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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	4.657	-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.

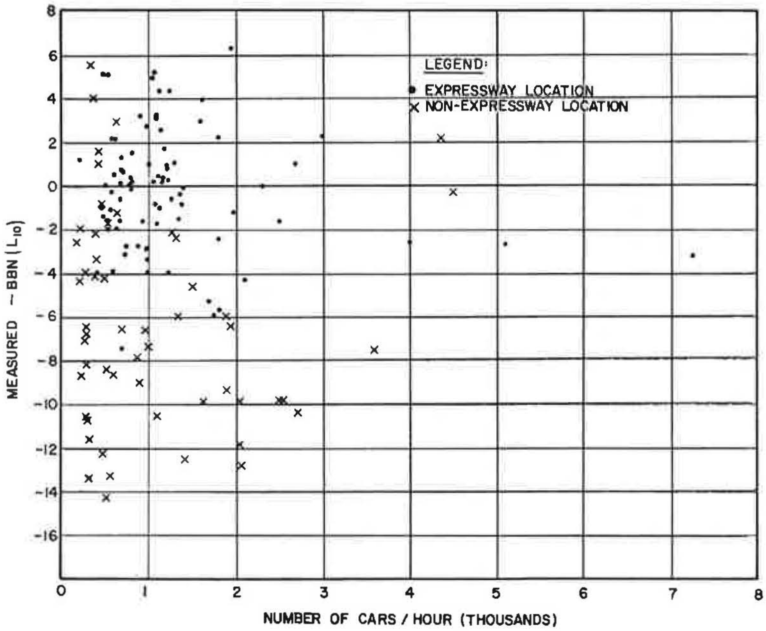

Table 3. Statistical parameters of Ontario models.

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.

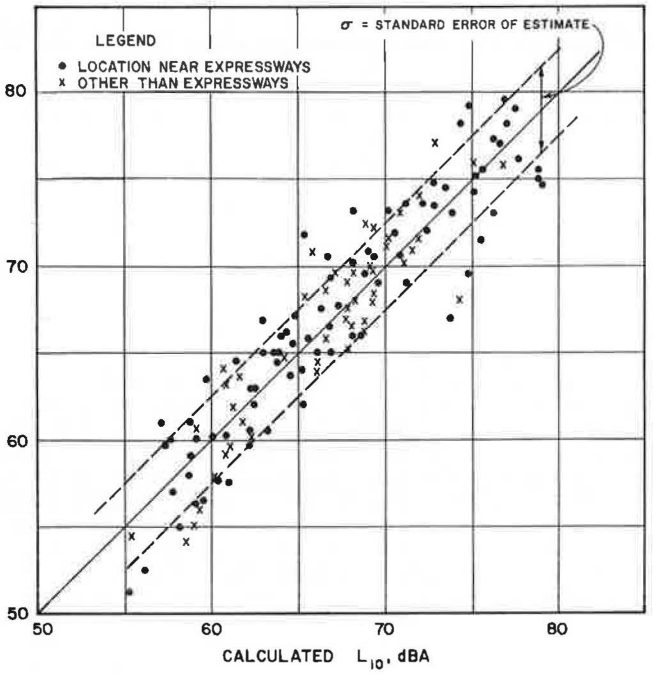

Figure 3. Measured L_{50} sound levels versus sound levels calculated by the Ontario method.

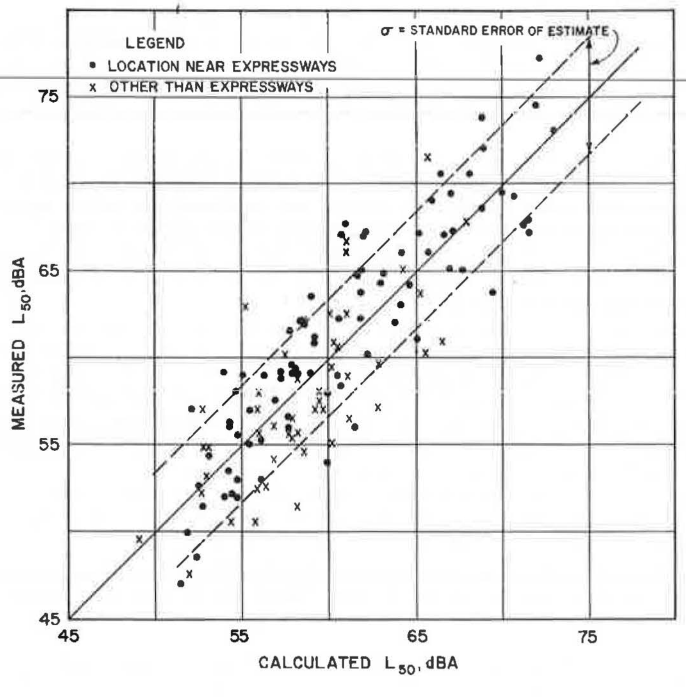

Figure 4. Nomograph for L_{50} sound level prediction.

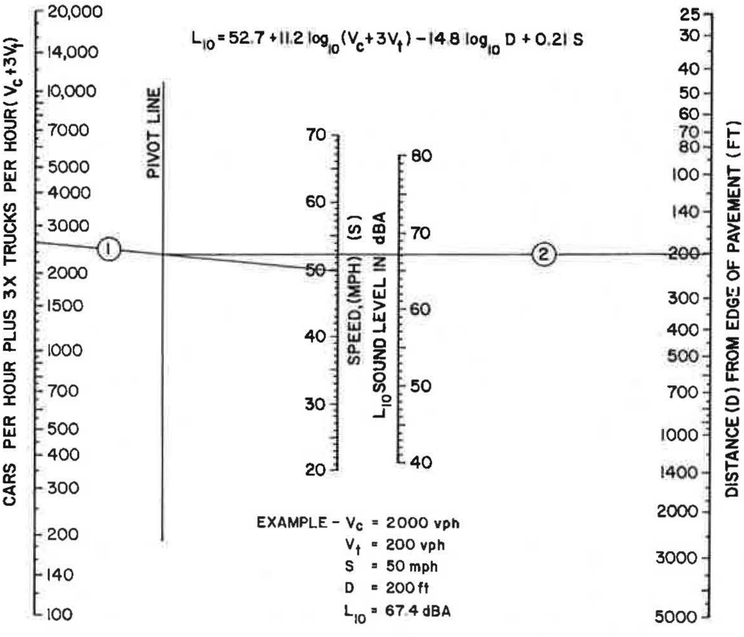

Figure 5. Nomograph for L_{10} sound level prediction.

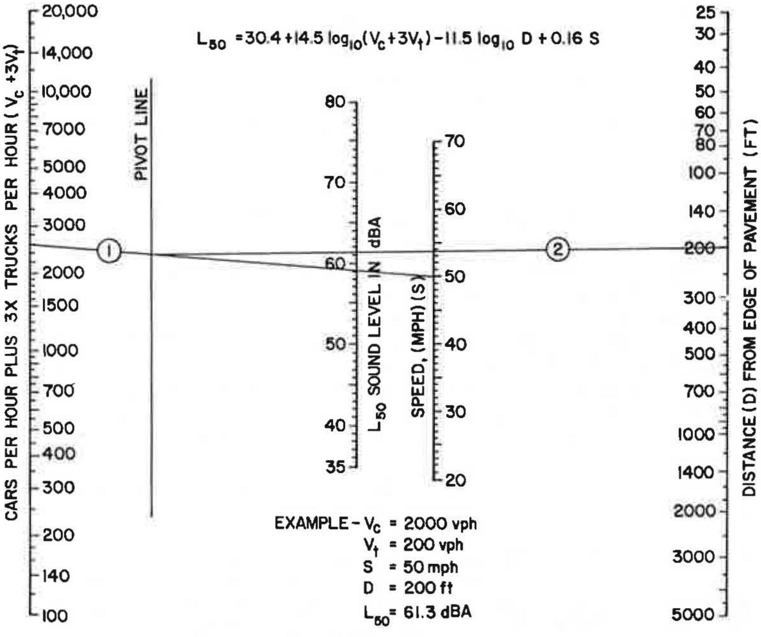

Table 5. Corrections in dBA to ground attenuation of grassland.

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

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