# THE ACCURACY OF HIGHWAY TRAFFIC NOISE PREDICTIONS

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## ABSTRACT

The free-field prediction accuracies of four highway traffic noise prediction models (FHWA, CMHC, RDG, and ONTARIO) were compared over a wide range of the basic variables of traffic noise prediction. The average error, in terms of standard deviation of difference between the predicted and measured sound levels, was found to be about 2 dBA. A review of the free-field prediction accuracies of major North American models developed since 1971 revealed similar results. In order to improve prediction accuracy, effects such as ground conditions and atmospheric influences on the propagation of traffic sound must be better understood and incorporated into prediction models. Also, noise generated due to tire-pavement interaction and sound emission levels of various vehicle types must be better characterized in existing prediction procedures.

## SOMMARIE

On compare la précision de la prédiction en champ libre de quatre modèles de prédiction des bruits routiers (FHWA, SCHL, RDG, et Ontario) sur une gamme très étendue des variables de base de la prédiction des bruits routiers. On a trouvé que l'erreur moyenne, on terme de déviation normalisée des différences entre les niveaux sonores prédits et les niveaux mesurés, est de 2 dBA. L'examen de la précision de la prédiction en champ libre des plus importants modèles nord-américains crées depuis 1971 donne des résultats similaires. Afin d'améliorer la précision des prédictions, il faut mieux comprende certains effets tels que l'état du sol et les influences atmosphériques sur la propagation des bruits routiers et les incorporer dans les modèles de prédiction. De plus, it faut mieux caractériser le bruit résultant de l'interaction entre les pneus et le revetement et le niveau d'émission sonore des divers types de véhicules dans les procédures existantes.

## 1/ INTRODUCTION

A reliable and accurate highway noise prediction method is a cornerstone for control of acoustical environment along highways. A reliable prediction method should be accurate, not only as far as overall results are concerned, but it should also correctly predict changes in sound levels due to specific highway design features such as pavement surface type and highway grade.

The purpose of this study was to verify the accuracy of a newly developed prediction method for Ontario conditions and to determine if any further improvements are required. More specifically, the objectives of the study were:

a) To compare the prediction accuracy of the new Federal Highway Administration highway noise prediction model [1], referred to subsequently as the FHWA model, with other prediction models, namely CMHC [2], RDG [3] and Ontario [4] models.

b) To determine the minimum standard deviation of differences between the predicted and measured sound levels which can be expected if only customary, basic variables are used for predictions.

c) To quantify prediction errors which may arise from variables not included in the current prediction models.

## 2/ METHODS

The prediction accuracies of the models were determined by comparing predicted and measured energy equivalent sound levels. The predicted levels were obtained by inputting the actual traffic, geometric, and other required parameters into the four models (FHWA, CMHC, RDG, ONTARIO) The measured levels were obtained at 27 sites specifically selected for the purposes of this study. The sites were selected with the objective to obtain a general data base for overall evaluation of the models. The sites encompassed a wide range of traffic flow conditions (traffic volume, composition, and speed) and highway facilities. Approximately one-half of the sites bordered on freeways and the rest on regional roads and arterial streets. The sequence of measurements on individual sites was randomized as much as possible.

All sites approximated free-field conditions. The subtended angles of at least 150° at the measurement locations were unobstructed by houses, barriers, or other shielding features. The ground between the roadway and the measurement locations was covered mainly by grass. Measurements were conducted using the procedures and techniques recommended in Reference 5. To minimize variation, the measurements were conducted only along straight roadway sections with asphalt pavement surfaces and with highway grades less than 2%.

The total traffic volume ranged from 40 to 8800 vehicles per hour with the mean of 2500. The total truck percentage, including both medium and heavy trucks, ranged from 2% to 45% with a mean of 15%. The medium trucks were defined as 2-axle trucks with four tires on the rear axle, the heavy trucks were defined as trucks with three or more axles. The percentage of the heavy trucks in the total truck flow ranged from 0 to about 90% with a mean of 70%. Sound level measurements were taken at a height of 1.2 m above roadway pavement elevation and at equivalent distances (equivalent distance is defined as a square root of the product of the perpendicular distance between the measurement location and the centrelines of the near and far traffic lanes, respectively) ranging from 10 to 115 m with a mean of 50 m.

The total number of observations was 85 indicating that, on the average, three sound level measurements were carried out at each site. These were not duplicate measurements but rather measurements done at different distances from the roadway. The maximum number of measurements performed at any one site was limited to four in order to minimize the influence of any site-specific features, such as ground cover or prevailing wind conditions, on the statistical evaluation of model accuracies.

## 3/ RESULTS OF MODEL COMPARISONS

The prediction accuracies obtained for the four models are compared and summarized in Table 1 in terms of means and standard deviations of differences between the predicted and measured sound levels.

Table 1/ Comparison of Prediction Accuracy

| Prediction Model | Mean Difference Between Predicted and Measured Values, dBA | Standard Dev. of Differences dBA | Intercept of Regression Line dBA |
|---|---|---|---|
| A) Overall Comparison, All 85 Observations | | | |
| FHWA | 0.78 | 1.59 | 8.01 |
| CMHC | -0.10* | 1.62 | 8.72 |
| RDG | 1.61 | 1.99 | 14.44 |
| ONTARIO | 0.23 | 1.68 | 6.43 |
| Empirical | 0.00 | 1.47 | 2.71 |
| B) Comparison for Freeways, 46 Observations | | | |
| FHWA | 0.71 | 1.77 | 14.32 |
| CMHC | -0.75 | 1.36 | 7.46 |
| RDG | 0.97 | 2.07 | 21.00 |
| ONTARIO | 0.52 | 1.74 | 13.94 |
| C) Comparison for Non-Freeways, 39 Observations | | | |
| FHWA | 0.87 | 1.35 | 7.30 |
| CMHC | 0.68 | 1.57 | 7.76 |
| RDG | 2.36 | 1.60 | 6.77 |
| ONTARIO | -0.11 | 1.54 | 12.05 |

* Negative values indicate underprediction.

The comparison was done separately for all 85 observations, 46 freeway observations, and 39 non-freeway observations. Also shown are results for an empirical model developed by multiple regression analysis which will be discussed later. The following conclusions are based on the statistical indicators given in Table 1.

1/ For all 85 observations, the prediction accuracy of the four models (FHWA, CHMC, RDG, ONTARIO) was quite similar. The standard deviation of the models was in a narrow range from 1.62 dBA, obtained for the CMHC model, to 1.99 dBA, obtained for the RDG model.

2/ For 46 freeway observations, all models tended to overpredict with the exception of the CHMC model which underpredicted by an average of 0.75 dBA. However, the CMHC model had the lowest standard deviation of 1.36 dBA.

3/ For 39 non-freeway observations, the RDG method overpredicted by an average of 2.36 dBA and should be considered deficient for these sites. The differences in prediction accuracies calculated for the other three models were only marginal.

# 4/ MODEL SELECTION

Since the accuracies of several prediction models were similar, the decision as to which model to use was based on additional considerations such as their analytical qualities, flexibility, and expected enhancement. In this respect, the FHWA model is clearly superior and was, for this reason, adopted by the Ontario Ministry of Transportation and Communications as the recommended model.

For illustration, let's examine how the traffic flow parameters are accounted for by different methods. The computerized version of the FHWA model, STAMINA 2.0 [6] accepts up to eight classes of highway vehicles which can be defined by the user in terms of the average emissions levels, for each octave band centre frequency, at the distance of 15 m from the vehicle centreline. This analytical approach enables the user to calculate sound levels along specialized facilities, for example, along busways and logging roads. On the other hand, the CMHC and ONTARIO models use only two fixed vehicle classes, namely cars and trucks, and tend to predict well only for average traffic conditions and for typical highway facilities. For example, correlation analyses performed on the CMHC model using the survey data indicated a negative linear dependence of the model accuracy on the percentage of heavy trucks. The model underpredicts, with the significance level of about 0.02, at higher percentages of heavy trucks (approximately 1 dBA for 15% of heavy trucks).

The four prediction models analysed use only the basic, customary variables of highway noise prediction -- distance from observer to source, traffic volume and composition, and average speed of traffic flow. To determine the potential accuracy attainable by employing only those variables, an empirical prediction equation was constructed and calibrated to fit the survey data for all 85 observations using multiple regression analysis. The empirical equation is given by:

$$L_{eq} = 21.5 + 11.1 \log(V_C + 10\ V_{MT} + 15\ V_{HT}) - 15.4 \log D + 15.0 \log C$$

where: $L_{eq}$ = energy equivalent sound level, dBA

$V_C$ = volume of cars, vehicles per hour
$V_{MT}$ = volume of medium trucks, vehicles per hour
$V_{HT}$ = volume of heavy trucks, vehicles per hour
$D$ = equivalent distance, m
$S$ = average operating speed of traffic flow during an hour, km/h

The multiplication factors of 10 and 15 for medium and heavy trucks, respectively, were obtained by substituting trial factors into the equation and selecting the factors which resulted in the smallest standard deviation of differences between predicted and measured sound levels. Further work would be required to optimize these factors and to determine their speed dependance.

The statistical indicators of the prediction accuracy of the empirical model are compared with those obtained for the four prediction models in Table 1. As expected, the empirical model outperformed the other models. It should be noted, however, that the improvement in terms of standard deviation was only marginal (1.47 dBA versus 1.62 dBA obtained for the CMHC model) and is not expected to change substantially even if the multiplication factors of the empirical model were adjusted for speed dependence. These results indicate that there is a "maximum" accuracy attainable using only the basic variables of highway noise prediction. To improve the accuracy of the current prediction methods, it is not sufficient just to characterize better the basic prediction variables and to improve their functional relationships, it is necessary to incorporate other factors and variables into the models.

## 5/ REVIEW OF PREDICTION ACCURACIES

In the past, a number of studies have been conducted to assess accuracies of highway traffic noise prediction models. The results of these studies, dealing with major North American prediction models, are presented in a summary form in Figure 1. The results obtained in this study are also included. Figure 1 shows a relationship between an approximate date a specific model was developed and its accuracy, in terms of standard deviation of differences between the predicted and measured values, as reported by the author of the model or by an independent evaluator. For completeness, two additional North American models, TSC model [16] developed in 1972, and Wyle Laboratories model [17] developed in 1974 should have also been included and compared in Figure 1 but appropriate data were not available.

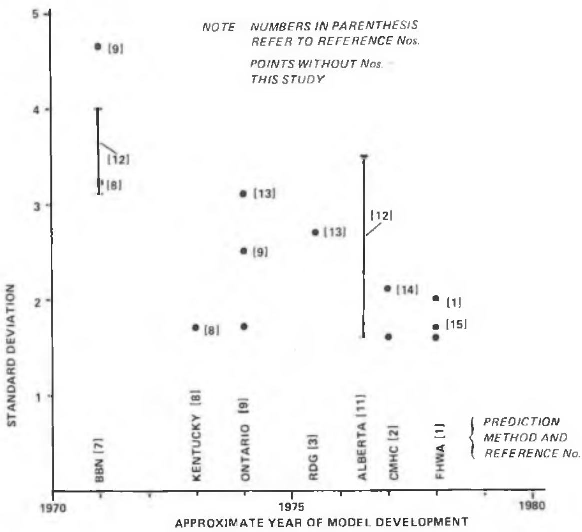



Figure 1/ Prediction Accuracy of Traffic Noise Prediction Models
*Sites without artificial barriers only.*

The relatively narrow range of errors reported by different investigators for the seven most recent highway noise prediction models evaluated in Figure 1 indicates that there is indeed a limit on the prediction accuracy which can be achieved by current models using only the basic, customary variables. This limit appears to be approximately 2 dBA in terms of standard deviation of differencies between the predicted and measured levels. It may be noted that the mean difference between predicted and measured sound levels was not used to compare model accuracies since it is easily influenced, in the case of empirical models, by model calibration, or in the case of analytical models, by adjustments to average vehicle emission levels.

According to Figure 1 data, there has not been any noticeable improvement in prediction accuracy since 1973. The spread of values reported for the different prediction methods and by different investigators can be attributed largely to differences between the studies (e.g., site selection criteria). The relatively low standard deviations obtained in this study are probably the result of the strict site selection criteria used (e.g., only asphalt concrete pavements, flat, grass-covered terrain between the roadway and the receiver).

It should be noted that the errors plotted in Figure 1 were obtained for generally unshielded locations, i.e., locations not shielded by houses or artificial barriers. For the sites shielded by houses, the error can increase by about 20% [14] and for sites shielded by artificial barriers the error can actually double [15, 18].

## 6/ NEW PREDICTION MODELS

To significantly improve prediction accuracies of the existing models, the effects of several specific factors (e.g., pavement texture and highway grade) must be better understood and additional factors related to sound propation over ground and weather-related influences must be incorporated into the models. The trend to increase the number of variables included in the prediction models, and incidentally their complexity, is shown in Table 2 which classifies the existing models and models under development into four categories as first, second, third and fourth generation models.

**Table 2/ Traffic Noise Prediction Models**

| Model Class | Example and Date of Development | Selected Model Features |
|---|---|---|
| 1st Generation | BBN [7], 1971<br>ONTARIO [9], 1974 | Only two highway vehicle classes.<br>Overall dBA level calculation.<br>Only limited recognition of ground attenuation. |
| 2nd Generation | FHWA<br>STAMINA [6]*<br>1979 | Several highway vehicle classes.<br>Octave or third octave centre frequency calculation.<br>Some recognition of ground impedance. |
| 3rd Generation | FHWA-N [19], 1982<br>STOP-GO [20], 1982 | Same as 2nd generation plus:<br>Explicit recognition of ground impedance and its variation between the source and the receiver. |
| 4th Generation | Under Development | Same as 3rd generation plus weather-related variables. |

* This is a computerized version of the original model [1].

For example, the third generation models now under development account for coherence between direct and ground reflected sound propagation. The ground cover is modelled by several contiguous planes using 3-dimensional coordinates. Sound absorption properties of these planes are characterized by their complex ground impedance values given for each of 24 one-third octave band center frequencies spanning the 50 to 10 000 Hz range. This illustrates the increase in the model complexity which may be required to significantly improve the accuracy of the existing prediction methods.

## 7/ CAUSES OF ERRORS

Some of the major causes of errors associated with highway traffic noise prediction methods are quantified in the following.

### 7.1/ Emission Levels of Highway Vehicles

The assumptions regarding the noise emission levels of highway vehicles are paramount for prediction accuracy at all distances. Figure 2 shows that while the assumptions made by different agencies on the sound emission levels of passenger cars are quite similar, the assumptions on the sound emission levels of heavy trucks, made by the same agencies, can differ by up to 5 dBA. These differences can be attributed to variations within the class of heavy trucks which encompasses vehicles with gross weight ranging from about 12 000 to 65 000 kg and to the prevalence of certain types of heavy trucks in some localities. Since the contribution from heavy trucks often dominates highway traffic sound levels, better site-specific characterization of their emission level is required.

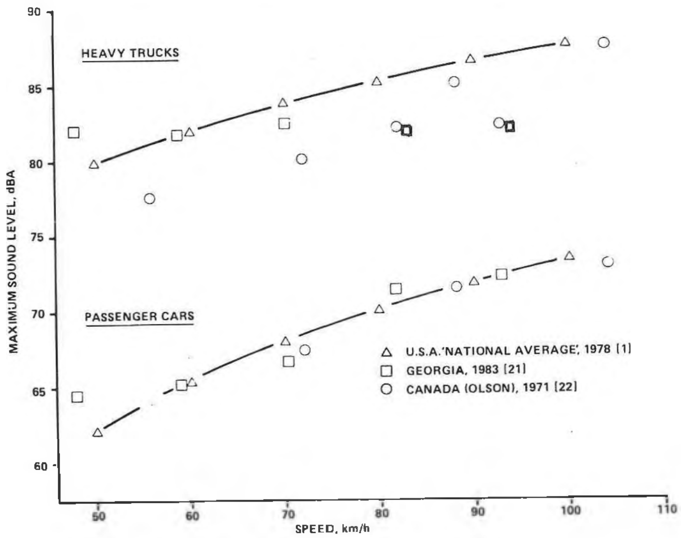
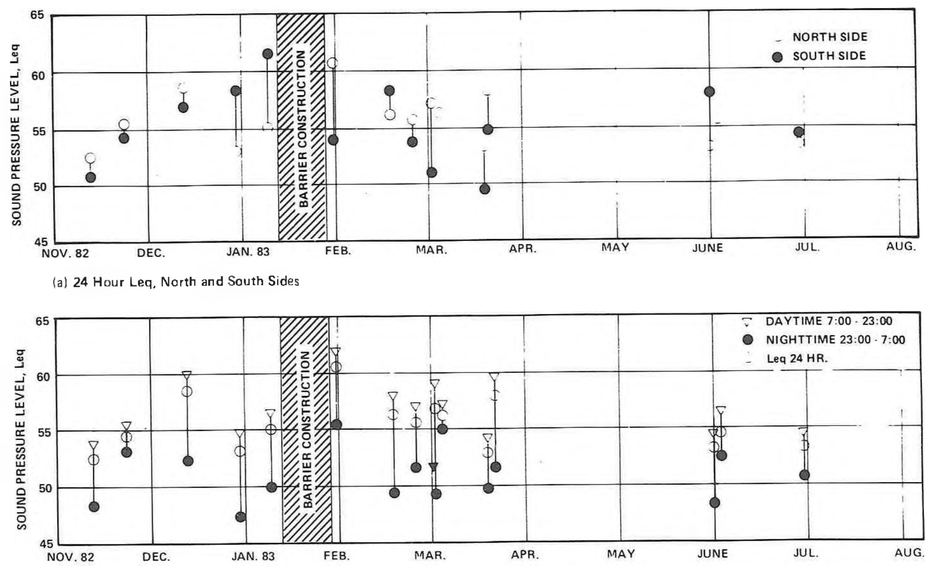



Figure 2/ Variation in Maximum Sound Level of Highway Vehicles
*The standard deviation of individual points was approximately 2 dBA for passenger cars and 3 dBA for trucks.*

### 7.2/ Sound Propagation

Sound propagation is influenced by a number of factors such as geometry between the source and the receiver, environmental weather-related effects, ground impedance and its variation, source frequency and source shape (or traffic volume) [23]. To quantify the influence of some of these factors we have conducted a series of long-duration 24-hour measurements along a six-lane freeway. The measurements were conducted at two locations on the opposite sides of the freeway, approximately 350 m from the centreline. Five 24-hour sound level measurements were conducted at each location before a barrier construction and eight to ten 24-hour measurements were conducted after the barrier construction during an eight-month period spanning virtually all four seasons. The dominant noise source at these locations was traffic noise.

Results given in Figure 3 show a considerable day-to-day variation in sound levels. The standard deviation of this variation was approximately 2.5 dBA and was not influenced by the barrier construction nor by measurement location (north side and south side in Figure 3a). The nighttime sound levels were about 6 dBA lower than the daytime levels (Figure 3b) both before and after barrier construction. The standard deviations of the daytime sound levels and night-time sound levels measured during the eight-month period were similar (2.38 and 2.47 dBA, respectively).




(a) 24 Hour Leq, North and South Sides

(b) Daytime and Nighttime Leq, North Side

Figure 3/ Long-Term Changes in Sound Levels Along a Major Freeway Before and After Barrier Construction
*Locations approximately 350 m from centerline.*

The influence of weather-related variables (such as wind velocity and temperature which were also monitored) on the measured sound levels was also analysed, but it was difficult to quantify due to the transient nature of these variables. Thus, the observed variation in sound levels should be attributed to weather-related factors, the change in the ground cover during the seasons and to some extent, to the influence of community noise sources which could not be eliminated. The barrier erection may have also contributed to the variation in the measured sound levels but its influence was overshadowed by the aforementioned factors. It should be noted that the distance between the barrier and the measurement locations was more than 300 m.

## 7.3/ Pavement Surface Type

The contribution of tire-pavement interaction noise increases with vehicle speed and often dominates traffic noise in most highway situations where the average operating speed of traffic flow approaches or exceeds 80 km/h. The tire-pavement interaction noise generating mechanisms is rather complex and depends mainly on pavement surface characteristics, tire type, number of tires, vehicle speed and vehicle weight. Nevertheless, the relative noise generation potential of typical pavement surfaces has been established and is summarized in Table 3.

Table 3/ Relative Change in Overall Sound Levels Due to Pavement Texture, dBA*

| Pavement Surface Type | dBA |
|---|---|
| ASHPALT CONCRETE PAVEMENTS | |
| Typical pavement (HL-1) | 0 |
| Open-graded friction course | -2 |
| Surface treatment | +5 |
| PORTLAND CONCRETE PAVEMENTS | |
| Used pavement | -1 |
| New, wire-brushed finish | +5 |
| New, plastic-grooved finish | +7 |

* For traffic flow containing about 10% of trucks with an average operating speed about 100 km/h. Pavements in good structural condition. Distance about 30 m from the centre-line. Results may vary by several decibels depending on actual pavement texture.

Data presented in Table 3 indicate that typical highway traffic travelling on an open-graded asphalt concrete pavement may be, on the average, about 9 dBA quieter than the same traffic travelling on a new plastic-grooved Portland cement concrete pavement. To reduce prediction errors, the influence of the pavement surface type on traffic noise generation should be explicitly included in highway noise predictions, preferably by modifying vehicular noise emission levels.

## 8/ SUMMARY AND CONCLUSIONS

1/ The prediction accuracy of the four highway noise prediction models evaluated in this study (FHWA, CMHC, RDG and ONTARIO) was relatively similar with the exception of the RDG model which was found deficient for non-freeway situations.

2/ Since the differences in prediction accuracies between the models are marginal, the model selection should be based on its analytical properties, flexibility and whether or not the model development will continue. On this basis, the FHWA method has been selected for the use of the Ontario Ministry of Transportation and Communications.

3/ The average prediction error which can be expected from the currently used highway traffic noise prediction methods employing only basic, customary variables is about 2 dBA in terms of standard deviation of differences between the predicted and actual sound levels.

4/ The prediction accuracy of the existing models can be improved by using vehicle emission levels reflecting actual vehicle population, by better characteriza- of the noise generation potential of different pavement surfaces and by inclusion of additional unconventional variables related to atmospheric propagation of sound over ground.

5/ Additional research is required to determine which parts of highway noise prediction methodology contribute most to the overall prediction error and thus are in greatest need of improvement.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