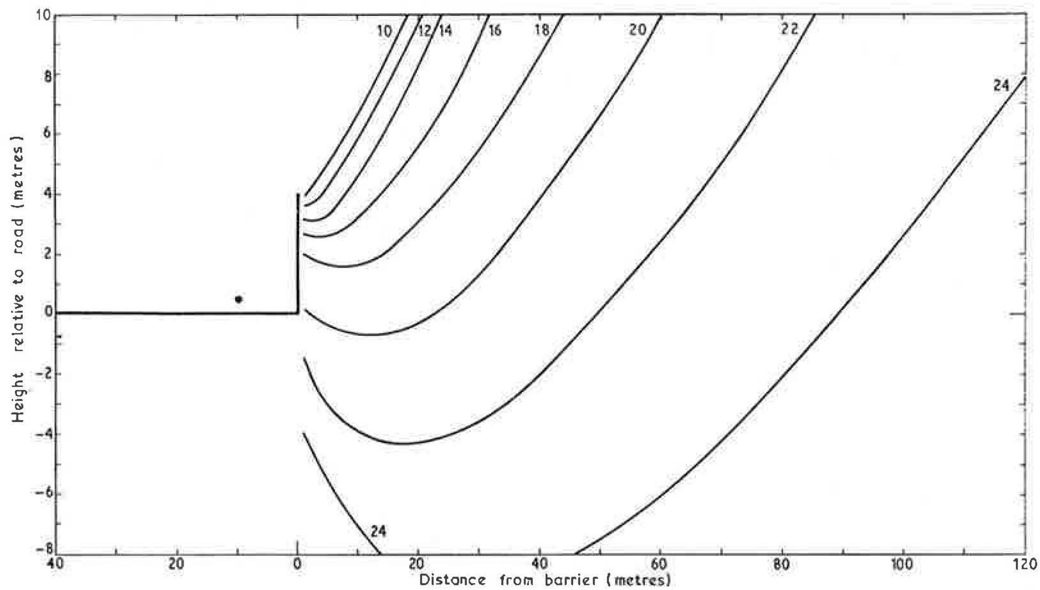
$$L_{eq} = 2.4 + L_{50}' + 10 \log (V/DS) - A \quad \text{dBA}$$

where A represents the sum of various attenuation factors, due to the atmosphere, ground absorption (shrubbery and thick grass, or tree zones), barriers, and reflections. The TSC manual also includes a simple pencil-and-ruler nomograph for first-approximation calculations of L_{10} levels. Statistical relationships were included in TSC computer program for converting the basic L_{eq} values to L_{10}, L_{90}, L_{50}, and NPL. Also in 1972, Delany(8) published a manual for calculating L_{10} levels from highway traffic noise in support of the British Land Compensation Act of 1973. Delany based his model on analyses of traffic noise measurements in Great Britain and through regression analyses obtained the relation:

$$L_{10} = 21.4 + 8.9 \log (V) + 16.2 \log (S) + .117T \quad \text{dBA @ 10 m.}$$

He then entered distance into his calculations through a series of cross-sectional contours, which included the effects of a variety of barriers (see Figure 1).

Figure 1.



4 metre high barrier, 10 metres from traffic stream

Figure 2.

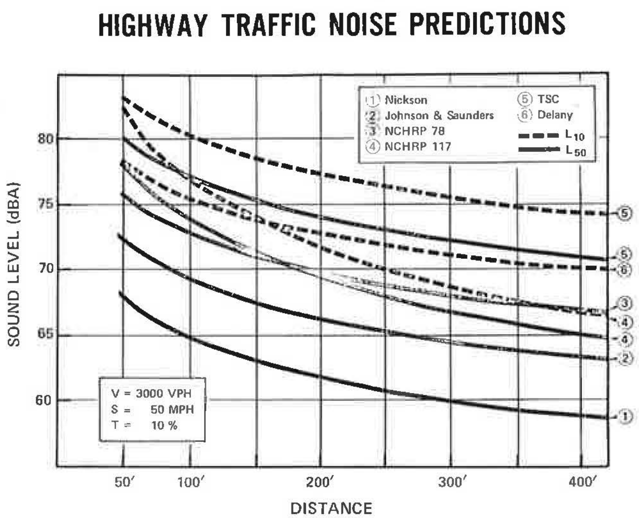
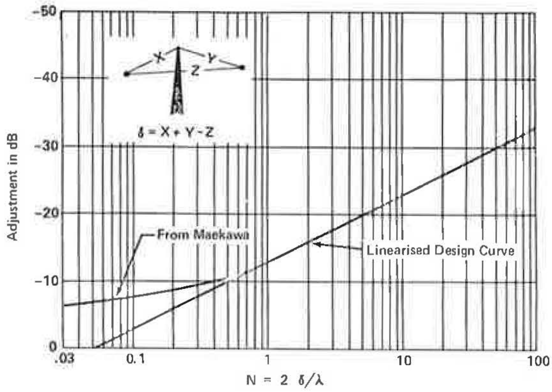
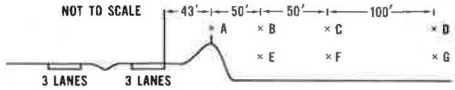


Figure 3.



$$D_B = \begin{cases} 0 & \text{for } N \leq -0.2 \\ 20 \log \left(\dfrac{\sqrt{2\pi|N|}}{\tan \sqrt{2\pi|N|}} \right) + 5 \text{ dB} & \text{for } -0.2 < N \leq 0 \\ 20 \log \left(\dfrac{\sqrt{2\pi N}}{\tanh \sqrt{2\pi N}} \right) + 5 \text{ dB} & \text{for } 0 < N \leq 12.5 \\ 24 \text{ dB} & \text{for } N > 12.5 \end{cases}$$

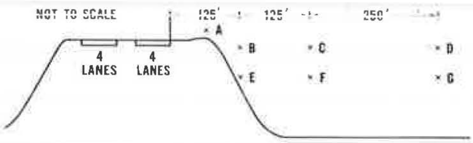
Figure 4.



	A	B	C	D
MEASURED L_{10}(dB(A))	73.1	58.9	56.7	54.7
NCHRP 117	69.2	55.1	52.1	50.9
TSC	71.6	68.2	68.5	63.7

	A	E	F	G
MEASURED L_{10} (dB(A))	73.6	57.0	54.3	53.0
NCHRP 117	71.2	51.1	48.1	45.1
TSC	70.6	54.8	55.1	54.6

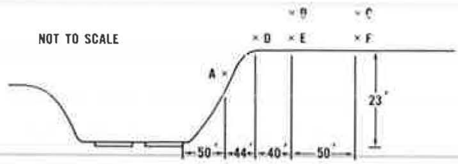
Figure 5.



	A	B	C	D
MEASURED L_{10}(dB(A))	81.2	67.1	68.6	67.3
NCHRP 117	78.5	64.3	63.4	61.6
TSC	83.2	68.6	71.5	72.7

	A	E	F	G
MEASURED L_{10}(dB(A))	81.6	63.4	65.7	67.9
NCHRP 117	78.5	64.8	63.9	62.1
TSC	84.1	66.7	67.1	71.1

Figure 6.



	A	B	C
MEASURED L_{10}(dB(A))	85.9	79.6	73.2
NCHRP 117	83.5	70.6	67.0
TSC	85.3	79.4	74.5

	A	D	E	F
MEASURED L_{10}(dB(A))	85.4	78.2	74.0	69.2
NCHRP 117	77.9	74.8	68.8	65.1
TSC	84.0	81.9	77.9	77.9

More recently, J. J. Hajek(9) and NCHRP Project 3-7/3(10) have also published additional highway noise prediction procedures. These will both be described in more detail in later papers.

Quite obviously, the use of these several relations, described briefly above, will result in somewhat different answers for highway noise levels. Figure 2 displays the results for an assumed situation—single lane, 3000 vph, 10 percent trucks, at 50 mph (80 km/h).

The NCHRP 117 (with the subsequent revisions of NCHRP 144), TSC, and Delany procedures noted above also include provisions for calculating the effects of barriers in the vicinity of the highways under study. All three are based on the work of Maekawa(11). either in graphical form or mathematical representation (Figure 3). The addition of the barrier component will, of course, cause further differences in the results of noise level predictions since another factor is introduced. For example, Figures 4 through 6 illustrate the results of comparisons using the NCHRP 117 procedure (Michigan computerized version) and the TSC procedure to reproduce some of the measurements made preliminary to the NCHRP 144 revision. There seems to be no logical pattern among these results. And, I am sure, we will hear similar inconsistencies and lack of agreement with predictions and the real world throughout this workshop.

Thus, our problem. Is there a "best" highway traffic noise prediction procedure? Can the "best" procedure be further improved? Can we achieve consistency in predicting highway traffic noise levels?

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NOISE PREDICTION MODELS—THEIR IMPORTANCE AS A KEYSTONE IN APPLYING NOISE STANDARDS

Harter M. Rupert, Federal Highway Administration

Analytical noise models are extremely important in highway work. They are needed for the planning and design of highway projects. They are needed in research activities and special studies to better understand how noise impacts are created.

Use of Noise Models

A more detailed look at these models would show a widespread use and demand. Models are an important supplement to measurements of existing noise levels. Where the noise is predominantly from highway traffic, the model can be used as a time- and money-saving aid to interpolate between sites where measured data have been obtained. Such measured data are needed on approximately 5,000 federal-aid highway projects annually to describe existing background noise levels. Measured noise data are also needed in research and special impact studies.

Noise prediction models serve an important function in examining various mitigation strategies. One of the more important is the assessment of the reduced noise doses to which the public would be exposed if motor vehicle noise emission levels were reduced at the source by various amounts. Another problem of concern is establishing the relationship between noise levels and residential property values. FHWA presently has several contracts under way to examine different abatement strategies and their costs on a national basis. Included are barrier construction, soundproofing of private structures, and acquisition of impacted properties. In each of these special studies analytical models are a substantial if not the sole basis for determining the noise exposure.

A very great responsibility for preventing future noise impacts rests (or should rest) with local officials and developers of undeveloped property in the vicinity of busy highways. The future noise levels (on which local government controls and future development plans are based) must come from highway traffic noise models.

The use with which most highway designers are concerned is in forecasting future traffic noise levels. These levels are used for the assessment of noise impacts on highway improvements. In recent years, many people have expressed concern about the lack of uniform measurement procedures and equipment for determining existing noise levels. The keystone, however, in determining noise impacts for FHWA's standards is the design year noise levels. Only the noise model can predict what these noise levels are going to be.

As a continuation of this assessment, models are used to examine different location and design alternatives. Decisions to soundproof public-use buildings and to construct costly barriers will depend on the outcome of studies using these models.

Stakes in Use of Noise Models

An idea of the stakes involved in the use of noise models can be obtained from some facts and figures on the highway program. In FY 1974 about $13 billion was spent in local, state, and federal funds on highway improvements. Nearly $5 billion of this amount was from the federal trust fund.

The best current estimates indicate that about $32.5 million per year will be spent on noise barriers as part of the construction or reconstruction of freeways and expressways on the federal-aid system. This is over and above the $730 million that could be spent for barriers to correct existing noise impacts. These substantial figures only account for those situations where noise barriers can be built. If we were to try to solve the remaining noise impacts by buying the impacted residences, it would increase the annual bill by $3 billion and the backlog bill for existing problems by nearly $70 billion. This clearly shows how costly significant errors in our models could be.

To illustrate in another fashion, assume that the 70 dB contour was calculated with one of our models to be 800 ft (243.84 m) from the edge of the roadway. If the model overpredicted by 5 dB, the 70 dB contour would be only 300 ft (91.44 m) from the roadway. If the overprediction were 10 dB, the 70 dB contour would be only 100 ft (30.48 m) from the roadway. These kinds of errors (whether high or low) are serious. If the errors are overprediction, there may be unwarranted and expensive expenditure of public funds. If the errors are underprediction, there may be unwarranted exposure of the public to unnecessary noise impacts.

Essential Ingredients of a Noise Model

Because of the many needs that noise models serve, their essential ingredients are very demanding. Most models, especially the basic ones, must be versatile and comprehensive. They must be able to account for traffic characteristics (volume, speed, and truck traffic), topography (vegetation, barriers, height, and distance), and roadway characteristics (configuration and grades). In special situations, meteorological conditions and pavement characteristics may be necessary variables.

The models must be easy to use. Because of the large number of highway projects involved, and the large number of potential locations of impact, the models must be relatively simple and not too time consuming to exercise. In order to serve the wide range (very large to very small) of highway agencies that use the models, they must include both manual and computer options.

The most important criterion for the noise model is accuracy. Since most of our noise abatement decisions are based on predictions, it is imperative that they be used with confidence. They must have the confidence of the highway agencies that use them, the public that will be affected by them, and the courts that may someday be called on to arbitrate disputes.

Noise prediction models are the keystone to dealing with highway traffic noise impacts. It is imperative that we have the very best models we can get.

RECENT DOT STUDY EVALUATING NCHRP 117 AND TSC HIGHWAY NOISE PREDICTION METHODS

James Steinberg, Transportation Systems Center

Let me begin this discussion by giving you an overview of where the Transportation Systems Center fits into the highway noise prediction program. This is not intended to be one of the formal organization, but rather an indication of how information flows and of how we communicate with other groups involved in highway noise prediction. As shown in Figure 1, there are two divisions within TSC that give technical support to the Office of Noise Abatement within DOT. The Mechanical Engineering Division has the people, equipment, and expertise for recording and analyzing highway noise measurements, while the Information Sciences Division is more involved in the prediction of highway noise values using various computer models. Our responsibilities in this area include the implementing of various prediction models, debugging of these models to some extent, maintenance, upgrading, and distribution of the TSC model, and the comparison and analysis of the various models for validation purposes.

Since most of you are quite familiar with the TSC and 117 models, I will not go into the models themselves to any great extent. Figure 2 gives the basic equations for each model, shows that the 117 model is fundamentally an empirical one, while the TSC model is based on theoretical considerations. As far as use of the models is concerned, the TSC model, using roadway and barrier endpoints and receiver locations expressed in a Cartesian coordinate system, greatly reduces the structuring of the input case and does not require that the user calculate the various subtended angles. The running of subsequent cases with changes to only individual parameters is more straightforward with the TSC model. Both models were intended to be used in free-flowing traffic situations and do not behave well (or at all) in urban or interrupted traffic flow situations.

TSC has recently undertaken a study of the TSC and Michigan 117 models (and BBN's revised design guide in the near future) for the purposes of comparison of the models and validation against field measurements. Figure 3 illustrates the primary functions involved in the study. Hourly noise measurements, traffic counts and mix, site geometry, and single-truck spectrum measurements are being taken at 3 locations [50 ft (15,24 m), 100 ft (30.48 m), and 200 ft (60.96 m) from the roadway] for several sites in each of four states. Included in each state is a site where measurements are taken for 24 consecutive hours. At TSC, the noise measurement data are handled by the Mechanical Engineering Division where they analyze it to determine the L_{10}, L_{50}, and L_{eq} levels at each location for each hourly interval of measurement. The traffic flow and site geometry is formatted by the Information Sciences Division for input to the noise prediction models. The models are then used to predict the L_{10}, L_{50}, and L_{eq} levels for each hour. The field measurement and prediction models results are then combined and input to a program that produces 9 graphs. Each graph shows the TSC, 117, and field data versus time for one receiver [50 ft (15.24 m), 100 ft (30.48 m), and 200 ft (60.96 m)] and one measurement type (L_{10}, L_{50}, or L_{eq}). A sample of one of these graphs is shown in Figure 4.

Figure 1.

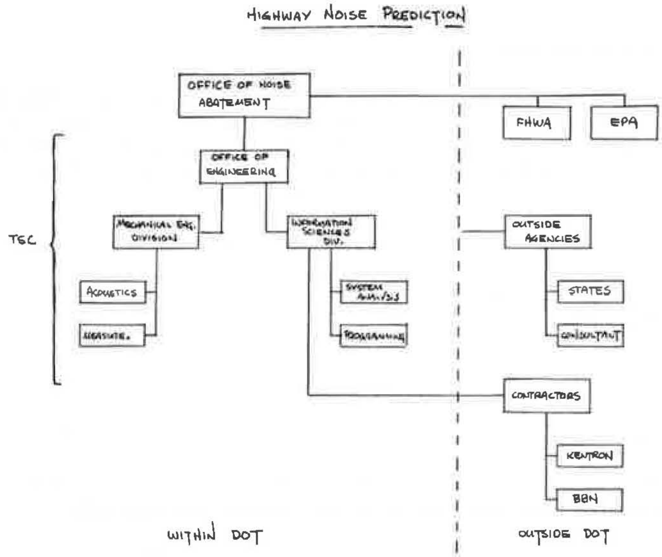


Figure 2.

BASIC EQUATIONS FOR EACH MODEL

	TSC	MICHIGAN 117
L_{50}	$L_e - \sigma_L^2/8.7$	$10\log\rho - 15D + 30\log S + 10\log\left[\tanh(1.19\times10^{-3}\rho D)\right] + 31$
L_{10}	$L_{50} + 1.28\sigma_L$	$L_{50} + 10\log\left[\dfrac{\cosh(1.19\times10^{-3}\rho D)}{\cosh(1.19\times10^{-3}\rho D) - 0.951}\right]$
L_{90}	$L_{50} - 1.28\sigma_L$	NOT USED
L_e	$10\log I$	$L_{50} + 0.07(L_{10} - L_{50})^2$
L_{np}	$L_e + 2.56\sigma_L$	$L_e + 2(L_{10} - L_{50})$
TNI	$L_{50} + 8.76\sigma_L + 30$	$L_{10} + 6(L_{10} - L_{50}) - 30$

WHERE: L_e = SOUND ENERGY MEAN LEVEL
σ_L = STANDARD DEVIATION OF SOUND PRESSURE
I = MEAN SOUND INTENSITY
ρ = MEAN VEHICLE CONCENTRATION (VEH PER HOUR/VELOCITY)
D = RECEIVER DISTANCE
S = VEHICLE SPEED

Figure 3.

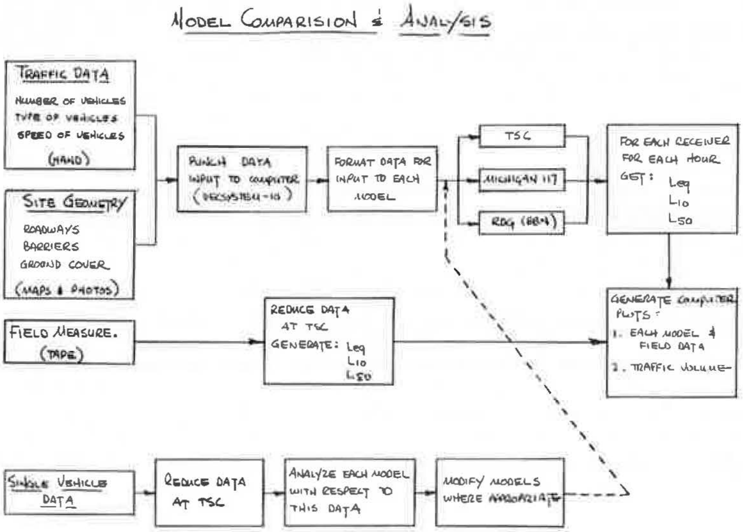


Figure 4.

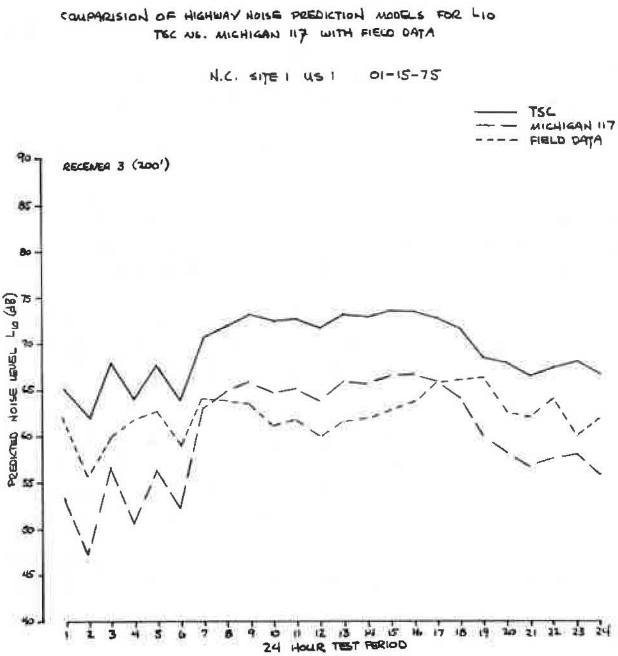


Figure 5.

PRELIMINARY & PARTIAL COMPARISION OF MODELS
(NORTH CAROLINA - SITE 1)

TIME OF DAY TRAFFIC VOLUME		4AM (LIGHT)	9AM (HEAVY)	2 PM (MEDIUM)	6 PM (HEAVY)
NO. CARS (NEAR/FAR)		5/12 (17)	525/480 (1005)	185/255 (440)	360/540 (900)
NO. TRUCKS (NEAR/FAR)		13/14 (27)	30/25 (55)	30/38 (68)	40/23 (63)
SPD. CARS (NEAR/FAR)		50/49	40/47	49/50	45/49
SPD TRUCKS (NEAR/FAR)		43/54	42/48	42/43	43/47
50'	L10 (TSC/117/MEA.)	69/60/66	79/76/73	79/76/73	77/75/72
	Leq	67/59/67	75/75/69	75/74/70	74/72/69
100'	L10 (TSC/117/MEA.)	67/55/64	76/71/67	75/71/66	75/69/67
	Leq	64/54/63	73/69/65	72/69/64	71/66/64
200'	L10 (TSC/117/MEA.)	65/51/63	74/66/64	73/66/62	72/64/66
	Leq	61/49/59	70/63/59	69/63/57	68/61/62

Figure 5 summarizes some of the results for the 24-hour site in North Carolina for selected traffic densities.

These preliminary results show that the values from the TSC model are much higher than the field data (6 to 10 dB), while the Michigan 117 model results are not quite as high, they still remain above the field data. It is also interesting to note how the two models follow each other fairly well, although separated by several dB. Both models exhibit erratic behavior at low traffic volumes.

As I have mentioned, these are only preliminary results from a first pass at the data. We are still in the process of ensuring that the procedures used to structure the input for the models from the raw data are valid and that the noise measurements were not affected by conditions that are not considered by the models (wind, humidity, etc.). These results seem to be holding for the two states processed to date (North Carolina and Florida). We are anticipating additional data from Washington and Colorado.

Coincident with this straightforward processing of the data, we are undertaking an analysis of the field measurements to determine the noise decrease with doubling of distance and the relationship between L_{eq} and V/DS for events where one vehicle type predominates.

Each state is also providing single-vehicle data that will allow us to generate the 50-ft (15.24-m) spectrum for each vehicle class and to then compare these spectra against those used in the models. If appropriate, the spectra of the models will be modified and all of the cases rerun with the modified models to determine the effects of the new spectra, and hopefully, bring the results into closer agreement with the field measurements.

One final word, since the workshop, we have received and implemented the revised design guide on TSC's Decsystem-10. The initial results using this model are encouraging.

EXPERIMENTAL DATA SUPPORTING THE NCHRP 3-7/3 REVISED DESIGN GUIDE FOR HIGHWAY NOISE PREDICTION AND CONTROL

B. Andrew Kugler, Bolt Beranek and Newman, Inc.

Introduction

The revised design guide for highway noise prediction and control, developed as a result of research conducted under NCHRP Project 3-7/3 contains many changes and modifications to the procedure presented in NCHRP Reports 117/144 designed to improve the accuracy and to extend the range of applicability under which the prediction may be used. These changes and modifications resulted from the experience gained through the use of 117/144 and the TSC models by highway departments and from further research conducted under the NCHRP 3-7/3 program. (The TSC model, developed by the Transportation Systems Center is one of two highway noise prediction procedures approved by the FHWA; the other is the NCHRP 117/144 procedure.)

The objective of this presentation is to bring forth field noise data in support of the revised design guide model. Since the revised design guide was only recently completed and since only a very limited amount of field data is available for a valid comparison, this analysis can be judged as preliminary at best. However, the data presented may be viewed as a first order test of the model in the sense that it provides an estimate of the prediction accuracy under a variety of highway conditions.

Before we explore the main topic of this presentation, a few words of comment about the acquisition and analysis of the field noise data are in order. The assumption that any field data regardless of how they were acquired and how well the site parameters are known can be fairly compared to a prediction procedure is false. More often than not such practice has led to incorrect and misleading conclusions as to the accuracy of the model being tested.

The validation of a prediction procedure like the one being offered here requires more than a cursory examination of a field test site. First of all, we must strive to acquire acoustic data that are valid for the type of descriptor (i.e., L_{10}, L_{50}, or L_{eq}) being used in the prediction procedure. It also must be remembered that a prediction procedure of this type, by its very nature, implies that the calculated noise levels are "typical" for the given traffic conditions considered. That is, the prediction procedure will and should predict the noise levels that will be experienced at the given location if this same condition is measured repeatedly.

Second, if the model is to be tested properly, the traffic and geometric roadway parameters that govern the model must be properly measured and identified. There is very little reason to measure the noise levels repeatedly and establish the L_{10} level to within 0.1 dB if only a vague description of the highway, surrounding terrain, and traffic conditions under which the measurements were made are available.

When analyzing the applicability and accuracy of the highway noise model, it is helpful to evaluate separately the major sub-models on which the overall procedure is based. The three major ingredients in the noise prediction model are (a) noise source model, (b) free field propagation model, and (c) barrier noise reduction model.

The noise source model, using the parameters of traffic volume, traffic mix, and average speed, predicts the total magnitude of acoustic energy being generated in terms of sound levels in the close proximity to the roadway. The free field propagation model, using the description of the highway horizontal configuration and surrounding terrain, predicts how this acoustic energy is propagated between the source and receiver. Finally, the "barrier" noise reduction model evaluates how obstructions such as the vertical roadway configuration, walls, houses or other definable terrain characteristics modify and reduce the noise levels reaching the receiver. The experimental data presented here will be analyzed in terms of these three models and the accuracy of the prediction procedure will be discussed in terms of these categories.

Field Test Sites

The field noise data used in the noise source and barrier model analysis were acquired under two separate projects (1,2) for TRB and FHWA. Fourteen test sites are analyzed as identified in Table 1.

Although by no means exhaustive in terms of national coverage, the test noise data collected includes five states and covers a number of weather conditions (i.e., summer in California, winter in Minnesota).

Extensive noise measurements were performed at each site under a wide range of traffic conditions. In each instance, simultaneous microphone locations were monitored and recorded on analog tape. The data were later reduced in terms of the noise descriptors of interest. Reference 1 provides a detailed description of the measurement procedures and data analysis technique. Furthermore, the site identifications utilized in this analysis are kept the same as in the original references for use of comparison.

Noise Source Model Assessment

The assessment of the noise source model was performed by selecting, from each test site, noise measurements that were made at a close proximity to the roadway; typically between 25 to 100 ft (7.62 m to 30.48 m) from the near lane. The controlling requirements in the site selection were that the highway approximates the infinite line geometry [straight and level for at least 1000 ft (304.8 m) in each direction] and that a free field view be afforded from the microphone position to the entire line source. These requirements eliminated from consideration all variables except the traffic conditions present during the measurement.

Each traffic condition for which noise measurements were available was then used to input the revised design guide model and to compute the predicted noise levels. Typically, 10 to 25 independent conditions were computed for each test site and the overall discrepancy at each test site calculated by summing the individual sample discrepancies and dividing by the number of conditions evaluated. Figure 1 presents these data as a function of each site average discrepancy versus site location.

In each case, the individual discrepancy is defined as the difference between measured and predicted noise levels. That is, a positive discrepancy indicates an underprediction of measured values and a negative discrepancy indicates an overprediction of measured values. Ideally, when the prediction and measurement are the same, the discrepancy is zero.

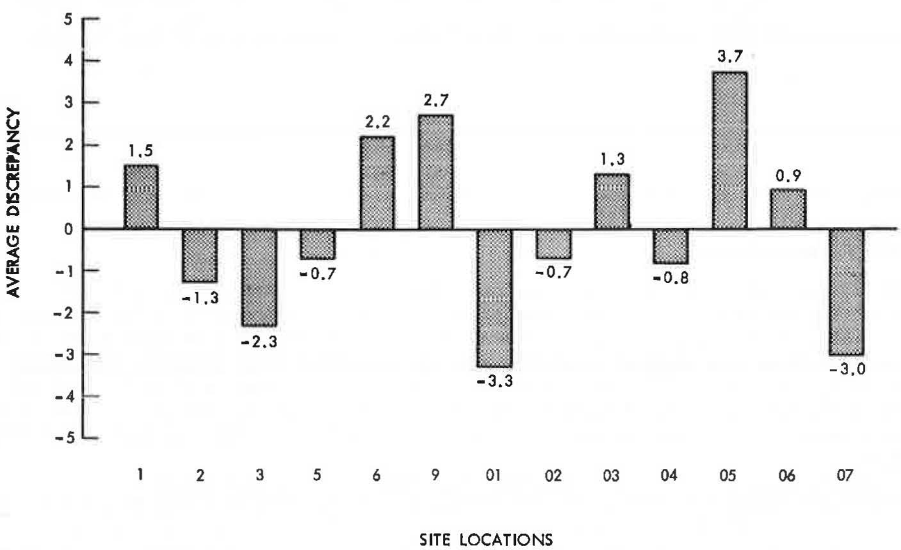
An evaluation of Figure 1 leads to a few important conclusions with respect to the gross accuracy of the source model.

1. The average of the discrepancy between measured and predicted values over all 13 sites is negligible (in the order of 0.02 dB). This suggests that the model, for "an average site in the country," correctly predicts measured values.
2. From one site to the next there is a definite variability resulting in an average overprediction or underprediction of the noise levels. The range of average discrepancy is approximately ±3.5 dB.

Table 1. Location of test sites at which traffic noise data were collected.

Site No.		
1.	1-680 Milpitas, California	(TRB)
2.	US-101 Encino, California	(TRB)
3.	1-405 Van Nuys, California	(TRB)
4.	I-494 Bloomington, Minnesota	(TRB)
5.	I-35W Richfield, Minnesota	(TRB)
6.	I-94 Ypsilanti, Michigan	(TRB)
01.	SR-7 Long Beach, California	(FHWA)
02.	I-605 Long Beach, California	(FHWA)
03.	I-10 San Gabriel, California	(FHWA)
04.	I-75 Allen Park, Michigan	(FHWA)
05.	I-94 Kalamazoo, Michigan	(FHWA)
06.	I-94 Milwaukee, Wisconsin	(FHWA)
07.	I-94 Minneapolis, Minnesota	(FHWA)
09.	I-80 Sacramento, California	(FHWA)

Figure 1. Average discrepancy between measured and predicted noise levels.



3. There is no clear regional tendency as to the underprediction or overprediction of the noise levels. For example site locations 01 and 02 (refer to Table 1) located in Long Beach, California, were measured under the same climatic conditions and due to their proximity, with apparently the same type of vehicle distribution, however, the average discrepancy differed by almost 3.0 dB between these sites. The same conclusion may be arrived at for other sites used in the analysis.

4. There is no apparent climatic dependence as to the overprediction or underprediction of the noise levels. For example, site locations 04, 05, 06, and 07 were measured during the winter period with snow on the ground while the remaining site locations were measured during summer or mild temperature conditions.

To explore further the individual site discrepancy problem, an evaluation of the data based on the traffic parameters used in the source model was conducted as a function of (a) average speed, (b) vehicle class as function of heavy truck to automobile/medium truck ratio, and (c) total volume.

Figure 2 presents a dispersion diagram of all individual data points used in the analysis as a function of discrepancy and average speed. Although only the speed range of 50 to 75 mph (80 to 112 km/h) is covered,the data points out the lack of tendency as a function of speed. Furthermore, the subclassification as a function of the truck/auto ratio does not further explain the discrepancy.

Figure 3 presents a similar comparison, this time as a function of heavy truck to auto ratio (T/A). The T/A covers a range of 0 to 24 percent and again the data show no apparent trend. Finally, the same analysis was performed as a function of total volume and indicated in Figure 4 with the same general conclusion.

Statistical tests in the form of correlation and regression analysis were performed to support the above conclusions. The overall conclusion is that the model predicts source levels correctly based on vehicle class, average speed, and total volume, and that these parameters are not responsible for the observed discrepancies from site to site. The individual standard deviations were approximately 2.5 dB.

The above analysis will seem to indicate that the observed site discrepancy is site dependent and not a function of the model parameters or regional/climatic conditions. A further conclusion is that individual measurements of L_{10} levels at any given site may be different from predicted values by as much as ±4.0 dB with an expected standard deviation of 2.5 dB.

These differences between measured and predicted values may be due to one or a combination of the following:

1. The instability of the L_{10} measure, especially for low traffic volumes;
2. The apparent variability of the actual sources as compared to the "average source" used in the model for each vehicle category;
3. The effect of environmental conditions (i.e., wind and temperature gradients) at the site during the measurement period; and
4. The site topographical factors that are beyond the models capability.

From all these, the site dependent topographical factors is probably the most influential parameter. It remains to be seen if long-term measurements at a given site and given location will show a better agreement with the model, on the average, or if in fact there is a bias error associated with each site that is site dependent and beyond the model capability.

Free Field Propagation Model Assessment

The propagation of traffic noise away from the highway is complicated by the presence of ground plane and environmental factors. The model permits for the use of two propagation constants—3.0 dB and 4.5 dB per distance doubling. Very little field noise data compatible with free field propagation evaluation are available, however, what data exist do confirm the variability of the propagation factor between the above two values.

The data presented below represents a summary of the conclusions reported in Volume 3 of NCHRP Project 3-7/3 (3). Figures 5, 6, and 7 present some typical examples of the measured noise levels as a function of equivalent distance from the roadway for three test sites investigated. The different symbols correspond to different traffic conditions under which simultaneous noise measurements were acquired.

Analysis of the field data brings forth the following conclusions:

1. It is acceptable to assume that the free field noise levels due to highway traffic are proportional to the logarithm of equivalent distance from the roadway, at

Figure 2. Measured minus predicted noise source levels.

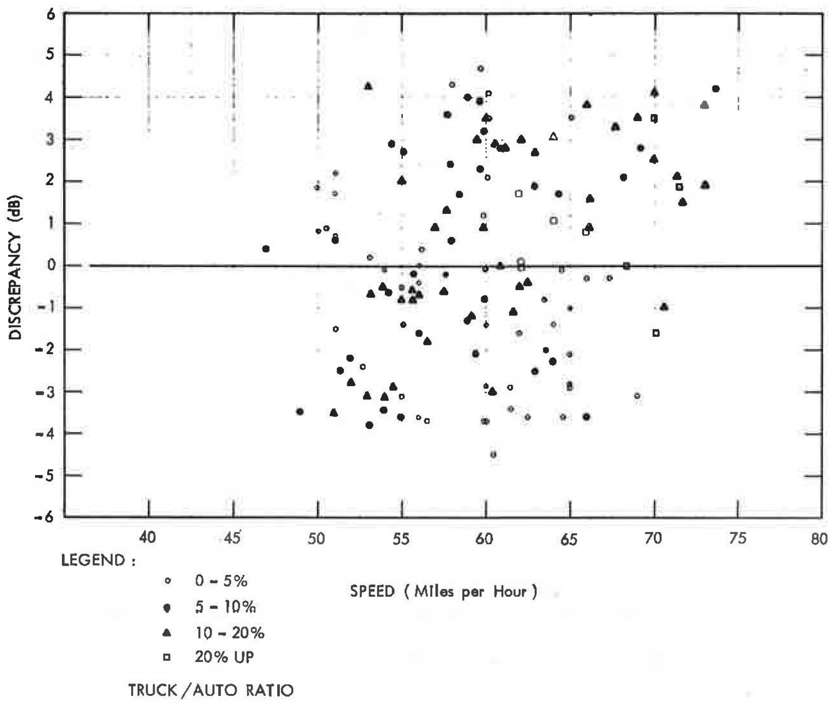


Figure 3. Measured minus predicted noise source levels.

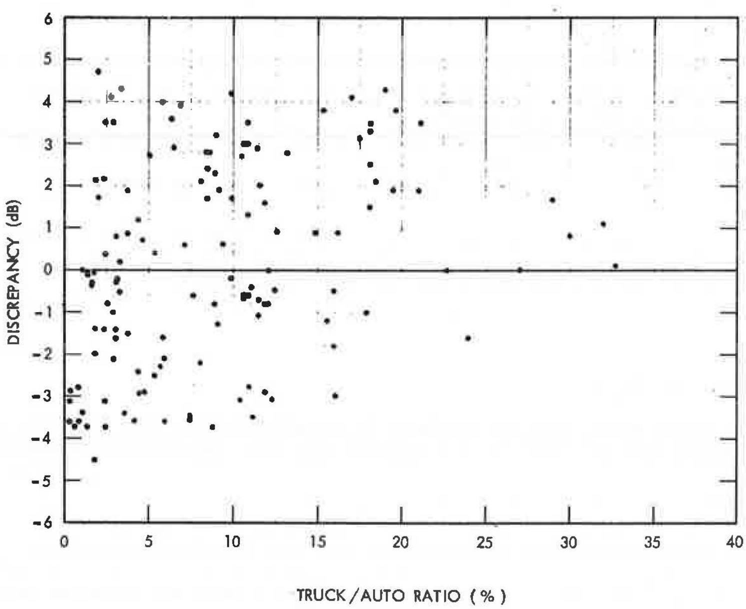


Figure 4. Measured minus predicted noise source levels.

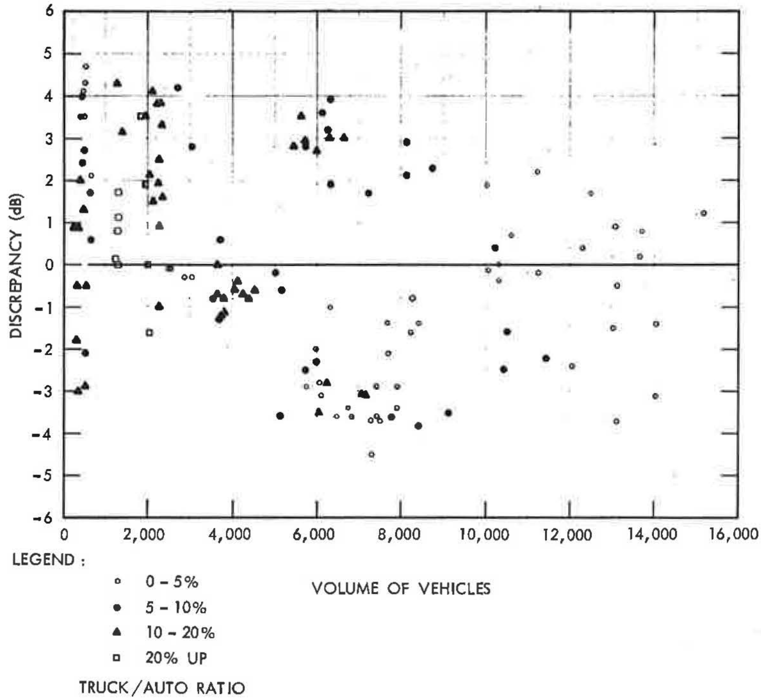


Figure 5. Free field noise propagation measurements at Site 1.

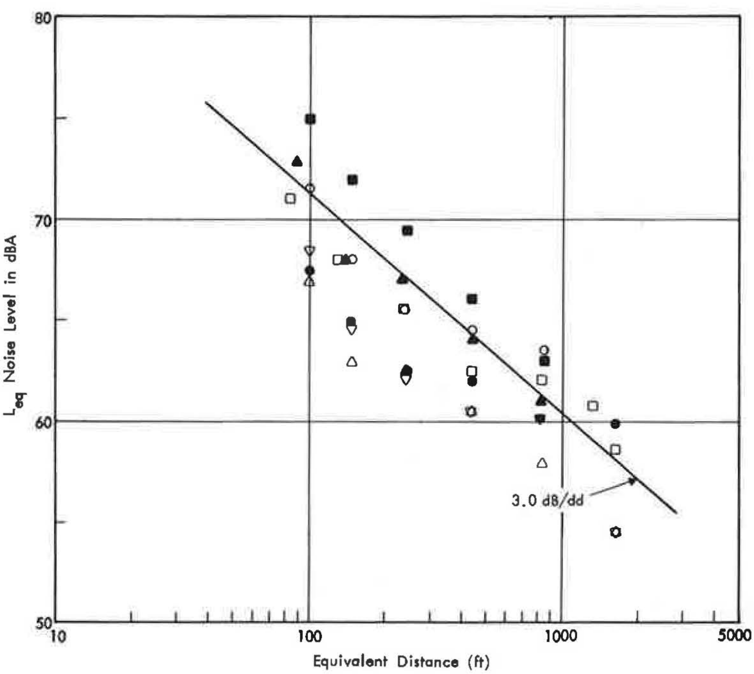


Figure 6. Free field noise propagation measurements at Site 2.

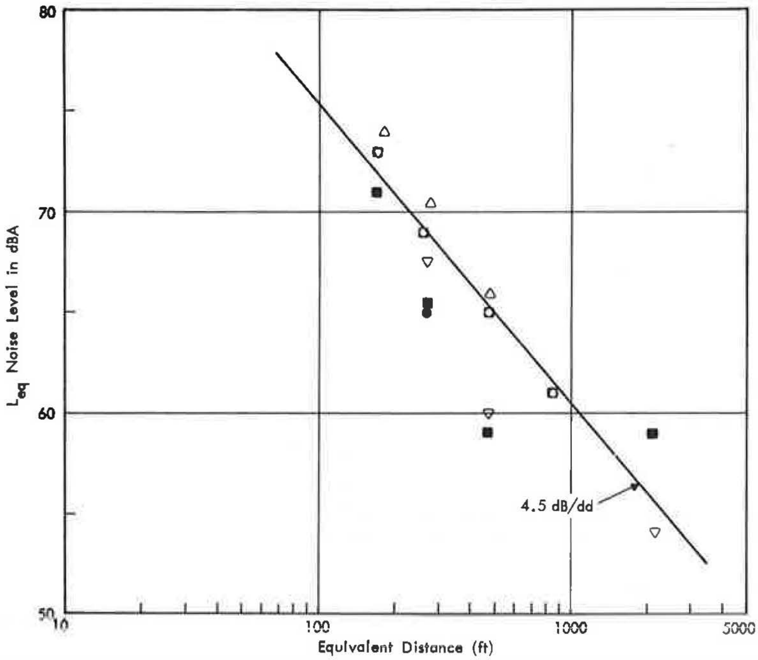
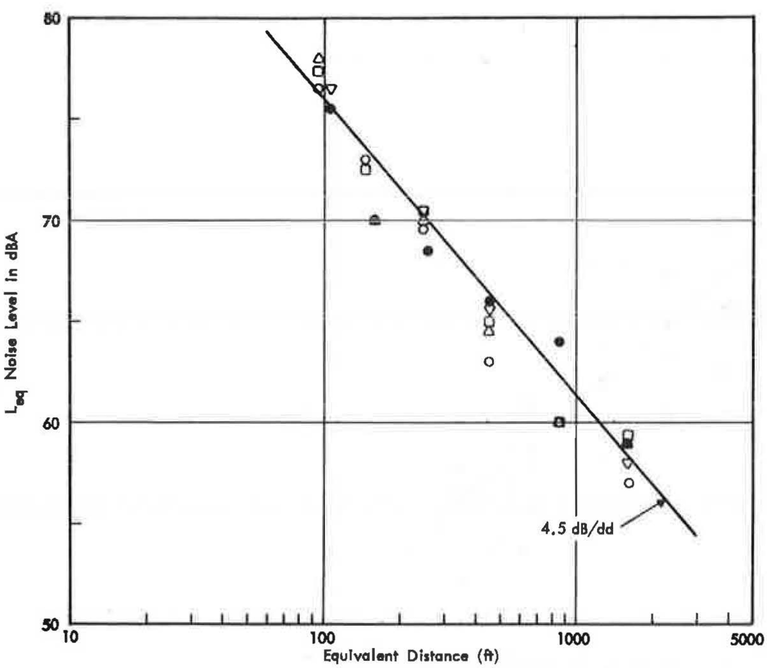


Figure 7. Free field noise propagation measurements at Site 3.



least for distances up to 1600 ft (487.68 m) and traffic volumes down to 250 vph.

2. The constant of proportionality in the relationship (the propagation loss factor) varies about 10 (3 dBA decrease per doubling of distance) for the case of clear, reflective and level ground to about 15 (4.5 dBA decrease per doubling of distance) for the more lush absorptive terrain or for terrain where the line of sight to the highway may be interrupted by small topographical changes (short of barriers). This is given in Table 2.

3. The propagation loss factor does not vary significantly with observer height above the ground up to 15 ft (4.57 m).

4. For relatively high traffic volumes, say greater than 2500 vph, the propagation loss factor does not vary significantly with the percentage level of the noise distribution.

5. For relatively low traffic volumes, say less than 2500 vph, the propagation loss factor for small percentage levels is significantly higher than the loss factor for high percentage levels. An example of this is given in Table 3.

6. The propagation loss factor for mean energy levels (L_{eq}) is stable for all traffic volumes.

The full understanding of what is termed as free field propagation is by no means complete and this study area perhaps is one that most needs further research and validation. However, the correct assessment of the ground conditions in terms of one of the two propagation loss factors gives results which are consistent with the overall prediction procedure accuracy of ±2.0 dB.

Barrier Noise Reduction Model Assessment

The excess noise reduction provided by "barriers" is predicted by the barrier noise reduction model. In this context, the word "barriers" includes the highway vertical configurations such as elevated or depressed and all other continuous physical obstructions between the source and receiver such as walls, berms, and berm-wall combinations.

Accurate field noise data for 12 of the 14 sites described in Figure 1 were available to assess the accuracy of the barrier model. Figure 8 presents a summary of measured minus predicted average discrepancies for all sites evaluated in terms of 5 basic barrier configurations. Each barrier was evaluated by a series of simultaneous noise measurements taken at different distances and heights behind the barrier; these were then repeated for various traffic distributions. In total, 15 to 25 measurement locations were chosen behind each barrier. The average discrepancy for each site represents the average of the individual discrepancies between measurement and prediction evaluated in terms of "Equivalent A-weighted" sound levels (L_{eq}). A more detailed analysis of these data for sites 1, 2, 3 and 5 is presented in Table 4.

The data in Figure 8 show reasonable agreement between measured and predicted values except in the case of berms where the prediction procedure definitely underpredicts measured value by an average of 2.8 dBA. That is, the revised design guide, based on the available data, seems to correctly predict the effect of elevated/depressed highway configurations and walls as long as the "thin edge" geometry can be assumed. When a finite width barrier is considered, such as is the case with berms with a flat top, the prediction procedure underpredicts measured values significantly. This conclusion may be further reinforced by analyzing the data in Figures 9, 10, and 11.

Figure 9 displays a scatter diagram for the case of wall configurations (sites 03, 04 and 07). The data show no apparent trend with a random scatter around the ideal relationship in terms of both increased attenuation and distance from the barrier. The standard deviation for this case is below 2.0 dB. The analysis of the wall-berm combination shown in Figure 10 is similar to the wall configuration with only a slight tendency for underprediction at low attenuation values. However, the case of the finite-width berm shown in Figure 11 shows a definite bias toward underprediction with most of the data lying above the ideal relationship.

Conclusions

The limited field noise data base used to evaluate the accuracy of the revised design guide shows general agreement between measured and predicted values for the three main ingredients of the model. The data further suggest that an accuracy of ±2.5 dBA (one standard deviation) may be expected from this method when applied properly. Without grossly increasing the complexity of the prediction, the author feels that the stated accuracy might be the limit that may be expected. However, further validation of the revised design guide is necessary in order to definitely establish its accuracy and

Table 2. Summary of propagation loss factors for high traffic volumes (L_{eq}).

Site No.	Site Description	Propagation Loss Factor (ε)
1	Freshly plowed farmland	10.9 ± 0.5
2	Planted farmland (an asparagus field)	15.8 ± 0.7
3	Parkland (grass and shrubs)	15.4 ± 1.4

Table 3. Summary of propagation loss factors for low traffic volumes—Site 1.

Propagation Loss Factor (ε) for Various Percentage Levels at Site 1				
L_{01}	L_{10}	L_{50}	L_{90}	L_{eq}
13.6 ± 2.2	10.5 ± 1.8	10.2 ± 1.8	8.7 ± 1.9	10.4 ± 1.3

Figure 8. Average discrepancy between measured and predicted noise reductions at 12 sites.

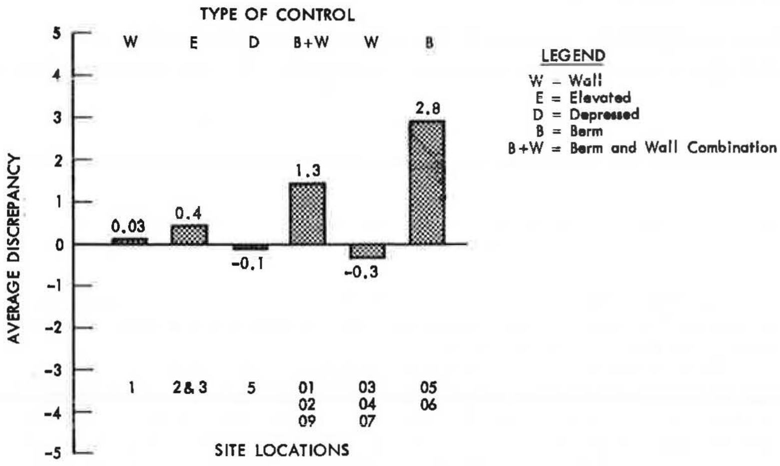


Table 4. Agreement between predicted and measured noise reduction.

Site and Sample Size	Assessment Parameter	Computed Result	Ideal Result	Difference* Statistically Significant?
Roadside Barrier Site 1 n=50	Ave. Discrep., $\bar{\Delta}$	0.03 dBA	0	No
	Std. Dev., s_Δ	1.64 dBA	0	--
	Slope, , b	1.19	1.0	No
Elevated Roadway Site 2&3 n=24	Ave. Discrep., $\bar{\Delta}$	0.38 dBA	0	No
	Std. Dev., s_Δ	1.39 dBA	0	--
	Slope, , b	1.29	1.0	No
Depressed Roadway Site 5 n=24	Ave. Discrep. $\bar{\Delta}$	-0.10 dBA	0	No
	Std. Dev., s_Δ	1.60 dBA	0	--
	Slope, b	0.91	1.0	No

*tested at the 1% level of significance.

Figure 9. Measured versus predicted scatter diagrams for wall configurations.

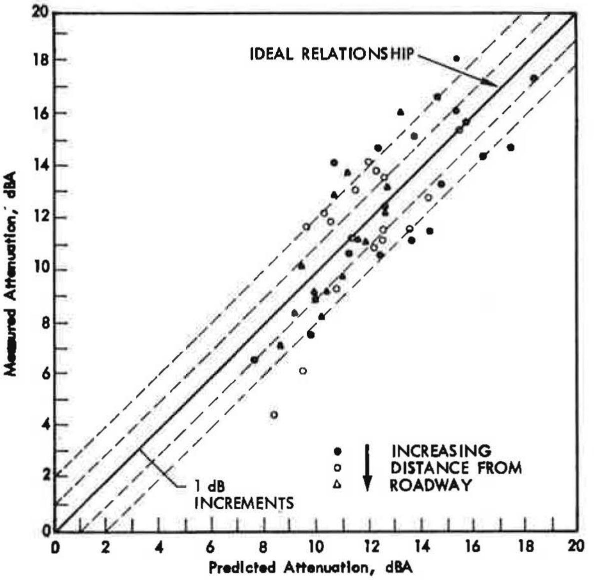


Figure 10. Measured versus predicted attenuation scatter diagrams for berm-wall constructions.

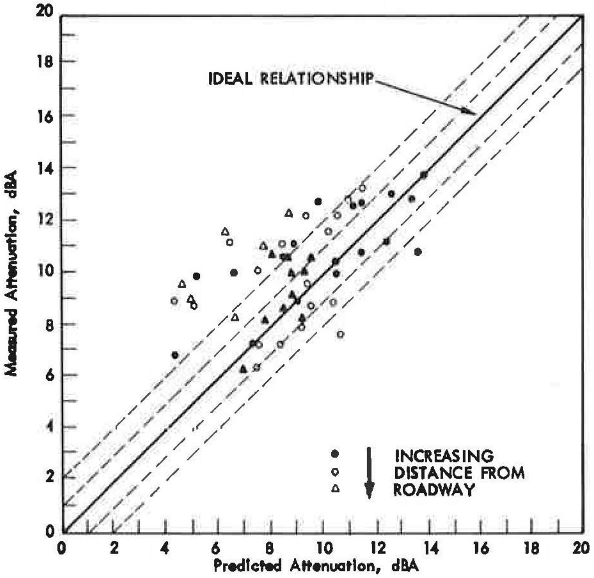
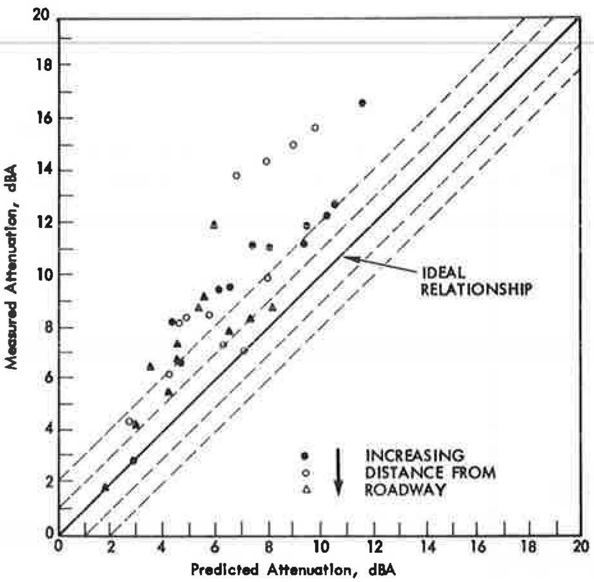


Figure 11. Measured versus predicted attenuation scatter diagram for berm configuration.



applicability. This requires the evaluation of not only simple site configurations as was undertaken in this paper but also of complex geometries where the full extent of the model is exercised. Finally, it is recommended that, as a result of this analysis, further investigation of site-to-site bias error and the noise reduction performance of berms is warranted from this analysis.

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SPECIFIC DIFFERENCES BETWEEN THE "REVISED DESIGN GUIDE" AND THE TWO AUTHORIZED NOISE PREDICTION METHODS OF THE FHWA

Grant S. Anderson, Bolt Beranek and Newman, Inc.

The National Cooperative Highway Research Project 3-7/3 has recently resulted in the publication of a revised design guide for prediction of roadway traffic noise. This guide is a composite product of NCHRP Reports 117/144 and the Transportation Systems Center prediction methods—the two methods authorized by the Federal Highway Administration for use on federal-aid highway projects. The revised design guide (RDG) supplements these two authorized methods (117/144 and TSC) with data taken as part of NCHRP 3-7/3 and as part of an FHWA research project on noise barrier effectiveness. In addition, the RDG supplements the two authorized methods with additional mathematical structuring, derived from physical reasoning, with the hopes of extending the prediction validity to low-volume traffic situations.

In brief, the RDG structure consists of an L_{10} nomograph (similar to the TSC nomograph but with revised source data and revised distance dependence), a barrier nomograph (similar to the FHWA barrier nomograph but with revised distance dependance and revised estimates of the noise around the barrier ends), and a series of worksheets—all leading to a hand-method calculation for simple roadway geometrics. As a partner to the hand method, the RDG includes a computer program (similar to the TSC program but with revised source levels, variable propagation drop-off, revised low-volume mathematics, segment adjustment and many other factors) for the detailed prediction of roadway noise levels, both for complex roadway geometrics and for detailed barrier design. In addition, this computer program contains a diagnosis capability that pinpoints "hot spots" along the roadway and enables the user to balance any barrier design up and down the roadway, to avoid under- or over-design of expensive roadway barriers.

In this paper, these three noise prediction methods (117/144, TSC, and RDG) are coalesced into a common framework, to enable users of these methods (a) to compare the physical assumptions of the methods step by step in the calculation logic; and (b) to anticipate how the RDG will change the predicted noise levels, relative to those predicted by 117/144 and TSC. The common framework consists of three graphs and two equations that coalesce the three methods into the following calculation logic: emission levels (EL) of individual vehicles at 50 ft (15.24 m); to the energy-mean A-level (L_{eq}) at 50 ft (15.24 m), from the entire stream of traffic; to the L_{eq} at any distance D; and finally, to the 10-percentile A-level (L_{10}) at this same distance (with an ad hoc adjustment, necessary only in the 117/144 method).

We first present this common framework, for predicting the L_{10} for an infinite straight roadway. Next, we present three examples using the framework to compute the noise levels for medium, high, and low density traffic. Then we present a series of graphs and tables that complete the comparison of the three prediction methods, in all their finer details. And finally, we summarize the framework and identify under what conditions the RDG predictions will differ from 117/144 and TSC by 5 dBA, by 10 dBA, and by 15 dBA. In this summary, we emphasize the RDG improvements that result from (1) inclusion of medium trucks as a noise source; (2) a variable propagation constant; (3) more realistic low-volume mathematics; and (4) the inclusion of a diagnostic print-out in the RDG computer program.

The Common Framework for Roadway Noise Prediction

In this section, we present the common framework for roadway traffic noise. This framework coalesces the distinctly individual mathematics of the three prediction methods of interest: the 117/144 method, the TSC method, and the RDG method. The framework was designed to illuminate the logical relationships among these three distinct methods. It is not the "official" framework for any of the three. Instead, it is a physically realistic composite of each method's stated physical assumptions, unstated assumptions and generally unstated physical logic. Our emphasis is upon the common attributes of each method.

Use of the framework for noise computation results in predictions within 1 or 2 dBA of "official" predictions, i.e., predictions using the actual mathematics of each method separately.

The framework consists of five steps:

1. Emission levels (EL) of individual vehicles at 50 ft (15.24 m);
2. Conversion to L_{eq} at 50 ft (15.24 m) from an entire stream of vehicles;
3. Conversion to L_{eq} at Distance D;
4. Conversion to L_{10} (and L_{50}) at Distance D; and
5. An ad hoc adjustment, necessary only in the 117/144 method.

Emission Levels

Figure 1 contains all the emission level (EL) assumptions of the three prediction methods. Plotted are the emission levels as a function of speed for three types of roadway vehicles: automobiles (which include 4-wheel trucks); medium trucks (all 6-wheel vehicles, including 6-wheel buses); and heavy trucks (all vehicles with more than 6 wheels, including applicable buses). Only the RDG incorporates medium trucks. The other two methods prescribe heavy-truck EL's for medium trucks as well. Note that the level-mean EL's are plotted in Figure 1, rather than the energy-mean EL's, which are from 1 to 3 dBA higher.

In 117/144, the emission level assumptions are explicit, but the distinction between level-mean EL's and energy-mean EL's is neglected; this neglect effects the subsequent step in our framework. In TSC, the emission level assumptions are also explicit and listed as level means. In RDG, the emission level assumptions are again explicit and listed as energy means.

Conversion to L_{eq} at 50 ft (15.24 m)

Equation 1 converts from emission levels (EL) to L_{eq} at 50 ft (15.24 m) in engineering units.

$$L_{eq}\underset{(50\text{ ft.})}{(15.24\text{ m})} = (\text{Level-mean EL}) + 10\log\left(\frac{V}{S}\right) - 12 - \begin{cases} 4 \text{ for RDG} \\ 2 \text{ for TSC} \\ 0 \text{ for 117/144} \end{cases} \tag{1}$$

where

V = vehicle volume, in veh/hr, and
S = vehicle speed, in mph.

To convert to SI units, replace the -12 with +20. Then V must have units of veh/sec and S units of meters/sec.

This equation follows directly from integrating the passage of V vehicles along an infinite straight roadway located 50 ft (15.24 m) from the observation point. The equation assumes a 3 dBA difference between level-mean EL's and energy-mean EL's, as was explicitly measured in the RDG study.

Note that empirical adjustments to this equation are required for each of the three prediction methods. The -4 dBA adjustment is explicit in the RDG, as an empirical adjustment required to match predictions with measurements. The -2 dBA adjustment is necessary in TSC to account for a lesser difference between the level-mean and energy-mean EL's. This lesser difference follows directly from the supporting EL data in TSC. (The scatter of EL's about the level-mean EL is less than in the RDG data.) The 0 dBA adjustment for 117/144 results from neglecting the distinction between level-mean EL's and energy mean EL's; by this neglect, the level was not increased to convert from level-mean to energy-mean in the development of 117/144, and therefore the level did not have to be decreased empirically to match L_{eq} measurements.

Note that these empirical adjustments tend to wash out the differences in emission levels among the three prediction methods.

Conversion to L_{eq} at Distance D

Figure 2 converts from L_{eq} at 50 ft (15.24 m) to L_{eq} at Distance D. Plotted are the two propagation lines that correspond to divergencies of -3 dB per distance-doubling and -4.5 dB per distance-doubling.

In TSC, the -3 dB/DD follows directly from the line-source mathematics incorporated; this divergence is derived for an incoherent line source, infinitely long. In 117/144 the -4.5 dB/DD is forced upon the mathematics and justified by comparison with many experimental measurements. The great bulk of these measurements was made some 4 or 5 ft (1.2 m or 1.5 m) above absorptive, flat terrain, and therefore incorporates the influence of the nearby ground (which is ignored in the TSC mathematics). In addition, the bulk of these measurements was made adjacent to heavy traffic flows, where the level difference between L_{eq} and L_{50} is very small, and therefore unimportant. These data therefore obscured the conceptual differences between L_{eq} and L_{50}, and as a result this propagation factor was ascribed to L_{50} under all traffic conditions. In our common framework, we associate the propagation factor with L_{eq}, as is physically reasonable, and account for the confusion between L_{eq} and L_{50} in a subsequent step in the framework (ad hoc adjustment).

In the RDG, the divergence switches from -3 dB/DD to -4.5 dB/DD, as a function of observer height and type of ground cover, as shown in the figure.

Conversion to L_{10} at Distance D

Figure 3 converts the L_{eq} to the L_{10} at Distance D. Also plotted are conversion lines to L_{50}. Both the TSC and the RDG methods incorporate a computer program and a simplifying nomograph. The conversion to L_{10} differs for computer and nomograph, and therefore four L_{10} conversion lines are plotted.

Conversion to L_{10} is a function of the parameter VD/S, which is "parameter A" of 117/144. In effect, VD/S is the Distance D, normalized by the average spacing between vehicles on the roadway. The statistics of the noise fluctuations depends only on this parameter VD/S, when the vehicles are equally spaced along the roadway. This equal spacing is explicit in the RDG method. Since the statistics of the fluctuations depend only on VD/S, then so do the conversions from L_{eq} to any of the percentile levels.

This figure is the most complex portion of the common framework; its interpretation is reasonable, but not immediately intuitive.

The two nomograph conversions are easiest to interpret. They indicate a conversion that is independent of VD/S; i.e., the L_{10} nomographs ignore the statistics of the fluctuations and are essentially nomographs for L_{eq} (plus three decibels). Both methods state this explicitly.

The computer conversions for RDG are next easiest to interpret, since they are explicit in RDG. In RDG, a Gaussian conversion curve is developed for high values of VD/S and a conversion curve for equally spaced vehicles is developed for low values of VD/S. Then these two conversion curves are patched together in the vicinity of 300 ft/mile (91.44 m/km), to result in the conversion curves shown in Figure 3.

Figure 4 aids in interpreting the 10 log (VD/S) slope for low VD/S. At the top of Figure 4, a vehicle proceeds along a roadway, past an observer location. The vehicle is illustrated at two successive positions on the roadway, corresponding to its L_{10} position under two traffic conditions: volume = V_o and volume = $2V_o$.

The level history for these two traffic conditions is shown underneath the roadway. For a volume of V_o, the vehicle noise increases slowly from a relative level of -35 dB to a peak of 0 dB, and then recedes. Also shown are the tail ends of the level histories for the vehicle immediately preceding and the one immediately following. Since the traffic is equally spaced, the interval between (normalized) distances -55 and +55 includes the full statistics of the noise history. The level exceeded for 10 percent of this interval is the L_{10} for the full hour. This L_{10} is shown in the figure, and is 15 dB down from the peak level. The vehicle's position on the roadway, when it is producing the L_{10} at the observer, is shown at the top.

If now the volume doubles to $2V_o$, then the interval between vehicles is halved, as shown in the middle illustration. Again the L_{10} is shown, this time down only 9 dB from the peak. In the process of doubling the traffic volume the L_{10} has thereby increased 6 dB. The reason is apparent from the roadway sketch at the top. The vehicle's

Figure 1. Emission levels (level mean).

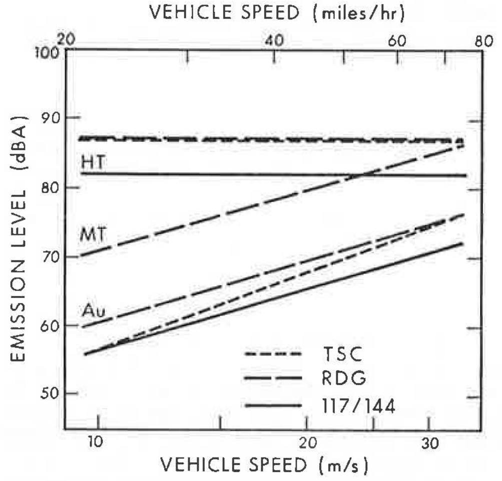


Figure 2. Conversion of L_{eq} from 15 m (50 ft) to other distances.

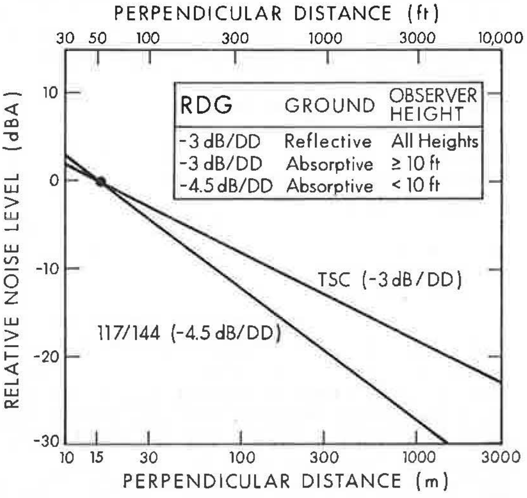


Figure 3. Conversion from L_{eq} to L_{10} and L_{50}.

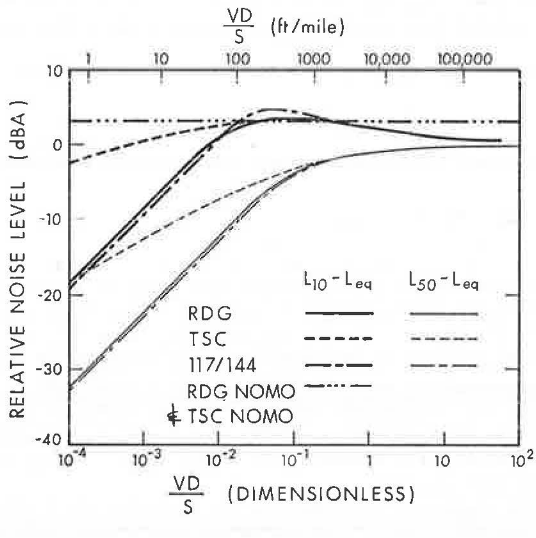
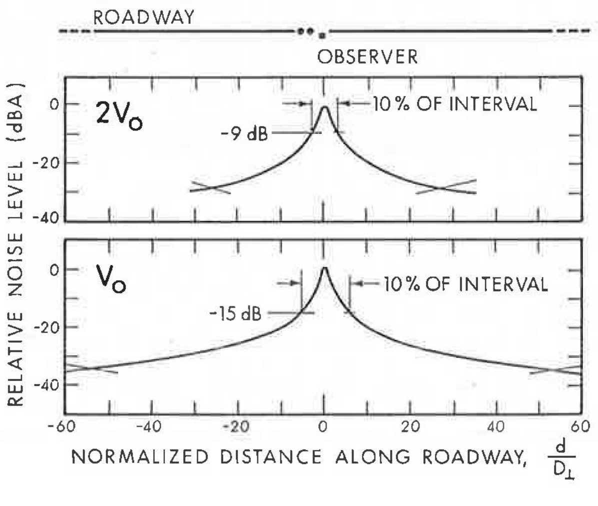


Figure 4. 6 dB/double-volume at low VD/S.



position when it actually produces the L_{10} at the observer has been cut in half as the volume was doubled; and the level from this point source has therefore increased the expected 6 dB. A similar figure for L_{50} would show the same 6 dB increase per double-volume, at these low traffic volumes (strictly, at low values of VD/S). The resulting 6 dB/double-volume increase is incorporated explicitly for L_{50} in 117/144, where it was generated from a computer simulation of randomly spaced vehicles at low traffic volumes. As is apparent, the L_{10} does not obey conservation of energy principles, as does the L_{eq}.

Another strange attribute of the L_{10} at the low VD/S is its distance dependence; this attribute is apparent from Figure 5, also. If the observer in this figure were to halve his distance to the roadway, the L_{10} would not increase; he would be halving his distance to an empty portion of the roadway. When he observes his L_{10}, no vehicles occupy the roadway in front of him; the nearest vehicle is far down the roadway, as shown. In fact, he could walk directly across the roadway and the L_{10} would still not increase. (The peak noise would increase, of course.) In essence, the L_{10} has become an "ambient" noise statistic, produced by distant traffic far down the roadway.

These two attributes of the L_{10} (6 dB/DD and 0 dB/DD) are implicit in Figure 3 of our framework. For low VD/S, as the volume is doubled, VD/S doubles also, and the conversion to L_{10} increases 3 dB. Added to the 3 dB increase in L_{eq}, this conversion results in 6 dB/double-volume. Similarly, as the distance is halved, VD/S is halved also, and the conversion to L_{10} decreases by 3 dB. This decrease cancels the 3 dB increase in L_{eq}, for a net change of zero.

For 117/144, this same conversion behavior exists, as shown in Figure 3. Since the equations in 117/144 were initially generated by randomly scattering vehicles onto a simulated roadway, this L_{10} behavior was expected. In fact, the difference between the L_{10} and the L_{50} curves in Figure 3 (i.e., the $L_{10} - L_{50}$), is explicit in the 117/144. And as mentioned above, the 6 dB/double-volume dependence for L_{50} also is explicit in 117/144. The distance dependence, however, is obliterated in 117/144 by the confusion between L_{eq} and L_{50}. As a result, the "official" distance dependence of 117/144 can only be fit into our common framework by an ad hoc adjustment, discussed below. This confusion lies not in the equations of 117/144 (which are not generally used) but only in the (commonly used) graphs. To duplicate the graphs from the equations, all distances D in the hyperbolic tangent functions must be frozen at 100 ft (30.48 m). (Note also the error in equation 20 of 117/144, where the speed term should have a coefficient of 20 rather than 30.)

In the TSC computer method, the statistics are intermediate between the RDG statistics and the statistics of the nomographs, as shown in Figure 3. It can be shown that the statistics behind this TSC conversion are not valid for very low VD/S.

This completes our discussion of Figure 3. As is apparent, conversion to L_{10} is the most complex part of roadway noise prediction.

Ad hoc Adjustment for 117/144

Equation 2 is the ad hoc adjustment for 117/144.

$$\begin{aligned}&\text{ADD } L_{50} - L_{eq} \text{ at 30 m [100 ft (30.48 m)]}\\&\text{SUBTRACT } L_{50} - L_{eq} \text{ AT PROPER DISTANCE}\end{aligned} \qquad (2)$$

As discussed above, this adjustment is necessary to force our common framework to predict the "official" (graphical) noise levels of 117/144. The adjustment follows directly from the discussion in the paragraphs above.

Three Examples Using the Common Framework

Here we present three examples of roadway noise predictions, using the common prediction framework developed above. We present these examples to show how the framework illuminates the relationships among the three methods, and how it indicates the seeds of discrepancy among the three methods.

Each example is given in Tables 1, 2, and 3. Along the left side are the successive steps in the common framework. Each line shows the computation result after that particular step has been accomplished. Along the top are columns for the three prediction methods, further subdivided into "computer method" and "nomograph method". Calculations are reported separately for automobiles and heavy trucks. In these examples, we ignore medium trucks, since their inclusion would only cloud the differences due to other factors. Changes in predicted levels caused by inclusion of medium trucks are relatively obvious.

The bottom line of each table includes the "official" results, i.e., the noise levels calculated using the actual published procedures. This line is included for comparison purposes to illustrate the accuracy of this common framework in predicting the "official" levels. The line immediately above (line 8) results from the common framework calculations.

Medium VD/S Example

Table 1 summarizes the medium VD/S example. VD/S equals 100 ft/mile (30.48 m/km) for trucks and 2000 ft/mile (609.60 m/km) for automobiles. At these values, the conversions from L_{eq} to L_{10} are nearly equal for all prediction methods (see Figure 3). In addition, the example distance of 100 ft (30.48 m) eliminates the ad hoc adjustment for the 117/144 method. For both these reasons, the predicted levels do not differ markedly among methods (see line 8 of the table).

Predicted automobile levels are all within 2½ dBA of each other. Predicted truck levels show the expected difference between 117/144 and TSC; the TSC level is approximately 5 dBA higher. As the progressive steps of the calculation indicate, most of this difference is due to the higher emission levels assumed in TSC, aided somewhat by the conversion from 50 to 100 ft (15.24 m to 30.48 m). For trucks, the RDG predictions fall closer to 117/144 than to TSC in spite of the higher emission levels. As steps 5 and 6 indicate, this higher emission level is mostly washed out by the different conversion from EL to L_{eq} at 50 ft (15.24 m). In summary, this example contains no surprises. We consider it the typical case for moderate traffic volumes and low to moderate distances.

High VD/S Example

Table 2 summarizes the high VD/S example. VD/S equals 9100 ft/mile (2773 m/km) for trucks and 91,000 ft/mile (27730 m) for automobiles. A comparison along line 8 shows that 117/144 and TSC differ by up to 12½ dBA, while the RDG predicts levels intermediate between the two.

In comparing 117/144 with TSC, approximately 5 dBA of the discrepancy enters as a result of TSC's louder trucks (line 5), while another 5 dBA is due to the propagation to 1000 ft (304.80 m). The difference is made slightly larger by the ad hoc adjustment to 117/144, although not seriously.

The RDG predictions fall closer to those of 117/144, for two reasons: (1) the increased truck noise emissions are washed out by the empirical adjustment in the conversion to Leq at 50 ft (15.24 m) (lines 5 and 6), and (2) we used the -4.5 dB/DD divergence for our RDG predictions, which equals that used in 117/144 (line 7). Note that if we had used the -3 dB/DD divergence in RDG, our result would have more nearly equalled the TSC result. This variability in the propagation divergence in the RDG method greatly enhances its usefulness for predictions at these large distances.

Low VD/S Example

Table 3 summarizes the low VD/S example. VD/S equals 12 ft/mile (3.65 m/km) for trucks and 55 ft/mile (16.7 m/km) for automobiles.

First examine the automobile columns along line 8. The predictions of 117/144 exceed those for TSC by 6 dBA. This entire discrepancy is due to the ad hoc adjustment to 117/144, resulting from an incorrect transferral from equations to graphs.

Next, examine the truck columns along line 8. The very low VD/S applies only to the trucks in this example. For this reason, the conversion to L_{10} is legitimately negative; however, this legitimate conversion only appears in the RDG computer and in 117/144, line 8a. The conversion is washed out in 117/144 (line 8b), however, by the ad hoc adjustment, which prevents the legitimate statistics at low traffic volumes from surfacing in the 117/144 method. We believe that the RDG computer program realistically predicts the noise levels at these low VD/S conditions. Note that the RDG nomograph does not. In fact, both nomographs predict higher values than their computer counterparts in this region where the conversion to L_{10} is not in the vicinity of +3 dBA.

Many subtleties can be detected in Tables 1 through 3. We pass over the remaining distinctions among the methods and will summarize them later.

Table 1. Medium VD/S example.

	117/144		TSC Comp.		TSC Nomo.		RDG Comp. (-4½dB/DD)			RDG Nomo.		
	Au	HT	Au	HT	Au	HT	Au	MT	HT	Au	MT	HT
1. Volume	800	40	800	40	800	40	800	0	40	800	0	40
2. Speed	40	40	40	40	40	40	40		40	40		40
3. Distance	100	100	100	100	100	100	100		100	100		100
4a. VD/S	2000	100	2000	100	2000	100	2000		100	2000		100
4b. (V(100ft)/S)	2000	100										
5. EL	64	82	65½	87	65½	87	68		87	68		87
6. L_{eq} at 50 ft	65	70	64½	73	64½	73	65		71	65		71
7. L_{eq} at D	60½	65½	61½	70	61½	70	60½		66½	60½		66½
8a. L_{10} at D	63½	68½	64½	73	64½	73	63½		68½	63½		69½
8b. L_{10} at D (with ad hoc adj.)	63½	68½										
9. L_{10} at D per "official" method	64½	69	64½	73	65	73	63½		67½	62½		68

Table 2. High VD/S example.

	117/144		TSC Comp.		TSC Nomo.		RDG Comp. (-4½dB/DD)			RDG Nomo.		
	Au	HT	Au	HT	Au	HT	Au	MT	HT	Au	MT	HT
1. Volume	5000	500	5000	500	5000	500	5000	0	500	5000	0	500
2. Speed	55	55	55	55	55	55	55		55	55		55
3. Distance	1000	1000	1000	1000	1000	1000	1000		1000	1000		1000
4a. VD/S	91000	9100	91000	9100	91000	9100	91000		9100	91000		9100
4b. (V(100ft)/S)	9100	910	-----		------		---		--	---		--
5. EL	68	82	71	87	71	87	72		87	72		87
6. L_{eq} at 50 ft	75½	79½	76½	82½	76½	82½	75½		80½	75½		80½
7. L_{eq} at D	56	60	63½	69½	63½	69½	56		61	56		61
8a. L_{10} at D	57	62	64½	71½	66½	72½	57		63	59		64
8b. L_{10} at D (with ad hoc adj.)	56½	60										
9. L_{10} at D per "official" method	57½	61½	65	71½	66	72	56		63	58		63½

Table 3. Low VD/S example.

	117/144		TSC Comp.		TSC Nomo.		RDG Comp. (-4½dB/DD)			RDG Nomo.		
	Au	HT	Au	HT	Au	HT	Au	MT	HT	Au	MT	HT
1. Volume	100	15	100	15	100	15	100	0	15	100	0	15
2. Speed	45	30	45	30	45	30	45		30	45		30
3. Distance	25	25	25	25	25	25	25		25	25		25
4a. VD/S	55	12	55	12	55	12	55		12	55		12
4b. (V(100ft)/S)	222	50	---	--	---	--	---		--	---		--
5. EL	65½	82	67½	87	67½	87	69½		87	69½		87
6. L_{eq} at 50 ft	57	67	57	70	57	70	57		68	57		68
7. L_{eq} at D	61½	71½	60	73	60	73	61½		72½	61½		72½
8a. L_{10} at D	62	65½	63	74½	63	76	62½		67½	64½		75½
8b. L_{10} at D (with ad hoc adj.)	69	71										
9. L_{10} at D per "official" method	68	72½	62	74½	63	77	61½		67½	63		74

Completion of the Comparisons Among the Three Prediction Methods

The three roadway noise prediction methods (117/144, TSC, and RDG) differ in many of their smaller details. Here we attempt to summarize these remaining differences in graphical form.

The first comparisons are illustrated in Figures 5 through 8. These figures compare (a) the level adjustments for upgrade roadways, (b) the barrier attenuation for barriers subtending the full line source, (c) attenuation due to intervening rows of buildings, and (d) the attenuation due to intervening vegetation. The differences among methods are large in some instances, as the figures show.

These figures are generally self-explanatory, although some comments are necessary concerning the larger differences. The TSC gradient adjustment is zero, since the TSC method assumes that all trucks are "full throttle" along any expressway. The model therefore assumes no additional noise on up-grades. The barrier attenuations differ mainly in the upper limits they allow on maximum attenuation achievable. These differences reflect different engineering conservatism. TSC does not incorporate attenuation due to rows of buildings. In practice, this additional attenuation is grafted onto the TSC method from 117/144. Attenuation due to vegetation is significantly overestimated in the TSC method. For example, the attenuation due to thick grass, as shown in Figure 8, applies whenever the line-of-sight between source and observer comes within 3 m of the ground surface. In addition, the upper limits of 30 dBA attenuation are not achievable in practice, with any practical reliability.

Several miscellaneous, but important, differences remain. They are summarized in Figure 9. The ground-effect attenuation is extremely important. In the RDG method, the difference between the -4.5 dB/DD at low observer heights over absorbent ground and the mathematically derived -3 dB/DD is attributed to the effect of the absorbent ground. As a corrollary, whenever a barrier is built to shield an observer from the roadway, if the resulting propagation path from barrier top to observer makes an angle greater than 10 degrees with the horizontal plane, this ground effect is lost. The resulting insertion loss of the barrier is therefore computed as less than the barrier attenuation by the amount of the lost ground-effect attenuation.

Also as a result of this ground-effect attenuation, the noise energy received from the far ends of the roadway is deemphasized in the RDG computer program, analogous to the natural deemphasis due to atmospheric absorption, increased ground-effect attenuation, and miscellaneous intervening trees, shrubs and houses, as well as due to wind and thermal gradients (which affect propagation from large distances). This deemphasis follows directly from the mathematical manner in which the RDG computer program generates the reduction from -3 dB/DD to -4.5 dB/DD. As a result, less energy is predicted around the ends of very long roadside barriers in the RDG method than is predicted for 117/144 and TSC.

Summary of the Important Differences Among the Three Prediction Methods

In the section on common framework for roadway noise prediction, the graphs and equations of the common framework contain within them the major differences among the three roadway noise prediction methods, as these methods are used to predict unobstructed noise from infinite, straight roadways. These differences center around the improved RDG predictions at low VD/S, the inclusion of medium trucks in the RDG method, and the flexibility in the rate of divergence (-d dB/DD to -4.5 dB/DD) in the RDG method. The differences among the three methods are explicit in the graphs and equations of the common framework.

These differences were also illustrated in the three examples of the section on examples using the common framework, where the common framework was used to approximate the "official" predictions.

Tables 4 and 5 summarize all the major differences among the three methods. The tables are constructed in this manner: (a) for users who have been using 117/144 for their noise predictions, Table 4 summarizes the changes in predicted noise levels if a switch is made to the RDG method; (b) similarly, for TSC, Table 5 summarizes the change in predicted noise levels if a switch is made from TSC to the RDG method.

With each change is tabulated the particular circumstances that will produce the change. Some of these circumstances are extreme, such as D = 3000 ft (4828 m), but are included for completeness.

Changes of 10 dBA are relatively prevalent in the tables, while extreme changes of 15 dBA are rare. We hope this common framework and summary table will be of use to engineers and planners who use these methods for roadway noise prediction.

Figure 5. Gradient adjustment.

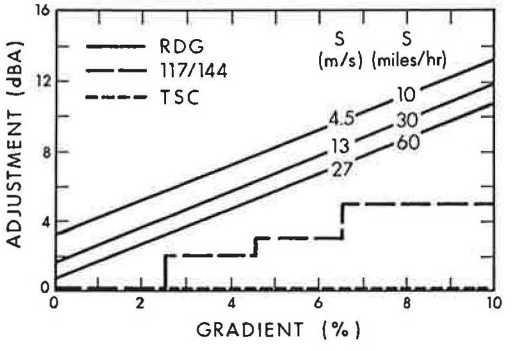


Figure 6. Barrier attenuation.

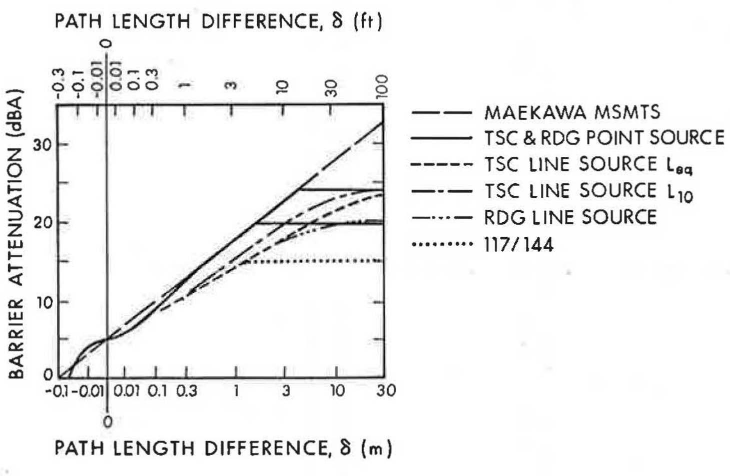


Figure 7. Attenuation due to rows of buildings.

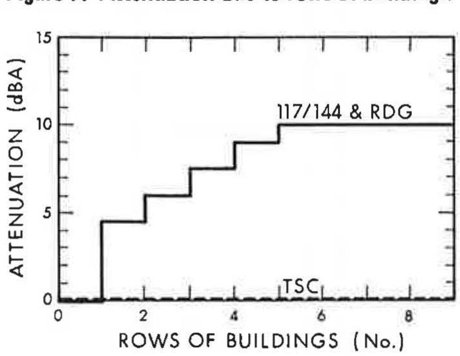


Figure 8. Attenuation due to vegetation.

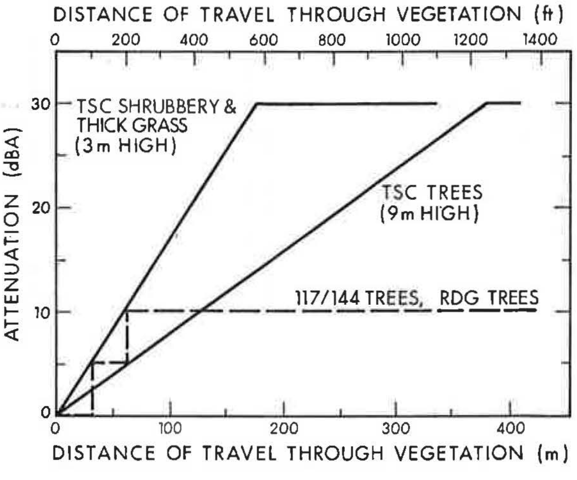


Figure 9. Miscellaneous comparisons.

ADJUSTMENT	117/144	TSC	RDG
Road Surface	yes	no	yes
Interrupted Flow	yes, but not valid	no	no
Ground-Effect	Ignored	Ignored	Incorporated (Computer)
RDWY ___ OBS	Ignored	Incorporated (Computer)	Incorporated (Computer)
Computer Input	Laborious	Manageable, Poorly Defined	Manageable, Well Defined
dB-Addition	Poor	OK	OK

Table 4. Summary of changes: 117/144 to Revised Design Guide.

	5 dBA Change	10 dBA Change	15 dBA Change
Auto EL's, including conversion to L_{eq}	---	---	---
HT EL's, including conversion to L_{eq}	---	---	---
MT's separated from HT's	↓ 55 miles/hr	↓ 30 miles/hr	↓ 20 miles/hr
Gradient adjustment	↑ lower speeds	↑ 15% grade	---
	↑ higher speeds, 8% grade		
Road surface adjustment	---	---	---
Distance	↑ 600 ft, hard ground or upper floor	↑ 3000 ft, hard ground or upper floor	---
Ad hoc adjustment	↑ D=300 ft, and VD/S <1000 ft/mile	↑ D=1000 ft, and VD/S <1000 ft/mile	↑ D=3000 ft, and VD/S <1000 ft/mile
	↓ D=30 ft, and VD/S <1000 ft/mile		
Conversion from L_{eq} to L_{10} (computer)	↓ VD/S=50ft/mile	↓ VD/S=10ft/mile	---
Conversion from L_{eq} to L_{10} (nomograph)	---	---	---
Barriers	↓ δ > 100 ft	---	---
		---	---
Vegetation	---	---	---
Rows of buildings	---	---	---
Interrupted flow	↓ trucks dominate	---	---

Table 5. Summary of changes: TSC to Revised Design Guide (RDG).

		5 dBA Change		10 dBA Change		15 dBA Change
Auto EL's, including conversion to L_{eq}	↑	low speed		---		---
HT EL's, including conversion to L_{eq}		---		---		---
MT's separated from HT's	↓	55 miles/hr	↓	30 miles/hr	↓	20 miles/hr
Gradient adjustment	↑	3% grade	↑	8% grade	↑	15% grade
Road surface adjustment	↑ ↓	rough, autos and MT's only smooth, autos and MT's only				
Distance	↓	600 ft, absorptive, ground and 1st floor	↓	3000ft, absorptive, ground and 1st floor		---
Ad hoc adjustment		---		---		---
Conversion from L_{eq} to L_{10} (computer to computer)	↓	VD/S=20ft/mile		---		---
Conversion from L_{eq} to L_{10} (nomograph to nomograph)		---		---		---
Barriers	↑	δ > 60 ft		---		---
Vegetation	↓	100 ft of trees	↓	200 ft of trees		
Rows of buildings	↓	1 row of bldgs	↓	> 4 rows of bldgs.		
Interrupted flow		---		---		---

TRAFFIC NOISE MODELS: HOW THEY ARE USED, HOW WELL THEY WORK, AND WHY

Walter Winter, California Department of Transportation

Introduction

This presentation describes the training and expertise of the people within California who are using noise models and the kinds of studies in which the models are used. Correlation of the models with field measurements will also be discussed and some speculations will be made as to the sources of error. Three points are presented for consideration in future modeling efforts:

1. Modeling should be done in terms of L_{eq} and peaks. Peaks are easy to measure and peak information along with vehicle speed are the essential inputs to calculate L_{eq}. More attention to the propagations of peaks may give valuable insight as to weaknesses in the L_{eq} methods.
2. Emission models should be considered separately from propagations in any design methodology. Emissions should have a rigorous field validation procedure.
3. Design methodology should be simple. There are many potential users who lack access to extensive computational facilities.

Who Uses Noise Models?

Caltrans is divided into 11 geographical districts plus headquarters, the laboratory, and a few other offices. Most project noise studies are carried out by district personnel. The districts have developed a good deal of noise expertise over the years but there is little uniformity throughout the state. In some districts, the noise program is handled entirely by one group or even one individual. In other districts, two or three units may share the responsibility. In only a few cases, noise experts within the districts have close contact with computer expertise.

How Are the Models Used?

There are several types of studies with which Caltrans becomes involved. Different prediction techniques are used as the need arises.

Project Noise Reports

Generally, the 117/144 methodology is used for project noise reports on completely new alignments. Field measurements are the obvious and necessary choice for improvement type projects. However, we have used peak-level methods (method No. Calif. 701-A) for low-density situations and other special cases.

School Noise Studies

California has a law that limits traffic peak levels within schools to 50 dBA. We use the California 701-A exclusively for these studies.

Noise Problem Inventory

Caltrans has a policy to retrofit existing facilities with noise barriers. The program requires a priority system based on objective criteria. Noise problem areas were defined for the most part by using 117/144, however, the TSC nomograph was used in some cases and field measurements were made in some districts that had only a few problem areas.

Noise Element for Local Agencies

The California Legislature has mandated local and regional agencies to produce general plans. A noise element is to be a part of that plan and Caltrans is to supply the highway portions. The districts generally supplied contour maps generated by the 117/144 methodology but the TSC nomograph was used in many cases. Calif. 701-A was used for the sparsely settled areas. The cities and counties had mixed reactions to the information they received. Many had also received inputs from the department of aeronautics in terms of CNEL and they wanted to know how to put that together with an L_{10} or L peak.

How Well Do They Work?

Let us first state that some of our problems may be due to inaccurate input data. It is fairly difficult to get accurate traffic data without a considerable expenditure of man hours. In many cases, traffic predictions were used instead of actural vehicle counts.

The 117/144 methodology was close for heavily traveled freeways with at-grade sections. Two of our districts reported the predicted level to be about 2 dBA above the measured. Some said actual versus predicted was off by a maximum of 4 to 5 dBA in most freeway cases. The accuracy of this method reportedly diminishes as we get away from the heavy volume and at-grade sections. It is considered poor for stop-and-go traffic.

The TSC nomograph has received very little validation. Where it was used, it was considered good for high volumes and poor for low. It was reported unrealistic past 1000 ft (304.80 m).

The TSC computer program was put up on our computer but its input deck proved too much for those who tried to use it and the work was redone using the 117/144 methodology.

Method California 701-A was reported to work very well under all conditions. A methodology developed by Wyle for the San Diego Comprehensive Planning Organization is available, but as yet, not used. The revised design guide recently supplied by BB&N is up on our computer but we have not yet had a chance to put it through its paces.

What Causes the Problems?

The primary problem with low-volume roads probably is within the L_{10} parameter itself. The distribution of vehicles must be known to a greater degree than it is now to handle the low-volume case.

The 4.5 dB per doubling of distance is suspect. This assumes that excess attenuations are a function of distance doubling. Some strong arguments could probably be made against that assumption.

Vehicles in different parts of California probably have different emission levels.

The existing models are so interwoven that it is difficult, to the point of being impractical, to check the components of the models.

Conclusion

We are fairly sure that L_{eq} based parameters will be used in the future. This type of parameter is necessary to handle multimodal transportation studies.

California has had good success with peak levels. We find that they are very useful in describing low-volume conditions. We also use them for validating truck noise emission levels and barrier attenuations. We find them easy to work with and easy to explain to the layman. If we are required to report the variance of noise (L_{np} type thinking) we will probably use the difference between the peaks and the L_{eq} for that purpose.

Although greater rigor should be incorporated in our noise modeling, so should simplicity. We are not at all convinced that these are mutually exclusive goals. What is needed is an accurate foundation in proven theory so that we know, with confidence, the limits on achievable accuracy. We should avoid computational overkill based on questionable basic assumptions.

APPLICATION AND FINDINGS OF TSC NOISE PREDICTION METHODOLOGY

Terry Hatcher and Marvin Patrick Strong,
North Carolina Division of Highways

The North Carolina Division of Highways has found the DOT-TSC-FHWA-72-1 Noise Prediction Program to be a very useful design tool within certain limits. From its orginial program version as issued by the Federal Highway Administration, the program has been adapted to the IBM 370 computer system. Modifications to the input format and output display associated with this adaptation have improved the overall utility of the program affording highway design engineers and technicians a readily comprehensible means to quantitatively assess various traffic noise situations. As a design measure, the methodology is responsive to traffic flow volume changes, roadway geometrics, and topographical variations, and these qualities of the program provide the highway design engineer a sense of appreciation and understanding of specific roadway-receptor relationships.

The methodology is generally exact in its design application requiring a limited number of arbitrary judgments; this moderate degree of exactness further enhances the acceptability of the program as a design tool.

Experience within the North Carolina Division of Highways has shown that the DOT-TSC-FHWA-72-1 program produces considerable inaccuracy when utilized during the preliminary stages of project development. Overpredictions on the order of 10 dBA or more are common and the level of detail available during the planning stage of a project is generally insufficient to warrant the useage of the prediction methodology.

Major problem areas and limitations have been concerned with the consideration of traffic flow and capacity, the inability in certain situations to accurately account for noise attenuation resulting from natural and artificial barriers, and the observance of inconsistencies between measured and predicted noise level data. As the methodology is independent of highway capacity constraints, it assumes that all traffic flow conditions are uninterrupted and it has no measure to account for variations in level of traffic service. The flow condition factor creates inaccuracies in applications pertaining to high-volume urban thoroughfares with no access control, whereas the level of service judgment may generate inaccuracies in design applications for rural highway sections. These specific types of program inaccuracies have been observed in comparisons of predicted versus measured noise level data.

Recent field investigations have been conducted by the North Carolina Division of Highways that suggest that the 87.0 dBA heavy duty spectrum and 3.0 dBA drop-off rate standard to the TSC program generate considerable inaccuracy in noise level predictions. Computer tests were run to compare the accuracy of measured versus predicted data utilizing the 87.0 dBA heavy-duty vehicle spectrum, an 86.0 dBA tractor-trailer vehicle spectrum [50-59 mph (80-95 km/ph) speed interval] as reported in Olson's "Survey of Vehicle Noise". The Journal of the Acoustical Society of America, April 1972, and the 82.0 dBA heavy-duty vehicle spectrum reported by Galloway in NCHRP 117 (see Figure 1). Drop-off rate variables considered during these computer correlation tests were 3.0 dBA and 4.5 dBA.

Four test sites were selected, all of which involved highway sections with 55 mph (88 km/h) speed limits and roadway gradients less than or equal to 2 percent. None of the sites were influenced by interrupted traffic flow, industrial background noise, or other transportation noise. These sites had low ground cover and had little or no hard reflective surfaces within the immediate microphone-roadway survey limits. Figures 2, 3 and 4 depict the traffic flow characteristics observed at these locations. Hourly light-duty-vehicle traffic flows varied from 500 veh/h to 3500 veh/h. Hourly heavy-duty vehicle flows (with the heavy-duty vehicles categorized as 2-axle, 6-tired vehicles and all larger vehicles with 3 or more axles) varied from approximately 70 to 600 veh/h. Tractor-trailer variations as a percentage of all heavy-duty vehicles ranged from 30 to 80 percent.

Tables 1 through 4 give the measured versus predicted L_{10} noise level comparisons utilizing the heavy-duty vehicle spectrum and the drop-off rate variables. Data comparisons were made at receptor locations situated 50, 100, and 200 ft (15.24 m, 30.48 m, and 60.96 m) from the near edge of pavement. Table 5 provides a collective summary of the margin of error for all four study sites.

The individual site data comparisons presented variable results. For the US 1 Raleigh site, the 82.0 spectrum -4.5 dBA drop-off rate produced the most favorable comparison with the measured data. As further investigation for this particular study site, noise level predictions were also made utilizing the 82.0 dBA heavy-duty vehicle spectrum and a 6.0 dBA point source drop-off rate. These variables produced even more favorable correlation with the measured L_{10} data and in general the predictive accuracy improved with increased distance from the roadway. It is interesting to note that the traffic flow conditions at this particular test site were hourly automobile flows less than 1000 veh/h, heavy-duty vehicle flows less than 100 veh/h and tractor-trailer populations comprising 50 percent or less of the total class of heavy-duty vehicles. L10 data correlation for the I-95 Benson site was excellent with the 82.0 dBA heavy-duty vehicle spectrum and the 4.5 dBA drop-off rate. The average margins of error for the L_{10} data comparisons at this particular site were less than 0.1 dBA underprediction at the 50-ft (15.24-m) receptor location, 0.8 dBA overprediction at the 100-ft (30.48-m) receptor location, and 0.8 dBA overprediction at the 200-ft (60.96-m) receptor location. The data results at the I-85 Burlington site and the I-85 Charlotte site were similar in that the 86.0 dBA heavy-duty-vehicle spectrum and 4.5 dBA drop-off rate produced results within approximately 1 dBA of the measured L_{10} values at the 50-ft (15.24-m) receptor location for each site. Accuracy diminished with increased distance from the roadway, which may be attributable to either minor topographical variations or more absorptive ground cover conditions.

Figure 1. Heavy-duty vehicle spectra.

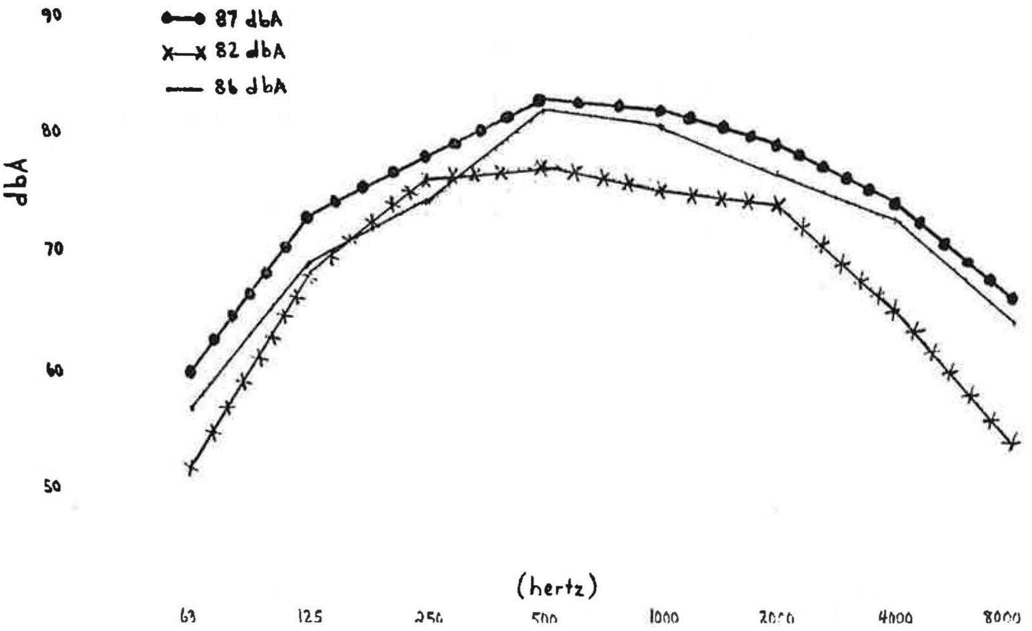


Figure 2. Hourly light-duty vehicles.

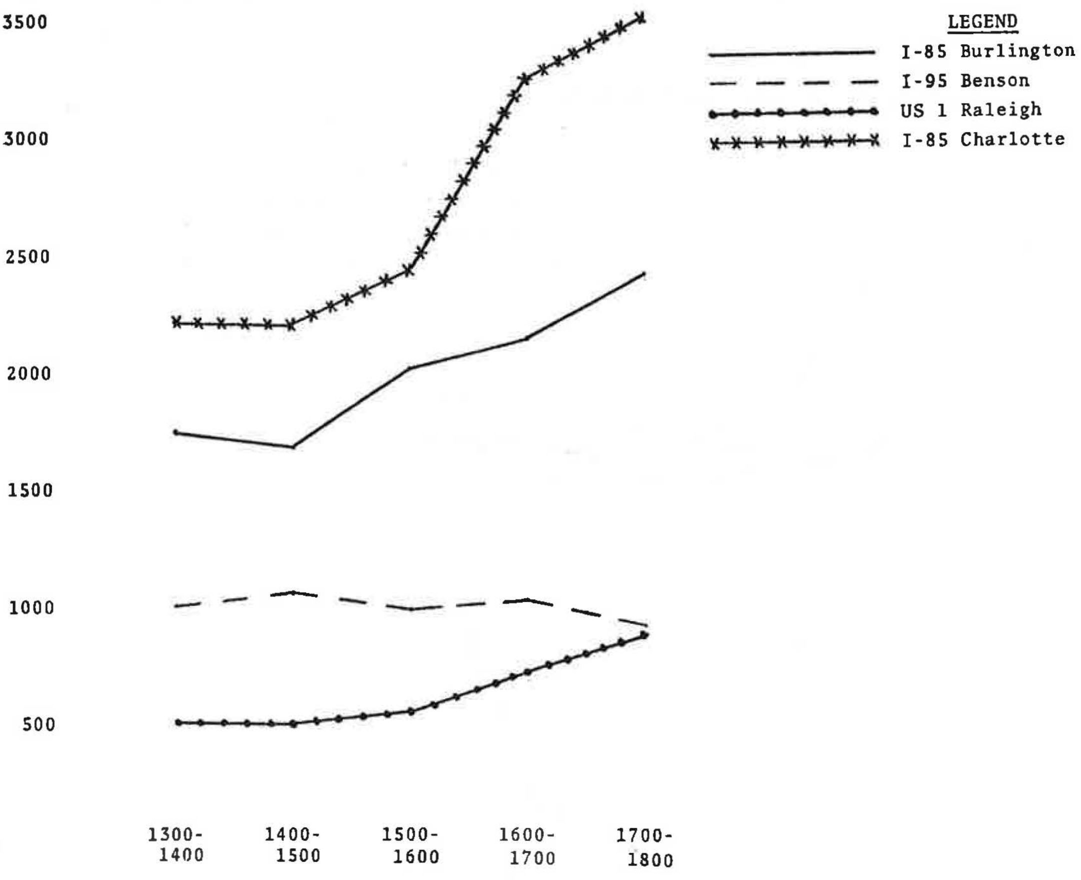


Figure 3. Hourly heavy-duty vehicles.

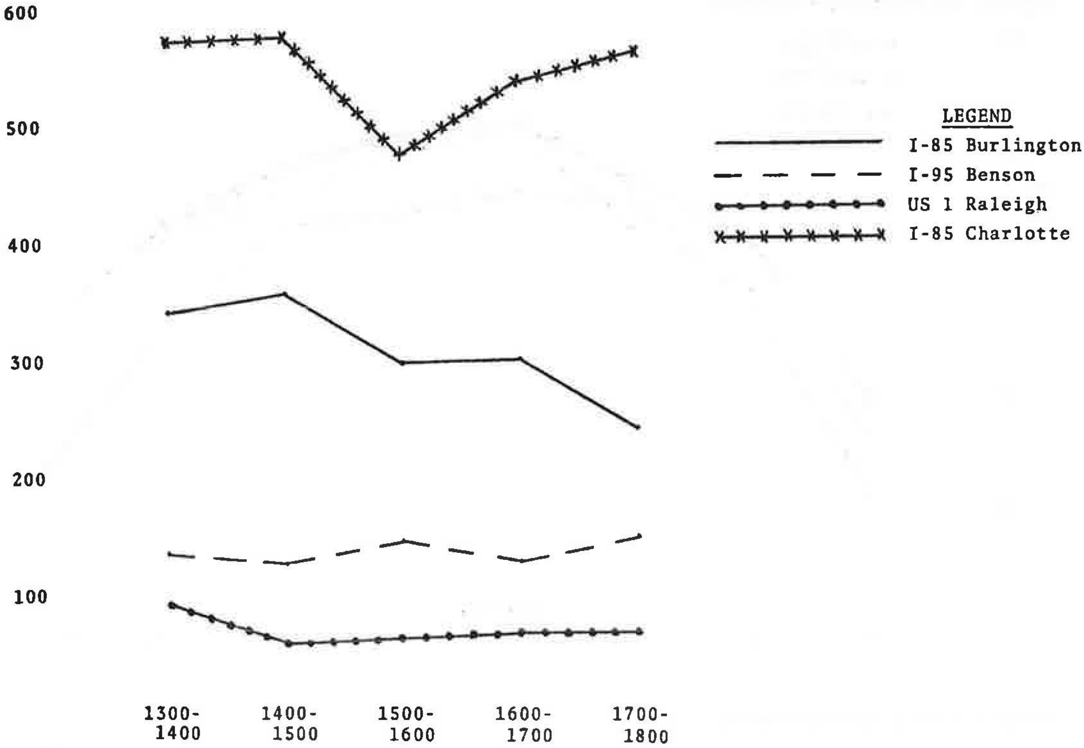


Figure 4. Percent TTST by hour (percent of HDV).

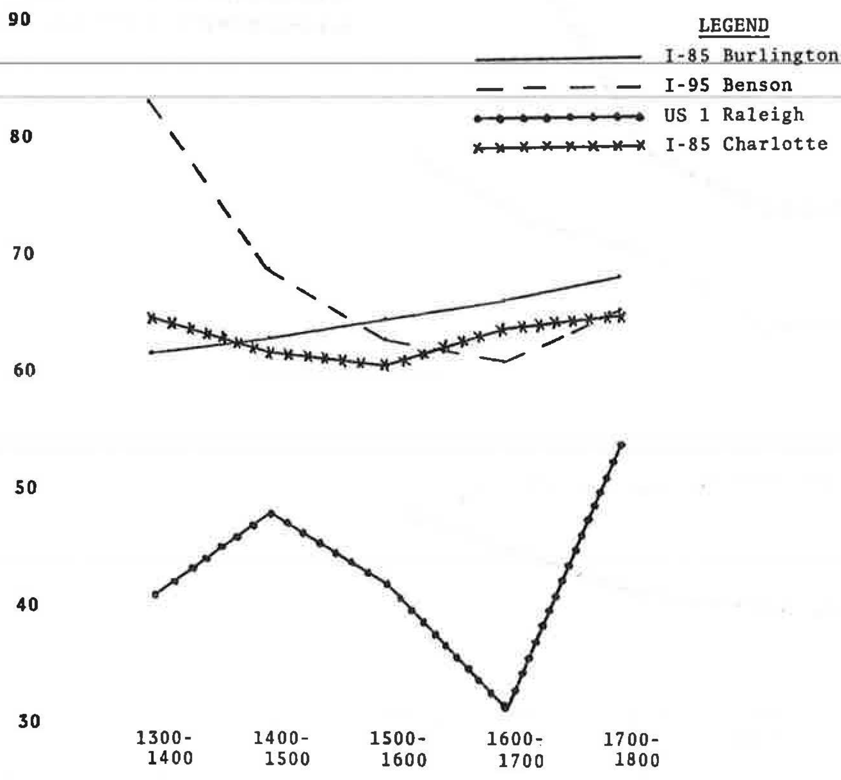


Table 1.

Comparative Traffic Noise Survey
US 1, Raleigh, Wake County
August 11, 1975

Time Period	Measured L10 (dbA)	Predicted L10 87.0 HDV Spectrum 3.0 dbA dropoff (dbA)	Predicted L10 87.0 HDV Spectrum 4.5 dbA dropoff (dbA)	Predicted L10 86.0 HDV Spectrum 3.0 dbA dropoff (dbA)	Predicted L10 86.0 HDV Spectrum 4.5 dbA dropoff (dbA)	Predicted L10 82.0 HDV Spectrum 3.0 dbA dropoff (dbA)	Predicted L10 82.0 HDV Spectrum 4.5 dbA(6,0dbA) dropoff (dbA)
Receptor Location - 50 Feet From Edge of Pavement							
1300-1400	71.0	78.7	78.3	77.2	76.8	74.4	74.0 (73.5)
1400-1500	70.5	77.1	76.6	75.7	75.2	73.2	72.7 (72.3)
1500-1600	71.0	77.3	76.8	75.9	75.5	73.5	73.0 (72.6)
1600-1700	70.5	77.7	77.2	76.4	75.9	74.1	73.6 (73.2)
1700-1800	71.0	77.8	77.4	76.6	76.1	74.4	74.0 (73.6)
Receptor Location - 100 Feet From Edge of Pavement							
1300-1400	66.5	75.8	73.8	74.3	72.4	71.6	69.6 (67.6)
1400-1500	65.0	74.1	72.1	72.7	70.7	70.3	68.3 (66.3)
1500-1600	65.0	74.4	72.4	73.0	71.0	70.6	68.6 (66.7)
1600-1700	65.0	74.8	72.8	73.5	71.5	71.2	69.3 (67.3)
1700-1800	66.0	74.9	72.9	73.7	71.7	71.6	69.7 (67.8)
Receptor Location - 200 Feet From Edge of Pavement							
1300-1400	60.5	72.7	69.0	71.2	67.5	68.4	64.8 (61.1)
1400-1500	60.5	70.9	67.2	69.6	65.9	67.1	63.5 (59.8)
1500-1600	60.5	71.2	67.5	69.8	66.1	67.5	63.8 (60.1)
1600-1700	60.5	71.6	67.9	70.3	66.6	68.1	64.5 (60.8)
1700-1800	61.5	71.7	68.0	70.5	66.9	68.5	64.9 (61.3)

Note: 1 ft = 0.3048 m.

Table 2.

Comparative Traffic Noise Survey
I 95, Benson, Johnston County
August 14, 1975

Time Period	Measured L10 (dbA)	Predicted L10 87.0 HDV Spectrum 3.0 dbA dropoff (dbA)	Predicted L10 87.0 HDV Spectrum 4.5 dbA dropoff (dbA)	Predicted L10 86.0 HDV Spectrum 3.0 dbA dropoff (dbA)	Predicted L10 86.0 HDV Spectrum 4.5 dbA dropoff (dbA)	Predicted L10 82.0 HDV Spectrum 3.0 dbA dropoff (dbA)	Predicted L10 82.0 HDV Spectrum 4.5 dbA dropoff (dbA)
Receptor Location - 50 Feet From Edge of Pavement							
1300-1400	74.5	79.3	78.2	77.8	76.8	75.2	74.2
1400-1500	73.5	78.8	77.7	77.8	76.3	75.3	73.8
1500-1600	74.5	79.2	78.1	77.8	76.7	75.1	74.0
1600-1700	74.0	79.2	78.2	77.8	76.8	75.2	74.2
1700-1800	74.0	79.3	78.2	77.9	76.8	75.2	74.1
Receptor Location - 100 Feet From Edge of Pavement							
1300-1400	70.5	76.8	74.5	75.4	73.0	72.8	70.5
1400-1500	68.5	76.5	74.0	75.3	72.6	72.9	70.2
1500-1600	70.0	76.9	74.5	75.5	73.0	72.9	70.5
1600-1700	69.0	76.7	74.4	75.3	73.0	72.8	70.5
1700-1800	70.0	77.0	74.6	75.5	73.1	72.9	70.5
Receptor Location - 200 Feet From Edge of Pavement							
1300-1400	67.0	74.0	70.1	72.6	68.7	70.1	66.3
1400-1500	64.0	73.7	69.8	72.5	68.4	70.1	66.1
1500-1600	65.0	74.2	70.2	72.8	68.8	70.2	66.3
1600-1700	65.0	73.9	70.0	72.5	68.6	70.0	66.2
1700-1800	66.0	74.3	70.3	72.8	68.9	70.2	66.3

Note: 1 ft = 0.3048 m.

Table 3.

Comparative Traffic Noise Survey
I 85, Burlington, Alamance County
August 13, 1975

Time Period	Measured L10 (dbA)	Predicted L10 87.0 HDV Spectrum 3.0 dbA dropoff (dbA)	Predicted L10 87.0 HDV Spectrum 4.5 dbA dropoff (dbA)	Predicted L10 86.0 HDV Spectrum 3.0 dbA dropoff (dbA)	Predicted L10 86.0 HDV Spectrum 4.5 dbA dropoff (dbA)	Predicted L10 82.0 HDV Spectrum 3.0 dbA dropoff (dbA)	Predicted L10 82.0 HDV Spectrum 4.5 dbA dropoff (dbA)
		Receptor Location - 50 Feet From Edge of Pavement					
1300-1400	79.5	83.0	82.0	81.5	80.4	78.5	77.5
1400-1500	79.5	83.1	82.1	81.6	80.6	78.6	77.6
1500-1600	79.5	82.6	81.6	81.1	80.2	78.4	77.4
1600-1700	79.0	82.5	81.4	81.1	80.0	78.3	77.3
1700-1800	79.0	81.7	80.6	80.3	79.3	77.9	76.9
		Receptor Location - 100 Feet From Edge of Pavement					
1300-1400	75.0	80.7	78.3	79.2	76.9	76.3	74.0
1400-1500	75.0	80.9	78.5	79.4	77.0	76.4	74.1
1500-1600	75.0	80.3	78.0	78.8	76.5	76.1	73.9
1600-1700	74.5	80.2	77.8	78.8	76.4	76.1	73.8
1700-1800	75.0	79.4	77.0	78.1	75.7	75.7	73.4
		Receptor Location - 200 Feet From Edge of Pavement					
1300-1400	68.5	78.1	74.2	76.6	72.8	73.8	70.0
1400-1500	68.0	78.3	74.4	76.8	72.9	73.9	70.1
1500-1600	68.5	77.6	73.8	76.2	72.4	73.5	69.8
1600-1700	68.5	77.6	73.7	76.2	72.4	73.6	69.8
1700-1800	69.0	76.8	72.9	75.5	71.6	73.2	69.4

Note: 1 ft = 0.3048 m.

Table 4.

Comparative Traffic Noise Survey
I 85, Charlotte, Mecklenburg County
August 28, 1975

Time Period	Measured L10 (dbA)	Predicted L10 87.0 HDV Spectrum 3.0 dbA dropoff (dbA)	Predicted L10 87.0 HDV Spectrum 4.5 dbA dropoff (dbA)	Predicted L10 86.0 HDV Spectrum 3.0 dbA dropoff (dbA)	Predicted L10 86.0 HDV Spectrum 4.5 dbA dropoff (dbA)	Predicted L10 82.0 HDV Spectrum 3.0 dbA dropoff (dbA)	Predicted L10 82.0 HDV Spectrum 4.5 dbA dropoff (dbA)
		Receptor Location - 50 Feet From Edge of Pavement					
1300-1400	82.5	85.4	84.5	83.8	82.9	80.6	79.7
1400-1500	82.5	85.4	84.5	83.8	82.9	80.7	79.8
1500-1600	81.5	84.7	83.8	83.2	82.3	80.1	79.3
1600-1700	82.0	85.3	84.4	83.8	82.9	80.8	79.9
1700-1800	82.0	85.2	84.2	83.7	82.7	80.8	79.8
		Receptor Location - 100 Feet From Edge of Pavement					
1300-1400	78.5	83.1	80.9	81.6	79.4	78.5	76.3
1400-1500	78.0	83.2	81.0	81.6	79.4	78.5	76.3
1500-1600	78.0	82.4	80.2	80.9	78.7	78.0	75.8
1600-1700	78.0	83.1	80.9	81.6	79.4	78.7	76.6
1700-1800	78.0	83.1	80.8	81.6	79.3	78.7	76.6
		Receptor Location - 200 Feet From Edge of Pavement					
1300-1400	74.0	80.5	76.8	79.0	75.3	75.9	72.3
1400-1500	73.5	80.6	76.9	79.0	75.3	76.0	72.3
1500-1600	73.5	79.8	76.1	78.3	74.6	75.4	71.8
1600-1700	74.0	80.5	76.8	79.0	75.3	76.2	72.6
1700-1800	74.5	80.6	76.8	79.1	75.4	76.3	72.7

Note: 1 ft = 0.3048 m.

Table 5.

VARIABLE PARAMETERS (HDV SPECTRUM-DROPOFF RATE-OBSERVER DISTANCE TO EDGE OF PAVEMENT)	MARGIN OF ERROR (MEAN OF THE DIFFERENCE ± SAMPLE STANDARD DEVIATION) L10 DESCRIPTOR
87.0 DBA - 3.0 DBA - 50 FEET	4.6 DBA ± 1.5 DBA
87.0 DBA - 3.0 DBA - 100 FEET	6.7 DBA ± 3.4 DBA
87.0 DBA - 3.0 DBA - 200 FEET	8.8 DBA ± 1.8 DBA
86.0 DBA - 4.5 DBA - 50 FEET	3.1 DBA ± 1.6 DBA
86.0 DBA - 4.5 DBA - 100 FEET	3.0 DBA ± 2.5 DBA
86.0 DBA - 4.5 DBA - 200 FEET	3.7 DBA ± 1.8 DBA
82.0 DBA - 4.5 DBA - 50 FEET	-0.2 DBA ± 2.1 DBA
82.0 DBA - 4.5 DBA - 100 FEET	0.9 DBA ± 2.0 DBA
82.0 DBA - 4.5 DBA - 200 FEET	1.1 DBA ± 2.0 DBA

Note: 1 ft = 0.3048 m.

The general summary for all study sites as given in Table 5 clearly indicates that the comparative results were poor with the 87.0 dBA heavy-duty-vehicle spectrum and 3.0 dBA drop-off rate. The margin of error for this particular pair of variables is shown to be 8.8 dBA ± 1.8 dBA at 200 ft (60.96 m) from the roadway, and this degree of overprediction is clearly unacceptable. The 82.0 dBA heavy-duty-vehicle spectrum and 4.5 dBA drop-off rate produced the best overall correlation between measured and predicted data. All of the test data clearly support the use of a 4.5 dBA per doubling of distance drop-off rate for better predictive accuracy with the TSC Program. The test data do not, however, overwhelmingly support the 82.0 dBA heavy-duty-vehicle emission level over the 86.0 dBA emission level. The test data do infer that slightly higher individual truck emission levels may occur on some interstate highways and major urban freeways. This inference may be correct in that the percentage of 5 or more axle tractor trailers to the total number of heavy trucks will be higher on these types of highway facilities and this particular subclass of trucks will be transporting the greatest payload with the net result of producing louder overall noise levels.

The North Carolina Division of Highways has not had the opportunity to perform noise abatement barrier evaluations with the TSC Program involving pre-existent traffic noise conditions. Nevertheless, the North Carolina Division of Highways has utilized the TSC Program to evaluate noise barriers for probable future traffic noise conditions. Until program modifications were recently issued to eliminate a path length difference error associated with sound wave diffraction, much uncertainty existed concerning the noise reduction effectiveness of both natural and artificial barriers. It is anticipated that this program modification will prove beneficial in making more accurate assessments of future noise abatement considerations.

The Federal Highway Administration is encouraged to bring to prompt completion its investigations pertaining to noise emission levels from heavy duty vehicles as well as drop-off rate determinations. Issuances from these findings will provide program modifications that should improve the accuracy of the TSC Program. Recent findings concerning tire-pavement surface noise level relationships should also be investigated to determine the feasibility of utilizing pavement surface correction factors either generally or on specific types of highway evaluations. The Federal Highway Alministration is also encouraged to perform additional studies to authenticate the claim that the optimum Level of Service 'C' traffic condition generates higher traffic noise levels than less desirable traffic flow conditions.

MINNESOTA'S EXPERIENCE WITH TRAFFIC NOISE PREDICTION

Ronald M. Canner, Jr., Minnesota Department of Highways

Introduction

The Minnesota Highway Department is grategul to those who had the foresight to initiate traffic noise research and develop a noise prediction model under the National Cooperative Highway Research Program (NCHRP). Reports 78 and 117 (3 and 4) could not have been timed better to meet our needs. We would have little hope of completing our interstate freeway program in Minnesota without a way to predict noise and mitigate noise from proposed urban freeways.

We are also grateful to the Federal Highway Administration (FHWA) who assisted us in our first noise barrier design and participated in its construction as an experimental project. FHWA also arranged for the National Highway Institute training class on Fundamentals and Abatement of Highway Traffic Noise and the Noise Measurement Equipment Demonstration, which were helpful to us.

Implementing NCHRP 117

As we became familiar with the format of the NCHRP 117 model, we found that it could be streamlined for use by our highway engineers and technicians. We consolidated charts and tables and developed a one-page work sheet (now revised several times). We later developed tables for the commonly used parts of the charts eliminating the need for repeated visual interpolation.

One of the most useful changes we made in the manual prediction charts was in the shielding chart, a change that eliminated trial and error from the barrier design process. To do this we adapted Maekawa's chart in the 117 report using a simple trigonometric approximation (which yields an error of one to two decibels when the source or receiver is less than one unit of barrier height from the barrier). The revisions in

144 have altered that simple relationship so I will not go into the mathematics involved. We hope to develop a similar chart and computer program that will enable direct barrier height design for simple situations. We already have a mathematical procedure to do so, using a pocket slide rule calculator (Fig. 1).

We have programmed the 117 model into a desk top Hewlett Packard calculator (model 9810) with a typewriter terminal. The input sheet is simple; the output is complete (Figs. 2 and 3). The program is stored on one small program card and is easily reproduced. Each district design office has been trained in the use of the program. It has cut prediction time in half and costs about 80 cents per run after the input has been determined. Our computer program stores or computes all of the noise parameters as does the Michigan terminal model (5). (We did not have on-line capability at the time so we resorted to programable desk top calculators, which we did have.)

One feature of our desk top calculator program is the direct use of D_e for computation of L_{50}. This procedure improves L_{50} predictions at receptors closer than 100 ft (30.48 m) to the source. The program also enables a prediction of a double barrier, using Maekawa's relationships (10). Information is desired to verify the benefits and problems associated with double shielding, man-made or natural.

We have tried the TSC (DOT Transportation Systems Center) program (15) on our IBM 360 but have had problems getting reliable answers and excessive computer costs. We did not have people or time to de-bug it so we had to drop it for the time being. We would prefer a model like TSC that, when given topographic and traffic data input, does the rest. We are aware of the susceptibility of 117 to error because of the judgment needed to properly select elements in complex situations. Inputs for home and vegetation shielding, pavement noise, and interrupted traffic flows also require judgment. Neither our computer program nor Michigan's eliminated these judgment decisions. Therefore, the user must be well trained and experienced to assure useful predictions. We are hopeful that the problems with TSC or the new NCHRP (Project 3-7/3) computer model can be overcome so that the element selection problem can be eliminated.

To design a noise barrier a number of representative sites are chosen and predictions are made using our adaptation of the 117 model. The barrier height is designed and checked for each site for all possible exposures to the freeway traffic. One quick way we use to obtain a preliminary barrier profile is to make a simple prediction for abutting receptors every 200 ft (60.96 m) along the road, assuming an infinite roadway element for each site. We then go back, using the prediction model, and check the preliminary barrier top profile with representative receptors to assure that blanking and "leaks" do not occur over low places. Inclusion of distant lengths of roadway that come into audible range when a barrier is erected helps assure against flanking. Subdivision of wide roadways into 2 separate roadways will help to account for the lesser barrier effectiveness that accompanies the greater source to barrier distance of the far lane. An 8-ft source height for trucks is used to account for their higher centroid of noise.

Trucks and other loud moving point sources (motorcycles, some cars) are not normally numerous enough to be considered a line source. Barriers and other shielding are more efficient in reducing point source noise. Also, roll-off of sound level with distance is usually greater for point sources than line sources. These two phenomena combine to reduce the accuracy of the model but tend to improve the practical efficiency of noise barriers. The proposed NCHRP Revised Design Guide (RDG) (2) probably handles moving point sources better than previous models.

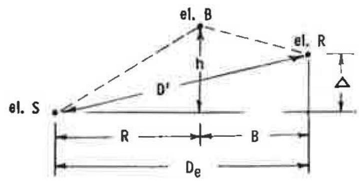
Some additional descriptions of our use of the 117 prediction model are included in the following examples. Some problems encountered are also described.

Example 1: Noise Barrier

Our first major use of the 117 was in designing an experimental noise barrier subsequently built along a section of I-35W in Minneapolis. It cost $400,000 to construct. I-35W is a 6-lane freeway carrying about 100,000 vehicles daily including some 6,000 trucks. The site selected was 3,900 ft (1188 m) long. The fronting homes are about 250 ft (76.2 m) from the freeway centerline and at varying elevations. The barrier design heights were provided by R. F. Lambert, an acoustical consultant who subsequently evaluated the completed barrier. Some of his findings may be of interest here. His report also includes an annoyance survey by T. J. Bouchard, Jr., a consulting behavioral scientist (9).

Sound level predictions for pre-barrier and post-barrier conditions tended to vary both ways from measured levels. However, measured reductions in L_{50} averaged 3 decibels less than predicted by the 117 model. Differences in L_{10} reductions were greater. These observed differences are apparently due to a complex interaction of a number of factors in the model and measurements.

Figure 1. BARRIER ELEVATION FORMULA



el. S = source elevation
el. R = receiver elevation
el. B = barrier top elevation

Δ = el. R − el. S

$D' = \sqrt{D_e^2 + \Delta^2}$ $\qquad \alpha = D' + \delta$

δ = path length difference corresponding to a chosen attenuation Fig. C-1 NCHRP 144.

$$h = \frac{\Delta \pm \sqrt{\left[\Delta^2 - 2B\left(\frac{D_e}{R}\right)\right] \cdot \left[D_e - \alpha + \frac{\Delta^2}{2B}\right]}}{\frac{D_e}{R}}$$

el. B_e = el. S $\pm$ h

Note: $\frac{h}{R} \leq 1$ and $\frac{h - \Delta}{B} \leq 1$

Figure 2.

Computed by
Date
Checked by
Date

MINNESOTA HIGHWAY DEPARTMENT
TRAFFIC NOISE PREDICTION
for use with
Hewlett Packard Model 9810

Traffic Year _____ Level of Service _____ Land Use _____

T.H. 335
S.P. 2788-01 Location Station 810 + 00
Cross Section No.
Listener Position No.

TRAFFIC	Element Number		1	2	3	4
	Total Hourly Volume	HV	3000	3000	3000	
	Truck %	Tr%	7	7	7	
	Auto Speed	SA	50	50	50	
	Truck Speed	ST	45	45	45	
GEOMETRY	Equivalent Lane Dist.	DE	310	200	235	
	Subtendend Angle	ANG.	25	93	61	
	Ground Elevation	GE	852	852	852	
	Barrier Elevation 1	BE 1	850	862	850	
	Barrier Elevation 2	BE 2	–	–	–	
	Highway Elevation	P.G.	846	847.5	849	
	Barrier Distance 1	R-1	95	90	60	
	Barrier Distance 2	R-2				
ADJUSTMENT	Gradient	Grade	0	0	0	
	Pavement	Pavt.	0	0	0	
	Bldg. Vegetation	Misc.	0	0	0	
	Interrupted	Floa	0	0	0	
	Traffic	Flot	0	0	0	

Figure 3.

```
                    MINNESOTA HIGHWAY DEPARTMENT
                     TRAFFIC  NOISE  PREDICTION
                      TH 335   SP 2788.001

                      CROSS SECTION NO     1
                      LISTENER POS NO      1
                      ELEMENT NO           1

HV=  3000     Tr%=   7.0    Va=  2790    Vt=    210    Sa=     50    St=     45
De= 310.0     Ang=  25.0    GE= 852.0    BE= 850.0     PG= 846.0     R =   95.0
Grade   0     Pavt     0    Misc    0    Flo A    0    Flo T    0

 AUTO                 TRUCK
L50= 51.5            L50= 52.8

 AUTO                 TRUCK
L10= 53.5            L10= 58.4

                      ELEMENT NO           2

HV=  3000     Tr%=   7.0    Va=  2790    Vt=    210    Sa=     50    St=     45
De= 200.0     Ang=  93.0    GE= 852.0    BE= 862.0     PG= 847.5     R =   90.0
Grade   0     Pavt     0    Misc    0    Flo A    0    Flo T    0

 AUTO                 TRUCK
L50= 46.8            L50= 53.0

 AUTO                 TRUCK
L10= 49.1            L10= 59.8

                      ELEMENT NO           3

HV=  3000     Tr%=   7.0    Va=  2790    Vt=    210    Sa=     50    St=     45
De= 235.0     Ang=  61.0    GE= 852.0    BE= 850.0     PG= 849.0     R =   60.0
Grade   0     Pavt     0    Misc    0    Flo A    0    Flo T    0

 AUTO                 TRUCK
L50= 57.2            L50= 58.5

 AUTO                 TRUCK
L10= 59.4            L10= 64.8

 TOTAL                TOTAL
L50= 62.5            L10= 67.6

                      CROSS SECTION NO
```

Figure 4.

DOMINANT ELEMENT EFFECT

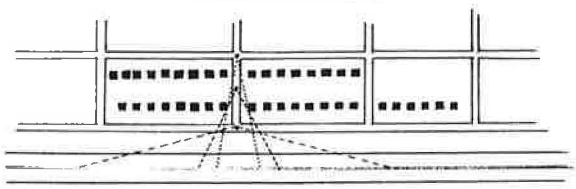
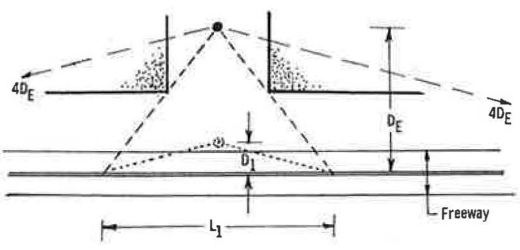


Figure 5.

DOMINANT ELEMENT ADJUSTMENT



$$D_1 = \frac{L_1}{8}$$

$$\text{Par A} = \frac{VD_1}{S}$$

D_1 Is used as an effective D_E

One factor is that noise prediction is highly sensitive to kind of trucks assumed. The percentage of diesel trucks, and the percentage of heavy trucks (three axles or more), and some knowledge of the sound level distribution of these is essential to produce an accurate prediction. However, urban truck data are often very sparse and predictions of future truck traffic volumes and noise-related characteristics are fraught with difficulties, particularly in urban areas. If strict national truck noise maximums are set, they will tend to greatly narrow the distribution of noise levels generated. Hopefully vehicle emission levels will then be better defined than at present.

Another uncertainty that was troublesome to the barrier evaluation, and continues to be so, is the question whether the correct value for building shielding was applied. Some other measurements we have made indicate that rows of very closely spaced 2-story homes will reduce noise levels to a greater degree than the 144 report indicates. More definitive quantification of this factor is needed.

Another factor involved properly accounting for pre-barrier measurement site conditions in pre-barrier predictions. While predicted pre-barrier L_{50} averaged only 2 decibels higher than measured, predicted pre-barrier $(L_{10} - L_{50})$ was up to 4 dB higher than measured. However, Lambert suspected some site characteristics peculiar to pre-barrier conditions could account for some of the differences observed, because they were not provided for in the 117 prediction procedure. Pre-barrier measurement sites in streets perpendicular to the freeway were partially shielded by rows of homes parallel to the freeway. The angular opening to the freeway at the end of the street was relatively smaller for sites further from the freeway. The observed variation $(L_{10} - L_{50})$ of the noise did not decrease with distance but was about the same for all sites. After the barrier was built, the effects of partial shielding from the homes was not as significant and observed $(L_{10} - L_{50})$ did decrease with distance. Traffic exposed by these street openings apparently was the predominant source of noise observed at the measurement sites before the barrier was built (Fig. 4). This noise was more variable than expected because the number of vehicles exposed in the opening at any time is smaller than the number of vehicles influencing the observed noise after the barrier was completed. This variation increases as the degree of adjacent shielding is increased or as the observers' distance from the opening increases.

Lambert suggested a way to roughly compensate for the dominant element effect just described (Fig. 5). To determine parameter A he used a fictitious distance D_1 computed as follows:

$$\frac{D_1}{D_e} = \frac{L_1}{L_{total}}$$

Since L_{total} is usually considered in 117 to be about 8 times D_e:

$$D_1 = L_1 \times \frac{D_e}{8D_e}; \text{ or } D_1 = \frac{L_1}{8}$$

This step essentially assumes the dominant element is the only source and treats it as an infinite element for purpose of determining $(L_{10} - L_{50})$ and L_{10}. Using the dominant element correction, correlation of the predicted variance $(L_{10} - L_{50})$ with that measured was improved from up to a 4-decibel discrepancy to about 1 decibel.

The 117 model was used to predict reflections using a virtual image of the source behind the opposing barrier. The addition of a reflective image source increases the apparent distance thereby reducing $(L_{10} - L_{50})$ as calculated from Par A = VD/S (Fig. 6). At close locations reflected noise from far side barriers appears to decrease L_{10}.

Even with the dominant element correction and consideration of reflections predicted, L_{10} was about 2 decibels high for the pre-barrier situation and about 1 decibel low for the post-barrier situation. These total to about a 3-decibel overprediction of expected reduction due to the barrier (Figs. 7 and 8). From a practical standpoint, this is about as close as we could expect, considering other uncertainties in truck emissions and home shielding values and variables involved.

Use of the 144 barrier curve may improve predictions. However, neither the 144 nor the proposed NCHRP RDG models appear to include the dominant element effect on $(L_{10} - L_{50})$. However, we note that Kurze does recognize the problem and handles it in the mathematical derivation of the RDG model. Equation G.14 (2, Vol. 3, p. G20) shows that variance is dependent on the length of intercepted angle of element observed. However, as far as we can tell, this relationship has not been incorporated into the model itself. Perhaps it should be. We need a way to cope with gaps, as we get numerous requests for visual openings from residents or businesses behind proposed barriers.

Figure 6.

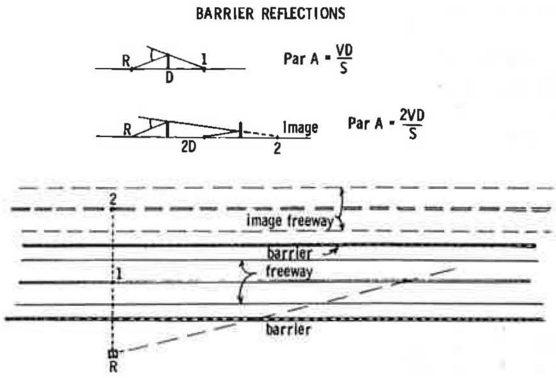
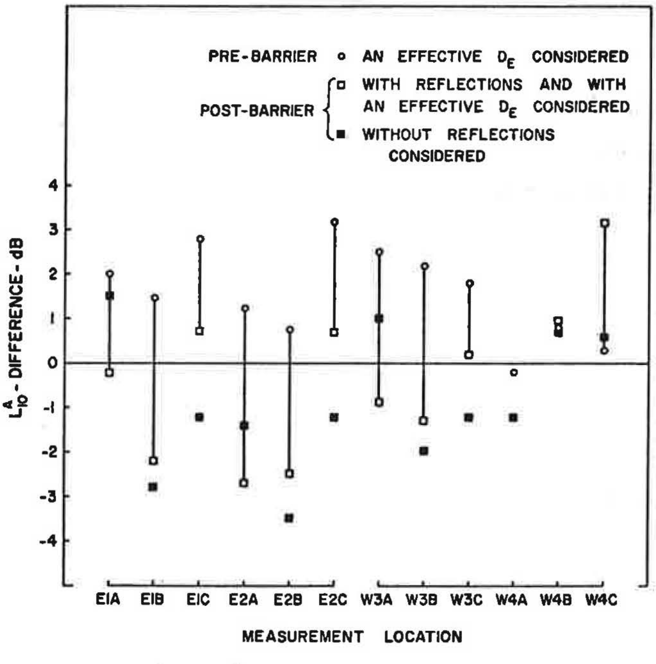
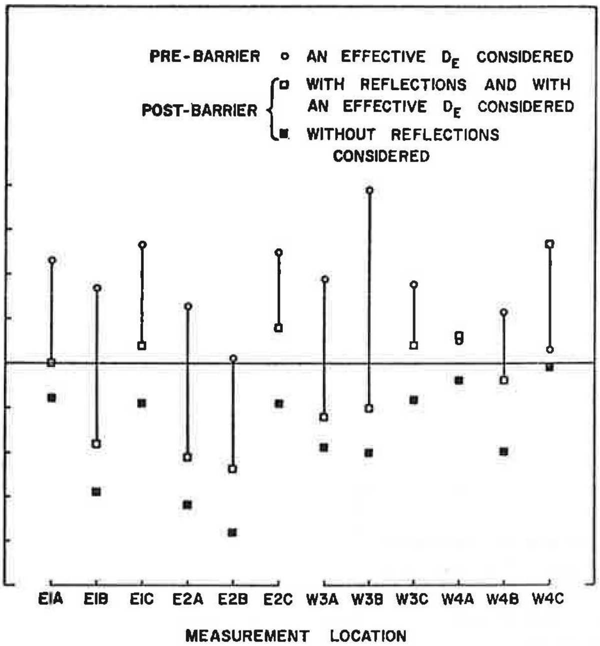


Figure 7.



$(L^A_{10})_{pred.} - (L^A_{10})_{exp.}$ FOR PRE AND POST BARRIER CONDITIONS

Figure 8.

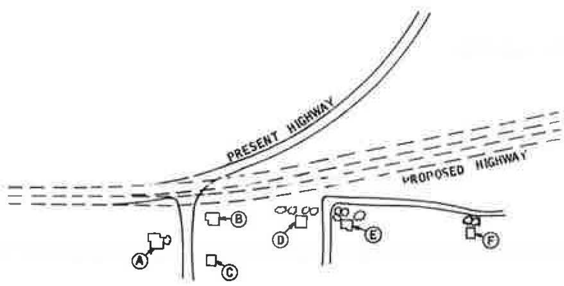


$(L^A_{50})_{pred.} - (L^A_{50})_{exp.}$ FOR PRE AND POST BARRIER CONDITIONS

Figure 9.

US-169 Blue Earth Minnesota

Traffic:	Autos	290-350
	Trucks	60- 85
	Speed	30 mph
Homes:	80' to 200' from road	
Measurements:	Check off method (dbA)	
	30 second reading interval	
	45 minute measurement period	



Summarizing, the barrier evaluation showed we slightly overpredicted the value of the barrier. However, it also shows that further work is needed to develop rational modifications to the model to make it more responsive to the realities of traffic noise, terrain, and shielding conditions.

Example 2: Environmental Impact

Usually we measure sound levels along a proposed route for use as a basis for assessing the environmental impact of a proposed highway. Predicted future levels are compared with ambient (measured) levels at each site. We also make a prediction using the traffic volumes counted at the time of measurement to calibrate the model with site conditions. Often the predicted levels differ from measured levels. If so, we may adjust the predicted future level by an amount equal to the difference between the present predicted and measured levels.

For example, this practice was used to evaluate reconstruction of an existing 2-lane highway to 4 lanes at Blue Earth, Minnesota. The predicted sound levels exceeded measured levels by 3 to 9 decibels. The adjusted 1990 L_{10} was 62 to 64 dBA, a more acceptable level than the 71 to 75 dBA uncorrected prediction (Fig. 9, Table 1).

We feel that some caution is required when comparing predictions with measured sound levels. We attempt to limit any adjustments to the site where the measurement was made. Notice the wide variation in adjustment between sites in this example. There are just too many unquantified site conditions and ground effects that may not apply to a site other than that where the adjustment is made. Another factor perhaps often overlooked is wind. A light breeze (5 to 10 mph) can apparently have an effect on the sound level received from the roadway being surveyed. Measured levels upwind or downwind can differ from predicted levels by several decibels. An adjustment based on such measured levels may well be in error, one way or the other, if wind during model calibration measurements is ignored.

Prevailing light winds also seem to cause greater noise impacts to downwind receptors. We have noticed that downwind receptors complain more than upwind receptors at a site with prevailing winds. Some research papers seem to show that even a light breeze may negate the benefits of a noise barrier to downwind receptors. Further research may be needed to quantify wind effects and incorporate them into the prediction model. Perhaps meteorological statistics used in traffic air quality analysis will be useful in noise analysis also. Those interested in wind effects may refer to Refs. 1 and 12.

Example 3: Urban Arterial Street

One general case that we have great difficulty handling with any available noise model is the low-traffic city arterial or rural farm-to-market roads. These streets and highways do not normally lend themselves to barrier construction. Their relocation away from the adjacent residents is contradictory to the purpose they serve. Yet, we are asked to assess noise impacts of these roads and may be required to meet state ambient standards soon. Some measurements of noise from a city arterial street were made as part of the FHWA Region 15 noise equipment demonstration project in Minnesota. This street carries about 9000 ADT, 7½ percent trucks. Flow during the measurement period was 750 veh/h and 7½ percent trucks at about 30 mph (48 km/ph). Because of nearby traffic signals, flow was highly queued with lulls between. Reflections occurred from a row of homes across the street from the park where measurements were made. The ground was snow covered and low banks of plowed snow lined the street.

Analysis of the data shows that traffic flow was non-Gaussian and better described by a Poisson distribution. The "roll off" with distance was 10 dB per doubling distance. By correcting the distance adjustment and vehicle emissions to conform to the measured values, and assuming a Poisson distribution we predict within 0 to 2 decibels of measured values (Table 2). We feel that these adjustments were made with mathematical and statistical logic that fit field conditions observed. In this case, truck emissions fit the model well but auto emissions were higher than expected. The distance roll-off was unusually high. Perhaps a procedure is needed whereby certain field conditions, such as distance roll-off and vehicle acoustical power, can be measured and then empirically introduced into a model on a site-by-site basis. A semi-empirical model may be the only way to adequately handle complex urban situations.

The Future

Improvements and refinement of traffic noise prediction models are particularly important to Minnesota. In 1974 the state established ambient noise standards based on public

Table 1.

L_{50} (dbA)

site	measured 1974	predicted 1974	predicted 1990	adjusted 1990	adjustment
A	56	63	64	57	-7
B	60	65	63	58	-5
C	52	60	62	54	-8
D	53	62	63	53	-9
E	53	60	60	56	-7
F	-	-	60	-	avg = -7

L_{10} (dbA)

site	measured 1974	predicted 1974	predicted 1990	adjusted 1990	adjustment
A	69	74	74	69	-5
B	73	76	75	72	-3
C	61	70	71	62	-9
D	64	72	74	66	-7
E	63	69	73	67	-6
F	-	-	68	-	-
					avg = -6

Table 2.

Urban Arterial Traffic Prediction

Distance	L_{10}	L_{50}	Leq	Data
35'	73	64	69	
70'	64	57	61	Measured
100'	60	54	56	
35'	78	66	-	Predicted:
70'	76	64	-	NCHRP 117
100'	74	63	-	and 144
35'	71	62	68	
70'	63	57	61	Predicted:
100'	60	54	57	Minn. Hwy. Dept.*

*Using observed values of:

Truck emissions = PWL (T) = 125
Auto emissions = PWL (A) = 115
Distance roll-off = 35 log $\frac{D_2}{D_1}$
Poisson distribution of traffic.

Table 3.

MINNESOTA STATE REGULATION

NPC - 2

NOISE STANDARDS

Noise Received By:	Day 0700-2200 L_{50}	Day 0700-2200 L_{10}	Night 2200-0700 L_{50}	Night 2200-0700 L_{10}
Residential	60	65	50	55
Commercial	65	70	65	70
Industrial	75	80	75	80

measured in dbA - loudest hour

health and welfare. The standards were issued after public hearing by the state Pollution Control Agency under authority of a 1971 state law (Table 3) (11). These standards are more stringent and more comprehensive than the FHWA guideline in Federal Highway Program Manual 7-7-3. Maximum levels for both L_{10} and L_{50} levels are set for peak daytime and nighttime hours. Therefore, an L_{10} and L_{50} prediction model is essential to our state. There is no legal enforcement regulation for these standards, as yet, but the Department of Highways is attempting to meet them where reasonably attainable. The Minnesota Pollution Control Agencies are currently developing regulations to enforce the standards along both new and existing highways. Implementation of the state standards on all roadways (not just freeways) will require a model that accurately predicts noise from low traffic volumes and speeds, particularly in urban streets with congested, interrupted, or intermittent flows and some within reverberant "canyons" formed by tall buildings.

Another rather unique event occurred this summer. The state legislature directed the department to spend one percent of its share of the state gas tax on noise abatement along residential areas adjacent to existing interstate freeways in metropolitan areas. With 90 percent federal aid, this program will amount to over $10,000,000 annually. With the advent of this rather sizable commitment of funds to a state highway noise abatement ("highway retrofit") program, we are especially concerned that we are designing adequate barriers, yet not overdesigning them and wasting money.

These developments, together with the continuing need to evaluate environmental impacts, substantiate our need for a reliable noise prediction model (although one sometimes wonders that, if the 117 had not been available, all this would have occurred as soon). This need led us to review as much material on noise prediction as we could obtain. Several items that should give food for thought have emerged from regarding our work. I will but mention them because they are really a little beyond the bounds of my assigned project.

1. The distribution of traffic at volumes below 1,000 veh/h is usually not Gaussian and probably is more closely represented by a Poisson distribution. Vehicles are not equally spaced but tend to bunch up.

2. The distribution of trucks mixed in moderate freeway traffic is also usually not Gaussian and also resembles a Poisson distribution.

3. The errors of determining L_{eq} from measured sound pressure levels should be investigated.

4. Longer sampling periods may be needed to assure that traffic volumes measured truly represent the hour's traffic particularly at low volumes or slow speeds. The statistical tests used in the "check off" measurement method indicate whether sound measurements reliably represent the traffic actually passing during the sampling period. They do not tell if the measurement period represents the traffic passing during the hour.

5. L_{eq} is a measure of average intensity but does not relate to how those intensities are distributed. Perhaps L_{eq} should be used with an appropriate indicator of statistical variance when representing variable traffic noise.

We are generally pleased with the advances of the proposed NCHRP-RDG model. The developer has obviously taken pains to describe and quantify such essentials as vehicle emission levels and distance roll-off rates. On the other hand, we are still vitally concerned that we have a more accurate L_{10} and L_{50} prediction model. Several recent technical papers are of interest and should be reviewed in depth. If valid, the findings should be incorporated into a new L_{10} model (8, 13, and 14). These papers develop some mathematical bases for estimating the variance of traffic noise depending on traffic characteristics and site conditions not available in present or proposed models. We welcome opportunities to discuss further some of the statistical attributes of traffic noise modeling with others concerned.

Summary of Needs

The following items should be researched, quantified, and modeled, particularly with the effects on L_{10}, $(L_{10} - L_{50})$, as well as L_{50} and L_{eq}:

1. Model low-volume traffic conditions; often queued and intermittent flow, apparently requiring the application of non-Gaussian statistics to model. Actually, truck traffic on most roads, even freeways, fits this category.

2. Determine what are the real health benefits, if any, associated with noise abatement below hearing loss thresholds. Is physical or mental health at stake and, if

so, to what degree? Is annoyance reduction the best measure of benefit or is some health-related parameter needed? How do we quantify benefits?

3. Develop appropriate model for effects of barriers on noise statistics such as (L_{10} - L_{50}) and L_{10}.

4. Develop appropriate model for effects of dominant roadway elements and reflections on noise statistics such as (L_{10} - L_{50}) and L_{10}.

5. Categorize and quantify shielding provided by various sizes, spacing, and alignment of homes and other buildings.

6. Develop a procedure for measuring vehicle acoustical power levels to be used in and introduced into the model.

7. Categorize and quantify effects of reflections and scattering of sound due to air turbulence, trees, and buildings above and behind barriers.

8. Develop noise rating of tire-pavement systems so that reductions available from resurfacing can be predicted. This will become more critical when truck noise is reduced enough so that tire-pavement noise dominates.

9. Determine effects of prevailing winds on upwind and downwind receptors, particularly behind barriers; techniques to correct field measurements to calm conditions.

10. Determine value of barriers in reducing noise impacts to indoor receptors particularly with windows shut, conversely the value of "sound proofing" buildings behind barriers or natural shielding. This item relates to low-frequency sounds passing over and through noise barriers and through building walls.

I trust these remarks will not be viewed as mere criticism but rather as a spring-board for further discussion and research. The NCHRP 117 and 144 models have served us well. We have already spent over $8,000,000 on noise abatement works based on its predictions, and, as far as we can tell, with substantial and beneficial reductions in noise impacts near freeways.

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ONTARIO HIGHWAY NOISE PREDICTION METHOD

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This paper describes the development, accuracy, reliability, and application of a new Ontario highway noise prediction method. It is an empirical method based on 135 sound level measurements taken at 120 locations near rural and urban freeways, highways, and along residential streets.

At the beginning of the report, measured sound levels were compared with the sound levels calculated by the Design Guide and Delany methods. The results of this comparison indicated a need for a more accurate highway noise prediction method. The less complex Delany method was found to be more accurate for nonfreeway locations than the more comprehensive Design Guide method.

The report, then, outlines the construction and the statistical evaluation of mathematical models that form the basis of the Ontario highway noise prediction method. The Ontario highway noise prediction method enables calculations of L_{50} and L_{10} sound levels with a higher level of accuracy than the two methods evaluated. The standard error of estimate for L_{10} levels calculated by the Ontario method was about 2.2 dBA. This indicated that 3 predictions out of 4 will be within ±2.5 dBA. The standard error of estimate for L_{50} levels was about 2.8 dBA.

The paper also briefly outlines a procedure for the application of the method.

Introduction

A reliable highway noise prediction method is an essential tool for predicting the impact of new highways on the environment and for evaluating different highway noise attenuation features and strategies. The highway noise prediction method should enable planners and designers to utilize fully and efficiently the land surrounding highways and to minimize the adverse effects of highways on the environment.

The highway noise prediction method most widely used in Ontario was developed by the firm of Bolt, Beranek and Newman (1). The method will be referred to as the Design Guide Method or simply as the BBN method. Earlier studies indicated that the BBN method does not provide noise estimates with the desired precision (2).

Since 1970, the Ontario Ministry of Transportation and Communications has been collecting data on sound levels in the vicinity of proposed and existing provincial freeways and highways for various planning and design purposes. Due to the amount and comprehensiveness of these data, it was decided to utilize them in a study with the following objectives: (a) to determine the accuracy and reliability of existing highway noise prediction methods using province-wide data, and if warranted, (b) to develop a more accurate highway noise prediction method.

Data Base

Description of Locations

Most of the data used in this study were collected on a day-to-day basis between 1970 and 1973. To make generalizations with unbiased estimates from observed data, the observations should be chosen in a random manner from all possible observations in the area where future predictions are to be made. Since this requirement could not be satisfied (data had already been collected), all available, suitable observations were included in this study to eliminate any personal bias.

Some of the observations were rejected if any of the essential variables such as distance, traffic volumes, and shielding effects were missing or if a number of observations (i.e., noise measurements) were conducted at the same location.

In this latter case, observations included in this study were randomly selected from all available observations. A total of 135 observations, taken at 120 locations were used.

Noise measurements included in this study were taken near various rural and urban highways, freeways, and local streets. Eighty-nine observations were taken in the vicinity of freeways and 46 were taken in the vicinity of highways and streets. The type of facility and number of observations are given in Table 1.

A list of all observations, including description of location, number of vehicles, speed, and distance is given by Hajek (3).

Sound Measurements

In general, sound levels were measured for a duration of 15 min. Tbe microphone was located on a tripod approximately 4 ft (1.2 m) above ground. No sound measurements were conducted when wind velocity exceeded 10 mph (16 km/h) or when the pavements were wet.

Sound levels monitored by a 1-in. (25.4-mm) wind-shielded condenser microphone were measured by a precision sound level meter (B & K 2204) and were recorded by a tape recorder (Uher Report 4200L).

Analyses of the sound recorded on tape were conducted in the laboratory using a graphic level recorder and a statistical distribution analyzer. Results of these analyses yielded sound levels that were exceeded 5, 10, and 50 percent of the time (L_5, L_{10}, L_{50}) on A-weighting network.

Description of Observations

Traffic Volumes. During the period of sound measurements, highway vehicles were classified into 4 categories: passenger cars; light trucks; heavy 2 or 3-axle trucks; and combination unit trucks and buses. Volumes in each category were recorded. Passenger cars and light trucks were then grouped into 1 category and referred to as cars. All remaining vehicles were categorized as trucks due to the difficulties experienced in forecasting volumes for different truck categories. The truck category included all vehicles having gross vehicle weight higher than about 10,000 lb (approx. 4500 kg). The 15-min vehicle counts were multiplied by a factor of 4 to obtain hourly vehicle volumes used for subsequent calculations.

The 2-directional traffic volumes ranged from 292 veh/h to 9,150 veh/h. The average traffic volume was 1,382 veh/h. Truck percentage in the vehicle flow varied from 2 to 38 percent and averaged 15.8 percent.

Speed. With the exception of 7 observations, the speed of vehicular flow was not measured simultaneously with sound measurements. The speed was estimated using the following information: (a) traffic flow speed surveys at the locations in question conducted by the Ministry's Traffic Control personnel; (b) volume-speed relationships given in the Highway Capacity Manual (4); and (c) posted speed limits. The speed of vehicular flow ranged from 12 to 68 mph (19 to 109 km/h) with an average of 55.5 mph (89 km/h).

Distance. The distance between the edge of pavement of the first traffic lane and the sound measurement location, determined by direct field measurements, ranged from 25 ft to 1,370 ft (7.5 to 420 m) with an average of 259 ft (79 m).

Highway Noise Attenuation Features. Twelve observations used in this study were shielded by 1 or 2 rows of houses, and 4 observstions were shielded by natural barriers. The shielding effect of houses and barriers was added to the measured sound levels and the observations were then treated as unshielded. The attenuation effect of houses was taken as 4.5 dBA for 1 row of houses and 6 dBA for 2 rows of houses (5).

The attenuation effect of natural barriers was calculated using the BBN method (1). Statistical tests comparing variances of differences between the measured sound levels and the sound levels calculated using the two noise prediction methods evaluated (methods are defined subsequently) showed that the 16 shielded observations were not significantly different from the unshielded observations.

Other Variables. Sound measurements were conducted along old and new concrete and bituminous pavements. The highway grade was below 3 percent at all locations. Weather during measurements ranged from cloudy winter weather to sunny summer weather. Ground surface attenuation varied from location to location and also according to seasonal conditions.

It should be stated that there was some disadvantage in using these data for research purposes because of the inclusion of observations taken under a variety of conditions and due to the lack of rigorous attention to data accuracy. However, results and conclusions based on these data should be practical and applicable for a variety of commonly encountered situations.

Reliability of Existing Highway Noise Prediction Methods

Methods Evaluated

Two highway traffic noise prediction methods were evaluated: (a) the Design Guide or the BBN method (1) developed in the United States, and (b) the Delany method (6) developed in England. The BBN method is a well-known method based on a theoretical traffic noise simulation model and will not be reviewed here. The Delany method is an empirical method based on field measurements conducted in England. The method predicts L_{10} sound levels using the following formula:

$$L_{10} = 18.1 + 8.9 \log V + 0.117p + 16.2 \log S \qquad (1)$$

where:

V = total traffic volume in veh/h,
p = percentage of heavy vehicles (weight greater than 1500 kg), and
S = mean traffic speed in km/h.

To facilitate computation, Eq. 1 was modified to include attenuation due to distance using the attenuation rate of 4.5 dBA per doubling of distance. This corresponds to the BBN recommendation for a modified line source (5) and to the Delany attenuation contours (6). Also, the trucks as defined previously were used in the calculations instead of the Delany category of heavy vehicles.

Result of Comparison

Differences between the measured L_{50} and L_{10} sound levels and the corresponding sound levels calculated using the BBN and the Delany methods are given by Hajek (3) for all 135 observations. Summary results of the comparison between the measured and the calculated sound levels are given in Table 2.

The precision of the two prediction methods was evaluated by using a standard deviation of differences between measured and calculated sound levels (i.e., standard error) and by using an average difference between measured and calculated levels. The comparison was made separately for all 135 observations: 89 expressway observations, 46 nonexpressway observations, and for all observations divided into two groups—one group included observations for which $\rho D > 600$ and the second group having $\rho D \leq 600$, where is traffic density in veh/mile, and D is the distance between the measurement location and the center of roadway in feet. The observations having $\rho D <$ about 600 ft veh/mile are typically low-volume roads for which the BBN prediction model may not apply (1).

The results of comparisons presented in Table 2 indicate that the Delany method is more accurate than the BBN method for all observation groups investigated. This result is somewhat surprising because the BBN method is based on North American vehicle populations and road usage and utilizes more variables and interactions between variables than the Delany method. Some major results from the evaluation of the 2 methods are given below.

1. The BBN method provides good estimates of L_{10} levels for expressway locations. The average difference between measured and calculated values was about -0.6 dBA (i.e., the calculated sound levels are, on the average, slightly overestimated) and the standard deviation was about 2.7 dBA.

2. Sound levels calculated by the BBN method for nonexpressway locations are inaccurate and of little real value. On the average, the BBN method overestimates by about 6 dBA. Figure 1, showing the relationship between the hourly volume of cars and the difference between the measured and calculated sound levels for all 135 observations, indicates that overestimations in the order of 10 dBA are common.

3. The Delany method provides reasonable estimates of highway noise levels regardless of the location of observation points. Sound levels for low-density observations ($\rho D < 600$) were overestimated, on the average, by only 1.1 dBA.

Table 1. Description of locations.

Facility	No. of Observations
6-or-more-lane (both directions) urban freeways	
Hwy. 401, Etobicoke	3
D.V.P., North York	2
4-lane rural or urban freeways	
Hwy. 401-Bay Ridges to Newcastle	66
Brantford Expressway	6
Q.E.W. near Hamilton	12
4-lane highways	
Hwy. 17, near S.S. Marie	1
Hwy. 27, near Rexdale Blvd.	1
2-lane highways	
Hwy. 7, Georgetown	4
Hwy. 17, near Sault Ste. Marie	6
Hwy. 17, Naughton-Whitefish	9
4 to 5-lane urban streets	
Woodbine Ave., North York	13
Finch Ave., North York	2
2 to 3-lane urban streets	
Brantford	10
TOTAL	135

Table 2. Precision of highway noise prediction methods, dBA.

Class of Observations	Number of Observations	Standard Deviation of Differences Between Measured and Calculated Values			Average Difference Between Measured and Calculated Values		
		BBN L_{10}	DELANY L_{10}	BBN L_{50}	BBN L_{10}	DELANY L_{10}	BBN L_{50}
All Observations	135	4.657	2.686	4.515	-2.757	0.501	-3.344
All Expressway Observations	89	2.745	2.619	3.496	-0.565	0.984	-1.807
All Non-Expressway Observations	46	4.832	2.615	4.857	-6.640	0.354	-6.065
Observations Having $\rho D > 600$	119	4.277	2.652	4.618	-2.245	0.720	-3.161
Observations Having $\rho D < 600$	16	5.694	2.446	3.510	-6.500	-1.100	-4.681

Figure 1. Difference between measured and calculated levels.

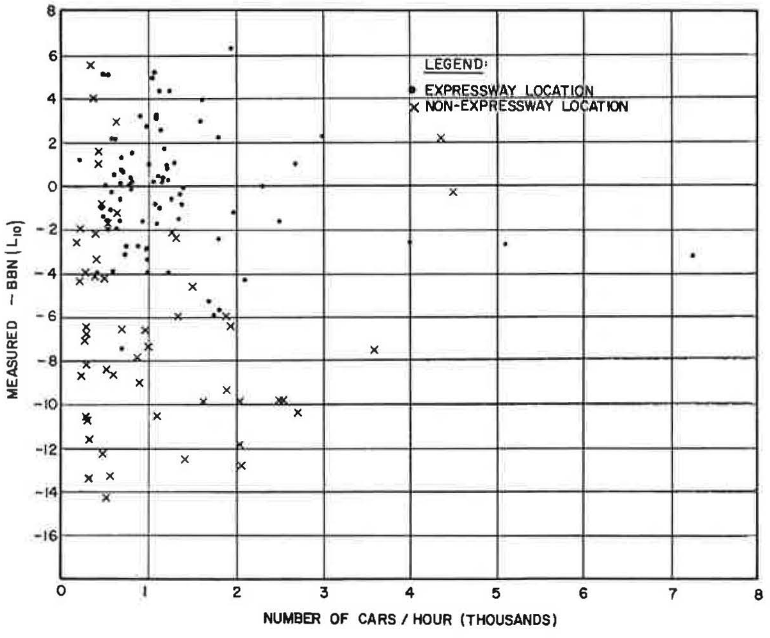

Table 3. Statistical parameters of Ontario models.

No. of Observations	Standard Error of Est. for L_{50}	L_{10}	L_5	Mult. Corr. Coeff. L_{50}	L_{10}	L_5
135	3.19	2.50	2.71	0.861	0.925	0.919
128	2.75[1]	2.17	2.21	0.897[1]	0.944	0.944

[1] For 120 observations

Table 4. Partial regression coefficients for L_{10} model with 133 observations.

Variable	Partial Regression Coefficient	Standard Error	Level of Significance
Volume of Cars + 3x Volume of Trucks	+ 11.17	0.767	0.1
Distance to Edge of Pavement	- 14.81	0.553	0.1
Average Speed of Traffic Flow	0.21	0.016	0.1

4. The standard deviation for L_{10} levels calculated by the Delany method was 2.69 dBA. The standard deviation was slightly reduced after removal of 5 percent of the observations for which the biggest differences between measured and calculated values occurred.

Ontario Highway Noise Prediction Method

In view of the good results obtained for the Delany method, it was thought desirable to attempt development of a new highway noise prediction method based on Ontario data and to assess the value of the new method.

More than 50 different mathematical models relating sound levels (L_{50},$L_{10}L_5$) to variables influencing them (i.e., volume and speed of passenger car and truck flows, and distance) were developed and evaluated. The models ranged from simple to more complex; the latter included various interactions (e.g., variables of a type: logarithm of truck volume multiplied by distance and divided by speed). Different models were also constructed for expressway and nonexpressway observations.

While it was possible to slightly improve the accuracy and reliability by including various interactions and by constructing different models for low-volume and high-volume locations, the prediction became rather complicated. The following 3 model equations predicting L_{50},L_{10}, and L_5 values were chosen for their accuracy and simplicity:

$$L_{50} = 30.4 + 14.5 \log_{10} (V_c + 3 V_t) - 11.5 \log_{10} D + 0.16 S \quad (2)$$

$$L_{10} = 52.7 + 11.2 \log_{10} (V_c + 3 V_t) - 14.8 \log_{10} D + 0.21 S \quad (3)$$

$$L_5 = 56.5 + 11.1 \log_{10} (V_c + 3 V_t) - 16.0 \log_{10} D + 0.23 S \quad (4)$$

where:

L_{50},L_{10},L_5 = sound levels in dBA that were exceeded 50, 10 or 5 percent of the time;
V_c = total volume of passenger cars (GVW $\leq$ 10,000 lb, in veh/h
V_t = total volume of trucks (GVW $>$ 10,000 lb), in veh/h;
D = distance to edge of pavement of the first traffic land, in ft; and
S = average speed of traffic flow, in mph (average speed of all highway vehicles over a given section of a highway during a specified time period).

Equations 2, 3 and 4 form the basis of the Ontario highway noise prediction method. The application of the method is briefly outlined in the last section. A step-by-step procedure is given by Hajek (3).

Statistical Evaluation

Table 3 summarizes results of statistical parameters for Ontario models. The results are given in terms of standard errors of estimate and multiple correlation coefficients for computer runs containing all 135 observations and for runs excluding 5 percent and 10 percent of the observations. The observations excluded were marginal observations for which the greatest differences between measured values and values calculated by the models were obtained. The marginal observations that were considered to be a typical (due to a combination of factors such as weather, ground attenuation, and pavement surface texture) or incorrect (the use of data in this study was secondary) were excluded in order to evaluate the sensitivity of the models to marginal observations.

The standard error of estimate for the model predicting L_{10} values was 2.50 dBA for 135 observations. By removing 7 marginal observations, the standard error decreased to 2.17 dBA. The standard error of estimate of 2.17 dBA suggests that in 2 our of 3 cases the predicted L_{10} sound levels will be within ±2 dBA or that in 14 out of 15 cases the predicted values will be within ±4 dBA of the measured values.

The prediction accuracy for the model predicting L_{50} levels (standard deviation of 3.19 dBA in Table 3) was lower than the prediction accuracy for L_{10} and L_5 models (standard deviation of 2.50 and 2.71 respectively). The lower accuracy achieved for calculation of L_{50} levels may be due to the susceptibility of L_{50} levels to the influence of background noise. Also, L_{50} levels are influenced by vehicles traveling on a longer section of a highway than L_{50} levels and thus they are subjected to a greater influence of terrain conditions.

When multiplied by 100, the squares of multiple correlation coefficients given in Table 3 indicate the percentage of the total variance explained by the models. For example, R = 0.944 with R^2 = 0.88 for L_{10} model indicates that 88 percent of the total variance is explained by the model. The partial regression coefficients of the independent variables for the L_{10} model based on 135 observations are given in Table 4. This table indicates that all coefficients are highly statistically significant.

Measured L_{10} sound levels are plotted against values predicted by the model for 135 observations in Figure 2. Generally, there is a good agreement between measured and predicted values. The difference between measured and calculated values approached 7 dBA in only one case out of the total 135 cases. With the removal of the 7 marginal observations, the highest difference between measured and calculated L_{10} levels was 4.6 dBA. Figure 3 shows a similar plot for L_{50} values for all 135 observations.

Discussion

A comparison of statistical parameters obtained for the BBN and Delany methods given in Table 2, and statistical parameters obtained for the Ontario model given in Table 3, indicates the higher level of accuracy and reliability of the Ontario model. For example, the standard error of estimate for L_{10} levels according to the BBN method was 4.7 dBA, while the corresponding standard error for the Ontario method was 2.5 dBA. On the other hand, it should be noted that the corresponding standard error for the Delany method (2.7 dBA) was only marginally improved by the Ontario model. Yet, the standard error for the Ontario model was obtained for a multiple regression model by minimizing the sum of squares of the deviation of the measured levels from their mean estimates. This result seems to indicate that the standard deviation for calculated sound levels of about 2.5 dBA, based on a number of observations taken on different locations, is the smallest standard deviation achievable with the noise prediction methods utilizing only the basic variables (volume and speed of passenger cars and trucks, and distance).

Effect of Distance. Equations 2,3 and 4 show that the rate of sound attenuation with distance increases with an increase in the percentile of sound level. The rate of attenuation for L_{50} levels was 11.5 log D or about 3.5 dBA per doubling of distance; the rate for L_{10} levels was 14.8 log D or about 4.5 dBA per doubling of distance; and the rate for L_5 levels was 16.0 log D or about 4.8 dBA per doubling of distance.

Using the t-test, the differences between attenuation rates for different percentile levels (L_{50},L_{10}, and L_5) were found statistically significant. The L_{50} sound levels are influenced by vehicles traveling on a longer section of a highway than L_5 or L_{10} levels. Consequently, the L_{50} levels tend to attenuate as sound emitted by a line source or incoherent line source, while L_{10} and L_5 levels tend to attenuate more as sound emitted by a point source.

Effect of Vehicular Volume. Highway vehicles used in this study were divided into 2 categories based on their gross vehicle weight (GVW): cars having GVW up to 10,000 lb (4,500 kg) and trucks with GVW of more than 10,000 lb to 80,000 lb (4500 to 36000 kg). In order to compensate for collinearity between car volumes and truck volumes, the 2 vehicular categories were combined into 1 variable by multiplying truck volumes by a coefficient of 3 and adding them to the car volumes. (The coefficient 3 was determined on the basis of statistical tests using a trial and error method.)

The multiplication coefficient of 3 suggests that the sound level of an average truck is about 5 dBA higher than the sound level of an average car. A recent extensive vehicle noise survey conducted in the state of Washington (7) shows that the average difference between sound levels of passenger cars with GVW of 6,000 lb (2700 kg) and less, and trucks with GVW of more than 6,000 lb (2700 kg) is about 7 dBA. This indicates that the derived difference of 5 dBA between sound levels of the 2 vehicular categories used in this study is reasonable and comparable to the Washington State survey.

Equations 2,3 and 4 suggest that L_{50} levels are more dependent on vehicular volumes than L_{10} or L_5 levels. The rate of change in L_{50} sound levels with vehicular volumes was found to be 14.5 log of traffic volume or about 4.4 dBA per doubling of traffic volume. The corresponding rate for L_{10} and L_5 levels was about 11.2 log of traffic volume. The difference between these two rates was found to be statistically significant.

Effect of Speed. The speeds of cars and trucks traveling in the same highway traffic flow are highly correlated. For this reason, only an average speed of traffic flow, defined as an average speed for all highway vehicles over a given section of highway during a specific period, was used in the model.

Figure 2. Measured L_{10} sound levels versus sound levels calculated by the Ontario method.

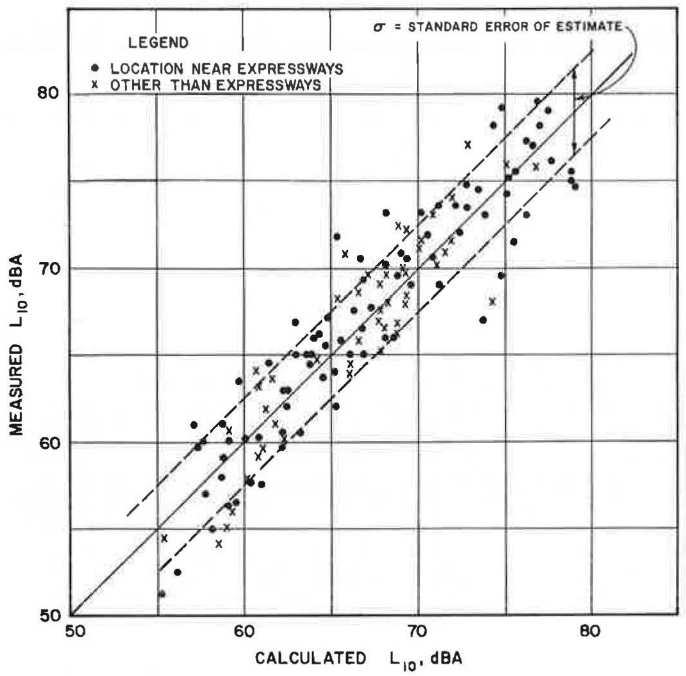

Figure 3. Measured L_{50} sound levels versus sound levels calculated by the Ontario method.

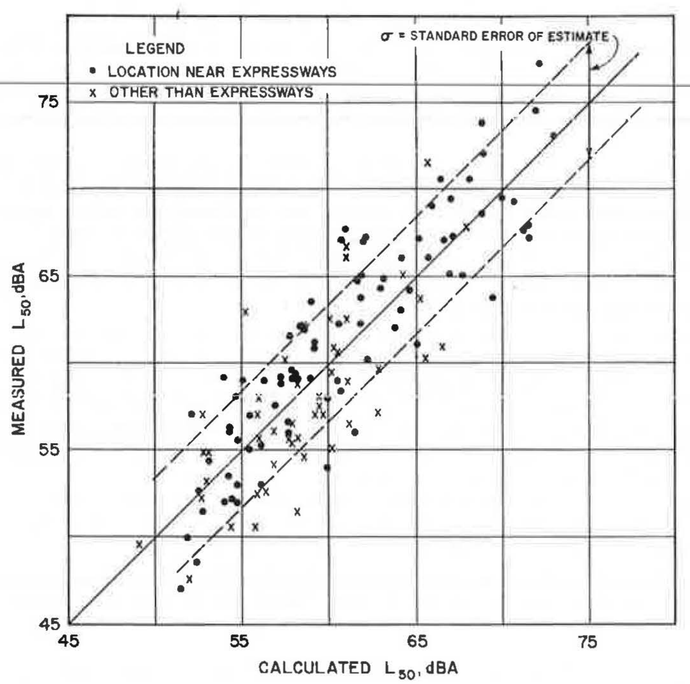

Figure 4. Nomograph for L_{50} sound level prediction.

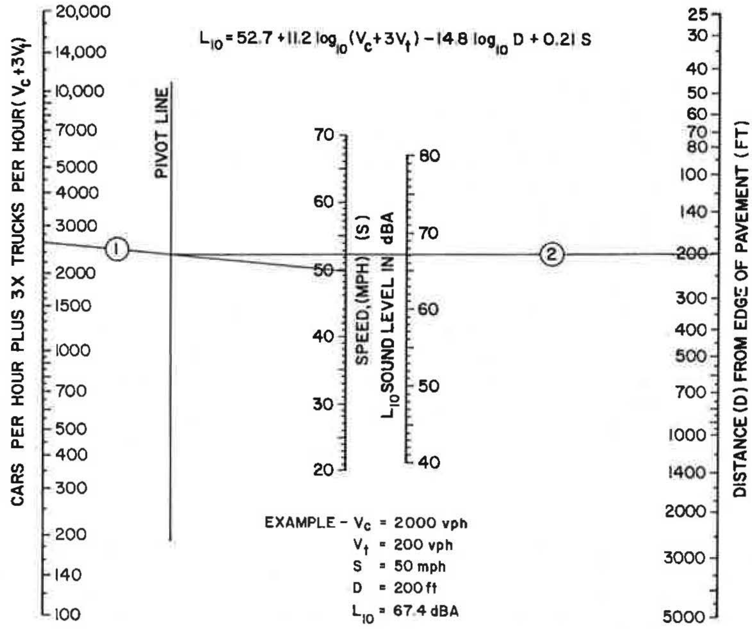

Figure 5. Nomograph for L_{10} sound level prediction.

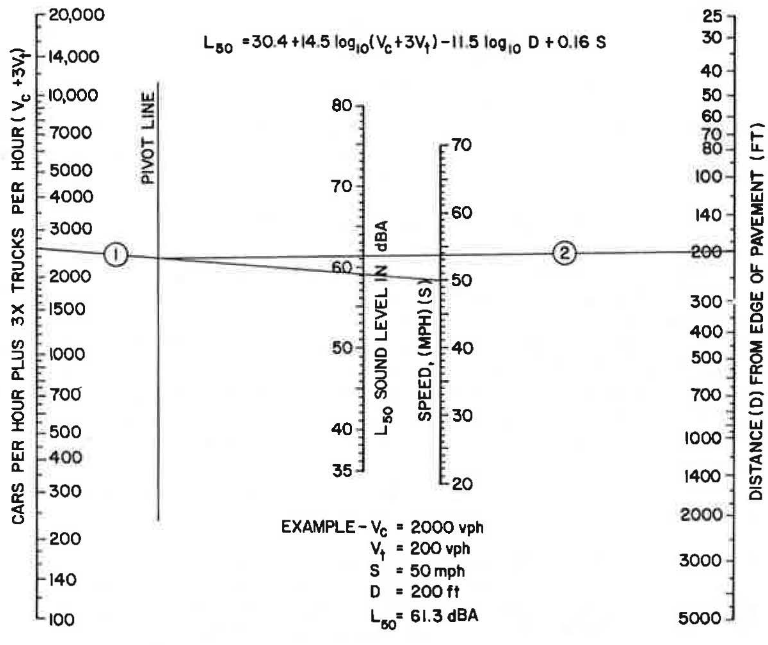

Table 5. Corrections in dBA to ground attenuation of grassland.

Mean Height of Propagation Path (ft.)	Distance From Edge of Pavement (ft.)[1]		
	100	200	300
4	0	0	0
10	+4	+3	+3
20	+5	+4	+3

[1] 1 foot = 0.3048 m

According to Eq. 2,3 and 4, the effect as speed increases with the percentile of sound level. L_5 sound levels were most sensitive to speed, probably because they are primarily controlled by the noisiest vehicles in the traffic flow and, in general, noise emitted by vehicles increases with speed.

The rate of change in L_{10} levels with speed was found to be 0.21 times the speed. This means, for example, that by increasing speed of traffic flow from 30 mph (48 km/h) to 60 mph (96 km/h) and by keeping all other variables constant, L_{10} levels would increase by about 6.3 dBA. The corresponding increase according to the Delany method would be about 5 dBA.

The speed function used in the model implies that the truck sound levels increase with truck speed. This result is supported by extensive surveys of truck population sound levels in the United States reviewed by Close and Atkinson (8), which indicate that the average maximum sound level of trucks at speeds lower than 35 mph (56 km/h) is about 79 dBA at 50 ft (approx. 15 m) and at speeds higher than 35 mph the corresponding sound level is 87 dBA. According to data collected by Foss (7), the maximum sound levels of trucks having GVW greater than 65,000 lb (29000 kg) also increase with speed.

Ground Attenuation Effect

Sound level measurements used for the development of the Ontario highway noise prediction method were measured 4 ft (1.2 m) above ground level. Thus, the method predicts sound levels at 4 ft (1.2 m) above ground. Results from an earlier study (2) and from more recent measurements have shown that sound levels in dBA increase with vertical distance above ground level due to a ground attenuation effect. The ground attenuation effect is dependent on ground conditions (the presence of grassland, concrete, snow) and also on the distance from the highway.

Table 4 gives corrections that may be added to the sound levels calculated by the Ontario method or measured 4 ft (1.2 m) above ground. The corrections in Table 4 are for level ground covered with short grass. The use of corrections should be considered carefully since the corrections depend on ground surface that is subject to frequent changes. Also, it has become customary to measure and report sound levels of highway traffic flow and sound levels of individual highway vehicles 4 ft (1.2 m) above ground and the existing noise design criteria probably reflect this fact.

Application of Ontario Highway Noise Prediction Method

The method utilizes the basic relationship between traffic flow density, traffic flow speed, distance, and the resulting L_{50},L_{10} and L_5 sound levels established in this study. The relationship is defined by Eq. 2.3 and 4. Equations 2 and 3 may be solved also by using nomographs given in Figures 4 and 5 respectively. Both the equations, and the nomographs calculate sound levels 4 ft (1.2 m) above ground assuming it is a simple case of continuous flow of traffic on an infinitely long, straight, and level roadway with no intervening structures. Thus, for example, the nomograph (Figure 5) or the equation (Eq. 3) for calculation of L_{10} levels essentially replaces Figures 3, 4, 5 and 6 of the Design Guide (1).

If the problem on hand involves more variables than those included in the nomographs (such as grade of highway or intervening structures), adjustments are made in a similar way as in the Design Guide (1). A step-by-step procedure for application of the Ontario method is given by Hajek (3).

The Ontario Ministry of Transportation and Communications, as well as many other agencies, has been systematically conducting traffic counting, and evaluation and recording of traffic volumes on highways for many years. The traffic volumes in terms of Annual Average Daily Traffic or in terms of the 30th highest hourly volumes are updated annually and form the basic information for highway management, planning and design (9). This information may be used also for prediction of existing sound levels along highways. Sound levels calculated by the new Ontario method utilizing traffic volumes based on comprehensive traffic counts may indeed be more representative than sound levels measured in the field during a selected 15-min period.

Conclusions

Evaluation of the Ontario highway noise prediction method led to the following conclusions:

1. The Ontario method provides more accurate estimates of highway noise levels than BBN (1) or the Delany (6) methods.

2. The standard error of estimate for the Ontario model predicting L_{10} values was 2.5 dBA for all 135 observations. By removing 7 marginal observations, the standard error decreased to 2.17 dBA.

3. The standard error of estimate of 2.17 dBA suggests that in 2 out of 3 cases the predicted L_{10} sound levels by the Ontario method will be within ±2 dBA.

4. The rate of sound attenuation with distance depends on percentile of sound level.

5. Sound levels emitted by trucks with gross vehicle weight of 10,000 or more pounds (4500 kg) increase with truck speed.

6. Due to the accuracy of the Ontario highway noise prediction method, the sound levels calculated by this method utilizing traffic volumes based on comprehensive traffic counts may often be more representative of actual environmental noise than the sound levels measured in the field during a selected 15-min period.

Acknowledgements

The author is grateful to Shirley Brown for her assistance with data reduction and to E. Shedler and the personnel of Engineering Surveys for organizing and conducting field measurements.

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ANALYSIS OF APPROVED AND RECENTLY DEVELOPED PREDICTION METHODS

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The necessity to accurately predict noise levels emanating from existing and proposed highways has become more apparent in the last few years, with the enactment of such legislation as the National Environmental Policy Act of 1969 and the Federal Aid Highway Acts of 1970 and 1973, along with the promulgation of noise standards from the United States Department of Transportation Federal Highway Administration (FHWA). In the past 5 years, many models have been developed expressly to meet the prediction needs. Among the more important models are the Transportation Systems Center computer program, the National Cooperative Highway Research Program (NCHRP) 78/117/144 report series, the NCHRP 3-7/3 Revised Design Guide (RDG) and the Ontario Highway Noise Prediction Method.

The New York State Department of Transportation (NYSDOT) made the decision to use NCHRP 117/144 in its highway noise prediction work and has been in the process of continually refining that model. The NYSDOT computer program HUSH is based on the so-called "Michigan model" computerized version of NCHRP 117/144, which was distributed by FHWA. Although HUSH represents significant improvements over both NCHRP 117/144 and the "Michigan model," it is still basically a freeway model and thus subject to limitations in many of the practical situations that highway designers face, especially in urban and suburban conditions.

In light of these limitations, the NYSDOT is continuously searching for new and improved methods to more accurately predict noise levels for all situations. Therefore it has undertaken a study aimed at evaluating 2 new prediction methods and comparing them with actual field measurements, and with results obtained using HUSH. The 2 new methods being evaluated are the NCHRP 3-7/3 Revised Design Guide and the Ontario method.

Briefly, the Revised Design Guide is a physical model designed for freely flowing traffic manifested in both a nomograph and computer program. For purposes of this study, the NYSDOT extracted the emission and propagation equations from the computer program and wrote simple programs for use with a programmable hand calculator and with the computer system used by the New York State Department of Environmental Conservation (DEC) Bureau of Noise Control. The equation used was

$$L_h = L_{og}\frac{V}{DS} + SL + 3.2 - 5\ L_{og}\frac{rn}{50} + 10\ L_{og}\frac{\theta}{180}\ \text{dBA}$$

where

SL (heavy trucks) = 86 dBA;
SL (medium trucks) = 28 + 30 $L_{og}S$ dBA;
SL (autos) = 18 + 30 $L_{og}S$ dBA;
L_h = hourly equivalent sound level, or L_{eq};
V = hourly volume;
D = normal distance to the line source, in ft (m);
S = average speed of vehicle class, in mph (km/h);
rn = distance from the observer to the closest element point in ft (m); and
θ = finite element subtended angle, in deg.

Conversions from L_h to L_{10}, the level exceeded 10 percent of the time, were made by using the following table, as taken from Chapter 3 of the November 1974 version of the RDG:

Class	Parameter A = VD/S	$L_{10} - L_h$
I	16,000 and above	1
II	3,000 to 16,000	2
III	200 to 3,000	3
IV	50 to 200	1
V	25 to 50	-2
VI	10 to 25	-5
VII	less than 10	-

The Ontario method is a regression line model, in the form of nomographs, based on 133 noise measurements taken at 120 locations near rural and urban freeways, highways, and residential streets in Canada. The nomograph for L_{10} uses

$$L_{10} = 52.7 + 11.2 \, L_{og} \, (Vc + 3V_t) - 14.8 \, L_{og} \, D + 0.21S$$

where

V_c = hourly car volume;
V_t = hourly truck volume;
D = distance to the edge of pavement, in ft (m); and
S = average vehicular speed, in mph (km/h).

This equation was also programmed into the New York DEC computer system. The Ontario method, as well as HUSH, provides no mechanism to obtain the equivalent sound level, L_{eq}.

Measurement Procedures

Up to this point in the study, some 60 measurements of traffic noise have been made. It is hoped that by the time the study has run its course, enough measurements will have been made so that statistical significance can be achieved for many combinations of vehicle volume, speed, and observer-receiver distances.

Three levels of sophistication have been used in data collection. The first is the "check-off"method as detailed in the FHWA course "Fundamentals and Abatement of Highway Traffic Noise." This method simply requires a technician to read a sound level meter at 10-sec intervals, enough times to develop 95 percent confidence that the L_{10} is within ±3 dBA. For purposes of the NYSDOT study, these confidence limits were achieved for ±2 dBA. However, this method does not give an accurate, reliable measure of the L_{eq} and, therefore, has not proven satisfactory for studying the RDG.

The second level of sophistication used in measurement is audio recording and playback through a graphic level recorder—statistical distribution analyzer system. However, this method has proven cumbersome when attempting to obtain the needed resolution of the data for purposes of the study.

The third level in measurement procedure sophistication has proven to be the most satisfactory. This method involves audio tape recording and playback through a real time analyzer. This allows for an accurate determination of the L_{10} and L_{eq} levels.

All measurements made thus far in the study have been performed by the NYSDOT Noise Measurement Unit. This group consists of 5 full-time, certified noise measurement technicians, usually working in teams of 2 or 3. During each measurement, precise counts of auto, medium truck, and heavy truck volumes are made.

Preliminary Results

Results for comparison purposes were obtained by inputting the actual traffic and geometric parameters into the 3 models (HUSH, RDG, and Ontario), and comparing the outprints to the field measurements. Below is a table showing the number of sites, means of the differences between predicted and measured values, and the standard deviation of the mean for various categories: md = mean of the differences, sd = standard deviation, ns = number of sites included, and EPD = edge of pavement distance.

Category	HUSH (L_{10})	Ontario (L_{10})	RDG (L_{10})	RDG (L_{eq})
All Sites	md=+3.3,sd=2.7 ns=61	md=-0.6,sd=3.1 ns=61	md=+0.5,sd=2.9 ns=61	md=+2.6,sd=2.7 ns=33
Low Volume Site	md=+3.1,sd=2.2 ns=14	md=-0.8,sd=4.0 ns=14	md=+1.2,sd=2.3 ns=14	md=+3.2,sd=1.0 ns=8
Medium Volume Site	md=+3.4,sd=2.7 ns=34	md=-0.7,sd=2.7 ns=34	md=+0.3,sd=2.9 ns=34	md=+2.2,sd=2.6 ns=20
High Volume Site	md=+3.6,sd=2.2 ns=13	md=+0.7,sd=2.3 ns=13	md=+1.1,sd=2.4 ns=13	md=+2.4,sd=2.4 ns=5.
EPD 50 feet	md=+2.3,sd=2.5 ns=25	md=-0.8,sd=3.5 ns=25	md=-0.2,sd=2.9 ns=25	md=+1.7,sd=2.7 ns=12

Category	HUSH (L_{10})	Ontario (L_{10})	RDG (L_{10})	RDG (L_{eq})
EPD 100 feet	md=+3.8,sd=2.2 ns=17	md=+0.1,sd=2.2 ns=17	md=+0.8,sd=1.6 ns=17	md=+1.3,sd=2.9 ns=9
EPD 200,400 feet	md=+4.6,sd=2.6 ns=15	md=-0.9,sd=3.7 ns=15	md=+2.1,sd=2.7 ns=15	md=+2.6,sd=2.9 ns=12

Note: 1ft = 0.3048 m.

For purposes of this study, a low-volume site is defined as having less than 600 veh/h, a medium volume site has 600 to 1800 veh/h, and a high volume site has more than 1800 veh/h.

It is clear from the data that HUSH, or NCHRP 117/144, overpredicts by 3 to 4 dBA for most situations. This agrees with conclusions that many other researchers have made. It is interesting to note that even at low volumes and close distances, HUSH does not do too badly. However, as distances increase, the overprediction gets larger, possibly indicating the influence of excess attenuation of the ground and atmosphere. For all the methods evaluated, HUSH generally displays the lowest standard deviations, thus indicating consistency in its overprediction.

From the data given in the table, the Ontario method appears to be the most accurate in terms of mean of the difference. There is a slight underprediction for low and medium volumes, and a slight overprediction for high volumes, but actually the differences are negligible. However, the standard deviations are somewhat larger than for HUSH, particularly at low volumes. More data will be gathered for low volume situations in order to more adequately examine what is happening.

The Revised Design Guide predicts very accurately and with low standard deviations for all situations for the L_{10} descriptor. As distances increase the RDG L_{10} starts overpredicting, although not as badly as HUSH. Again, this overprediction is probably due to ground and atmospheric attenuation. The measurement team noted significant intuitive differences in noise levels at the larger distances, depending on the type of ground cover between the receiver and the road.

For the 33 measurements taken by audio tape recording, it was possible to accurately determine the equivalent sound level L_{eq}; thereby providing a data base for a preliminary evaluation of the RDG L_{eq}. For all 33 sites, the RDG has an overprediction for L_{eq} of 2.6 dBA, and has a slightly higher overprediction, 3.2 dBA, for the light, low-volume sites. Since the RDG first obtains L_{eq} and then adds a conversion for L_{10}, it appears that there may be compensating errors in the L_{eq} and the (L_{10}-L_{eq}) parameters, because the RDG L_{10} is significantly more accurate than the RDG L_{eq}. However, no firm conclusions can be reliably drawn because there are too few measurements available at this point, particularly for low volumes.

An interesting trend in the data is developing with regard to the (L_{10}-L_{eq}) parameter. For the 33 measurements where an accurate L_{eq} has been determined, 31 have shown (L_{10}-L_{eq}) to be equal to 3 ±1 dBA. The other 2 measurements were atypical; that is, they were taken at the same location, and each time the number of heavy trucks exceeded the number of automobiles, and both were of extremely low volumes. Once, the (L_{10}-L_{eq}) parameter was 0, and the other time, -2.

These results indicate that the simple relationship for (L_{10}-L_{eq}) = 3 may apply for most practical situations. Also, there appears to be a range in volume below which the (L_{10}-L_{eq}) relationship complicates, or the L_{10} descriptor becomes unstable. In any event, there is a definite need to obtain more tape recorded data at the low volumes.

Conclusions

The preliminary results of this study clearly indicate that progress is being made in highway noise prediction. HUSH, which includes several revisions over NCHRP 117/144, is outperformed by the 2 newer models. The Ontario method is closer to the target on the average, but tends to have a larger spread on individual predictions. This may be explained by the fact that it is basically a regression line model and cannot therefore account for physical inconsistencies as well as a theoretically derived model can. However, the Ontario method shows the value of empirical data in model building.

The results from the Revised Design Guide are encouraging in that they show an improvement in physical modeling over HUSH. However the (L_{10}-L_{eq}) parameter, both in the model and in actual conditions, needs more empirical testing and input before confidence can be gained, especially for low vehicular volumes.

FUTURE PROJECTED VEHICLE SOURCE NOISE EMISSION LEVELS
FOR USE IN HIGHWAY TRAFFIC NOISE PREDICTION CALCULATIONS

Donald R. Whitney, General Motors Corporation

In any highway noise prediction scheme, it is imperative that realistic source emission levels be inserted into the mathematical models in order to produce results that will correlate with measured levels. Traffic flow rate and traffic mix must be taken into account. It is also necessary to insert vehicle source noise levels that are representative of the specific mode of operation that is being modeled. For trucks, each speed and acceleration condition will necessitate a separate consideration of powerplant related noise and tire-road surface interaction noise. Tire-road surface interaction noise is primarily vehicle speed dependent but is also influenced by tire design, expecially tread pattern, number of tires used on the vehicle, and road surface characteristics. A single level number can only be used to represent a class of vehicles if that number takes into account the specific conditions of engine operation and speed in the case being considered.

While EPA has not published new truck noise regulations as of this date, the fact is that the differences in the resulting highway traffic noise levels, which could occur due to regulation of truck powerplant sound levels, are small, regardless of which of the proposed levels are chosen. That is, the choice of any level at or below 83 dBA will have little bearing on future highway traffic noise levels. While the cost of lower levels will be significant to the user of the truck and ultimately to the public, the benefit, particularly in terms of lower highway noise levels, will be minimal. Even taking urban street scenarios into account, it can be shown that setting regulated levels for new trucks below 83 dBA is not cost beneficial (1).

More importantly, it must be recognized that the potential benefit of regulating new trucks will not be realized without an effective enforcement program locally as well as nationally to eliminate poorly maintained vehicles and those modified vehicles that produce excessive noise. It will also be necessary to control the noise from new tires on some basis of performance so that only the better, quieter tires will be produced in the future. As it stands today, the best known technology for control of tire noise can yield no promise of appreciable noise reduction below that of the lowest noise level tires currently being produced. However, there is a significant gain to be realized by removing the noisier varieties of tires from our roads.

General Motors submitted two documents (2) in response to the EPA Proposed Rule Making for Noise Emission Standards for New Medium and Heavy Trucks. The information contained herein constitutes part of the material developed for these documents. Details of the calculation procedures are included in the GM reports. The purpose of the calculations was to predict the potential incremental noise reduction in a community that could be achieved by reduced vehicle and tire source emission levels as a result of proposed standards. To allow the use of that previously developed information in calculations involving various proportions of traffic mix, it is necessary to present the data individually for heavy vehicles and light vehicles. Calculations have been performed on 2 modles that illustrate the urban freeway cruise situations with vehicles traveling at 55 mph (88 km/h) and the urban street cruise condition with vehicles traveling at 35 mph (56 km/h).

The EQL value used in these models was defined as the maximum passby level (dBA) of the representative vehicle, which is at the mean energy of the sound level distribution for the population of these vehicles. Figure 1 and Figure 2 show the projected EQL values according to various regulatory schedules of Tabel 1 for 2 classes of vehicles operating at 55 and 35 mph (88 and 56 km/h) respectively; i.e., medium and heavy trucks over 10,000 lb (4536 kg) GVWR and passenger cars and light trucks less than 10,000 lb (4536 kg) GVWR. It should be noted that truck powerplant noise and tire noise are presented as a single combined level notwithstanding that they were derived separately and that the levels shown are highly dependent on speed. The EQL values shown are the best available estimates of the noise levels of vehicles operating in the level road cruise condition and include a 1.5 dBA attenuation factor assumed for measurements made at typical highway sites as differentiated from a hard site test facility. The populations assumed in any given year are a proportioned mix of old and new vehicles extrapolated from data from U.S. Bureau of Census, "Truck Inventory and Use Survey" (1972). It will be seen by means of the equation, Figure 3, that the EQL value defined above is used as the level at 50 ft (15.24 m), $L_{(50\ ft)}$, to determine the hourly equivalent energy level [Leq(h)] that that vehicle class contributes.

Since it is impossible at this time to determine the effectiveness of the enforcement of the Interstate Carrier regulation and anticipated new tire regulations, 2 conditions are shown: (a) with 100 percent enforcement such that all trucks comply

Figure 1.

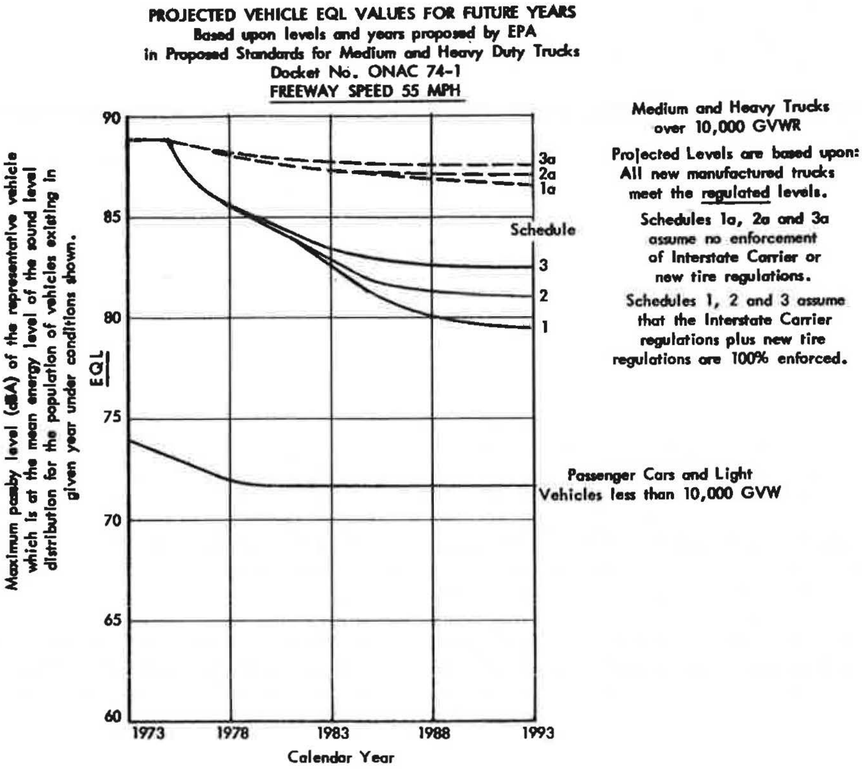

Figure 2.

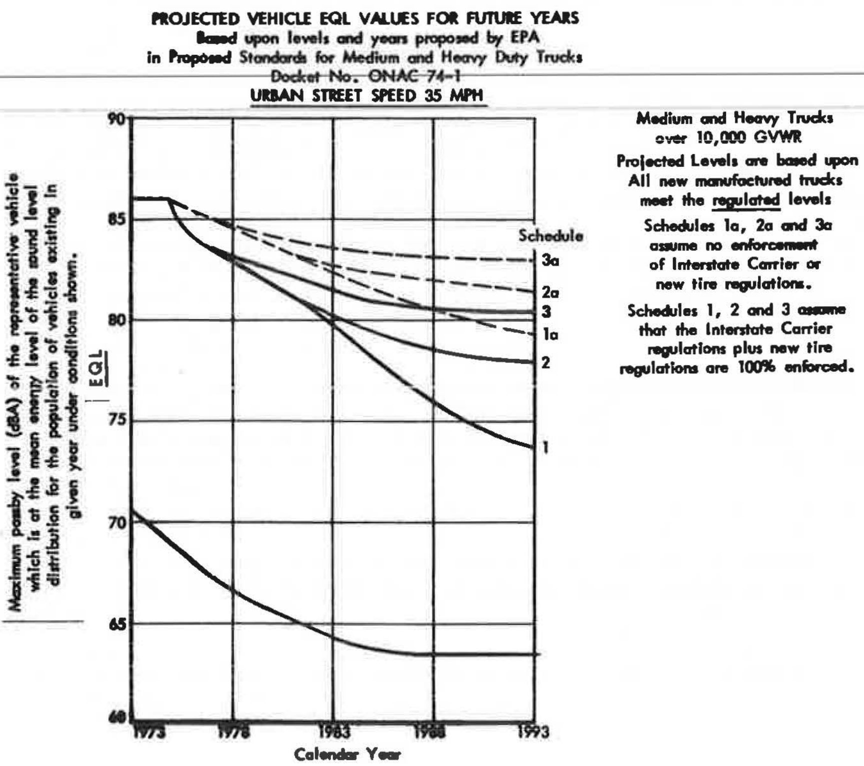

Table 1.

New Medium and Heavy Truck
Regulated Level Reduction Schedule
(per SAE J366b)

Schedule 1	83 dBA in 1977 80 dBA in 1981 75 dBA in 1983
Schedule 2	83 dBA in 1977 no further reduction
Schedule 3	86 dBA In 1977 no further reduction

Passenger Car and Light Truck Schedule (per SAE J986a)

80 dBA in 1975
no further reduction

Figure 3.

Equation for Determining $Leq_{(h)}$

$$Leq_{(h)}(dB) = L_{(50\ feet)} + 10 \log \left(\frac{V}{SD}\right) + 1.7$$

where $L_{(50\ feet)}$ = unit vehicle maximum passby noise level at 50 feet, (corresponds to the EQL value for a class of vehicles).

V = vehicles per hour

S = speed in miles per hour

D = distance from the roadway in feet

$Leq_{(h)}(dB)$ = hourly mean traffic noise level at distance D

Note: 1 ft = 0.3048 m.

with regulations, and are equipped with low noise rib-type tires, and (b) with no enforcement such that the existing fleet in 1973 typifies the levels of the trucks not covered by the new truck regulations. Since such a marked difference in truck noise on the streets occurs between a 100 percent enforcement condition and a no enforcement condition, it will be necessary when making the computations to qualify the conclusions according to the assessment of the degree of enforcement that can be forecast. Since the schedule and levels of new truck regulation are not known, the schedule and levels in the regulation proposed by EPA as of October 30, 1974, were assumed and are shown as Schedule 1 in Table 1. Schedule 2 is the General Motors recommendation for truck sound levels reduction to 83 dBA. Schedule 3 assumes no further reduction below the 86 dBA level as a new vehicle regulation.

Only 1 curve at each speed in Figures 1 and 2 are shown for passenger cars and light trucks less than 10,000 lb (4536 kg) GVW. These curves are derived from data starting with the population of these vehicles existing in 1973 that are now being replaced with vehicles of this class that are currently being produced to meet SAE J986a levels of 80 dBA. It was assumed that these new vehicles will dominate the population of light vehicles in the time frames shown. The realities of poor maintenance and modifications that produce excessive noise must be handled by user regulations, but no estimate of this effect is illustrated in this presentation. For the situations of 35 and 55-mph (56 and 88-km/h) cruise, the EQL values presented in Figures 1 and 2 can be used to determine the total equivalent energy $L_{eq(h)}$ of a given mix of vehicles representing the classes of vehicles being considered. The EQL levels for each class of vehicles must be converted to equivalent energy $L_{eq(h)}$ values to determine the energy contribution in accordance with the equation in Figure 3. The resultant $L_{eq(h)}$ values for the specified vehicle classes can then be summed logarithmically to obtain the total source emission equivalent energy level.

To determine the level of unit truck noise that should be used as input to highway traffic noise computations, the appropriate schedule that corresponds to the regulated level in effect must first be selected. As an illustration, assume that a regulated level of 83 dBA is chosen that corresponds to Schedule 2 or Schedule 2a. For a prediction in a given year, say 1985, the expected level of trucks at 55 mph from Figure 1 would be 82 dBA with 100 percent enforcement of in-use regulations, or 87.2 dBA with no enforcement. The importance of the enforcement aspect of noise control on the older vehicles is obvious. It is assumed that the newly manufactured vehicles comply with the new product regulations in effect to control low-speed engine-related noise. At this time, it is not possible to assess the degree of enforcement that will be attained. Although it is improbable that complete enforcement will be attained, the level of 82 dBA is chosen as an example.

For passenger cars and light trucks the corresponding value would be 71.7 at 55 mph (88 km/h) in 1985. This level is based on the levels of new light vehicles produced to meet a maximum level of 80 dBA per the SAE J986a standard. The initial (1973) level of 74 dBA was established from roadside data and therefore represents the maximum level which might be anticipated if local enforcement does not reduce the levels of the poorly maintained and modified vehicles. With reasonable maintenance of 1975 and later light vehicles in their "as manufactured" condition, the cruise passby levels under these speed conditions are determined by tire noise.

In this illustration the values to be used in establishing the L_{eq} equivalent energy levels for any given highway situation would be 82 dBA for trucks over 10,000 lb (4536 kg) GVWR and 71.7 dBA for passenger cars and light trucks. These values are then used in the equation shown previously in Figure 3 relating the maximum level at 50 ft (15.24 m) distance with the $L_{eq(h)}$ based upon traffic volume, speed and receiver distance. Thus the hourly energy contribution for each class of vehicles is determined. To obtain the total traffic equivalent energy level for that hour, $L_{eq(h)}$, the energy contributions of each component of the traffic mix for that traffic situation must be summed logarithmically.

References

1. GM comments to EPA; Letter USG 350-75-11, dated May 30, 1975.

   GM comments to Council on Wage & Price Stability; Letter USG 350-75-14, dated July 2, 1975.

2. GM comments to EPA; Report USG 350-74-22, dated December 20, 1974, Section VI.

   GM comments to EPA; Report USG 350-75-5, dated March 14, 1975, pages 40-56.

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