Development of Reference Energy Mean Emission Levels for Highway Traffic Noise in Florida

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Reference energy mean emission levels (REMELs) specific to Florida were developed. This became necessary because of an increase in the national speed limit from 55 to 65 mph on Interstate highways, changes in vehicle technology, and differences between emission levels measured in Florida and national averages. Past data bases specific to Florida were reviewed, data were collected and analyzed in the higher speed range of 55 to 70 mph (88 to 113 kph), and the final combined results of two Florida data bases were included in the computer program STAMINA 2.0. The work effort and results of developing and implementing the Florida-specific REMELs into the STAMINA 2.0 model are documented.

Noise prediction models help determine whether existing or planned roadways meet or will meet applicable noise criteria. The models are also used to design abatement measures. At the heart of these models, such as STAMINA 2.0 (*1*), are the reference energy mean emission levels (REMELs) for various vehicle types. These emission levels function as the basic building block of the model, representing the maximum, energy-averaged, A-weighted sound level of a specific vehicle type passing a location. Adjustments to this level can be made for other than reference conditions (e.g., at varying distances) and for multiple vehicle pass-bys (*2*). Accordingly, the accuracy of the reference level determines the accuracy of the model and the entire analysis. REMELs represent the maximum vehicle pass-by level, are a function of vehicle type and speed, and are fixed in space by defined distances and height during measurement. Updates are necessary to maintain or improve the accuracy of the mathematical model.

Two previously gathered data bases were determined to be directly relevant to Florida: a 1978 DOT report by Rickley et al. (*3*), which included four states, one being Florida, and a 1986 report by Dunn and Smart (*4*). The report by Rickley et al. was prepared under the authority of FHWA and will be referred as the FHWA report. The report by Dunn and Smart was similar to the FHWA report, and both determined speed-dependent equations using linear regression techniques to predict the REMELs. The equations as implemented from the FHWA report are as follows for automobiles, medium trucks, and heavy trucks, respectively (*2*), where S_{mph} is speed (mph):

$$(L_o)_{\mathrm{EA}} = 38.1\log S_{\mathrm{mph}} + 5.47 \qquad (1)$$

$$(L_o)_{\mathrm{EMT}} = 33.9\log S_{\mathrm{mph}} + 24.40 \qquad (2)$$

$$(L_o)_{\mathrm{EHT}} = 24.6\log S_{\mathrm{mph}} + 46.58 \qquad (3)$$

L_o represents vehicle-specific REMELs (dB). Subscripts A, MT, and HT refer to automobiles, medium trucks, and heavy trucks, respectively.

The data base collected by Dunn and Smart (*4*) is more recent, and REMEL values are specific to Florida roadways. The equations derived and reported from this later study for speeds (kph) are as follows for automobiles, medium trucks, and heavy trucks, respectively:

$$(L_o)_{\mathrm{EA}} = 32.283\log S + 10.803 \qquad (4)$$

$$(L_o)_{\mathrm{EMT}} = 23.221\log S + 36.129 \qquad (5)$$

$$(L_o)_{\mathrm{EHT}} = 14.058\log S + 56.234 \qquad (6)$$

where S is speed in kph.

A comparison of the FHWA and Dunn and Smart prediction equations is shown in Figure 1. As can be seen in the figure, automobiles tend to follow the same slope but are offset by roughly 2 to 3 dB (A-weighted). A review of medium truck data shows a fair agreement between the two linear regressions (see Figure 1). However, the two regression lines tend to diverge at the low and high speed ranges with the Dunn and Smart curve predicting lower sound levels at the higher speeds. Heavy trucks again show pronounced differences with somewhat good agreement at low speeds, but a strong divergence in the higher speed range is indicated.

These comparisons indicate either that changes in vehicle technology have occurred since the FHWA study or that regional trends make the Florida REMELs somewhat different. Accordingly, whereas the three vehicle types may be approximately characterized by the national reference levels, errors in prediction appear to occur.

Because the data base by Dunn and Smart lacked measurements in the higher speed ranges (greater than 55 mph), measurements of highway noise were taken at sites along the four Interstate highways in Florida to validate and extend the Florida data base. The actual data collection and subsequent data reduction were performed by the University of Central Florida (UCF) Civil and Environmental Engineering Department using the FHWA mobile noise laboratory. The measurements included individual pass-bys of highway vehicles divided into

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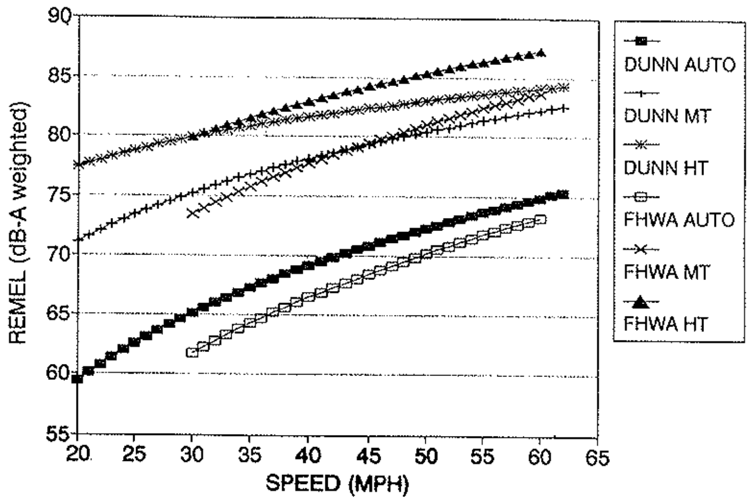


FIGURE 1 Comparison of REMELs by vehicle type.

the three standard categories depending on size, number of tires, and number of axles: automobiles, medium trucks, and heavy trucks. Concurrent measurements of vehicle speed and weather parameters were also performed.

METHODOLOGY AND RESULTS

Prescribed methodologies regarding equipment, site selection, measurement procedures, and analysis were carefully followed. The methodology used is described in this section.

Test Sites

To decrease the chance of site bias, one site along each Interstate highway within the state was selected for evaluation. Since 65 mph is only permitted outside urban areas, each site was away from many urban influences. Measurements were made between November 3, 1990, and April 2, 1991, and for safety considerations all measurements were made during daylight hours. Test site requirements were as follows:

- Only asphalt surfaces were used because of Florida's trend of using overlay asphalt exclusively on the Interstate highways, where the higher speed will occur.
- Only level, open sites were selected, free of large reflecting surfaces located near either the vehicle path or the microphones.
- Ground covering at all sites included a paved shoulder with predominantly low grass away from the highway.
- Only smooth, dry, level highway surfaces free of extraneous material such as gravel were selected.
- Ambient sound levels at least 10 dB (A-wt) lower than the level of the vehicle being measured were required.
- Freely flowing traffic was measured, operating under typical Interstate cruise conditions.
- A clear line of sight in either direction with an arc of 170 degrees was required to avoid possible errors.
- Microphones were located 50 ft from the centerline of the near lane of traffic, 5 ft above the pavement surface, and at multiple locations along the roadway to evaluate existing sound levels.

Three of the sites were weigh-in-motion stations, and the other was an unused weigh station. Each site had two lanes of traffic in each direction, separated by a median. At two sites no line power was available, so two portable power generators were required to provide electricity. Care was taken to shield the noise of the generators from the measurement area.

Instrumentation

Working closely with the Florida Department of Transportation (FDOT), UCF was able to obtain the FHWA mobile noise laboratory. The mobile laboratory included eight systems with ½-in. microphones and analyzers that permitted measurement of octave band data. Microphone cables (from 150 to 500 ft each) provided the capability to support microphone arrays. The output of the analyzers was fed through a specially designed interface to an IBM PC for data collection.

A portable meteorological station was also supplied by FDOT, and a system was available with the mobile laboratory. These systems provided a strip chart readout of ambient temperature, wind speed, and wind direction. FDOT also supplied a radar unit so that vehicle speeds could be determined. The vehicle speeds were measured just after the vehicle passed the microphone array to avoid influencing the speed of drivers who were using radar detectors. In addition, since only a single vehicle was passing, the research team was sure that the speed measurements were unbiased.

All measurement system specifications met or exceeded the recommendations outlined in the FHWA document *Sound Procedures for Measuring Highway Noise* (*5*).

Although only maximum sound levels were needed to develop REMELs, the equipment provided the capability to record the frequency spectra of each pass-by event in real time. These data provided a means to establish a very strict quality control methodology.

Operational Procedure

Instrumentation was deployed at each site according to methods outlined elsewhere (*5,6*). In addition to multiple microphones being used at the reference distance and height, other microphones were used at various locations along the roadway to permit further evaluation of the site characteristics and background sound levels. During data collection, the following criteria were strictly adhered to:

- Only individual vehicle pass-bys with sufficient separation between vehicles were measured to avoid unwanted vehicle noise.
- Test events included only vehicles traveling in the near lane, 50 ft from the reference microphones.
- No events were measured if the far lanes had truck traffic or perceptible automobile noise at the time of measurement.

The result of each sample was a histogram of the sound levels of individual vehicle pass-bys per time and frequency. The plots allowed determination of the maximum A-weighted sound level during any ⅛ sec as well as the change in frequency and amplitude for further considerations.

To ensure accurate data, calibrations (upscale and downscale) were performed at the beginning and end of each sample day.

Data Analysis

Data reduction was performed at the UCF campus using software developed by the Transportation System Center (TSC) especially for use with the mobile laboratory (*7*) and standard statistical software packages.

Before analysis, the data were carefully reviewed. The weather station's strip chart data were tabulated and searched for conditions that violated the defined meteorological criteria of excessive wind turbulence or wind gusts greater than 12 mph (*8*). Only one site was influenced in this way, and all suspect data were deleted from the data base. Any vehicles with greatly defective exhaust controls were noted during data collection, and data from these events (there were three) were discarded during data formatting. The data included loud or somewhat defective exhausts systems; data discarded were from vehicles that apparently had no exhaust controls and would be ticketed and removed from the fleet.

A "clean" vehicle pass-by was defined as a measured rise and fall of the sound level by 7 dB (A-wt) during passage of the vehicle in front of the microphones without being influenced by other noises. Several parameters could be identified and checked by plotting each pass-by using the TSC software.

As each pass-by was plotted, background levels were compared with the maximum pass-by sound level. Background levels were required to be at a minimum 10 dB down (A-weighted) from measured vehicle pass-by levels. This ensured that the maximum sound level was not biased by ambient events because of the logarithmic nature of decibels. This helped to ensure that the maximum level recorded was uninfluenced by other area sources as reported by the octave band analyzer.

To check that the upper limit of the octave band analyzers was not exceeded, any event that recorded an overload of any frequency (output parameter of analyzer) was further reviewed. If the event did indeed equal or surpass the upper limit of the equipment, the event was deleted.

To ensure that no data were included that may have been influenced by other vehicles, individual pass-by data plots were examined to ensure that no overlapping of peaks (in time) occurred.

After all criteria had been examined, each data point that passed all screening criteria was included in the final data base.

Calculation of REMELs

After quality control, the maximum pass-by sound levels per vehicle type (L_{oi}) were tabulated, and average pass-by levels for the multiple microphone array were calculated. The standard deviation (σ_o) of the sample distribution was also calculated.

As outlined elsewhere (*3*), $(L_o)_{Ei}$, or REMELs for prediction of L_{eq} values, are calculated from the relationship of the Gaussian probability density function and the acoustic pressure ratio. Mathematically this relationship may be reduced to

$$(L_o)_{Ei} = L_{oi} + 0.115\sigma_o^2 \quad (7)$$

Terms are as previously defined.

Use of linear regression techniques for speed band data lead to

$$(L_o)_i = A_i + B_i \log_{10} S \quad (8)$$

(S_{mph} may be used in Equation 8.) And for the overall distribution (aggregate data over all speeds of consideration),

$$(L_o)_{Ei} = A_i + B_i \log_{10} S + 0.115\sigma_o^2 \quad (9)$$

Here, $(L_o)_{Ei}$ is the developed REMEL over the entire applicable speed range used to predict L_{eq} values.

For this project, REMELs were computed in various ways to allow multiple reviews of the data.

Individual Site Analysis

During any in situ research, site bias must be considered. In an effort to avoid such bias, each of the four measurement sites was evaluated. First, average values and standard deviations were computed, and then linear regression analysis was used to determine predictive equations for maximum pass-by levels and REMELs for each site. By comparing the mean and variance for each site, it was determined that no site was significantly biased, although some differences occurred.

Speed Band Analysis

One way to approach building an equation for REMELs is to analyze the data by speed bands as previously stated. In other words, the data are grouped according to a user-defined speed range, an average value is calculated from all data in that speed range, and then linear regression techniques are applied. This analysis separates the data into smaller groups and provides another review of the data for uncharacteristic values. For this project, data were grouped in 2-mph ranges or speed bands for analysis. Average values for each speed band were then used to develop REMELs as previously described.

The speed band analysis showed good results with the exception of medium trucks. The large variation in this vehicle type's noise emission characteristics appear to be the cause of this scatter.

Aggregate Analysis

Data may also be analyzed using linear regression techniques for the data as a whole. This approach represents all measurements over the speed range of concern and was also used for this project. The advantage of this approach is that the linear regression analysis results more accurately reflect measurements at all speeds. Of course, average values of all reference microphones were still used to compute REMELs to avoid any bias that may have occurred from various analyzers.

A review of the automobile data indicated substantial scatter as expected, but a definite trend was apparent. This scatter is common for this type of data base. Some outliers exist [such as a measured level of greater than 84 dB (A-weighted)], but these values passed all quality control criteria and could not simply be discarded. Accordingly, some pass-by events may not be typical, but the overall averages are considered appropriate.

The overall measurements for medium trucks show much more scatter than do those for automobiles. The large degree of scatter for motor homes (considered medium trucks) is shown in Figure 2 and compared with the FHWA REMEL curve. Note that motor homes do not seem to fit in the medium truck or automobile classification. This scatter is as expected from a review of past research and the broad definition of medium trucks.

The heavy truck data analysis results showed that outliers still existed, but the trend was again quite obvious. Accordingly, the data collection effort was successful.

COMPARISON OF THE ANALYSIS RESULTS AND PAST DATA BASES

After all data were evaluated for sites, speed bands, and in the aggregate, a comparison of the data was necessary for validation and extension of the defined REMELs to be used in Florida. Comparisons were begun by plotting the derived REMEL data from the previous reports (FHWA and Dunn and Smart) and this project (Wayson et al.) for each vehicle type versus speed and reviewing the differences of the data.

The comparison for automobiles is shown in Figure 3. Medium and heavy trucks are shown in Figures 4 and 5, respectively. For this comparison, as well as for trucks, the lower speed ranges have been omitted in the graphs for clarity. The reason is that the project data were primarily to supplement Dunn and Smart's data for the higher speed ranges, and measurements during this project were made on Interstate highways where speeds seldom dropped below 55 mph. The Dunn and Smart and FHWA REMELs extend to the lower speed ranges and so are shown down to 45 mph for comparative purposes. The project data are listed as WAYSON1 for the aggregate analysis and WAYSON2 for the speed band analysis. The plot for WAYSON2 was derived for 2-mph bands but is plotted in 1-mph increments to allow a smooth curve in the figure.

The data were statistically tested, using a 95 per cent confidence limit, to determine whether they could be considered to belong to the same distribution as the Dunn and Smart or FHWA data. It would have been desirable to include the FHWA and Dunn and Smart data error bands, but this was not practical due to the specific data requirements of these past data bases. Figure 3 shows the automobile data with error bands included, whereas Figures 4 and 5 show the same analysis for medium and heavy trucks. The statistical testing veri-

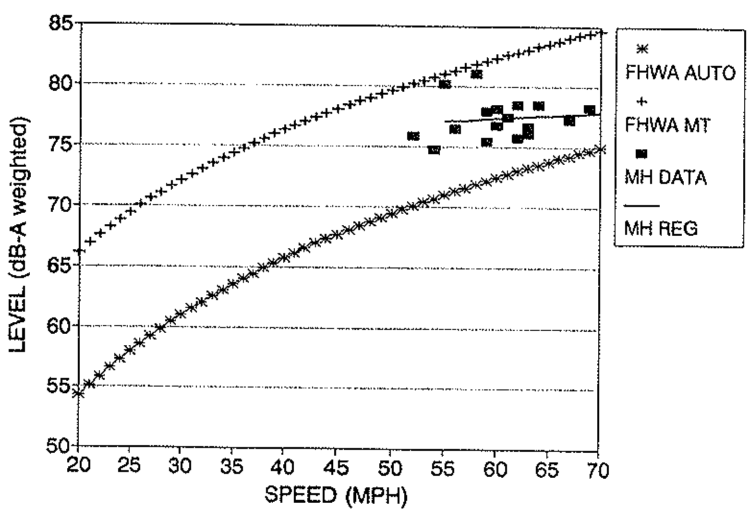


FIGURE 2 L_{max} **comparison, FHWA automobile and medium trucks with measured levels for motor homes.**

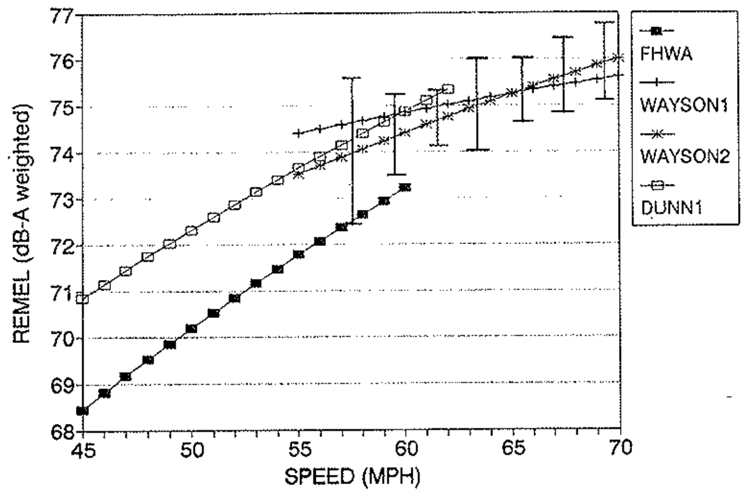


FIGURE 3 Comparison of REMEL models—automobiles.

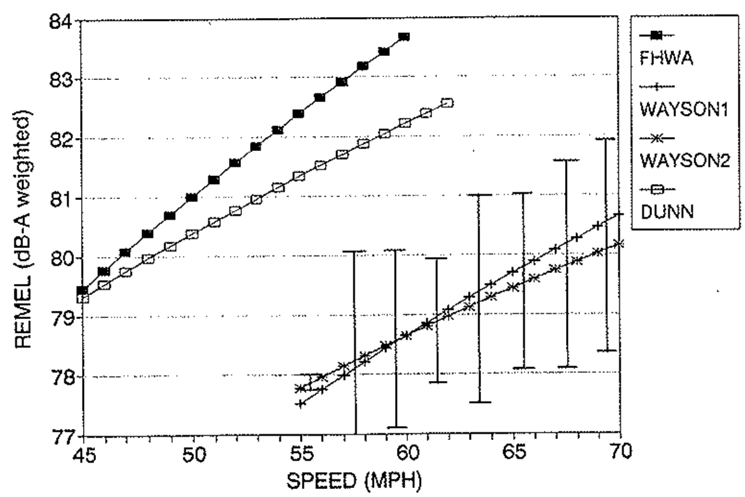


FIGURE 4 Comparison of REMEL models—medium trucks.

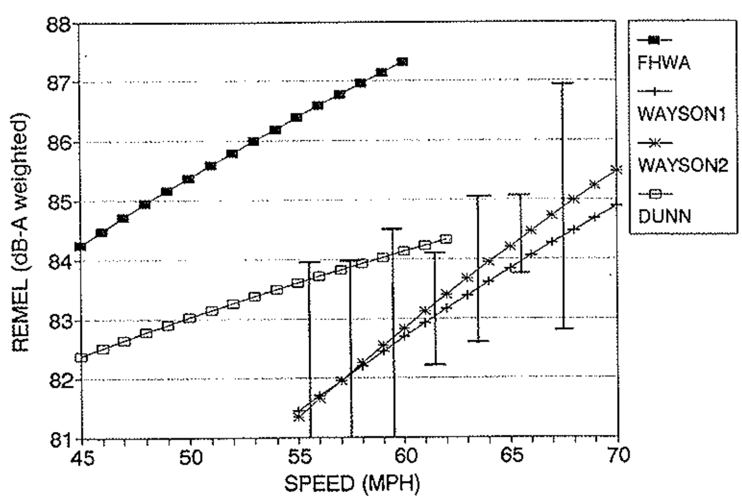


FIGURE 5 Comparison of REMEL models—heavy trucks.

fies that the Dunn and Smart and the measured data are compatible for cars and heavy trucks, as shown by the error limit bars in Figures 3 and 5. The very good agreement for automobiles is notable. For these two vehicle types, extension of the Dunn and Smart data base to 70 mph is considered statistically valid.

Figures 3 and 5 also show that the FHWA REMELs may be statistically different, and the previous opinion that the REMELs should be updated for Florida appears to be justified.

A review of the comparison for medium trucks does not show such close agreement (see Figure 4). Whereas the slopes are similar, the linear regression lines are offset by approximately 3 dB from Dunn and Smart. A difference of approximately 4 dB occurs between the project data and FHWA. When the 95 percent confidence limit was evaluated, statistical differences between the measured data, Dunn and Smart, and FHWA are apparent, as shown in Figure 4. Many hours were spent searching for errors in the project data base because of this comparison. After considerable effort, one reason is apparent. For the medium truck category, considerable leeway in the interpretation of the vehicle type occurs, as previously discussed. A review of the FHWA data shows that medium trucks are only specified as two-axle vehicles with six tires. Motor homes were not as prevalent in the early 1970s as they are today, and they most likely were included in very small numbers, if at all, in the FHWA data base. Dunn and Smart specifically point out that such vehicles were not included. Accordingly, since a significant portion of the project data base included such vehicles as motor homes, the sound levels tend to be lower.

As a check of this hypothesis, the project data base was searched and motor homes were deleted, which reduced the data base for medium trucks from 67 to 42 events. Figure 6 shows the relationship determined from this analysis. Figure 6 shows that the slope remains relatively unchanged, but the offset from the Dunn and Smart and FHWA curves is decreased by about 1 dB, resulting in a closer agreement of the data bases. With this change, Dunn and Smart's data base could be considered statistically the same as shown by the 95 percent confidence limits. Again, the FHWA data base does not appear to be statistically the same.

However, there is still roughly a 2-dB difference that cannot be explained unless other considerations such as pavement type are included. The lower speed data presented by Dunn and Smart included concrete pavements. Measurements for this project were done for the higher speed ranges on Interstate highways (>55 mph), which are all going to asphalt overlay in Florida, and concrete was not considered.

This analysis led to two possible conclusions: (*a*) medium trucks should be separated into at least two vehicle classes as discussed before or (*b*) pavement types influenced the data collection effort. The difference is not quantifiable without further extensive research. It is debatable which is the proper approach. One thought is to include mobile homes, since they are such a large percentage of the medium truck fleet in Florida (more than 37 percent of the random sample base). Another is to take the conservative approach and use the higher medium truck REMELs that do not include motor homes. For this project it was decided motor homes would be eliminated from the medium truck category. In this way, abatement may be slightly overdesigned, but not inadequate. Also, medium trucks represent the smallest category in terms of vehicle counts, which tends to lessen any expected error in predictions. This permitted the extension of Dunn and Smart's REMEL curve (it was realized that there might be a slight overprediction.

The comparison for heavy trucks is presented in Figure 5. As pointed out before, the data from Dunn and Smart show a much flatter curve than the FHWA REMEL linear regression curve. Whereas the project data have a much steeper slope, due to the small speed range used during data collection, the levels validate the Dunn and Smart study when the error limits are evaluated. It appears that a citation in the FHWA four-state study suggesting that overprediction may occur using the DOT four-state data in Florida may be correct. The FHWA text indicates that the prediction model (2) performed better for Florida when Florida-specific REMELs were used.

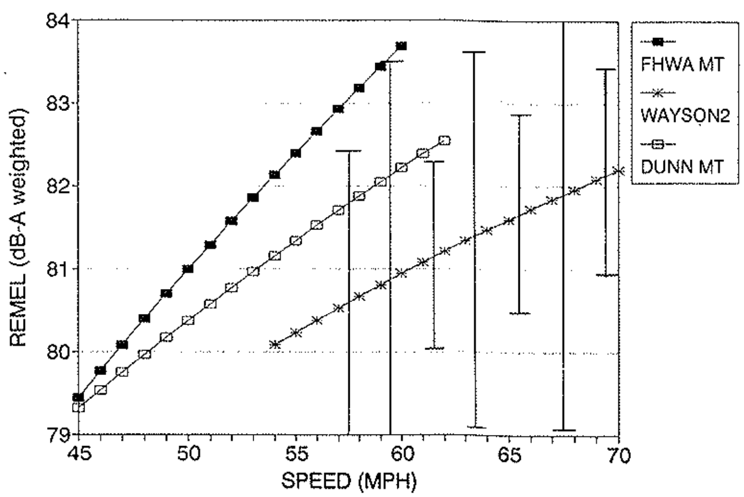


FIGURE 6 Comparison of REMEL models—medium trucks excluding motor homes.

IMPLEMENTATION

To derive the appropriate REMEL regression parameters, slope and y-intercept, linear regression analysis using the mean values of both data bases (Dunn and Smart and WAYSON2) was used. The solid lines in Figure 7 show the results of the best fit curve for automobiles, medium trucks, and heavy trucks, respectively. Figure 7b is shown with all medium truck data included.

Figure 7a (the results for automobiles) shows a good relationship for the final REMEL curve when the Dunn and Smart data base and the project speed band data (WAYSON2) are combined. The speed band data (WAYSON2) were used because it is the first method presented in *Determination of Reference Energy Mean Emission Levels* (6) and as such was considered to be the preferred method. Use of either the aggregate or speed band measured project data would have provided very similar results, so either could have been selected. The developed linear regression line shown for automobiles is

$$(L_o)_{EA} = 31.130\log(S) + 12.777 \quad (10)$$

The best fit for medium trucks, using the same method as for automobiles and all medium truck data, is shown in Figure 7b. This fit corresponds to

$$(L_o)_{EMT} = 16.951\log(S) + 46.775 \quad (11)$$

The same problem exists as described previously: noncompatibility of the two data bases leading to a large error at the higher speed. On the basis of the conservative approach previously discussed (elimination of motor homes), the following linear regression equation was derived and is plotted in Figure 7c:

$$(L_o)_{EMT} = 18.765\log(S) + 43.697 \quad (12)$$

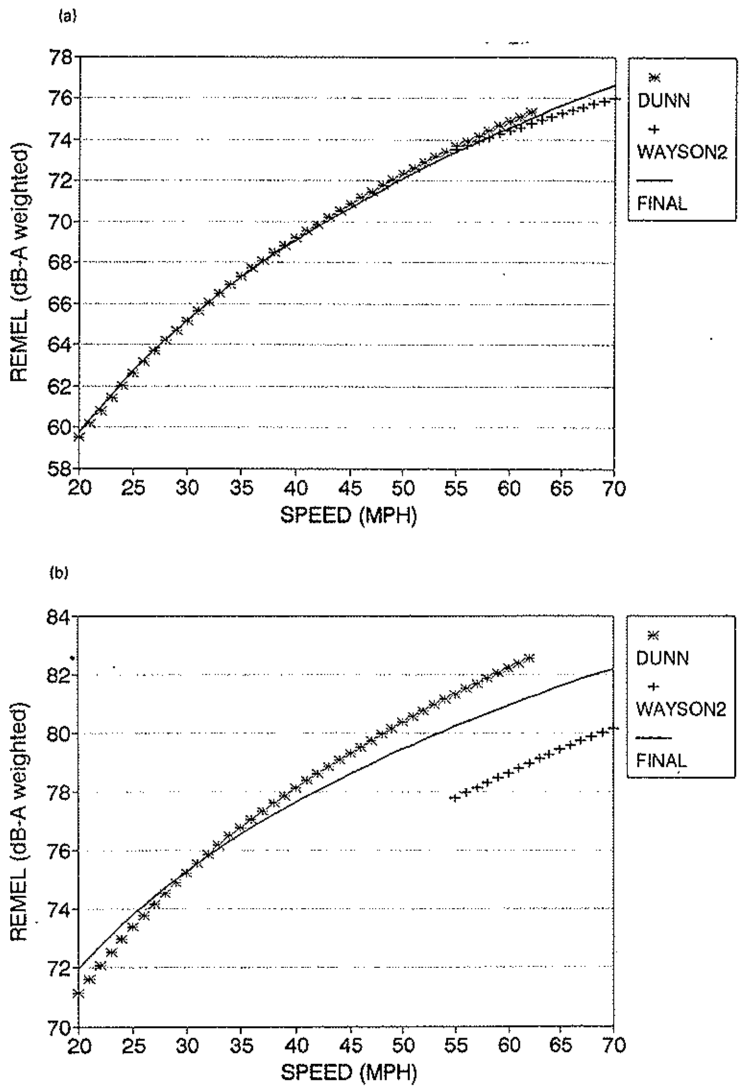
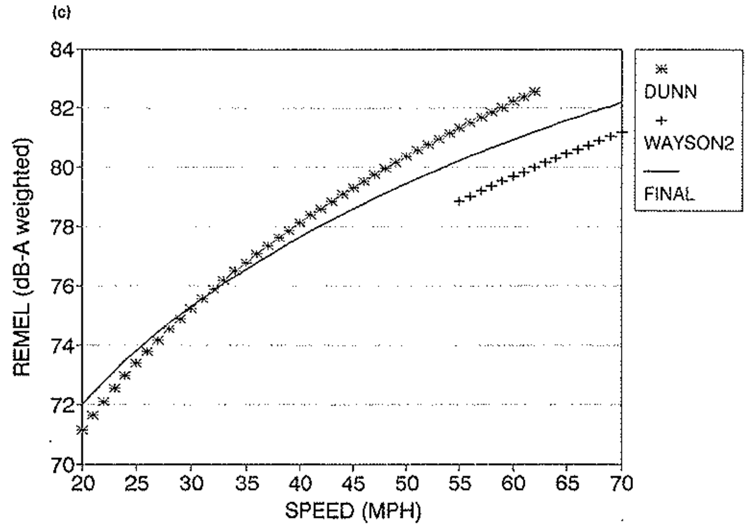


FIGURE 7 Derived REMELs: (*a*) automobiles, (*b*) medium trucks, (*c*) medium trucks excluding motor homes, and (*d*) heavy trucks. ***(Continued on next page)***



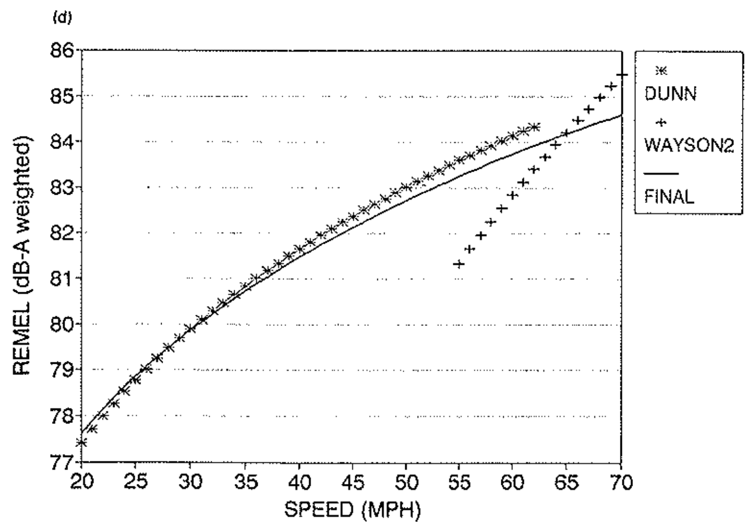


FIGURE 7 *(continued)*

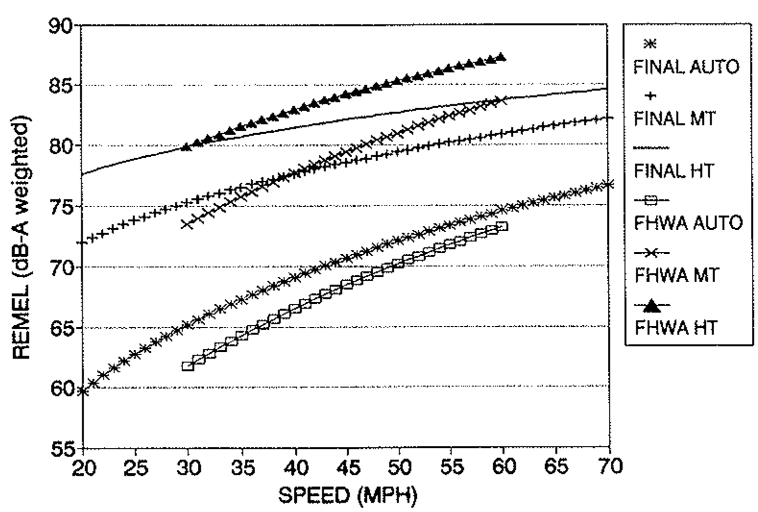


FIGURE 8 Comparison of FHWA with final REMELs.

This led to a much better fit of the data for the final derived curve.

Figure 7d is a graph of the heavy truck results for best fit. Although the slope of the project data appears to be too steep, probably because of the smaller data base only taken at the higher speeds, the regression analysis still verifies the Dunn and Smart data, and the derived curve appears to fit the two data bases well. The equation for this linear regression is

$$(L_o)_{EHT} = 12.831\log(S) + 58.270 \quad (13)$$

For the three vehicle types, then, Equations 10, 12, and 13 are recommended for implementation. The final recommended speed range to be used is 20 to 70 mph. These curves, compared with the FHWA curves they are intended to replace, are plotted in Figure 8.

The preceding results have been incorporated into STAMINA 2.0, and testing has been accomplished. Several lines of the FORTRAN program were changed to implement the results of the newly developed REMELs and the increased speed range.

OTHER FINDINGS

Work to study the changes in vehicle frequency spectra observed with changes in speed has begun. This is important since STAMINA now uses a frequency of 500 Hz during barrier analysis. A comparison of A-weighted ⅓ octave band frequency spectra of measured vehicle pass-bys for automobiles, medium trucks, and heavy trucks is shown in Figure 9. This small sampling indicates that the dominant frequency does not correlate well with a value of 500 Hz. Also, the spectra tend to shift to the higher frequency ranges as tire noise frequency increases with speed.

Analysis of these specific examples indicates that vehicle speed can have a visible effect on higher frequency sound levels. However, the changes in the lower frequency sound levels due to differences in vehicle speed are not as obvious and will require further analysis. Ongoing research is being performed at UCF to determine whether any trend in spectral changes exists, and, if so, to what extent the trend occurs and how it can be predicted.

Another important finding came out of this research. It appears that the three basic vehicle types should be expanded to at least four types. This is necessary because, whereas automobiles and heavy trucks tend to validate past studies, the medium truck category has a large variance attributable to the definition of the vehicle type. Since multiple vehicle types are needed for air pollution studies and are available, consideration should be given to expanding vehicle types.

CONCLUSIONS

Several conclusions can be drawn from this research. First and most important, the primary goal of the research, to validate and extend the range of the REMELs, has been accomplished. Using the lower speed range data reported by Dunn and Smart (*4*) and the project data collection effort, equations were derived from 20 to 70 mph. Equations 10, 12,

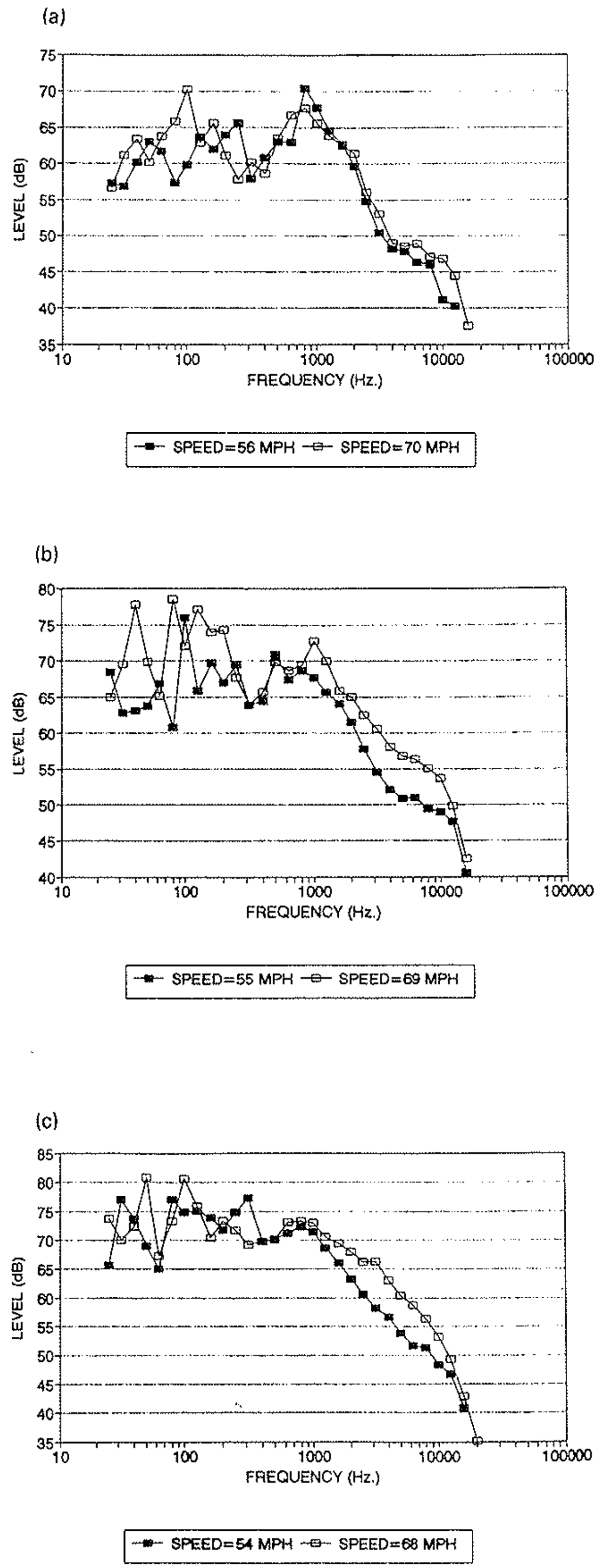


FIGURE 9 Comparison of frequency spectra for vehicles traveling at two speeds: (*a*) automobiles, (*b*) medium trucks, and (*c*) heavy trucks.

and 13 are considered to be the best fit of the Florida data bases using a linear regression analysis approach. These equations have been implemented in the computer program STAMINA 2.0 and tested.

The results of the measurements and developed emission levels show that the national reference levels (*2*) tend to underpredict for cars, overpredict for medium trucks in the higher speed ranges, and overpredict for heavy trucks. This could lead to significant errors in predictions and abatement considerations.

Another finding is that the three basic vehicle types may need to be expanded to at least four types. This appears necessary because, although automobiles and heavy trucks tend to validate past studies, the medium truck category has shown a large variance, most likely due to the very broad definition of the vehicle type. Multiple vehicle types are needed for air pollution studies and are available. More work is needed to determine the true return in accuracy for the increased effort.

The vehicle frequency spectra observed did not compare well with the basic frequency of 500 Hz used in STAMINA 2.0 during barrier analysis. Since frequency is a primary factor in wall height, additional considerations, such as multiple frequency analysis during barrier design, may be warranted.

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