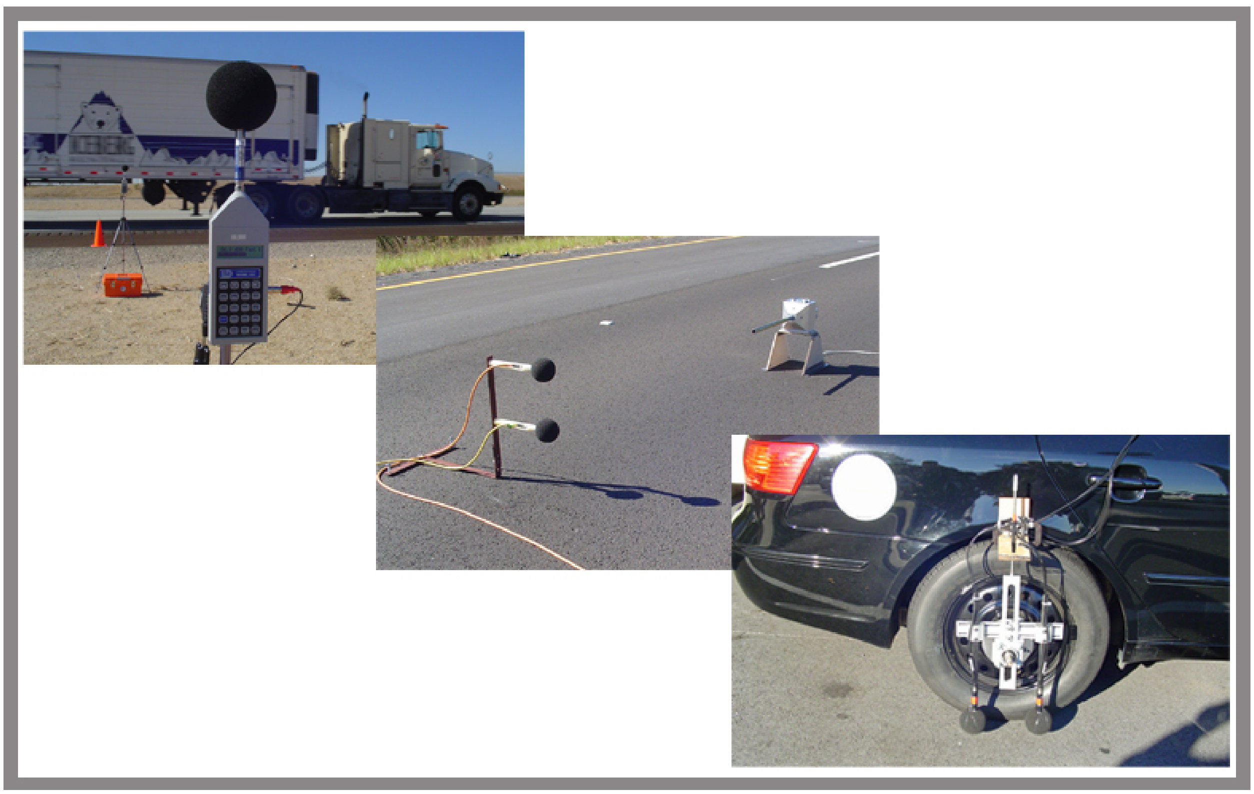
FHWA-HEP
DOT-VNTSC-FHWA-12-01

January 2012
Final Report

FHWA Traffic Noise Model (TNM) Pavement Effects Implementation Study: Progress Report 1



Prepared for:
United States Department of Transportation
Federal Highway Administration
Office of Pavement Technology
Office of Natural Environment
Washington, DC 20590

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE January 2012	3. REPORT TYPE AND DATES COVERED Final Report

4. TITLE AND SUBTITLE FHWA Traffic Noise Model (TNM) Pavement Effects Implementation Study: Progress Report 1	5. FUNDING NUMBERS HW66 / JL172
6. AUTHOR(S) Judith L. Rochat, Aaron L. Hastings, David R. Read, Michael Lau	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Research and Innovative Technology Administration John A. Volpe National Transportation Systems Center Environmental Measurement and Modeling Division, RVT-41 Acoustics Facility Cambridge, MA 02142	8. PERFORMING ORGANIZATION REPORT NUMBER DOT-VNTSC-FHWA-12-01
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Highway Administration (FHWA) Office of Pavement Technology Office of Natural Environment Washington, DC 20590	10.SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
FHWA program managers: Mark Swanlund, Mark Ferroni, Adam Alexander

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The Volpe Center Acoustics Facility, in support of the Federal Highway Administration (FHWA), investigated the implementation of pavement effects in the FHWA Traffic Noise Model (TNM). Three options were considered, resulting in the recommendation of two options: 1) implementation of user-defined pavement-specific emission levels (REMELs), with proof of adequate data; and 2) implementation of on-board sound intensity (OBSI)-adjusted tire/pavement noise source levels, implemented as a large database in the FHWA TNM and also as a user-defined option. Each option would also include adjusting for the pavement sound absorption by applying pavement-specific effective flow resistivity (EFR) values.

14. SUBJECT TERMS FHWA Traffic Noise Model, TNM, highway traffic noise, tire/pavement interaction noise, REMEL, on-board sound intensity (OBSI), sound absorption, effective flow resistivity, EFR, asphalt pavements, concrete pavements	15. NUMBER OF PAGES 110
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

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[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

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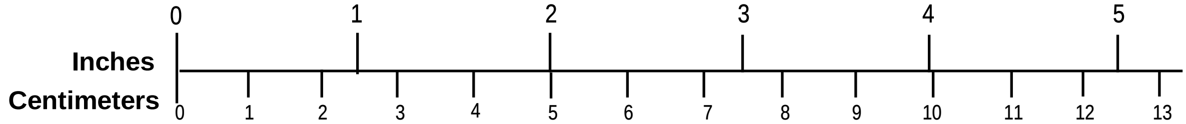
QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

ACKNOWLEDGEMENTS

The authors wish to thank the Federal Highway Administration (FHWA) for their vision and support of this study. The authors also wish to thank several U.S. State highway agencies and other organizations for cooperation in data collection logistics, sharing data, and discussions involving various aspects of this study; this includes: California Department of Transportation, Arizona Department of Transportation, Ohio Department of Transportation, Massachusetts Department of Transportation, The Transtec Group, and Illingworth & Rodkin. In addition to the authors conducting field measurements, other folks were also involved; the authors wish to thank Mark Ferroni, Adam Alexander, Trevor May, and Gina Barberio.

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EXECUTIVE SUMMARY

Tire/pavement noise substantially contributes to the overall highway traffic noise levels at highway speeds. Studies around the world, many conducted in the last 10 years, have shown that there are measureable noise level differences among roadway pavement types. As such, selection of pavement type for a highway can impact the amount of noise received in nearby communities.

It has been traditional for noise prediction models to use a reference pavement (either a national average or standard pavement type) to determine noise impacts and design noise abatement. More recently, the current understanding of the effects of pavement on noise has prompted policy makers and highway noise prediction software developers around the world to investigate the implementation of pavement effects into their models. At this point in time, enough information is known about the effects of pavements to understand that *not* accounting for the effects can lead to under- or over-predictions in sound levels.

Because there are still many questions to be answered concerning noise-related pavement benefits (e.g., amount of community benefit, longevity of benefit, etc.) for a large array of specific pavement types, the U.S. Federal Highway Administration (FHWA) is keeping with its long-standing requirement to use a national average pavement type for future highway noise predictions. As pavement noise studies progress, federal noise policy is being examined for potential changes. The FHWA Traffic Noise Model® (FHWA TNM) is directly linked to 23 Code of Federal Regulations, Part 772, and it must be used for noise predictions on highway projects receiving Federal aid. The FHWA TNM Pavement Effects Implementation Study was initiated to help determine how to incorporate a broad range of pavement effects in the FHWA TNM. This study is being conducted by the U.S. Department of Transportation / Volpe National Transportation Systems Center.

For the FHWA TNM Pavement Effects Implementation Study, three implementation options were considered:

1. integrating new data into the FHWA TNM vehicle noise database (REMEL) for specific pavement types and also adjusting the roadway effective flow resistivity (EFR, a measure of sound absorption);
2. adjusting the existing tire/pavement source level in the FHWA TNM using on-board sound intensity (OBSI) data and also adjusting the roadway EFR; and
3. applying a pavement type offset adjustment value to the predicted sound levels (post FHWA TNM calculations).

Investigations of pavement-specific REMELs, OBSI-adjustments, and EFR-adjustments allowed for the determination of the validity of each option.

Implementation Option 1 was determined to be a valid option for implementing pavement-specific effects in the FHWA TNM, assuming the REMEL data set collected is adequate, as described in Appendix B. Adequacy is determined based on the number of data points, number of sites represented, range of speeds, and tonal qualities of the average spectrum. Prior to implementation, further work required for this option includes the following:

- formalize the data adequacy-analysis-process;
- further validate the use of pavement-specific REMELs by comparing predicted data to measured data (include adjusting the pavement EFR value); and
- modify the software to allow for functionality and user input.

Because this option would require extensive cost- and time-prohibitive data collection in order to generate a database for the FHWA TNM for a broad array of pavement types, this option should be left open to FHWA TNM users; they would need to get FHWA approval prior to implementation.

Implementation Option 2 was determined to be a valid option for implementing pavement-specific effects in the FHWA TNM. Prior to implementation, further work required for this option includes the following:

- develop a large OBSI-adjustment database through additional data collection and by obtaining data from other organizations, as it becomes available;

- determine pavement groupings and the number of data points adequate to represent each group;
- develop an EFR database adequate to support each pavement group;
- further investigate the applicability of the OBSI adjustment to each vehicle type; and
- modify the software to allow for functionality and user input.

Because a large OBSI database already exists and is relatively efficient to augment, it is intended that the adjustment database will be included in a future version of the FHWA TNM. In addition, user-defined OBSI adjustments should be an option for FHWA TNM users; they would need to get FHWA approval prior to implementation.

Implementation Option 3 was determined not to be a valid option since current efforts established that pavement effects are distance-dependent and site-geometry dependent, and therefore, adjusting predicted sound levels by a single decibel offset or adjustment value would be inaccurate in many cases.

1. INTRODUCTION

1.1 Background

Highway traffic noise is comprised of sound from many vehicle types and many sources for each vehicle. One commonality among vehicle types is that the tire/pavement noise source substantially contributes to the overall highway traffic noise levels at highway speeds. Tire/pavement interaction noise studies have shown that there are measureable noise level differences among roadway pavement types. Such studies include international data [Sandberg 2002] [Gibbs 2005] and data from states and research centers throughout the U.S., such as Arizona [Scofield 2003][ADOT 2006][ADOT QPPP], California [Caltrans 2005][Caltrans 2010], Colorado [Hanson 2006][Rasmussen 2009], Florida [Wayson 2009], Kansas [Brennan 2006], New Jersey [Bennet 2004], Ohio [ODOT 2005], Texas [Trevino 2009-1][Trevino 2009-2], Virginia [McGhee 2009][McGhee 2010], Washington [Sexton 2010], National Center for Asphalt Technology [Fortier Smit 2008], National Concrete Pavement Technology Center [Rasmussen 2008], and MnROAD [Izevbekhai 2007]. (Note: A synthesis of these references can be found in Sohaney 2011.)

Because there are still many questions to be answered concerning noise-related pavement benefits (e.g., amount and longevity of community benefit, etc.) for a large array of specific pavement types, the U.S. Federal Highway Administration (FHWA) is keeping with its long-standing requirement to use a national average pavement type for future highway noise predictions. As pavement noise studies progress, Federal noise policy is being examined for potential changes. The FHWA Traffic Noise Model® (FHWA TNM) [Anderson 1998][Menge 1998] is directly linked to 23 Code of Federal Regulations, Part 772, and it must be used for noise predictions on highway projects receiving Federal aid. The FHWA TNM Pavement Effects Implementation Study was initiated to help determine how to incorporate a broad range of pavement effects in the FHWA TNM.* This study is being conducted by the U.S. Department of Transportation / Volpe National Transportation Systems Center.

* It should be noted that the future of highway noise prediction includes accounting for the effects of various pavement types. At this point in time, enough information is known about the effects of pavements to understand that *not* accounting for the effects can lead to under- or over-predictions in sound levels. Internationally, efforts are already well underway to account for the effects of pavements.

Three possible options were considered for implementing pavement effects in the FHWA TNM:

Implementation Option 1): integrating new data into the FHWA TNM vehicle noise database (Reference Energy Mean Emission Levels or REMELs, [Fleming 1995]) for specific pavement types and also adjusting the roadway effective flow resistivity (EFR, a measure of sound absorption);

Implementation Option 2): adjusting the existing tire/pavement source level in the FHWA TNM and also adjusting the roadway EFR for specific pavement types; and

Implementation Option 3): applying a pavement type offset adjustment value to the predicted sound levels (post FHWA TNM calculations).

1.2 Study Overview and Report Organization

This report describes three different investigations:

- Section 2 of this report discusses the use of pavement-specific noise emission levels (applicable to Implementation Option 1; includes study of distance-related effects also applicable to Implementation Option 3);
- Section 3 discusses the use of pavement-specific tire/pavement source level adjustments (applicable to Implementation Option 2); and
- Section 4 discusses the use of pavement-specific sound absorption values (applicable to Implementation Options 1 & 2).

In each section, data collection, data analysis, implementation methodology, and validity of the methodology are described. Section 5 of this report includes conclusions regarding each of the investigations, as well as recommendations for each implementation option listed in Section 1.1.

2. INVESTIGATING USE OF PAVEMENT-SPECIFIC NOISE EMISSION LEVELS

This section addresses elements applicable to two of the Implementation Options listed in Section 1.1.

Section 2.1 provides a brief review of the vehicle noise emission data base in the FHWA TNM (Reference Energy Mean Emission Levels or REMELs [Fleming 1995]). Section 2.2 then describes investigations using REMELs currently in the FHWA TNM to assess Implementation Option 3: adjusting the predicted sound levels (post FHWA TNM calculations). Next, Section 2.3 describes the investigation of using pavement-specific noise emission levels, to help assess Implementation Option 1: integrating new REMEL data into the FHWA TNM for specific pavement types and also adjusting the roadway effective flow resistivity (EFR, a measure of sound absorption).

Section 2.4 describes steps to assess the adequacy of a pavement-specific data set. This is followed by Section 2.5, where implementation recommendations are made.

2.1 FHWA TNM Reference Energy Mean Emission Levels Overview

The FHWA TNM uses Reference Energy Mean Emission Levels or REMELs [Fleming 1995] as the foundation of its source sound level computations. TNM has REMEL data for two vehicle operating conditions: cruise and full-throttle; and five standard vehicle types: automobiles, medium trucks, heavy trucks, buses, and motorcycles. TNM also has the ability to accept limited REMEL data for user-defined vehicle types. FHWA TNM v2.5 (the current version of the model as of the date of this report) and all previous versions include vehicle noise emission levels for three pavement types, listed in order from loudest to quietest: Portland Cement Concrete (PCC), Dense-Graded Asphaltic Concrete (DGAC), and Open-Graded Asphaltic Concrete (OGAC). Each of these is an average for a broad pavement category, and it is recognized that there can be substantial sound level variation within each category and overlap among categories. For highway projects receiving federal aid, it is required that highway noise impact analyses be conducted using “Average” pavement, which is an average of the DGAC and

PCC vehicle noise emission levels, except under a special program with FHWA*.

The REMEL database was calculated from approximately 6000 measured individual vehicle pass-by events, where maximum sound levels were extracted for each at a distance of 50 feet (15.2 meters) from the center of the vehicle travel lane and a height of 5 feet (1.5 meters) above the roadway plane. A regression analysis was applied to determine equation coefficients for input to the FHWA TNM, where the coefficients are dependent on the following: vehicle type (automobile, medium truck, heavy truck, bus, motorcycle), operating condition (cruise or full throttle), and pavement type (PCC, DGAC, OGAC, Average).

2.2 Noise Emission Levels and Associated Pavements in FHWA TNM v2.5 – Examining Distance Dependence of Pavement Effects

Using two of the general pavement types currently in the FHWA TNM (PCC and OGAC), an investigation was conducted to help determine the validity of Implementation Option 3 (see Section 1.1). Options 1 and 2 require that the *source* sound levels are adjusted to include effects of specific pavements, and Option 3 requires that the *received* sound levels are adjusted to include the effects of specific pavements. With a single adjustment value applied per pavement type, Option 3 could only be considered valid if the pavement effects were not dependent on distance from the roadway. A study was conducted with the general pavement categories available in FHWA TNM v2.5 to determine if pavement effects are distance-dependent.

Using FHWA TNM v2.5, a one-lane roadway with mixed traffic was modeled, with receivers placed 50-1600 feet (15-488 meters) from the center of the roadway lane. The following parameters were also examined:

- roadway elevation: on flat site [with and without a 14-ft (4-m) wall noise barrier]; roadway depressed 10 feet (3 meters); roadway elevated 10 feet (3 meters)
- pavement type: OGAC (quieter pavement); PCC (louder pavement) on roadway
- ground type: acoustically hard ground; acoustically soft ground (between the roadway and receivers)

Predicted sound levels were calculated on broadband and 1/3-octave band bases.

* http://www.fhwa.dot.gov/environment/noise/regulations_and_guidance/qpppeml.cfm

Figures 1-3 show results from this investigation. Figure 1 shows predicted sound levels as a function of distance for the flat site without a noise barrier, for louder and quieter pavement and for acoustically hard and soft ground. Figure 2 shows the predicted noise reductions (louder pavement minus quieter pavement) as a function of distance, for a flat site with acoustically hard and soft ground, a barrier site, a site with an elevated road, and a site with a depressed road. Figures 1 and 2 indicate that, in general, for a flat site, over acoustically soft ground, the difference between louder and quieter pavement decreases with increasing distance and eventually diminishes altogether. For hard ground, there is a similar effect, although the difference between louder and quieter pavement decreases less rapidly than for soft ground.

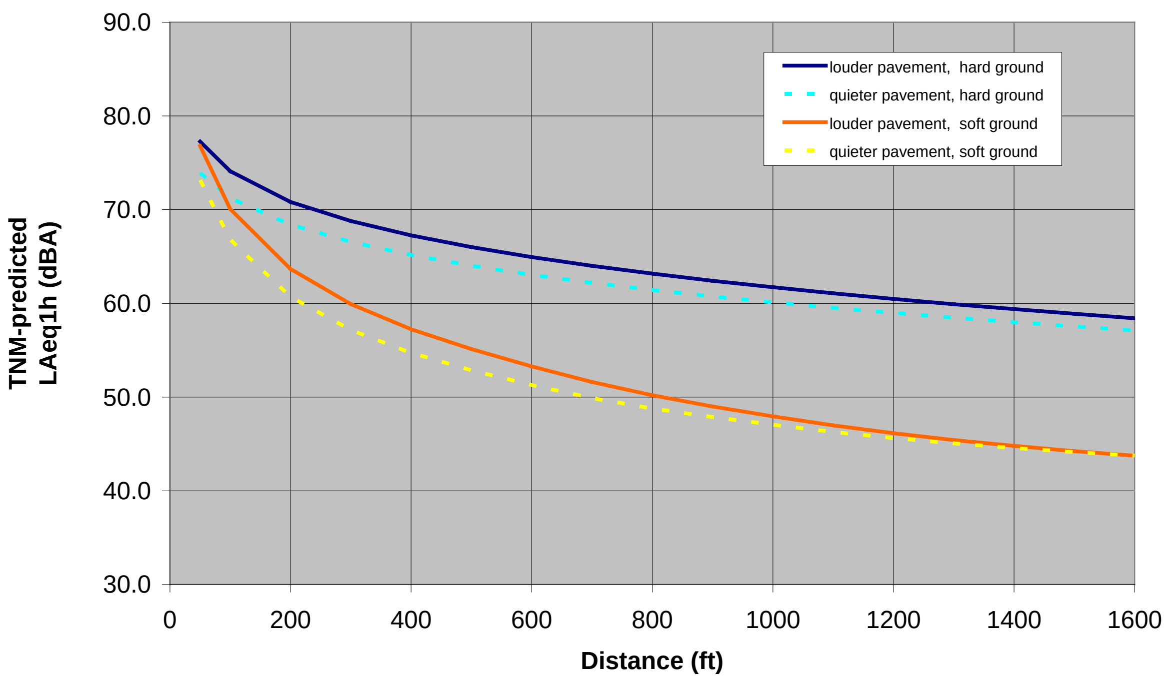


Figure 1. TNM-predicted sound pressure levels (L_{Aeq1h}) as a function of distance – flat site, no noise barrier. Variables: louder and quieter pavement, acoustically hard and soft ground.

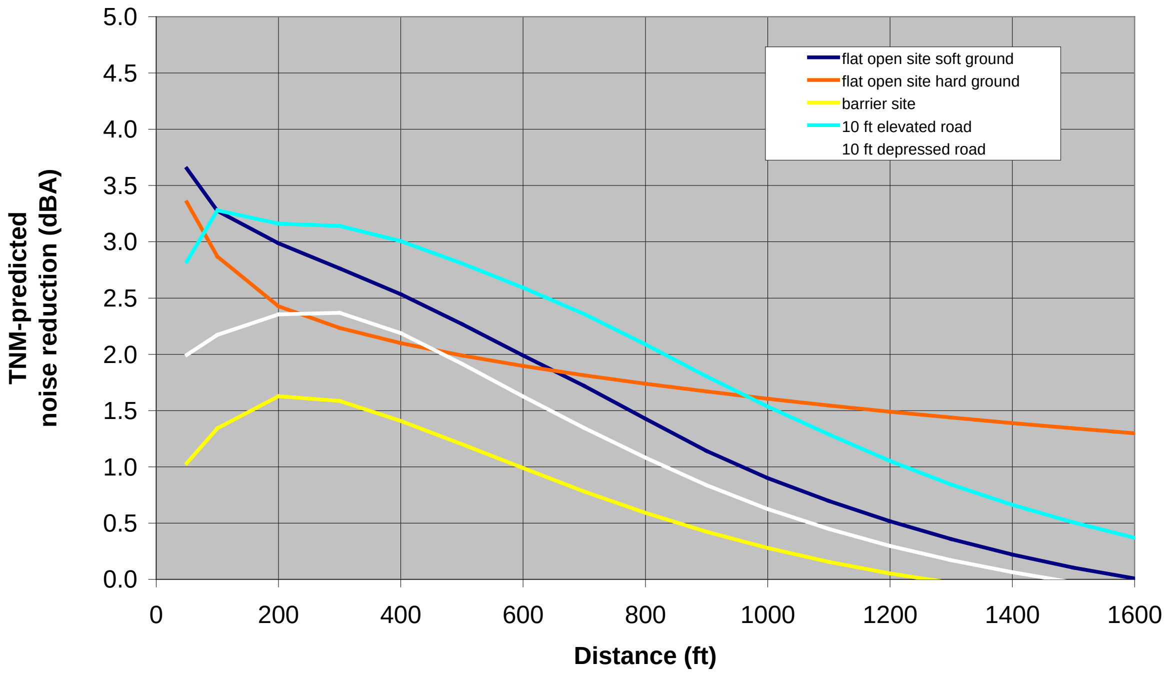


Figure 2. TNM-predicted noise reductions (L_{Aeq1h} for louder pavement minus quieter pavement) as a function of distance. Variables: flat site (with acoustically hard and soft ground), barrier site, elevated road, depressed road.

The spectral data results shown in Figure 3 help to explain the broadband level results seen in Figures 1 and 2. Figure 3 shows predicted 1/3 octave band sound levels as a function of distance for the flat site without a noise barrier and acoustically soft ground, for three distances (50, 500, and 1000 feet or 15, 152, and 305 meters) and for louder and quieter pavement. It can be seen that the spectral differences between the louder and quieter pavements occur in the 1/3-octave bands of 500 Hz and up; the sound levels are essentially the same for the lower frequencies. As the sound propagates, higher frequency energy dissipates more rapidly than lower frequency energy from the effects of propagation. At 50 feet (15 m), the dominant frequency range from 500 to 3150 Hz controls the broadband sound level. Out at 1000 feet (305 m), the frequency range of 80 to 250 Hz is contributing the most to the broadband sound level, with the range of 630 to 3150 Hz also contributing. As distance increases, lower frequencies become more dominant. Since there is little to no difference in sound levels between pavement types in the lower frequency range, noise reduction due to the quieter pavement diminishes over distance.

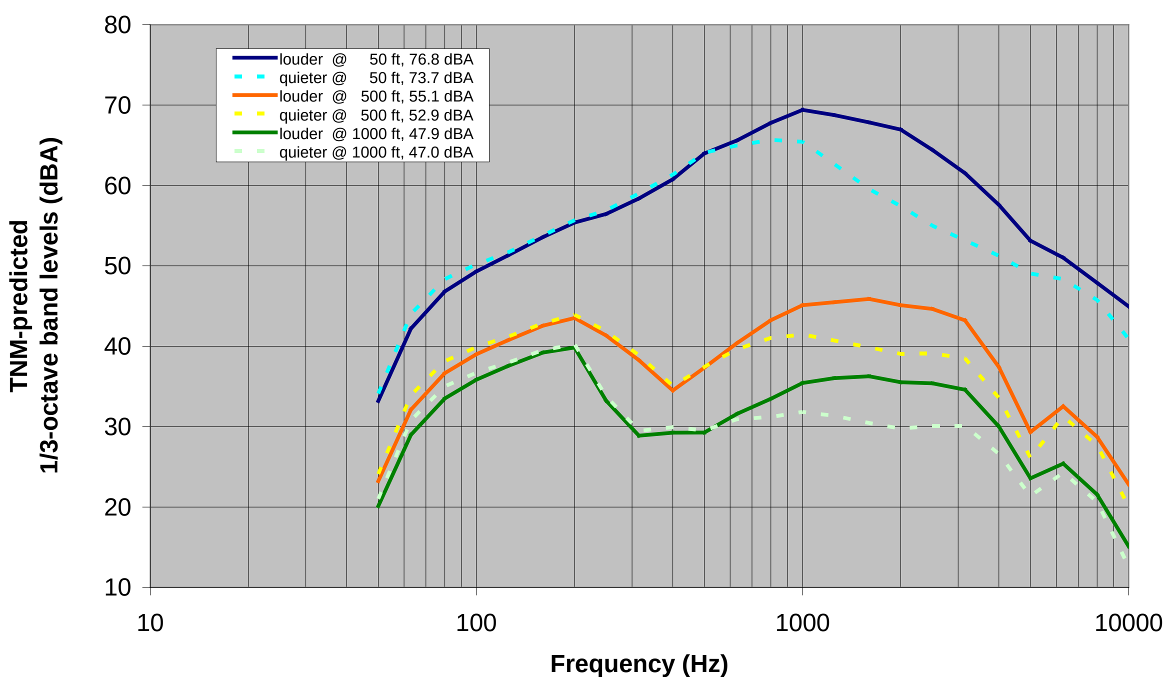


Figure 3. TNM-predicted sound pressure spectral levels (LAeq1h) – flat site, no noise barrier, acoustically soft ground. Variables: distance, louder and quieter pavement.

Referring back to Figure 2, as with the flat site, the barrier, elevated road, and depressed road sites also show the trend of decreased noise reduction with increasing distance. In addition, the sites that involve the most line-of-sight blockage between the sound source and receiver, barrier and depressed road sites, show less noise reduction than the other sites in general. Again, this can be attributed to a reduction in higher frequency energy; the noise barrier and the terrain in the depressed road case efficiently reduce higher frequency energy, resulting in lower frequencies becoming dominant at shorter distances than for cases without intervening objects. Again, louder and quieter pavements are essentially the same for lower frequencies, so the noise reduction is not as much as it could be without the intervening object.

The results found in this FHWA TNM investigation were supported by data measured as part of the Arizona Quiet Pavement Pilot Program [ADOT QPPP]. Data collected simultaneously near the highway and at various distances from the highway, for louder and quieter pavements, provide results indicating that there is a greater effect of pavement on noise levels closer to the highway as compared to farther from the highway.

Based on all the results, it was determined that the effect of pavement on noise levels is distance dependent and site dependent (including ground type, intervening objects, and site geometry). These parameters affect the noise reduction due to the pavement. In general, a greater effect due to the pavement is seen closer to the roadway and with no intervening objects (nothing to block the sound between the source and receiver).

The results of this investigation indicate that Implementation Option 3, accounting for pavement effects by application of an adjustment at receivers (post FHWA TNM calculations), is not a valid option, since the effects vary by distance and site parameters. Accounting for pavement effects at the source allows the FHWA TNM to properly account for propagation effects between the source and receiver, which requires Implementation Options 1 or 2.

Note: Tables of values for the data presented in Figures 1-3 can be found in Appendix A.

2.3 Demonstration Using Pavement-Specific Noise Emission Levels

For this demonstration, which was conducted as a proof-of-concept test, four pavement types were chosen: 1) open-graded rubberized asphalt (RACO); 2) dense-graded asphalt (DGAC); 3) Portland cement concrete (PCC) longitudinally tined; and 4) PCC transversely tined. Tire/pavement noise studies have shown that these four pavements represent a very broad range of noise levels, listed above from quietest to loudest, as measured at the tire/pavement interface and adjacent to the highway [Rochat 2003][Donavan 2006]. Although there are both loud and quiet PCC and asphalt pavements, the ones listed allow for use of existing and available validation data sets, and were thus chosen. It is recognized that these pavement types are still fairly general, but they are different enough to determine the validity for this option of implementing pavement effects.

2.3.1 Data collection

For this demonstration, data were collected in conformance with the REMEL method, as described in Fleming 1995 and Lee 1996 (please refer to Figure 4). A microphone was placed at a distance of 50 ft (15.2 m) from the center of the vehicle travel lane and a height of 5 ft (1.5 m) above the roadway plane. The acoustic signals for each pass-by event were recorded and used to extract the A-weighted maximum sound level (broadband and spectral). Measurements were conducted in Massachusetts in August 2006 for DGAC, in California in October 2003 (as part of the Caltrans Thin Lift Study) and in Arizona in October 2007 for RACO, and in California in September 2007 for longitudinally tined PCC. In addition, data were obtained from Ohio DOT for transversely tined PCC.

These data were collected to assess the regression analysis process with pavement-specific REMELs and to implement the REMELs in a special research version of TNM modified to allow for such predictions.

Figure 4. Photos of REMEL measurements.

2.3.2 Data analysis

All vehicle pass-by events used for final analysis were of high quality, with minimal wind influence and minimal influence from nearby vehicles or other noise sources. The wind speed did not exceed 11.2 mph (5 m/s) during any event. The maximum pass-by sound level was at least 10 decibel (dB) above any background noise (all sources other than vehicles on the road) and was approximately 10 dB louder than any other simultaneous vehicle noise sources (event max level was at least 6 dB higher than the beginning or end of the vehicle pass-by event, which typically equates to approximately 10 dB at the time of the maximum level).

The data were then processed according to REMEL analysis techniques, as described in Appendix B. It was during this analysis process that several questions arose regarding determining data set adequacy (e.g.: Were there enough events for each vehicle type? Does a regression technique properly capture pavements associated with tonal tire/pavement noise?) These questions are addressed in Section 2.4.

2.3.3 Implementation methodology

A special research version of TNM v2.5 was developed that allows the use of pavement-specific REMELs. This was accomplished by adding a new pavement type to the REMEL database, and choosing it as an input for roadway pavement type.

2.3.4 Validity of methodology

Once data set adequacy is determined, as described in Section 2.4, predictions will be made with pavement-specific REMELs and compared to measured data as described in Section 3.2. Some preliminary work has been done for this, but final results are not available.

2.3.5 Limitations of methodology

There can be substantial limitations regarding the implementation of pavement-specific REMELs. Because of the broad pavement categories in the current version of the FHWA TNM, the REMEL calculation method was appropriate for such large data sets. Broader pavement categories are more likely to exhibit the following data set characteristics (as compared to more specific pavements):

- enough events for each vehicle type for a broad range of speeds
- data for multiple sites
- little to no tonal qualities in the average spectrum

REMEL curves may not properly represent the pavement for narrow or specific pavement categories if any of the listed characteristics are not adequately addressed. Please see Section 2.4 for further explanation.

2.4 Determining Adequacy of Data for Implementation

Appendix B contains the following write-up, “Challenges Computing Reference Energy Mean Emission Level Coefficients using Small Datasets.” The write-up provides details leading to the following approach for computing REMELs using a small dataset:

A. Overall (Broadband) Levels

1. Collect a minimum of 30 samples over the speed range of interest. Depending on the number of sites this represents, the multiplier for variance is chosen accordingly.
2. Compute the overall level coefficients.
3. Choose a confidence probability and interval based on requirements specific to the study.
4. Compute and compare confidence intervals. Is the confidence interval sufficiently small
    a. to compare with an existing curve to determine uniqueness?
    b. to provide sufficient accuracy for future predictions?
5. If the answer is no to either question, more data are required.

B. One-third Octave Band Spectra

1. After determining that sufficient data are available for overall REMELs, spectral REMELs can be computed.
2. Compute the spectral coefficients.
3. Plot the computed spectra and the measured spectra.

4. The computed spectral levels should generally be within the range of measured data levels.
5. The computed spectra in the frequency range from 500 Hz to 5000 Hz should match closely.
6. An r^2 value greater than 0.9 for the entire spectral-speed region indicates good agreement.
7. If these criteria are not met, more data are required.

2.5 Implementation Recommendations

Implementation Option 3 is discounted and is not recommended since the effects of pavements on highway noise are distance-dependent. Applying a single value offset to all receivers, regardless of distance from a highway, could lead to an over-prediction of the pavement effect in communities.

Relating to Option 2, the REMEL method of implementing pavement effects is attractive for several reasons: 1) although the data may be somewhat expensive to collect, it can be used directly in the model, replacing more general noise emissions levels with pavement-specific ones; 2) adjusting for pavement effects directly at the source allows for propagation effects to be properly accounted for in noise level predictions adjacent to the highway; and 3) implementation in the FHWA TNM is simple (the structure for REMEL implementation is already available in the model).

Implementation Option 2, with proper care in producing high-quality vehicle pass-by data and by following the steps outlined in Appendix B, would allow utilization of pavement-specific REMELs in the FHWA TNM. The next steps in the analysis for this option would be:

1. Examine the pavement-specific data sets collected as part of this demonstration, as described in Section 2.3. Do further analysis to determine the adequacy of the data, as described in Section 2.4 and Appendix B; this will help to formalize the adequacy-analysis-process and to move on to the next step. Note that data sets should represent pavements that are at least 5 years old to account for aging effects.

2. Once the pavement-specific data sets have been approved and the REMEL curves have been calculated, compare wayside measured data to predictions using the implementation of the pavement-specific REMELs in the FHWA TNM. Determine if implementation in this manner validates the use of pavement-specific REMELs.
3. Develop a process in the FHWA TNM for allowing user-defined REMELs based on approval from FHWA.

3. INVESTIGATING USE OF PAVEMENT-SPECIFIC TIRE/PAVEMENT SOURCE LEVELS ADJUSTMENTS

This section describes the investigation of using pavement-specific tire/pavement source level adjustments, which is used to help assess Implementation Option 2: adjusting the existing tire/pavement source level in the FHWA TNM using on-board sound intensity (OBSI) data and also adjusting the roadway effective flow resistivity (EFR, a measure of sound absorption).

The FHWA TNM noise prediction calculations use two sound sources to represent each vehicle type. One source represents the tire/pavement noise, and the other source represents the remaining vehicle noise (such as the engine, exhaust stack, etc.). With direct measurements of tire/pavement noise, such as with the On-Board Sound Intensity (OBSI) Method [AASHTO OBSI], differences among pavement types can be computed and adjustments made to the tire/pavement noise source in the model to account for these differences.

Section 3.1 describes a proof-of-concept demonstration for implementing pavement effects via tire/pavement source level adjustment. Section 3.2 provides implementation recommendations. Section 3.3 reviews current OBSI data collection for the purpose of FHWA TNM implementation.

3.1 Demonstration of Using Pavement-Specific Tire/Pavement Source Level Adjustments

For this demonstration, which was conducted as a proof-of-concept test, four pavement types were chosen: 1) open-graded rubberized asphalt (RACO); 2) dense-graded asphalt (DGAC); 3) Portland cement concrete (PCC) longitudinally tined; and 4) PCC transversely tined. Tire/pavement noise studies have shown these four pavements to represent a very broad range of noise levels, listed above from quietest to loudest, as measured at the tire/pavement interface and adjacent to the highway [Rochat 2003][Donavan 2006]. Although there are both loud and quiet PCC and asphalt pavements, the ones listed were chosen for this demonstration because they allow for use of existing and available data sets for both source and wayside noise measurements. It is recognized that these pavement types are still fairly general, but they are different enough to determine the validity for this option of implementing pavement effects.

3.1.1 Data collection

There are several methodologies available to measure tire/pavement interaction source noise. Among them is the On-Board Sound Intensity methodology (OBSI) [AASHTO OBSI]. The OBSI method has been used to compare and rank pavements for several studies in the United States, and there is an adequate amount of data available for the four pavement types listed above. OBSI data were gathered from other practitioners from several studies, including ones for the California Department of Transportation (Caltrans), Arizona Department of Transportation, Iowa State University, and FHWA. Data were collected with the vehicle traveling 60 mph (97 km/h) and were provided on a 1/3-octave band basis, in the range of 500-5000 Hz. Note that these measurements were conducted with the Goodyear Aquatread tire (tire used for the OBSI method prior to the one listed in the current standard) and that results do not include data for the 400 Hz band (prior to the current OBSI standard, the 400 Hz band was not required to be reported).

3.1.2 Data analysis

For each general pavement type (RACO, DGAC, long. tined PCC, trans. tined PCC), data were averaged on a one-third octave band basis; please refer to Figure 5 and Table 1, which show the spectral data for each pavement type, where the order from quietest to loudest is RACO, DGAC, longitudinally tined PCC, transversely tined PCC. Then one-third octave band deltas were calculated between DGAC and each of the other pavement types. These deltas were used to adjust the sound energy in the FHWA TNM vehicle noise database for DGAC (the only pavement type of the four tested that is currently distinguished in the model). Note that Table 1 also shows the number of data points used to calculate the average for each pavement type. Each data point represents a unique section of pavement. Averages were comprised of all data points available to the study, where the population of data points represents a wide variety of highways, studies, and specific pavement parameters; pavement age was not considered as part of this proof-of-concept study.

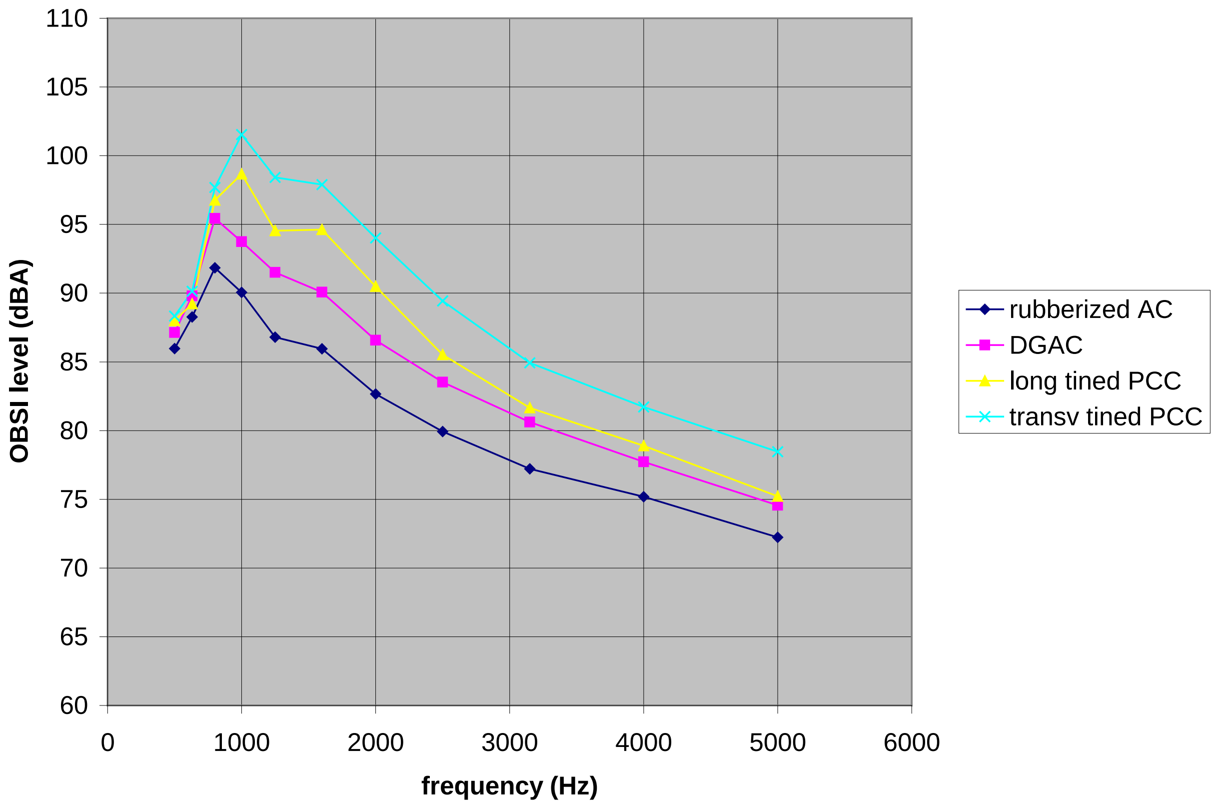


Figure 5. Plot of average OBSI data for each pavement type used for proof-of-concept study.

Table 1. Average OBSI data for each pavement type, used for proof-of-concept study.

Pavement Type	Number of Data Points	OBSI Level (dBA)[1]												
		Broad-band	1/3-Octave Bands											
			400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
RACO	19	97.0	NA[2]	86.0	88.3	91.8	90.1	86.8	86.0	82.7	79.9	77.2	75.2	72.2
DGAC	10	100.5	NA[2]	87.1	89.8	95.4	93.7	91.5	90.1	86.6	83.5	80.6	77.7	74.6
long tine PCC	29	103.3	NA[2]	88.0	89.2	96.8	98.7	94.5	94.6	90.5	85.5	81.7	78.9	75.2
transv tine PCC	35	106.2	NA[2]	88.3	90.1	97.7	101.5	98.4	97.9	94.0	89.4	84.9	81.7	78.5

[1]Data were collected using the Goodyear Aquatread tire, which is no longer the standard.
[2]Data for the 400 Hz band was not required or standardized at the time of data collection.

3.1.3 Implementation methodology

In the FHWA TNM, vehicle noise is represented by two sound sources for each vehicle type, with the lower-height source representing tire/pavement interaction noise. The lower source is isolated in the FHWA TNM, and it is at this point in the calculations that each one-third octave band adjustment due to pavement effects was applied. This was accomplished through a special research version of the FHWA TNM v2.5.

Adjustments for each of the three pavements [RACO, longitudinally tined PCC (LPCC), transversely tined PCC (TPCC)] were applied to account for differences between each of these pavements and DGAC. The vehicle noise emission levels in the FHWA TNM for DGAC were chosen for computations, and adjustments for one of the three pavements were chosen. Using this methodology, FHWA TNM predicted sound levels at chosen receiver locations for either RACO, longitudinally tined PCC, or transversely tined PCC.

3.1.4 Validity of methodology

After pavement effects were implemented in the FHWA TNM, predicted sound levels were compared to sound levels measured adjacent to a highway in order to assess the validity of implementing pavement effects by applying a tire/pavement noise source adjustment.

Many wayside data sets measured by the Volpe Center were used in this study, including those for the TNM Validation Study [Rochat 2002][Rochat 2004], Arizona Quiet Pavement Pilot Program (QPPP) [ADOT QPPP][ADOT 2006], and Caltrans Thin Lift Study [Caltrans 2010]. The data were measured at a distance of 50 feet (15.3 meters) from the center of the near travel lane, 5 feet (1.5 meters) above the roadway plane or at a distance of a noise barrier, 5 feet (1.5 meters) above the barrier. Data for the TNM Validation Study and the Arizona QPPP will be presented here; the measured free-flowing traffic data are presented in 5-minute A-weighted equivalent sound levels ($L_{Aeq5min}$), obtained in general conformance with the FHWA noise measurement guidance document [Lee 1996] and the Continuous-Flow Traffic Time-Integrated Method [AASHTO CTIM]. Caltrans data were obtained in general conformance with the Statistical Pass-By Method [ISO SPB] and the Statistical Isolated Pass-By Method [AASHTO SIP]; these data will not be presented here – further investigation is necessary to determine the effect of the pavement implementation for single vehicles. All wayside data used for comparison were measured on highways with one of the four chosen pavement types.

Each of the wayside data measurement sites was modeled in the FHWA TNM v2.5, including vehicle volumes and speeds for each travel lane on the highway. Also included were any terrain elevation changes and ground type changes between the source and receiver locations.

Current FHWA policy mandates that FHWA TNM Average pavement must be used in all future noise predictions. To determine if the pavement effect implementation using source adjustments provides improved sound level predictions over using TNM Average, three sets of FHWA TNM calculations were performed: 1) with FHWA TNM v2.5 and Average pavement; 2) with FHWA TNM v2.5 pavement-adjusted using the *average* OBSI values for the test pavements, as listed in Table 1; and 3) with TNM v2.5 pavement-adjusted using OBSI values *more specific to the actual pavement* at the validation measurement site.

Results indicate that implementing pavement effects in the FHWA TNM using an OBSI adjustment to the tire/pavement sub-source is a valid way to account for pavement effects.

The broadband results are shown in Figure 6. Each data point represents measured sound levels compared to FHWA TNM-predicted sound levels. It can be seen that the pavement-adjusted results provide improved sound level predictions for all three test pavement types. Where FHWA TNM was substantially over-predicting for RACO, the amount of over-prediction is reduced. Where FHWA TNM was slightly under-predicting for LPCC, the under-prediction is essentially eliminated. Where FHWA TNM was substantially under-predicting for TPCC, the under-prediction is essentially eliminated. For RACO and LPCC, using an adjustment more specific to the pavement at the validation site provides improved results over using the OBSI average adjustment; the use of a more specific pavement adjustment vs. the average adjustment did not make much difference for TPCC in this demonstration.

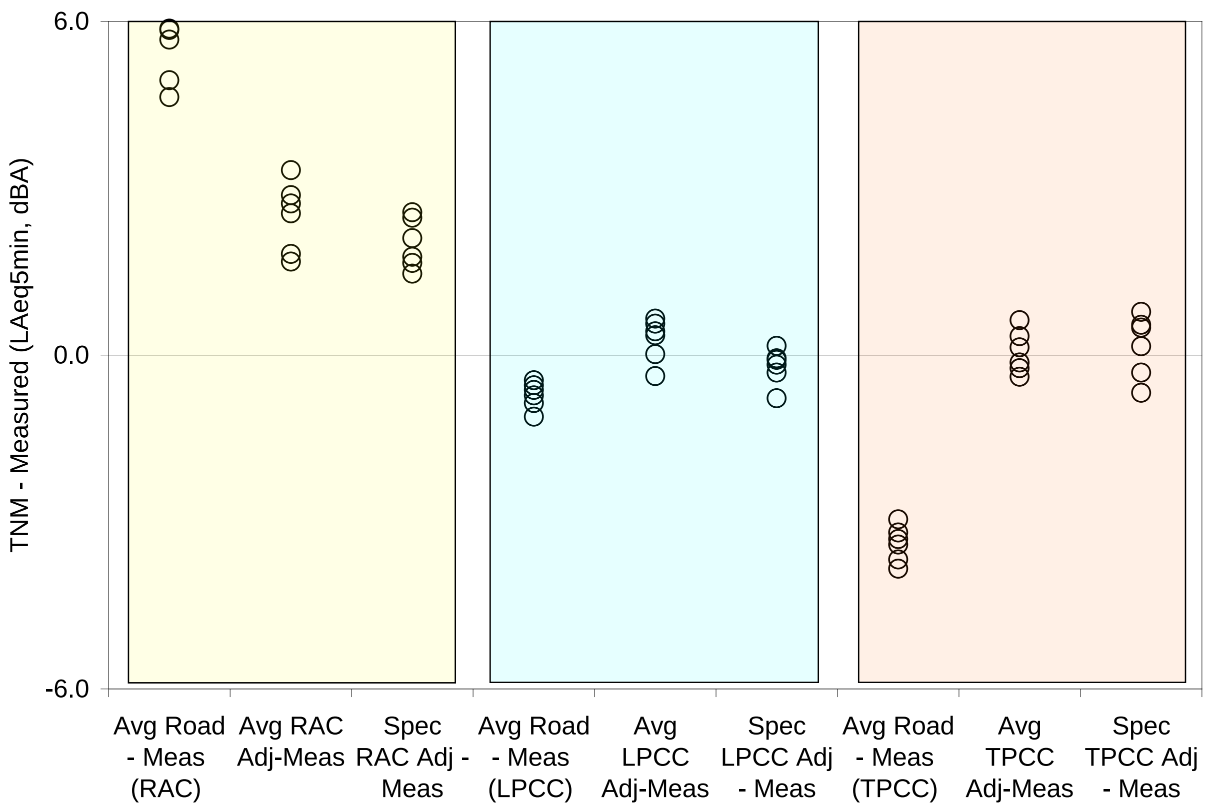


Figure 6. TNM-predictions compared to measured highway noise data, applying TNM Average pavement and TNM OBSI-adjusted pavement; broadband sound levels.

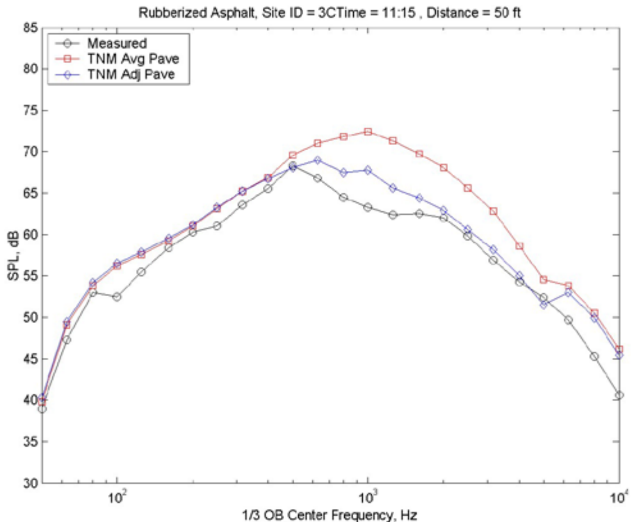
Example spectral results are shown in Figure 7. Results show that pavement-adjusted spectral shapes match more closely to measured spectra.

Figure 7 shows spectral plots of sound levels for measured data, FHWA TNM v2.5 predicted data (with Average pavement), and FHWA TNM pavement-adjusted predicted data using the *average* OBSI values for the test pavements. For RACO, it can be seen that FHWA TNM v2.5 over-predicts for a broad range of frequencies, including 315-2000 Hz, which are bands critical to the broadband sound level; FHWA TNM pavement-adjusted lowers the sound levels for a broad range, including 500-2000 Hz (the OBSI data sets did not allow for adjustments below 500 Hz), improving the results. It can also be seen for RACO that the range of 630-1600 Hz still shows over-prediction for the FHWA TNM pavement-adjusted data. It is thought that accounting for the following may help eliminate some of the over-prediction: 1) adjust for the appropriate pavement sound absorption in the prediction (see Section 4); and 2) adjust for the pavement effects below 500 Hz (a limit with the older OBSI data). Particularly for RACO, frequencies below 500 Hz may be important when accounting for the effect of this pavement type. The newest OBSI procedure and resulting data includes the 400 Hz 1/3-octave band, and further research is needed to determine the contributions of adjustments made at that frequency.

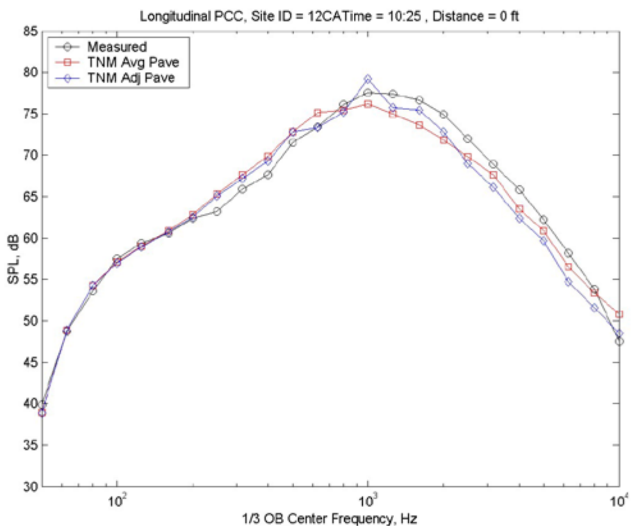
For PCC longitudinally tined, it can be seen that FHWA TNM under-predicts in the key frequency range of 1000-1600 Hz. FHWA TNM pavement-adjusted raises the sound levels in this range, greatly improving the results, although the results show more tonality than the measured data (spike at 1000 Hz).

For PCC transversely tined, it can be seen that FHWA TNM under-predicts in the key frequency range of 1000-2000 Hz. FHWA TNM pavement-adjusted raises the sound levels in this range, greatly improving the results, although the frequency of the tone is slightly shifted.

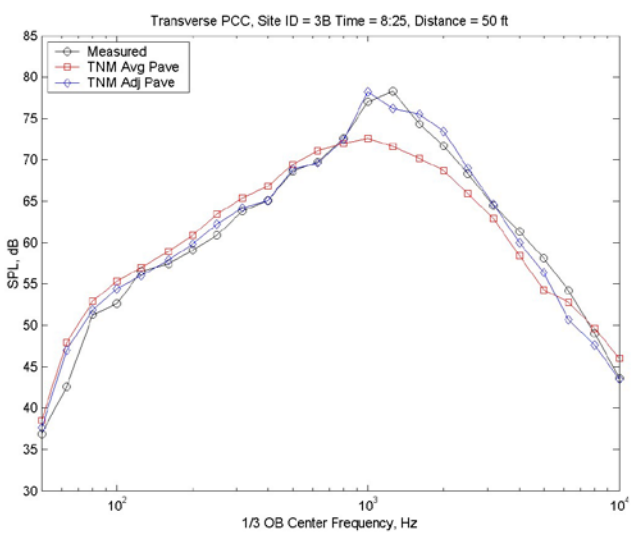
Although the results shown in Figure 6 are for single data points at specific sites, the same trends were seen with other data. (Note: Tables of values for the data presented in Figure 5 and Figure 6 can be found in Appendix A.)



Open-graded rubberized asphalt (RACO)



PCC, longitudinally tined



PCC, transversely tined

Figure 7. TNM-predictions compared to measured highway noise data, applying TNM Average pavement and TNM OBSI-adjusted pavement; spectral sound levels.

3.1.5 Limitations of methodology

There are some possible limitations in using OBSI-data-generated adjustments to the tire/pavement noise source to account for pavement effects in noise predictions using the FHWA TNM.

1. Making adjustments to noise emission levels already in the model requires the choice of an existing pavement category in the FHWA TNM to be used for all calculations. All existing noise emission level data were measured prior to 1996. Although this is not necessarily an issue, it should be pointed out that the adjusted levels are tied to the noise emissions database in TNM. If future versions of TNM have modifications to the emission level data, the predicted sound levels, including those adjusted for pavement effects, would be affected.
2. OBSI data are associated with one type of tire that best represents a car. There are two limitations associated with this: a) truck tires are not represented; and b) other car tires are not represented. OBSI data provides a good estimate of the noise effects associated with various pavements, but it is not necessarily fully representative of tire/pavement noise being generated by all vehicle and tire types on a road (the same would apply to other tire/pavement noise source measurement techniques, since they are also limited to results from specified test tires).
3. With the current OBSI standard [AASHTO OBSI], OBSI data are presented from 400-5000 Hz. Using the data, adjustments can be made in the 1/3-octave bands in that range. If there were any effect from pavement outside this range, it would not be captured or applied in the model. Particularly when considering broadband sound levels, this is typically not an issue since the dominant frequencies for highway traffic noise, which generally control the broadband sound level, are in the 400-5000 Hz range.

3.2 Implementation Recommendations

The OBSI source adjustment method of implementing pavement effects is attractive for several reasons: 1) tire/pavement source level data are fairly easy and inexpensive to collect; 2) for some source level measurement methodologies, a large, applicable database of many pavement types already exists; 3) adjusting for pavement effects directly at the source allows for propagation effects to be properly accounted for in noise level predictions adjacent to the highway; and 4) implementation in the FHWA TNM is fairly simple.

Since the demonstration proved to be a valid option for implementing pavement effects by applying adjustments to the tire/pavement noise source, the logical next steps are to:

1. Develop a large OBSI adjustment database in the FHWA TNM using the current specified test tire, the SRTT [AASHTO OBSI], where pavements represented in the database should be at least 5 years old to account for aging effects.
2. Determine how the pavements would be grouped.
3. Determine the number of data points required to properly represent a group.
4. Determine how a TNM user could choose a pavement in the model or enter data for a user-defined pavement for noise impact analyses.

Section 3.3 discusses gathering and collection of data for a large OBSI adjustment database.

In addition to the OBSI database plan, the vehicle/tire type limitation needs to be addressed. Further investigation is needed on the applicability of the OBSI adjustment to each vehicle type. The investigation should include:

1. Further examination of single vehicle pass-by events for various vehicle types and time-averaged traffic data, where TNM predictions with the pavement adjustment can be compared to wayside measurements. Although some of this was done as part of the proof-of-concept test, more data need to be examined to draw any conclusions. It is likely this could be accomplished through examination of existing data measured by the Volpe Center through various programs.
2. In addition to examining single vehicle pass-by events, it would also be useful to examine time-averaged data, seeing how TNM predictions with the pavement adjustment compare to wayside measurements for various percentages of heavy trucks. If it is proper to use the car-tire OBSI adjustments for heavy trucks, then predictions where there are lower and higher percentages of heavy trucks should yield similar results when comparing to wayside measured data. It is likely this could be accomplished through examination of existing data measured by the Volpe Center through various programs.
3. Examination of current literature that discusses the applicability of standard OBSI

measurements to various vehicle/tire types.

3.3 Collecting Additional Data for Implementation

Developing a large OBSI adjustment database, for eventual inclusion in TNM, has already begun, although much more work is required before formal implementation is possible.

3.3.1 Volpe Center OBSI data collection

To help gather OBSI data and validate data from other sources, the Volpe Center assembled an OBSI system in 2009 (please refer to Figure 8). It has since been tested and compared to other practitioners' systems. During OBSI system assembly, a list of valuable equipment requirements, pricing, and contacts was generated and made available to other practitioners. During system development and testing, OBSI data collection forms and an OBSI data entry spreadsheet were developed; these also have been made available to other practitioners, where the spreadsheet has become the official depository of OBSI data being collected as part of the transportation pooled fund group on tire/pavement noise [TPF].

In October 2009, the Volpe Center conducted OBSI measurements at the Honda Proving Center in California, where several pavement types were available for testing. The Volpe Center was joined by Illingworth & Rodkin (I&R), who have a validated OBSI system. This set of measurements allowed the Volpe Center to streamline and validate the system by comparisons to I&R.

In November 2009, the Volpe Center conducted OBSI measurements at the National Center for Asphalt Technology (NCAT) test track, where several asphalt pavement types were available for testing. The Volpe Center was again joined by I&R. This set of measurements allowed the Volpe Center to further validate the system and also to collect data for the OBSI database.

In early 2010, it was discussed with FHWA that it was important to get representative tire/pavement noise data from as many states as possible. The target was to get the following information from as many states as possible: list of most prevalent pavements being used in the state and the associated average OBSI level for each pavement, where the pavements tested should be at least 5 years old. In addition to gathering data from other practitioners (see Section 3.3.2) it was determined that the Volpe Center should start to collect State data, when possible, and as long as funding permitted. In the spring of 2010, the Volpe Center collected data in Massachusetts, for their most prevalent pavements. This data set was added to the database.

In September 2010, the Volpe Center participated in an OBSI rodeo in North Carolina, conducted through the transportation pooled fund group on tire/pavement noise [TPF]. OBSI data were collected for many North Carolina pavement types. This set of measurements allowed the Volpe Center to further validate the OBSI system, to validate other practitioners' systems (so FHWA and the Volpe Center can feel comfortable accepting OBSI data for the national database from these organizations), and to collect data for the OBSI database.

After gathering data from other practitioners (as described in Section 3.3.2), the OBSI database will be analyzed, and it will be determined if there are any gaps to fill. If there are gaps, the Volpe Center or another OBSI practitioner could conduct further measurements to fill in the gaps.

Figure 8. Photos of OBSI data collection system.

3.3.2 Gathering OBSI data from other practitioners

In addition to the Volpe Center adding data to the national OBSI database, other practitioners/States are contributing a substantial amount of data through the transportation pooled fund group [TPF]. The database is a top priority of the group, as voted during a July 2011 meeting, and gathering of these data will be ongoing.

4. INVESTIGATING USE OF PAVEMENT-SPECIFIC SOUND ABSORPTION VALUES

This section describes the investigation of using pavement-specific sound absorption values, which is used to help assess: 1) Implementation Option 1: integrating new REMEL data into the FHWA TNM for specific pavement types and also adjusting the roadway effective flow resistivity (EFR, a measure of sound absorption); and 2) Implementation Option 2: adjusting the existing tire/pavement source level in the FHWA TNM using on-board sound intensity (OBSI) data and also adjusting the roadway EFR.

For Implementation Options 1 and 2, adding an adjustment for the sound absorption of the pavement by changing the EFR value for the road in the FHWA TNM allows for more accurate sound propagation effects as the sound travels between the source and receiver, interacting with the road surface. Implementation in the FHWA TNM is simple.

Section 4.1 briefly describes EFR. Then, before reviewing the validity of applying pavement-specific EFR values, a brief study is described in Section 4.2 that investigates the influence of this parameter on predicted sound levels at distances associated with communities next to highways. The last part of this section reviews the current efforts in EFR data collection for the purpose of FHWA TNM implementation, and finally, implementation recommendations are made.

4.1 What is EFR?

Effective flow resistivity (EFR) is a measure of sound absorption. The FHWA TNM uses EFR values in ground reflection equations (part of sound propagation), where EFR equals flow resistivity plus other parameters based on ground material (e.g., tortuosity, porosity, and shape of ground surface). The FHWA TNM assumes a semi-infinite half-space (ground properties do not vary with depth). In the FHWA TNM version 2.5, the EFR value applied to roadways is 20000 cgs rayls. Example EFR values from literature are:

Ground material	EFR value (cgs rayls)
newly fallen dry snow	10-30
grass	100-600
roadside dirt	300-800
asphalt	5000-15000
old asphalt	30000
upper limit, paint-sealed concrete slab	10^5 - 10^6

[Hastings 2010] (in which values in the table were extracted from several sources)

As can be seen in the table, there is a very broad range of EFR values for pavements.

4.2 Influence of Pavement-Specific Sound Absorption Parameter

Before pursuing further sound absorption research, an investigation was conducted to determine the potential effects of accounting for pavement-specific sound absorption on the predicted sound levels in communities. The investigation was done using a research version of FHWA TNM v2.5 that allows for modification of the roadway EFR value. The following parameters were applied:

- Multiple distances from the road [50-1000 feet (15.2-305 meters)]
- Two lanes of traffic and eight lanes of traffic (allowing for less and more propagation distance over the pavement surface)
- Acoustically hard and soft ground

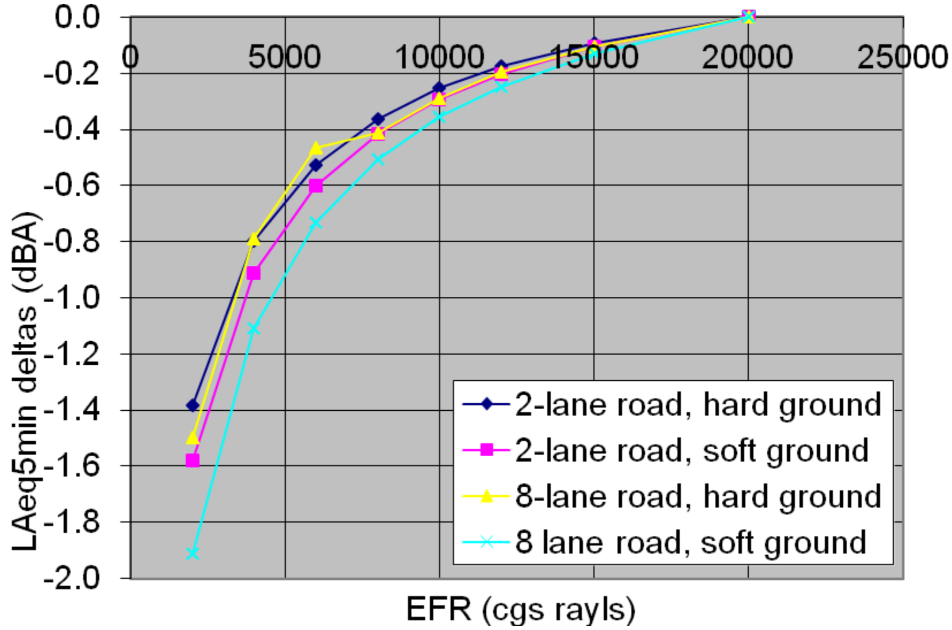
The FHWA TNM runs represent actual highways with real highway traffic, where all TNM objects were removed except roadways and receivers, and the ground between the sources and receivers was modified to be either lawn (300 cgs rayls, acoustically soft) or pavement (20000 cgs rayls, acoustically hard).

For the investigation, the EFR values applied to the pavements were 2000, 4000, 6000, 8000, 10000, 12000, 15000, and 20000 cgs rayls. The range of pavement EFR values were chosen based on literature reviews, EFR measurements (as described in the next section), and projections as to what an EFR value could be for a very sound absorbing pavement. It should be noted that it is not known at this time if a value of 2000 cgs rayls is reasonable for a very sound absorbing pavement, but it may be possible given the right pavement parameters.

For the parameters tested (distance from road, number of lanes, hard or soft ground next to the highway), results showed that changing the EFR value affects the sound level predictions in the following ways:

- The magnitude of the effect is dependent on the distance from the road, the number of lanes, and the ground type next to the highway (i.e., all parameters tested).
- The maximum effect was about 2 dB, where the EFR value of 2000 cgs rayls resulted in sound levels about 2 dB lower than the default TNM EFR value for roads of 20000 cgs rayls.
- The effect is more pronounced for multiple-lane highways, since the sound is propagating over more pavement.
- In general, the effect is more pronounced closer to the highway, although the 8-lane road with soft ground next to it does not show that trend.
- Spectrally, there is an effect from about 500 Hz and up (in general), which includes the range critical to the broadband sound level: 500-2500 Hz.

Please refer to Figure 9 for broadband results and Figure 10 for spectral results (tabular format in Appendix A). The results indicate that the effect is not insignificant, and pavement-specific EFR values should be included in predictions. Note, however, that aging pavement will likely decrease its ability to absorb sound, so implemented EFR values should represent pavements at least 5 years old.



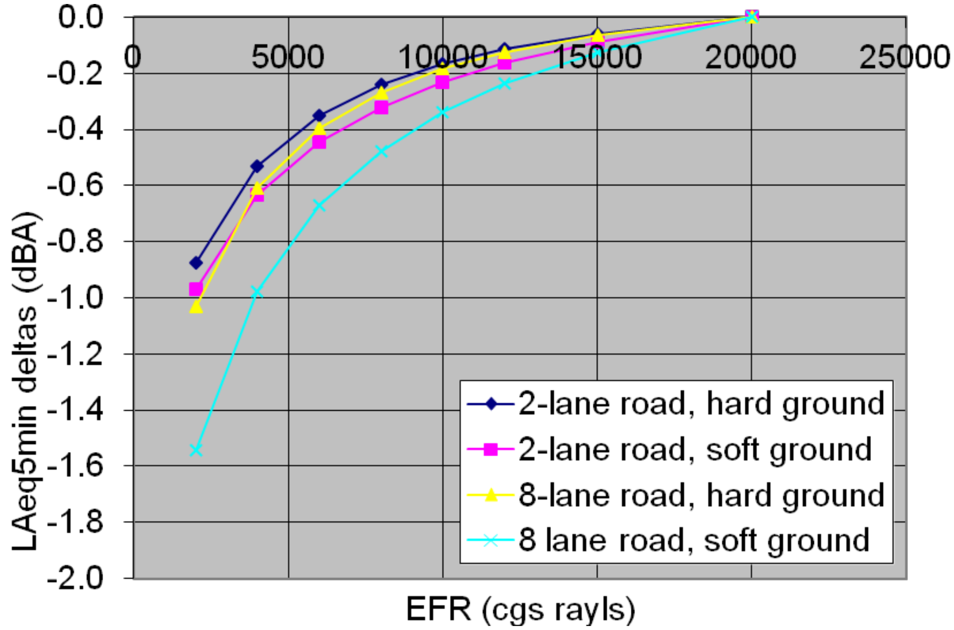
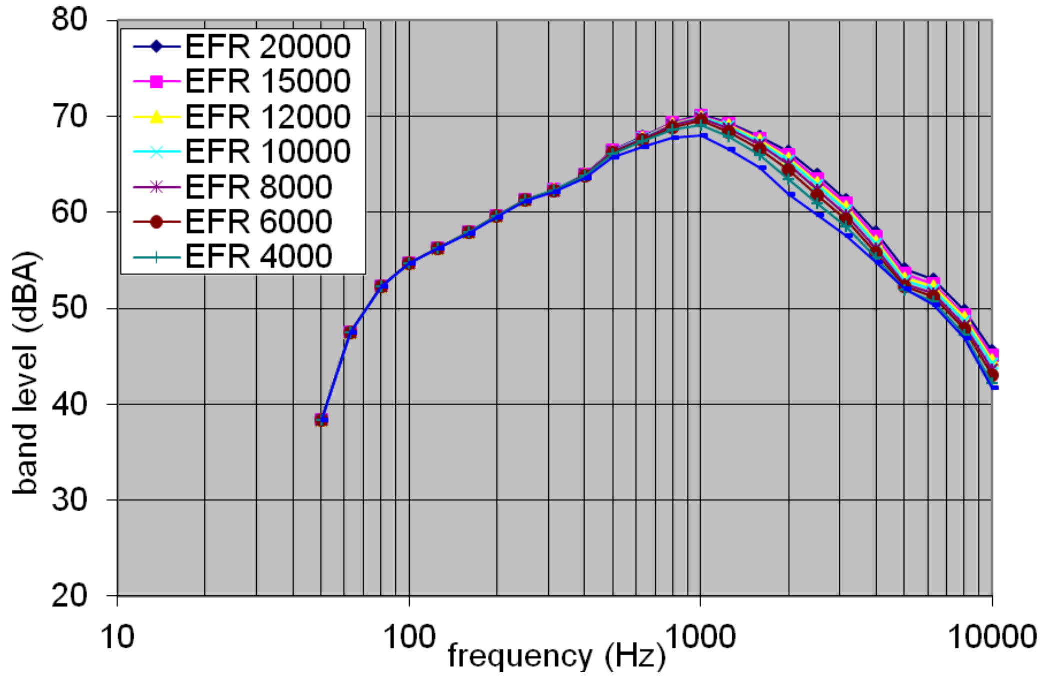


Figure 9. Sound level differences from that for 20K EFR as a function of EFR; 2- and 8-lane road, hard and soft ground. Top plot: distance = 50 ft, bottom plot: distance = 200 ft.



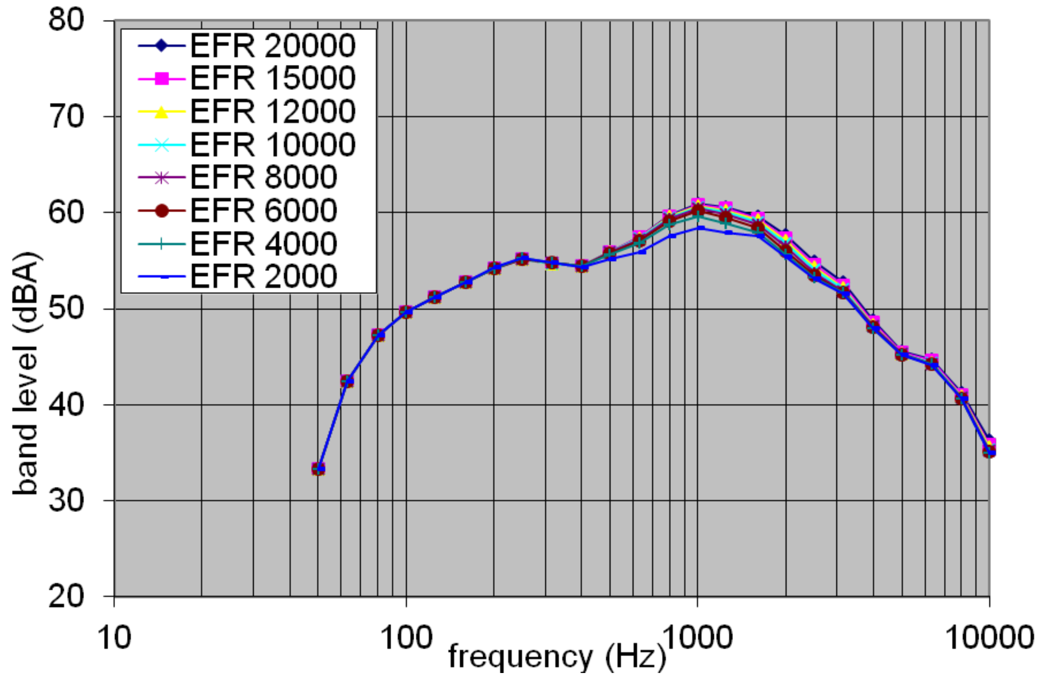


Figure 10. Spectral sound levels with varying EFR values; 8-lane road, soft ground. Top plot: distance = 50 ft, bottom plot: distance = 200 ft.

4.3 Demonstration of Using Pavement-Specific Sound Absorption Values

In order to demonstrate the use of pavement-specific sound absorption values or EFR values in the FHWA TNM it was first necessary to develop or adapt a method for data collection and analysis. With the proper method, it was possible to obtain pavement-specific EFR data. For one of the pavements discussed in Section 3, rubberized asphalt, a demonstration is made of adding the sound absorption effect to the tire/pavement noise source adjustment.

4.3.1 Data collection

Since the FHWA TNM requires the sound parameter of EFR as input to the propagation equations, a data collection technique was sought that allows measurement/extraction of EFR values for ground. ANSI S1.18, *Template Method for Ground Impedance*, provided such a technique, and data were collected in conformance with this standard, using "Geometry A" [ANSI S1.18].

The instrumentation set-up consists of a point source (compression driver with tube), and two microphones a set distance away at two different heights above the ground. Using a tone generator, 1/3-octave band center frequencies between 250 and 4000 Hz are transmitted and the difference in sound level between the two microphones is noted for each frequency. Please refer to Figure 11 for photos of the EFR instrumentation and measurements.

Typically, for each pavement type, four samples were collected with the point source tube pointing in different directions for each sample. For each of the 1/3-octave bands, data on roadways were collected with the point source tube pointing in the direction of travel and at 90, 180, and 270 degrees from the direction of travel.

Data were collected for numerous pavements, as listed in Table 2 in Section 4.3.4.

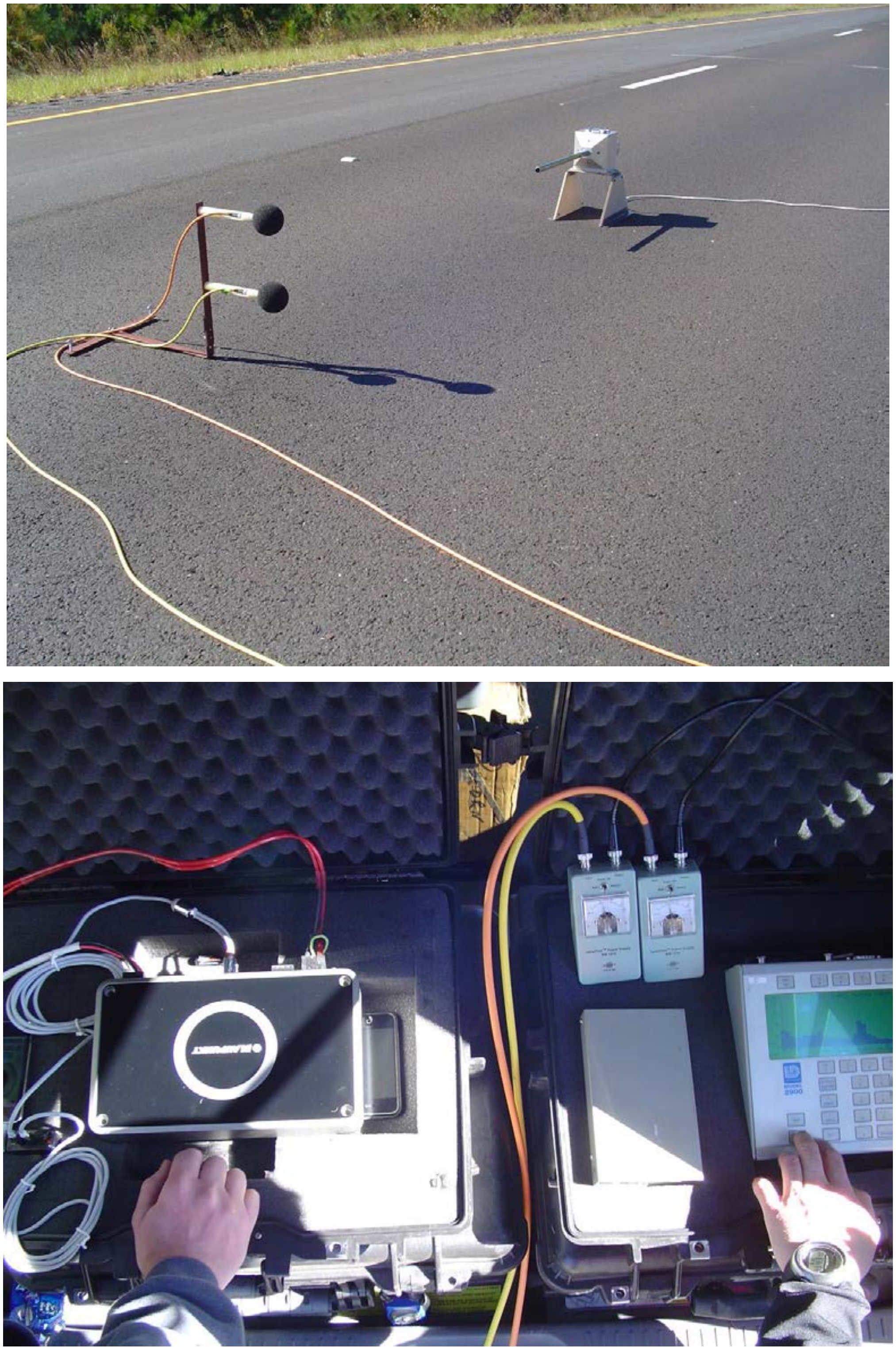


Figure 11. Photos of EFR data collection system.

4.3.2 Data analysis

Data analysis was conducted in general conformance with the ANSI S1.18 standard. There are limitations in using ANSI S1.18 when trying to extract EFR values from 2000 to 30000 cgs rayls from the measured data, the range important when trying to obtain useful sound absorption information for pavements.

The measured delta (difference in sound levels between the two microphones) for each frequency is used to help match *measured* EFR curves (sound level difference as a function of frequency) to *theoretical* EFR curves. In ANSI S1.18, the tables of deltas provided for curve matching are limited to the EFR values of 10, 32, 63, 100, 160, 320, 1000, 3200, and 10000 cgs rayls. As such, new theoretical EFR curves were generated to help with matching measured data to theoretical data. The expanded and refined EFR curves cover the range of 10-500 cgs rayls in steps of 10, 500-20000 cgs rayls in steps of 100, and 20000-30000 cgs rayls in steps of 2000. In-house software was developed based on Embleton 1983 sound propagation equations to generate the EFR curves. Figure 12 shows sample theoretical EFR curves in the range of 100 to 30000 cgs rayls, extracted from the new set of theoretical EFR data (tabular format in Appendix A).

The ANSI S1.18 curve matching process was modified to allow for extraction of pavement-related EFR data. ANSI S1.18 uses the following procedure: 1) for each theoretical EFR curve, sum the differences over all frequencies between the measured curve and the EFR curve; and 2) find the minimum sum among all EFR curves to identify an EFR value. It was found through research for the FHWA TNM Pavement Effect Implementation Study that using that process led to counter-intuitive results for pavements. The process seemed to be appropriate for identifying extreme, general ground types (e.g., lawn, pavement), but was inadequate for identifying sensitivities within a general ground type. As such, a different analysis process was developed.

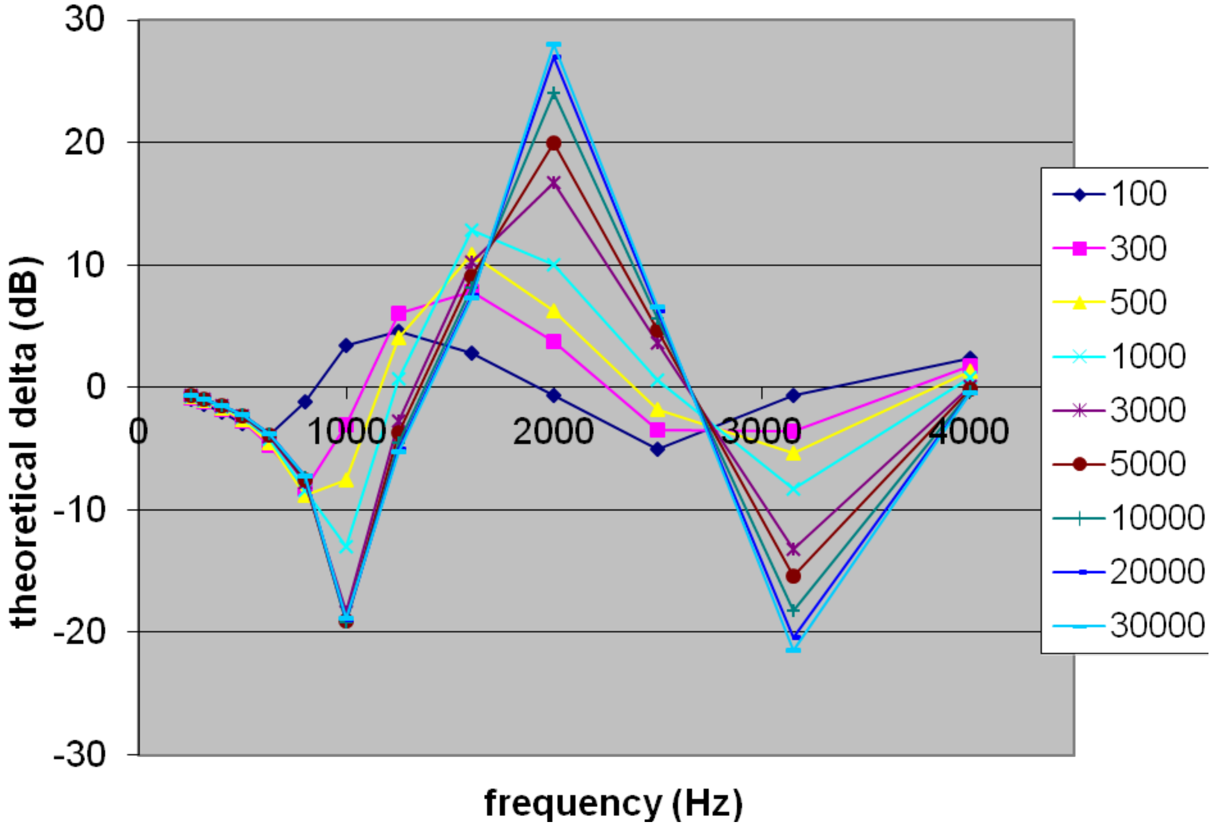


Figure 12. Example theoretical EFR curves. For each EFR value (cgs rayls), the data are presented as the delta sound level between the two microphones (upper minus lower) as a function of frequency.

The data analysis procedure used in this study is a twostep curve selection process:

1. Restrict the EFR range. This step is based on the location in frequency of the first dip and first peak in the measured EFR curve.

<table>
<tr><th colspan="2">Frequency requirement (Hz)</th><th>EFR range (cgs rayls)</th></tr>
<tr><td colspan="2">frequency of first dip < 1000</td><td>< 900</td></tr>
<tr><td rowspan="2">frequency of first dip ≥ 1000</td><td>frequency of first peak < 2000</td><td>900 ≤ x < 2300</td></tr>
<tr><td>frequency of first peak ≥ 2000</td><td>2300 ≤ x < 30000</td></tr>
</table>

These requirements were chosen based on examination of dips and peaks in the theoretical EFR curves. It was determined that the pavement range is 2300-30000 cgs rayls based on EFR values in literature for pavement and also on data collected for this study, and the frequency at which the first peak occurs for each of the delta curves, which was always 2000 or 2500 Hz for data that were considered to be of good quality.

2. For the pavement range of EFR values, 2300-30000 cgs rayls, the EFR value is then extracted by looking at the amplitude of the peak. (Note: for EFR values below 2300, the process described in ANSI S1.18 can be applied to the restricted EFR range.) First, the amplitude is normalized*, then it is compared to the theoretical peak amplitudes. The theoretical peak amplitude closest in value to the normalized measured peak amplitude is identified, and the corresponding EFR value is assigned to the pavement.

This process results in the most intuitive EFR values possible, based on a large sample of pavement types.

It should be noted that each measured EFR curve was an average of all good data samples for a single pavement type (typically four samples). In addition, the measured peak amplitude was based on the average of peak amplitudes for each sample, regardless of the peak location (2000 or 2500 Hz).

4.3.3 Implementation methodology

A special research version of the FHWA TNM v2.5 was used to implement pavement sound absorption effects. Rather than the default EFR value of 20000 cgs rayls, a new value could be assigned to all roadways, as specified in a special input file.

4.3.4 Validity of methodology

To validate the data collection and data analysis process, extracted EFR values were compared to those found in literature for various ground types and also compared to expectations for various

* It was found with examination of many EFR data points, that measured peak amplitudes are much lower than theoretical peak amplitudes. As such, to extract the most accurate EFR possible, it was assumed that the EFR value for measured old asphalt was 30000 cgs rayls; the difference between the measured and theoretical peak amplitudes for the old asphalt was determined, and this difference was then applied to all measured peak amplitudes for all other pavements in order to adjust for differences between measurements and theory. This process was termed the normalization process.

pavement types. To validate the implementation of pavement sound absorption effects in the FHWA TNM, one set of measured wayside sound levels were compared to predictions with the EFR modified appropriately for the pavement.

Regarding validating the data collection and analysis process, various ground types were examined, where measured EFR values for lawn ranged from 100 to 470 cgs rayls, and a measured EFR value for medium-packed dirt was 2300 cgs rayls. Also, Table 2 lists all pavements where data were collected and each corresponding extracted EFR value. It can be seen in the table that the EFR values range from 7200 up to 30000 cgs rayls. Also, most open-graded or porous pavements have EFR values in the lower half of the range. For the last three entries in the table, the EFR values could not be extracted, since these pavements were porous enough and thin enough to allow reflections from the underlying pavements, which contaminate the EFR results (please refer to Section 4.3.5 for further explanation) (Note: had the pavements been thick enough to not allow reflections from the underlying pavements, it’s likely that analysis would have shown that their associated EFR values would be below 7000). In summary, regarding validating the data collection and analysis process, the values for all the ground types either compared well with published EFR values or represented intuitive or reasonable results.

Table 2. Pavements tested and corresponding EFR values.

Pavement type	Age (years)	Reported maximum aggregate size (mm)	Reported % air void	Reported Thickness (mm)	Measured EFR value (cgs rayls)
old DGAC					30000
NCAT N4 Superpave		9.5	5.5		30000
NCAT W6 Superpave ARZ		4.75	4		24000
ARFC (AZ QPPP Site 3D)	6.5	9.5			24000
cement concrete sidewalk					20000
NCAT N8 SMA		19	4.7		20000
NCAT N12 SMA		12.5	4		17600
NCAT W8 OGFC		9.5			17100
BWC (LA138 Site 5)	new	12.5	7		16900
NCAT E5 Super dense		12.5	3.2		15400
NCAT W5 Super dense		12.5	1.7		13400
ARFC (AZ QPPP Site 3C)	5.5	9.5			13200
NCAT S1 SMA		12.5	2		12400
DGAC (LA138 Site 1)	new	12.5	9		12200
ARFC (AZ QPPP Site 3A)	4	9.5			12000
ARFC (AZ QPPP Site 3E)	6.5	9.5			11700
cement concrete parking lot, swirl texture					11100
DGAC parking lot	old				10400
ARFC (AZ QPPP Site 3C)	6	9.5			10300
ARFC new (Warner on-ramp)	new				10300
NCAT N5 Super fine		9.5	3.7		10200
NCAT S4 OGFC		12.5		33	10200
DGAC parking lot	old				10000
OGAC 30mm (LA138 Site 3)	new	12.5	15	30	9800
NCAT N13 twin layer OGFC		9.5	24	16/32	8000
ARFC (AZ QPPP Site 3B)	2.5	9.5	17	25	7600
RAC, Type O (LA138 Site 4)	new	12.5	12	30	7400
OGAC 75mm (LA138 Site 2)	new	12.5	12	75	7200
NCAT N2 PFC		12.5	16.8	18	na
NCAT S3 OGFC		9.5	21.8	33	na
NCAT S8 PFC		12.5	16.8	33	na

Dense-graded asphalts: DGAC, SMA, Super dense, Super fine
Open-graded or porous asphalts: OGAC, OGFC, PFC, RAC (rubberized), ARFC (rubberized)
Other: BWC = bonded wearing course

Regarding validating the implementation of pavement sound absorption effects in the FHWA TNM, an example is discussed here for open-graded rubberized asphalt (RAC) (Please refer to the RAC data shown in Figure 6 in Section 3.) Adding an EFR adjustment to the OBSI adjustment (with an EFR value of ~7000 cgs rayls), the broadband results (predicted compared to measured) are improved up to about 0.5 dB; this is for two different highway configurations, one a 6-lane highway, and one an 8-lane highway. The only distance from the highway examined was 50 ft (15.2 m), and it was not investigated yet as to how the results would have improved at farther distances. Figure 13 shows an example of the spectral results with the EFR adjustment added to the OBSI adjustment (tabular format in Appendix A). It can be seen that predicted sound levels slightly improve in the range of about 1250 to 2500 Hz, when accounting for the pavement-specific sound absorption.

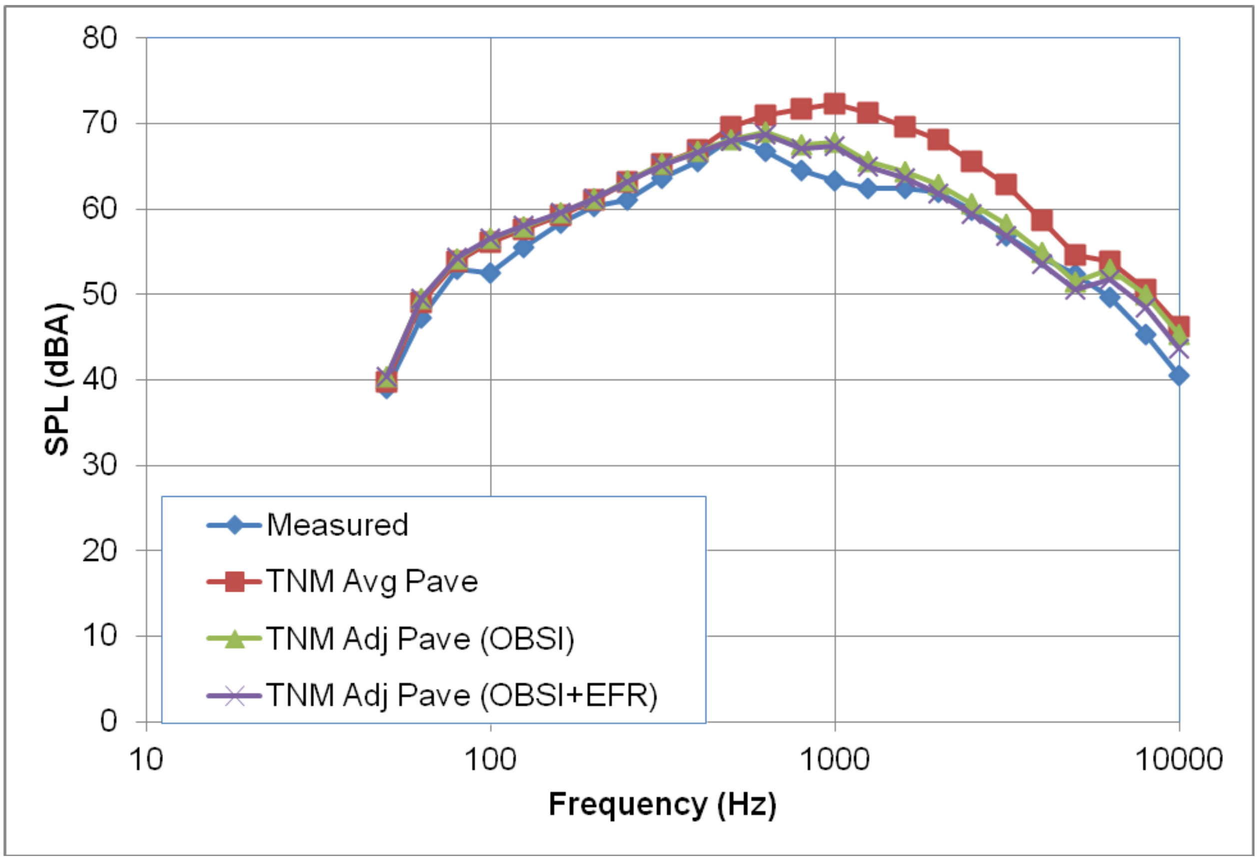


Figure 13. TNM-predictions compared to measured highway noise data, applying TNM Average pavement and TNM OBSI-adjusted and EFR-adjusted pavement; spectral sound levels.

The example above shows that for real highway cases, some improvement can be seen when accounting for the pavement sound absorption effect in predictions. The improvements are very slight in the example, but since it's possible to achieve greater improvement for other cases, it was determined that the EFR value should be accounted for in the predictions and that the EFR data collection and analysis process is a valid way to collect the EFR data for implementation.

4.3.5 Limitations of methodology

The one limitation found with the implementation of pavement-specific sound absorption in the FHWA TNM lies in the EFR data collection/analysis process for insufficiently thick porous pavements: the process breaks down when the pavement being tested is not seen as semi-infinite (i.e., there is a change in material as a function of depth, which affects the EFR data). Such cases include very porous pavements (please see last three entries in Table 2); when insufficiently thick, sound reflects off the underlying structure (usually a non-porous pavement) affecting the sound levels above the surface of the porous pavement.

Figure 14 shows a typical EFR curve for pavement measurements (tabular format in Appendix A); in this case, the EFR curve has the usual dip-peak-dip shape. Figure 14 also shows data with an atypical shape: dip-peak-peak-dip, where this extra peak is evidence of an underlying structure affecting the measurements. The atypical dip-peak-peak-dip shape was seen for the last three entries in Table 2, each a relatively thin layer of very porous pavement. To verify the cause, an experiment was conducted using a porous rubber mat (similar to a poroelastic road surface); the mat was placed over an acoustically hard ground surface (cement concrete sidewalk) and over an acoustically soft ground surface (lawn). If the underlying structure were to *not* affect the measurements, then the results should be the same whether the mat was placed on sidewalk or lawn. Such was not the case; the measurements were clearly affected by the underlying structure (please refer to Figure 15, tabular format in Appendix A). Also, the atypical dip-peak-peak-dip shape is evident with the mat over sidewalk, and even over the lawn. The placement (frequency) of the extra peak in each curve is indicative of the EFR value for the underlying structure*, and thus can be attributed to the underlying structure. Note that in these double-peak situations, although the peak location is indicative of the EFR value, the amplitudes of the peaks are assumed to be affected by interactions of both surfaces; thus a precise EFR value cannot be extracted.

Although it may be possible to overcome this limitation with more intricate data collection/processing techniques that include changes of material properties as a function of depth, it was determined that such an effort is out of the scope of the work, considering possible changes that would be required to the FHWA TNM ground reflection equations and that the cost per decibel improvement for such an effort would be high. An educated approximation on how to account for insufficiently thick porous pavements should be sufficient.

* Theoretical EFR curves were regenerated adding the extra height of a porous layer to the source and receiver locations; this assumes the porous layer is not being seen at all acoustically, but allows determination of the frequency location for the peak. The extra height pushes the peak to a lower frequency. So, as an example, where pavement may normally have a peak at 2000 Hz, the extra height pushes the peak to 1250 Hz, as seen in Figure 14, which shows one peak for the surface pavement and one for the underlying pavement.

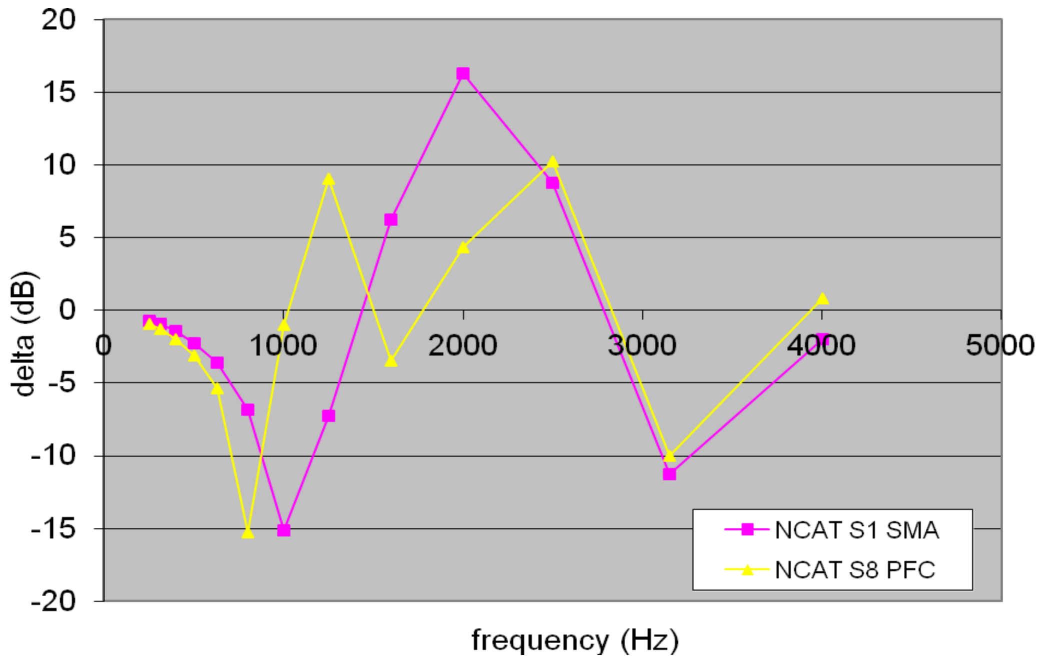


Figure 14. Example measured EFR curves, typical and atypical.

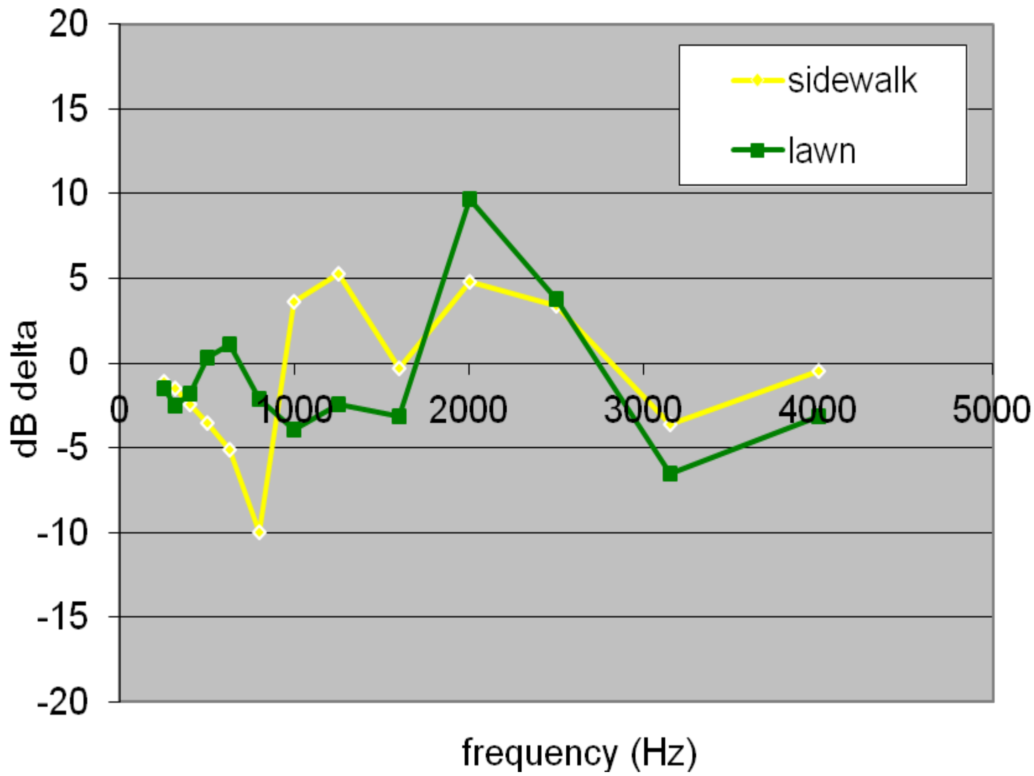


Figure 15. EFR curves for rubber mat experiment, both atypical.

4.4 Implementation Recommendations

Since the investigation showed the potential for up to 2 dB of effect due to pavement sound absorption, and since the demonstration showed that predicted results could be improved by applying pavement-specific EFR values, even if only a small amount for the cases examined, it has been determined that pavement-specific EFR values should be included with Implementation Options 1 and 2.

The logical next steps are to:

1. Organize the current EFR database in terms of pavement groupings (groupings identified as part of Implementation Option 2). For implementation in the FHWA TNM, use EFR values for pavements aged at least 5 years.
2. Determine if there is enough data for each pavement group and if there are gaps in the EFR database. It is already known that there is a gap for porous pavements. Data will need to be collected for thicker layers of porous pavements (>15 % air void content), where reflections from underlying structures do not influence the results. It needs to be determined how low an EFR value can be for a porous pavement. Although possibly out of the scope of the FHWA TNM Pavement Effects Implementation Study, the following should be determined: thickness requirement for porous pavements to minimize the influence from underlying structures, perhaps in terms of percent air void.
3. Determine how a TNM user could enter data for a user-defined EFR value for pavement.

Regarding assigning EFR values to pavement types for the implementation in the FHWA TNM, the following are some thoughts on how this could be accomplished:

1. Assigning EFR values to specific pavements:
    a. Where effects from an underlying structure *cannot* be seen, the EFR value obtained from measurements can be directly applied.
    b. Where effects from an underlying structure *can* be seen, the applied EFR value should be estimated to best represent the porous surface layer (see #2 in this list for limitations).

2. Applying a porous pavement in the FHWA TNM, here are suggested choices:
    a. The user must provide proof of no effects from an underlying structure for their pavement specifications in order to use the EFR values assigned to a pavement category or to use user-defined EFR values.
    b. Without proof, the FHWA TNM would need to account for the degraded acoustical absorption performance, possibly by applying a pavement absorption "penalty" (increase the EFR value) or use the current default EFR value of 20000 cgs rayls.

It should be noted that wayside noise measurements (REMEL), as are applied to Option 1 already include a small amount of pavement sound absorption effect due to propagation over the distance of the nearest travel lane and shoulder in a line perpendicular with the roadway. In most highway configurations, the sound absorption effect would be much greater, with the sound traveling over greater propagation distances over the pavement due to sound sources coming from multiple lanes and angles. Although a small amount of the sound absorption effect would be duplicated when applying a pavement-specific EFR value, the duplication should be small; it is thought that improvements in predicted results by applying a pavement-specific EFR value outweigh any adverse effect from duplication. This needs to be investigated, along with the possibility of correcting for the small amount of duplication.

5. CONCLUSIONS

For the FHWA TNM Pavement Effects Implementation Study, three implementation options were considered:

1. integrating new data into the FHWA TNM vehicle noise database (REMEL) for specific pavement types and also adjusting the roadway effective flow resistivity (EFR, a measure of sound absorption);
2. adjusting the existing tire/pavement source level in the FHWA TNM using on-board sound intensity (OBSI) data and also adjusting the roadway EFR; and
3. applying a pavement type offset adjustment value to the predicted sound levels (post FHWA TNM calculations).

Investigations of pavement-specific REMELs, OBSI-adjustments, and EFR-adjustments allowed for the determination of the validity of each option.

Implementation Option 1 was determined to be a valid option for implementing pavement-specific effects in the FHWA TNM, assuming the REMEL data set collected is adequate, as described in Appendix B. Adequacy is determined based on the number of data points, number of sites represented, range of speeds, and tonal qualities of the average spectrum. Prior to implementation, further work required for this option includes the following:

- formalize the data adequacy-analysis-process;
- further validate the use of pavement-specific REMELs by comparing predicted data to measured data (include adjusting the pavement EFR value); and
- modify the software to allow for functionality and user input.

Although this option would require extensive cost- and time-prohibitive data collection in order to generate a database for the FHWA TNM for a broad array of pavement types, this option should be left open to FHWA TNM users; they would need to get FHWA approval prior to implementation.

Implementation Option 2 was determined to be a valid option for implementing pavement-specific effects in the FHWA TNM. Prior to implementation, further work required for this option includes the following:

- develop a large OBSI-adjustment database through additional data collection and by obtaining data from other organizations, as it becomes available;
- determine pavement groupings and the number of data points adequate to represent each group;
- develop an EFR database adequate to support each pavement group;
- further investigate the applicability of the OBSI adjustment to each vehicle type; and
- modify the software to allow for functionality and user input.

Because a large OBSI database already exists and is relatively efficient to augment, it is intended that the adjustment database will be included in a future version of the FHWA TNM. In addition, user-defined OBSI adjustments should be an option for FHWA TNM users; they would need to get FHWA approval prior to implementation.

Implementation Option 3 was determined not to be a valid option since current efforts established that pavement effects are distance-dependent and site-geometry dependent, and therefore, adjusting predicted sound levels by a single decibel offset or adjustment value would be inaccurate in many cases.

The FHWA finds both Implementation Options 1 and 2 to be valid options for users, but Implementation Option 2 (using OBSI data to adjust for pavement effects) is the preferred option due to ease and efficiency of data collection, compilation, and implementation. It should be noted that both Implementation Options 1 and 2 would be dependent on FHWA policies or guidance and would require a change to federal noise policy 23 CFR 772.

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APPENDIX A. TABLES

A.1 Tables of Values for Plots in Section 2

Tables 3-5 in this section correspond to Figures 1-3 in Section 2.

Table 3. Tabular form: TNM-predicted sound pressure levels (L_{Aeq1h}) as a function of distance – flat site, no noise barrier. Variables: louder and quieter pavement, acoustically hard and soft ground.

Distance from center of near travel lane (ft)	Louder pavement sound level (dBA)		Quieter pavement sound level (dBA)	
	Hard ground	Soft ground	Hard ground	Soft ground
50	77.3	76.8	73.9	73.1
100	74.1	70.1	71.2	66.8
200	70.8	63.7	68.4	60.7
300	68.8	59.9	66.6	57.2
400	67.3	57.2	65.2	54.7
500	66.0	55.1	64.0	52.9
600	64.9	53.3	63.0	51.3
700	64.0	51.6	62.2	49.9
800	63.2	50.2	61.4	48.8
900	62.4	49.0	60.7	47.9
1000	61.7	47.9	60.1	47.0
1100	61.1	47.0	59.5	46.3
1200	60.5	46.1	59.0	45.6
1300	59.9	45.4	58.5	45.1
1400	59.4	44.8	58.0	44.6
1500	58.9	44.2	57.5	44.1
1600	58.4	43.7	57.1	43.7

Table 4. Tabular form: TNM-predicted noise reductions (L_{Aeq1h} for louder pavement minus quieter pavement) as a function of distance. Variables: flat site (with acoustically hard and soft ground), barrier site, elevated road, depressed road.

Distance from center of near travel lane (ft)	Flat open site sound level reduction (dBA)		Barrier site sound level reduction (dBA)	10-ft elevated road sound level reduction (dBA)	10-ft depressed road sound level reduction (dBA)
	Soft ground	Hard ground	Soft ground	Soft ground	Soft ground
50	3.7	3.4	1.0	2.8	2.0
100	3.3	2.9	1.3	3.3	2.2
200	3.0	2.4	1.6	3.2	2.4
300	2.8	2.2	1.6	3.1	2.4
400	2.5	2.1	1.4	3.0	2.2
500	2.3	2.0	1.2	2.8	1.9
600	2.0	1.9	1.0	2.6	1.6
700	1.7	1.8	0.8	2.4	1.3
800	1.4	1.7	0.6	2.1	1.1
900	1.1	1.7	0.4	1.8	0.8
1000	0.9	1.6	0.3	1.5	0.6
1100	0.7	1.5	0.2	1.3	0.4
1200	0.5	1.5	0.1	1.1	0.3
1300	0.4	1.4	0.0	0.8	0.2
1400	0.2	1.4	-0.1	0.7	0.1
1500	0.1	1.3	-0.2	0.5	0.0
1600	0.0	1.3	-0.2	0.4	-0.1

Table 5. Tabular form: TNM-predicted sound pressure spectral levels (LAeq1h) – flat site, no noise barrier, acoustically soft ground. Variables: distance, louder and quieter pavement.

Frequency (Hz)	Louder pavement sound level (dBA)			Quieter pavement sound level (dBA)		
	Distance = 50 ft	Distance = 500 ft	Distance = 1000 ft	Distance = 50 ft	Distance = 500 ft	Distance = 1000 ft
broadband	76.8	55.1	47.9	73.1	52.9	47.0
50	33.2	23.2	20.1	34.1	24.1	21.0
63	42.2	32.1	29.0	44.0	33.9	30.8
80	46.8	36.6	33.5	48.3	38.2	35.0
100	49.3	39.0	35.8	50.2	39.9	36.7
125	51.3	40.8	37.5	51.7	41.2	38.0
160	53.6	42.6	39.2	53.8	42.8	39.5
200	55.4	43.5	39.8	55.7	43.9	40.2
250	56.5	41.3	33.2	56.9	41.9	33.8
315	58.4	38.3	28.9	59.0	38.9	29.5
400	60.8	34.5	29.2	61.3	35.1	29.9
500	64.0	37.3	29.3	64.1	37.4	29.5
630	65.6	40.4	31.6	65.0	39.6	30.9
800	67.8	43.2	33.5	65.7	41.0	31.2
1000	69.4	45.1	35.4	65.4	41.5	31.8
1250	68.8	45.5	36.0	62.7	40.7	31.3
1600	67.9	45.9	36.3	59.5	39.9	30.4
2000	67.0	45.1	35.5	57.4	39.0	29.7
2500	64.4	44.6	35.4	55.0	39.1	30.1
3150	61.5	43.2	34.6	53.2	38.5	30.1
4000	57.6	37.4	30.0	51.2	33.6	26.6
5000	53.1	29.3	23.6	49.1	26.1	21.4
6300	51.0	32.5	25.4	48.3	31.2	24.3
8000	47.9	28.7	21.5	45.8	27.7	20.6
10000	45.0	22.8	15.1	40.9	20.0	12.6

A.2 Tables of Values for Plots in Section 3

Tables 6 and 7 in this section correspond to Figures 6 and 7 in Section 3.

Table 6. Tabular form: TNM-predictions compared to measured highway noise data, applying TNM Average pavement and TNM OBSI-adjusted pavement; broadband sound levels.

Broadband RAC			Broadband LPCC			Broadband TPCC		
Avg Road - Meas (RAC)	Avg RAC Adj- Meas	Spec RAC Adj - Meas	Avg Road - Meas (LPCC)	Avg LPCC Adj- Meas	Spec LPCC Adj - Meas	Avg Road - Meas (TPCC)	Avg TPCC Adj- Meas	Spec TPCC Adj - Meas
6.0	2.9	2.1	-0.6	0.4	-0.1	-3.7	-0.4	-0.7
5.7	2.5	1.8	-0.7	0.4	-0.3	-3.4	-0.2	-0.3
5.9	3.3	2.6	-0.5	0.7	-0.1	-3.0	0.1	0.8
4.6	1.7	1.5	-0.9	0.0	0.2	-3.8	-0.1	0.2
4.9	1.8	1.7	-1.1	-0.4	-0.8	-3.3	0.3	0.5
5.8	2.7	2.5	-0.5	0.6	-0.2	-3.2	0.6	0.5

Table 7. Tabular form: TNM-predictions compared to measured highway noise data, applying TNM Average pavement and TNM OBSI-adjusted pavement; spectral sound levels.

Frequency (Hz)	Rubberized asphalt sound levels (dBA)			Longitudinally tined PCC sound levels (dBA)			Transversely tined PCC sound levels (dBA)		
	Measured	TNM Ave. Pave.	TNM Adj. Pave.	Measured	TNM Ave. Pave.	TNM Adj. Pave.	Measured	TNM Ave. Pave.	TNM Adj. Pave.
broadband	75.2	80.2	77.0	84.9	83.8	84.6	82.9	79.4	82.6
50	39.0	39.8	40.3	39.9	39.0	38.9	35.6	37.3	36.4
63	47.3	49.1	49.5	48.7	48.9	48.9	40.8	46.7	45.8
80	53.0	53.8	54.2	53.6	54.3	54.3	48.6	51.9	51.0
100	52.5	56.2	56.5	57.5	57.1	57.0	51.3	54.8	53.9
125	55.5	57.6	57.9	59.4	59.0	58.9	54.6	57.1	56.3
160	58.4	59.2	59.5	60.6	60.9	60.7	57.3	59.4	58.7
200	60.3	61.0	61.2	62.4	62.8	62.5	58.3	61.3	60.5
250	61.0	63.1	63.3	63.2	65.3	65.1	60.4	63.1	62.1
315	63.6	65.2	65.2	65.9	67.6	67.2	61.9	64.6	63.4
400	65.5	66.9	66.7	67.6	69.9	69.3	63.2	66.0	64.4
500	68.3	69.6	68.1	71.5	72.8	72.8	65.9	68.2	67.6
630	66.8	71.0	69.0	73.4	75.1	73.3	68.3	70.1	68.4
800	64.5	71.8	67.5	76.1	75.4	75.2	72.0	70.7	71.0
1000	63.3	72.4	67.8	77.5	76.2	79.2	76.0	71.5	77.2
1250	62.4	71.3	65.6	77.4	75.0	75.7	78.2	70.7	75.4
1600	62.5	69.7	64.4	76.6	73.6	75.4	74.6	69.5	74.9
2000	62.0	68.1	62.9	74.9	71.8	72.8	71.7	68.1	72.9
2500	59.8	65.6	60.6	72.0	69.8	69.0	67.9	65.3	68.5
3150	56.9	62.8	58.2	68.9	67.6	66.1	63.8	62.1	63.8
4000	54.3	58.6	55.0	65.8	63.5	62.4	60.2	57.5	59.1
5000	52.4	54.6	51.5	62.2	60.9	59.7	56.9	52.6	54.5
6300	49.7	53.8	53.0	58.2	56.5	54.7	53.0	51.8	49.6
8000	45.3	50.5	49.9	53.8	53.4	51.6	47.9	48.8	46.8
10000	40.6	46.2	45.4	47.5	50.8	48.5	42.4	46.3	44.2

A.3 Tables of Values for Plots in Section 4

Tables 8 and 9 in this section correspond to Figures 9 and 10 in Section 4. Also, Tables 10-13 in this section correspond to Figures 12-15 in Section 4.

Table 8. Tabular form: Sound level differences from that for 20K EFR as a function of EFR; 2- and 8-lane road, hard and soft ground. Top plot: distance = 50 ft, bottom plot: distance = 200 ft.

Parameters	Dis-tance (ft)	EFR value (cgs rayls)							
		2000	4000	6000	8000	10000	12000	15000	20000
2-lane, hard ground	50	-1.4	-0.8	-0.5	-0.4	-0.3	-0.2	-0.1	0.0
	200	-0.9	-0.5	-0.4	-0.2	-0.2	-0.1	-0.1	0.0
2-lane, soft ground	50	-1.6	-0.9	-0.6	-0.4	-0.3	-0.2	-0.1	0.0
	200	-1.0	-0.6	-0.4	-0.3	-0.2	-0.2	-0.1	0.0
8-lane, hard ground	50	-1.5	-0.8	-0.5	-0.4	-0.3	-0.2	-0.1	0.0
	200	-1.0	-0.6	-0.4	-0.3	-0.2	-0.1	-0.1	0.0
8-lane, soft ground	50	-1.9	-1.1	-0.7	-0.5	-0.4	-0.2	-0.1	0.0
	200	-1.5	-1.0	-0.7	-0.5	-0.3	-0.2	-0.1	0.0

Table 9. Tabular form: Spectral sound levels with varying EFR values; 8-lane road, soft ground. Top plot: distance = 50 ft, bottom plot: distance = 200 ft.

8-lane, soft ground																
Frequency (Hz)	EFR value (cgs rayls)															
	2000		4000		6000		8000		10000		12000		15000		20000	
	Distance from center of near travel lane (ft)															
	50	200	50	200	50	200	50	200	50	200	50	200	50	200	50	200
50	38.3	33.4	38.3	33.4	38.3	33.3	38.3	33.3	38.3	33.3	38.3	33.3	38.3	33.3	38.3	33.3
63	47.5	42.4	47.5	42.4	47.5	42.4	47.5	42.4	47.5	42.4	47.5	42.4	47.5	42.4	47.5	42.4
80	52.3	47.3	52.3	47.2	52.3	47.2	52.3	47.2	52.3	47.2	52.3	47.2	52.3	47.2	52.3	47.2
100	54.7	49.7	54.7	49.6	54.7	49.6	54.7	49.6	54.7	49.6	54.7	49.6	54.7	49.6	54.7	49.6
125	56.2	51.2	56.2	51.2	56.2	51.2	56.2	51.2	56.2	51.2	56.2	51.2	56.2	51.2	56.2	51.2
160	57.9	52.8	57.9	52.8	57.9	52.8	57.9	52.8	57.9	52.8	57.9	52.8	57.9	52.8	57.9	52.8
200	59.5	54.3	59.6	54.2	59.6	54.2	59.6	54.2	59.6	54.2	59.6	54.2	59.6	54.2	59.6	54.2
250	61.2	55.3	61.2	55.2	61.3	55.2	61.3	55.2	61.3	55.2	61.3	55.2	61.3	55.2	61.3	55.2
315	62.1	54.9	62.2	54.8	62.3	54.8	62.3	54.8	62.3	54.7	62.3	54.7	62.3	54.7	62.3	54.7
400	63.5	54.3	63.8	54.4	63.8	54.5	63.9	54.4	63.9	54.4	63.9	54.4	63.9	54.4	64.0	54.4
500	65.7	55.2	66.1	55.7	66.2	55.8	66.3	55.8	66.3	55.9	66.4	55.9	66.4	55.9	66.4	55.9
630	66.8	55.8	67.4	56.8	67.5	57.1	67.6	57.2	67.7	57.3	67.8	57.4	67.8	57.4	67.8	57.5
800	67.8	57.5	68.6	58.7	68.9	59.1	69.1	59.3	69.1	59.5	69.2	59.5	69.3	59.6	69.3	59.7
1000	68.1	58.4	69.1	59.6	69.5	60.2	69.7	60.4	69.9	60.6	70.0	60.7	70.1	60.8	70.2	60.9
1250	66.5	58.0	67.8	58.9	68.4	59.5	68.7	59.9	68.9	60.1	69.1	60.3	69.2	60.4	69.4	60.6
1600	64.6	57.5	65.9	58.0	66.6	58.4	67.0	58.8	67.3	59.0	67.5	59.2	67.7	59.4	67.9	59.6
2000	61.9	55.3	63.5	55.6	64.4	56.1	65.0	56.5	65.4	56.8	65.7	57.1	66.0	57.3	66.3	57.7
2500	59.7	53.1	61.0	53.3	61.8	53.5	62.4	53.8	62.8	54.0	63.1	54.3	63.5	54.6	63.9	55.0
3150	57.6	51.6	58.5	51.6	59.2	51.7	59.8	51.9	60.2	52.0	60.5	52.2	60.9	52.4	61.3	52.7
4000	54.8	48.0	55.2	48.0	55.8	48.1	56.3	48.1	56.7	48.2	57.0	48.3	57.4	48.5	57.9	48.8
5000	52.0	45.2	51.9	45.2	52.2	45.2	52.6	45.3	52.9	45.3	53.2	45.4	53.6	45.4	54.1	45.6
6300	50.4	44.2	50.7	44.2	51.2	44.2	51.6	44.3	52.0	44.3	52.3	44.4	52.6	44.5	53.0	44.8
8000	46.9	40.6	47.2	40.6	47.8	40.7	48.3	40.7	48.7	40.8	49.0	40.9	49.3	41.0	49.8	41.3
10000	41.7	35.0	42.2	35.0	43.0	35.1	43.7	35.3	44.2	35.4	44.6	35.6	45.1	35.8	45.6	36.3

Table 10. Tabular form: Example theoretical EFR curves. For each EFR value (cgs rayls), the data are presented as the delta sound level between the two microphones (upper minus lower) as a function of frequency.

Frequency (Hz)	EFR value (cgs rayls)								
	100	300	500	1000	3000	5000	10000	20000	30000
250	-1.0	-0.8	-0.8	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7
315	-1.4	-1.2	-1.1	-1.0	-1.0	-1.0	-1.0	-0.9	-0.9
400	-2.0	-1.8	-1.7	-1.6	-1.5	-1.5	-1.5	-1.4	-1.4
500	-2.9	-2.8	-2.6	-2.5	-2.3	-2.3	-2.3	-2.2	-2.2
630	-3.9	-4.7	-4.5	-4.2	-3.9	-3.9	-3.8	-3.8	-3.8
800	-1.2	-8.3	-8.8	-8.4	-7.7	-7.5	-7.4	-7.3	-7.2
1000	3.5	-3.1	-7.5	-13.0	-18.4	-19.1	-19.2	-19.0	-18.9
1250	4.6	6.1	4.1	0.7	-2.7	-3.7	-4.5	-5.1	-5.3
1600	2.8	7.9	10.8	12.9	10.2	9.1	8.1	7.5	7.3
2000	-0.7	3.7	6.2	10.0	16.7	19.9	24.0	27.0	28.0
2500	-5.0	-3.5	-1.8	0.6	3.7	4.7	5.7	6.3	6.6
3150	-0.7	-3.6	-5.4	-8.2	-13.2	-15.4	-18.2	-20.5	-21.5
4000	2.4	1.8	1.4	0.8	0.1	-0.1	-0.3	-0.4	-0.5

Table 11. Tabular form: TNM-predictions compared to measured highway noise data, applying TNM Average pavement and TNM OBSI-adjusted and EFR-adjusted pavement; spectral sound levels.

Frequency (Hz)	Rubberized asphalt sound levels (dBA)			
	Measured	TNM Ave. Pave.	TNM Adj. Pave. (OBSI)	TNM Adj. Pave. (OBSI and EFR)
broadband	75.2	80.2	77.0	76.7
50	39.0	39.8	40.3	40.4
63	47.3	49.1	49.5	49.5
80	53.0	53.8	54.2	54.3
100	52.5	56.2	56.5	56.6
125	55.5	57.6	57.9	58.0
160	58.4	59.2	59.5	59.5
200	60.3	61.0	61.2	61.2
250	61.0	63.1	63.3	63.2
315	63.6	65.2	65.2	65.1
400	65.5	66.9	66.7	66.6
500	68.3	69.6	68.1	67.9
630	66.8	71.0	69.0	68.7
800	64.5	71.8	67.5	67.1
1000	63.3	72.4	67.8	67.3
1250	62.4	71.3	65.6	64.9
1600	62.5	69.7	64.4	63.5
2000	62.0	68.1	62.9	61.8
2500	59.8	65.6	60.6	59.4
3150	56.9	62.8	58.2	56.9
4000	54.3	58.6	55.0	53.5
5000	52.4	54.6	51.5	50.6
6300	49.7	53.8	53.0	51.7
8000	45.3	50.5	49.9	48.5
10000	40.6	46.2	45.4	43.7

Table 12. Tabular form: Example measured EFR curves, typical and atypical.

Frequency (Hz)	NCAT S1 SMA Typical shape	NCAT S8 PFC Atypical shape
250	-0.7	-0.9
315	-0.9	-1.3
400	-1.4	-1.9
500	-2.3	-3.1
630	-3.6	-5.4
800	-6.8	-15.3
1000	-15.1	-1.0
1250	-7.3	9.1
1600	6.2	-3.5
2000	16.3	4.3
2500	8.7	10.2
3150	-11.3	-10.0
4000	-2.0	0.8

Table 13. Tabular form: EFR curves for rubber mat experiment, both atypical.

Frequency (Hz)	Mat over sidewalk Atypical shape	Mat over lawn Atypical shape
250	-1.1	-1.5
315	-1.5	-2.5
400	-2.4	-1.8
500	-3.5	0.3
630	-5.1	1.1
800	-10	-2.1
1000	3.6	-3.9
1250	5.3	-2.4
1600	-0.3	-3.1
2000	4.8	9.7
2500	3.4	3.8
3150	-3.6	-6.5
4000	-0.5	-3.1

APPENDIX B. REMEL ANALYSIS

This appendix is a self-contained write-up concerning the FHWA TNM vehicle emission levels analysis and the adequacy of measured data sets.

Challenges Computing Reference Energy Mean Emission Level Coefficients using Small Datasets

Introduction

The Federal Highway Administration's Traffic Noise Model (FHWA's TNM), which is used "as a means of aiding compliance with policies and procedures under FHWA regulations"[1], uses Reference Energy Mean Emission Levels (REMELs)[2] as the foundation of its source sound level computations. TNM has REMEL data for two vehicle operating conditions: cruise and full-throttle; five standard vehicle types: automobiles, medium trucks, heavy trucks, buses, and motorcycles; and for five pavement types, dense-graded asphalt concrete (DGAC), open-graded asphalt concrete (OGAC), Portland cement concrete (PCC), and Average (a combination of DGAC and PCC). TNM also has the ability to accept limited REMEL data for user-defined vehicle types. Various agencies are also interested in developing custom REMELs for new pavements. Although TNM version 2.5 does not support user defined REMELs for new pavements, this functionality may be implemented in the future.

The intent of this document is to 1) provide an overview of the process for computing REMEL coefficients, 2) to identify conditions where the REMEL model is and is not applicable, and 3) to provide guidance on issues related to developing REMELs when using small datasets. The process for computing both overall A-weighted level coefficients, A to C, and for computing the spectral coefficients, D1 to K2, will be reviewed and a procedural flowchart will be developed to help guide the acoustician through the process of selecting the correct steps for their dataset. This overview will include a discussion of both historical recommendations and recommendations based on current statistical processing capabilities. Following this overview, several problem data sets will be considered and recommendations to deal with these datasets will be made. These recommendations will include the collection of additional data, the use of related existing data to supplement the modeling, and alternate methods to aggregate the data. In some cases the REMEL model will not be suitable. In such cases explanation as to why a dataset is not suitable for REMEL modeling will be given.

Overview of REMEL Model

The REMEL model was developed for use with the FHWA's Traffic Noise Model from individual vehicle pass-by data measured at (or corrected to) 50 feet from the center of the traffic lane of interest, 5 feet above the plane of the road surface. Key input parameters include: pavement type, operating condition, vehicle type, vehicle speed, maximum A-weighted sound pressure level during the pass-by event, vehicle speed at pass-by, the one-third octave band level associated with the maximum A-weighted sound pressure level, and the event quality, that is, whether or not there was contamination from other sound sources during the measurement.
The model assumes that the sound pressure level is an energy sum of two levels, a constant component, which can be determined from the idle level, and a speed dependent component, which can be determined from the level over a sufficient speed range. The combination of the two components is illustrated in Figure 1. In this example the overall level is dominated by the

constant component below speeds of about 10 mph. Between 10 and 20 mph, there is a transition where both components significantly affect the overall level. Above 20 mph, the speed dependent component dominates.

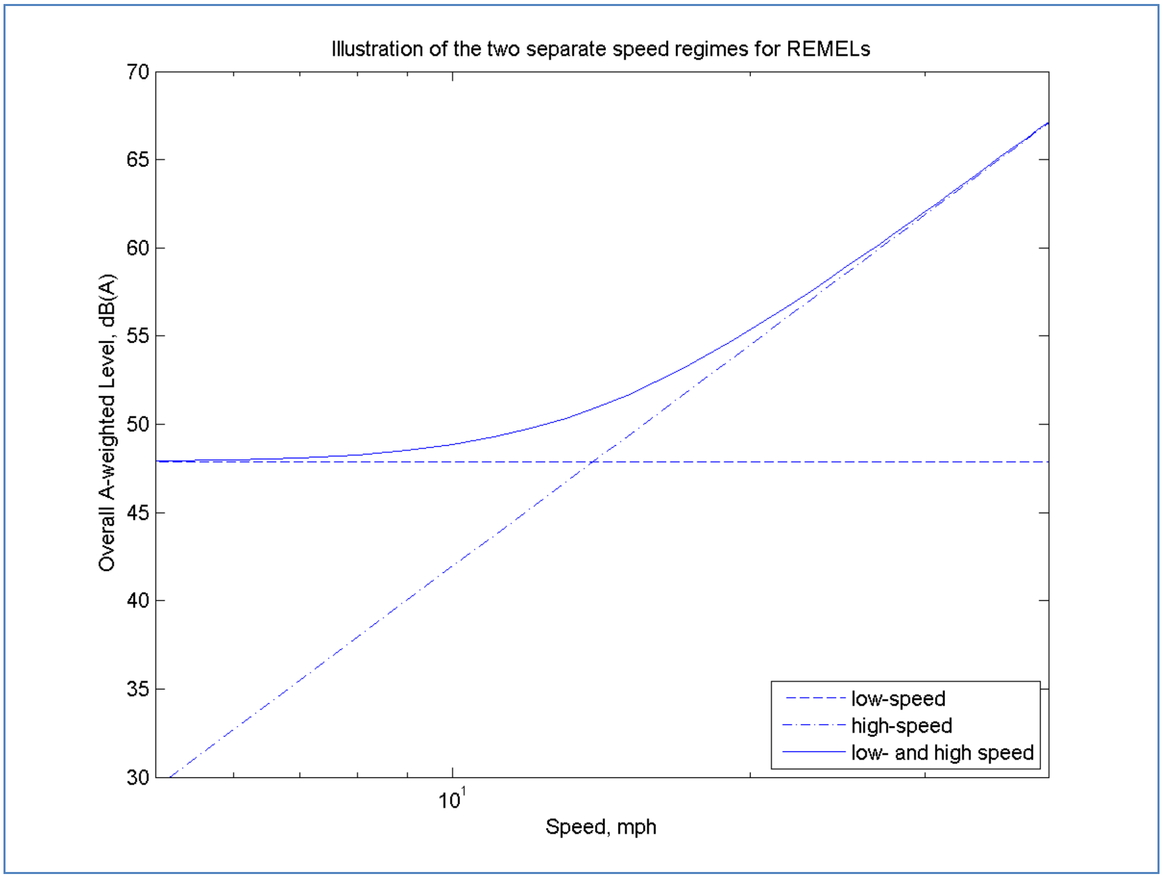

Figure 1: Overall A-weighted Level According to REMEL Model

The overall A-weighted sound pressure level model is given by:

Equation 1: REMELs Model for Overall A-weighted Level

$$L_{A,max}(s) = 10\log_{10}\left[10^{(C+\Delta E_c)/10} + \left(s^{A/10}\right)\left(10^{(B+\Delta E_b)/10}\right)\right]$$

Here, $L_{A,max}$ is the *energy mean* overall A-weighted level associated with the maximum level during pass-by, *s* is the speed in miles per hour; *A*, *B*, and *C* are REMEL coefficients associated with a specific vehicle type, pavement type, and engine operating condition; and ΔE_c and ΔE_b are corrections to convert from a level mean to an energy mean. $C + \Delta E_c$ account for the constant component. *A* accounts for the slope of the speed dependent component. $B + \Delta E_b$ account for the offset of the speed dependent component, that is, an increase in $B + \Delta E_b$ will result in the sloped portion of the overall level being shifted upwards in Figure 1. Note that there is no ΔE_A because the correction from level mean to energy mean for the speed dependent component is handled in the *B* coefficient. It is also important to note that ΔE is given not by the equation in Section 6.1.2 of Reference 2, but by:

Equation 2: Adjustment from Level Mean to Energy Mean

$$\Delta_E = 10\log_{10}\left(\frac{1}{N}\sum_{i=1}^{N}10^{r_i/10}\right)$$

where, N is the number of samples, $r_i = L_i - \bar{L}$, L_i is the overall A-weighted level for the i^{th} sample, and $\bar{L}$ is the linear average over all samples. The derivation for Equation 2 is given in Reference 95.

In addition to the overall A-weighted sound pressure level, the REMEL model accounts for the emission spectral shape. REMELs model the relationship between spectral content using the polynomial relationship given in Equation 3.

Equation 3: REMEL Model for One-Third Octave Band Spectra (Level Mean)

$$\begin{aligned}L_{A,max}(s,f) = {} & (D_1 + D_2 s) + (E_1 + E_2 s)log_{10}(f) + (F_1 + F_2 s)log_{10}(f)^2 \\ & + (G_1 + G_2 s)log_{10}(f)^3 + (H_1 + H_2 s)\,log_{10}(f)^4 + (I_1 + I_2 s)log_{10}(f)^5 \\ & + (J_1 + J_2 s)log_{10}(f)^6\end{aligned}$$

where, $L_{A,max}$ is the *level mean* overall A-weighted level associated with the maximum level during pass-by, s is the speed in miles per hour, f is the nominal center frequency of the one-third octave bands, and A_1 through J_2 are coefficients determined during the curve fitting process. An example of the spectral shapes obtained from this process is given in Figure 2.

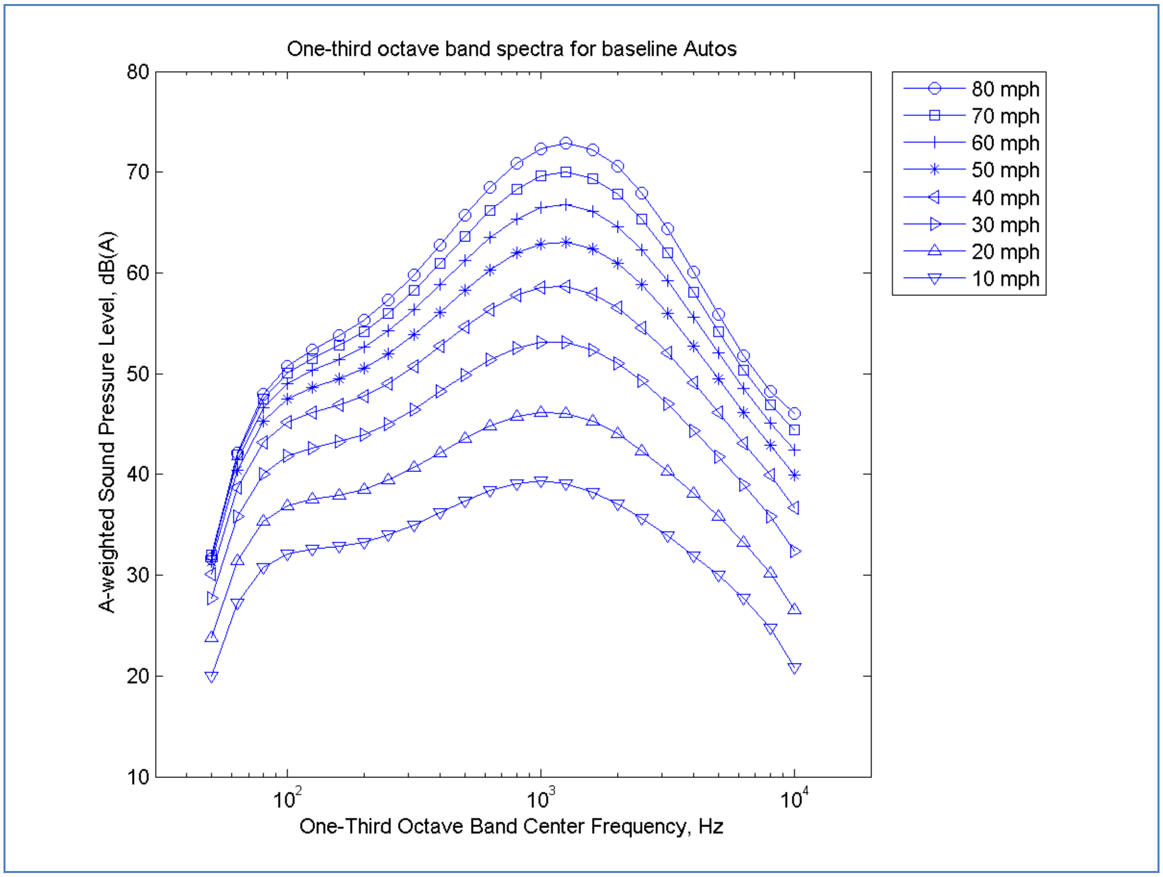

Figure 2: A-weighted Spectral Shape According to REMEL Model

Note, this model, does not include an adjustment from the level mean to the energy mean, therefore, this model represents the level mean. The overall energy mean and spectral level mean models can be unified by subtracting the overall A-weighted level mean as a function of speed alone from Equation 3 and then adding Equation 1.

Equation 4: REMEL Model for One-Third Octave Band Spectra (Energy Mean)

$$L_{A,max}(s,f) = 10\log_{10}\left[10^{(C+\Delta E_c)/10} + \left(s^{A/10}\right)\left(10^{(B+\Delta E_b)/10}\right)\right] - (K_1 + K_2 s) + (D_1 + D_2 s) + (E_1 + E_2 s)log_{10}(f) + (F_1 + F_2 s)log_{10}(f)^2 + (G_1 + G_2 s)log_{10}(f)^3 + (H_1 + H_2 s)log_{10}(f)^4 + (I_1 + I_2 s)log_{10}(f)^5 + (J_1 + J_2 s)log_{10}(f)^6$$

where, $L_{A,max}$ is the *energy mean* overall A-weighted level associated with the maximum level during pass-by and K_1 and K_2 remove the overall A-weighted level mean as a function of speed associated with Equation 3. Note, that since the first part of Equation 4 accounts for the adjustment from level mean to energy mean, and the second part of the equation provides no net change to the overall A-weighted level, an adjustment from level mean to energy mean is not required for the second part of Equation 4.

Guidance on Computing REMELs (and discussion of Sensitivities)

Although the REMEL model is straightforward, formal guidance is useful to help avoid pitfalls to modeling vehicle noise emissions using the approach. In this section, general principles for assuring data distribution in an ideal case will be discussed. Figure 3 shows the speed distribution for the auto baseline REMELs used for TNM 2.5. This distribution illustrates several key features of a good speed distribution:

1) Both high speed and low speed ranges are represented.
2) There is a gap in the data in the transition region.
3) The high speed data covers a wide range.
4) The speeds of most importance have greater representation.

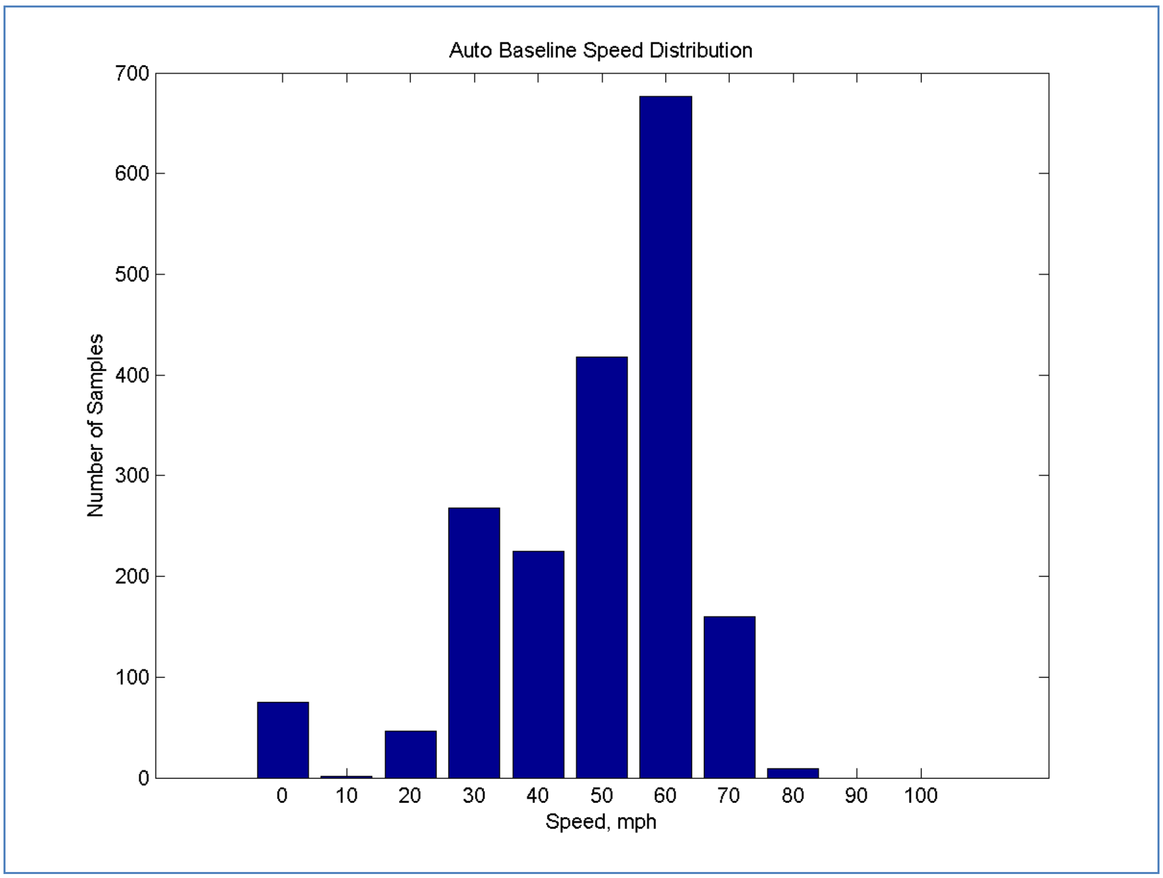

Figure 3: Data Distribution for Auto Baseline REMELs used in TNM 2.5

It is clear that having both high speed and low speed data allows for accurate estimates of both the *A* and *B* as well as the *C* coefficients is required. Assuming that the estimation of *C* is not dependent on *A* or *B*, Equation 1 can be reformulated as two linear equations, solving for *C* separately from *A* and *B*.

$$L_{A,max}(s) = 10\log_{10}\left[10^{(C+\Delta E_c)/10}\right]$$
$$L_{A,max}(s) = 10\log_{10}\left[\left(s^{A/10}\right)\left(10^{(B+\Delta E_b)/10}\right)\right]$$

This allows commonly available analysis tools to be used to solve for these parameters rather than having to rely on specialized non-linear solvers. However, in order to solve for the parameters separately, only data for the appropriate speed range should be used. When solving for *C*, only speeds where the low speed level dominates should be used. When solving for *A* and *B*, only speeds where the high speed level dominates should be used. The relationship between the data distribution and the linear portions of the curve can be seen in Figure 4. Having a speed distribution as shown in Figure 3 and Figure 4 allows all data to be used without risk of biasing the curve fitting results.

The independence assumption is valid provided that there is no relationship between the level at idle and at high speeds. A counter example to this independence assumption would be if all vehicles with higher than normal idle levels had higher than normal levels at, say, 55 mph. This would most likely happen if the vehicle's engine was the dominant source at high speed, but even then this is not a guarantee of dependency, it would still be possible for the engine operation to be sufficiently different at idle and at cruise that no relationship between the levels could be found. If there is doubt about the independence assumption, then it should be tested[*]. In cases where there is a significant dependence, then the non-linear form, Equation 1, must be used.

For the high speed portion of the curve, a slope needs to be estimated. This can only be done with confidence if the speed range creates a mean change in level greater than the random variation about the mean. If the data range is too small then the greatest portion of the variance will be explained by random factors rather than the growth of level associated with speed. Finally, a practical consideration is that REMELs are developed with a specific application in mind. Typically, this is to develop emissions for modeling traffic related noise adjacent to highways. In such cases, it is most useful to have the highest degrees of confidence in the speed range associated with highway traffic. In general it can be stated that, the greater the number of samples, the greater the confidence of a parameter's estimated value.

[*] A preliminary test of dependence that does not require non-linear modeling would be to determine the correlation between the level at idle and the level at, say, 55 mph. A non-zero correlation would indicate some level of dependency. It is suggested that any data set with a correlation of 0.3 or greater at least be further investigated using the non-linear model in Equation 1.

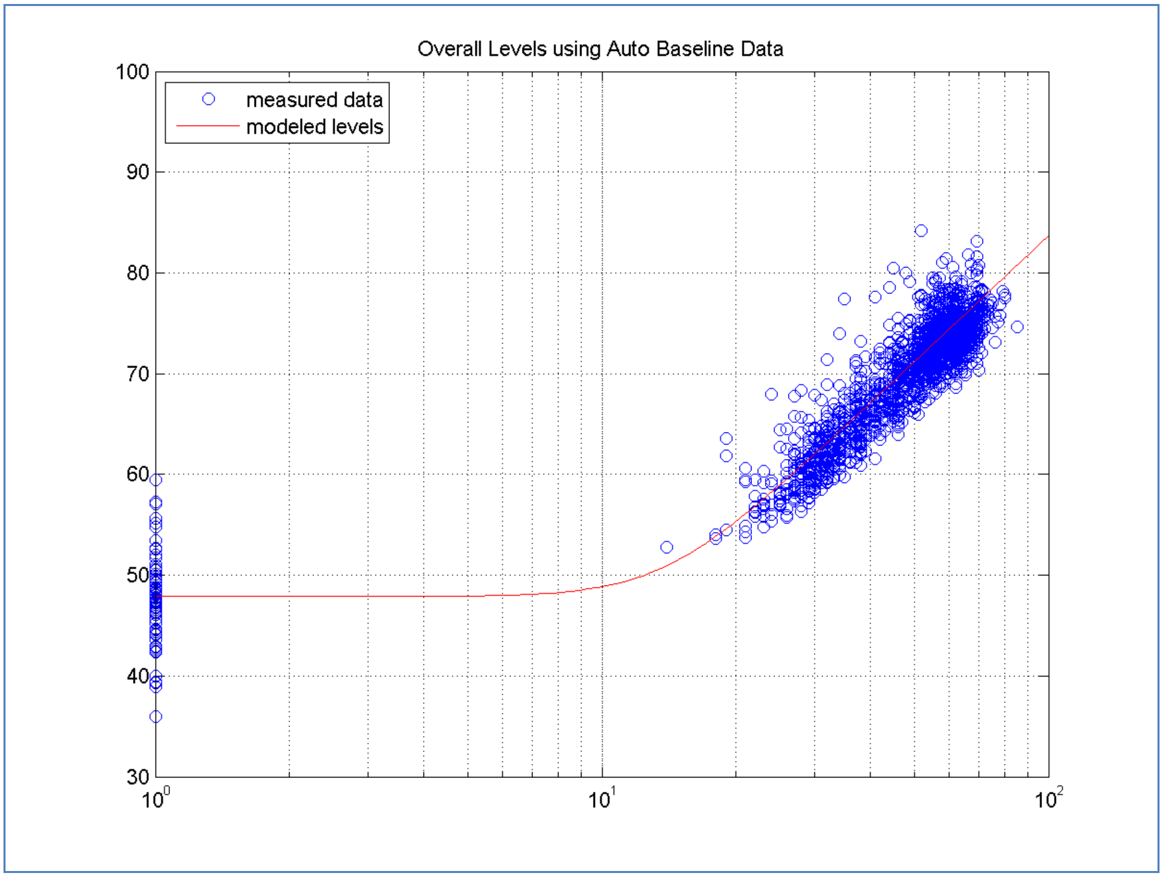

Figure 4: Ideal Speed Distribution of Data for Overall Levels with Respect to Curve Shape

Using an appropriate speed distribution for the data also results in spectral profiles that are well behaved as a function of speed, that is, the curves are anchored at the speed extremes to the data and the intermediate speed curves fit the data well. This can be seen in Figure 5, where the spectral curves fit the data very well and have smooth transitions from low speed to high speed. Note, that although the REMEL model fits the data very well above 1000 Hz, there is more unexplained variation below 1000 Hz. This is due in part to the form of the model and in part to the data. This will be discussed further in Section 5.

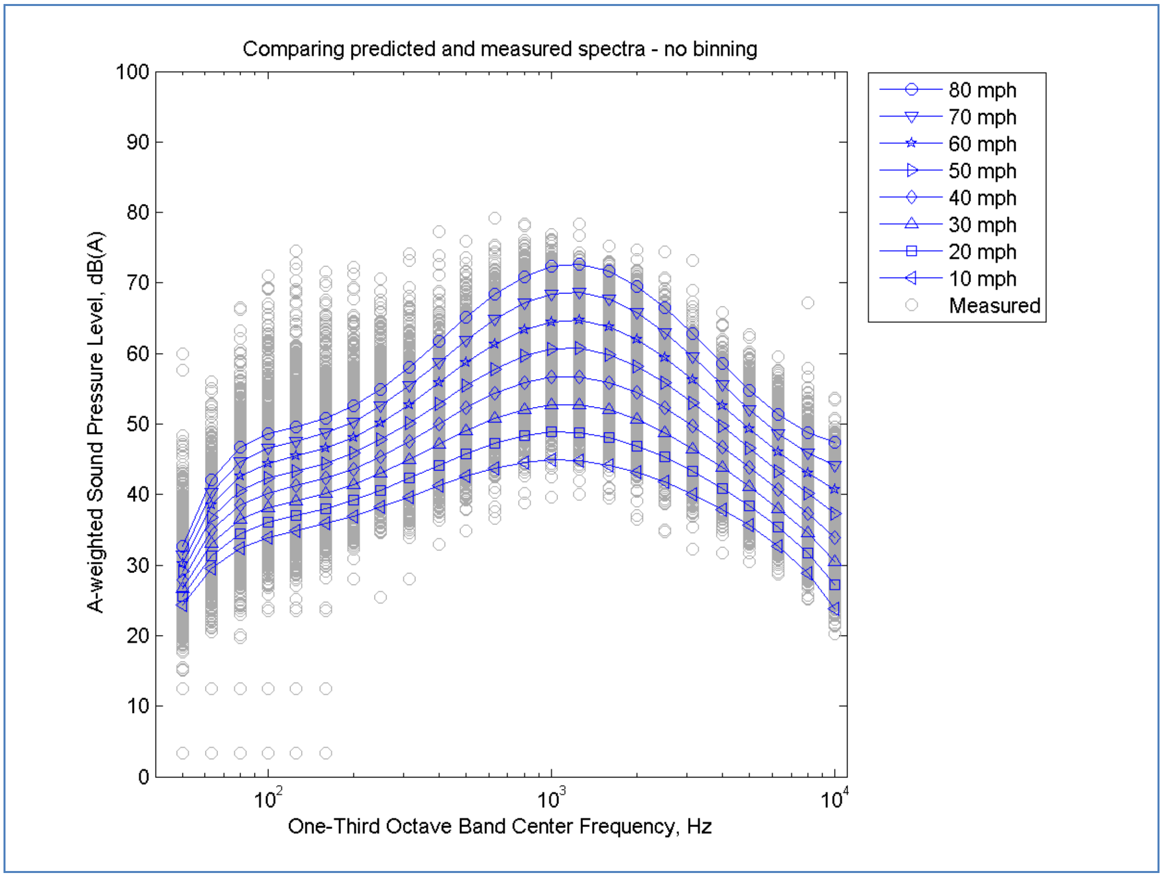

Figure 5: Example of Modeled Sprectral Content and Measured Data

Two additional questions to consider when modeling REMELs are: "What is the minimum number of samples required?" and "Should data be binned according to speed?" Both of these questions will be discussed in more detail in the following sections, however, a brief review of how these have been handled historically follows.

Historically, data have been computed without binning for computation of the overall A-weighted levels, but have been computed with binning for computation of the spectral coefficients[2]. Binning should not be used for overall A-weighted levels since confidence intervals rely on the assumption of no error on speed estimates, as discussed in Section 6. Binning is a direct violation of this assumption. Since ΔE is accounted for in the overall level, binning can be used for the computation of spectral coefficients. The main advantage to binning is that it is more convenient to work with speed-binned spectral data. For large data sets, depending on the analysis software available, it may not be practical to compute spectral coefficients without binning. Specific binning methods are discussed in Reference 2.

Historically, REMELs have been computed with the intention that they be generally applicable to a geographically diverse set of common pavements and vehicles. In order to have reasonable confidence of the estimated parameters for a diverse data set, a relatively large number of samples is necessary. The suggested minimum for general REMELs is given in Reference 5 and is repeated here for convenience.

Table 1: Minimum Number of Samples According to Reference 5

Speed, mph	Minimum Number of Samples
0-10	10
11-20	10
21-30	20
31-40	30
41-50	100
51-60	200
61-70	100

This document provides additional methods in the next sections for determining if sufficient samples have been obtained. Issues examined relate to the minimum number required for statistical validity, requirements for sufficient speed range coverage, appropriateness of the model, the effect of binning, and tests for statistical significance. By considering the issues explicitly, it may be possible to determine that a smaller data set is sufficient or that a large data set is required.

Identifying and Handling Problematic Data Sets for Overall Levels

The number of samples required and speed range that they should cover depends on a number of factors. At a minimum, there should be sufficient samples such that statistical analysis is valid. As mentioned before speed ranges need to cover the low and high speed ranges. However, when this is not the case, it may be possible to address the issue with substitute data. Finally, it goes without saying that the shape of the REMEL model must be appropriate for the data. REMELs do not allow for curve shapes other than those that can be described by Equation 1 and Equation 3. Several examples of potentially problematic data sets for overall A-weighted levels follow. Each example describes a typical problem and suggests appropriate responses.

Problem 1: Insufficient Data to Obtain Gaussian Estimate of Parameter

The data set is too small if the model parameter estimates are not Gaussian (or nearly Gaussian) in such cases the confidence interval will be artificially larger due to the need to use a t-distribution for confidence intervals rather than a normal distribution*. Fortunately it is expected that the parameter estimates will quickly take on a Gaussian distribution and the shape of the parameter estimate distribution is relatively insensitive to the shape of the data's distribution. For example, when idle data are distributed with a strongly skewed distribution, as in Figure 6, the resultant distribution for *C* is roughly normal with only 3 samples and is very close to a normal distribution with only 30 samples, as can be seen in Figure 7. (The rule of thumb is that a sample size of 30 is typically sufficient to obtain a normally distributed parameter estimation.) The argument for a normally distributed parameter estimation becomes even stronger for the same number of samples if the underlying data set is itself Gaussian. An example of a Gaussian data set and the corresponding parameter estimate distributions is given in Figure 8 and Figure 9. Here it can be seen that the shape of the parameter estimate quickly approaches normal. It should be noted that normally distributed parameter estimates indicates that statistical analysis based on Gaussian distributions requires a relatively small data set. This does not, however, indicate that there is sufficient data to estimate the parameter within an arbitrary level of confidence. This question is discussed in Section 6. In general it is recommended that at least 30 data samples be collected to assure a reasonably normal distribution when computing overall A-weighted level parameters and that at least 60 data samples be collected to assure reasonably normal distribution when computing spectral parameters†.

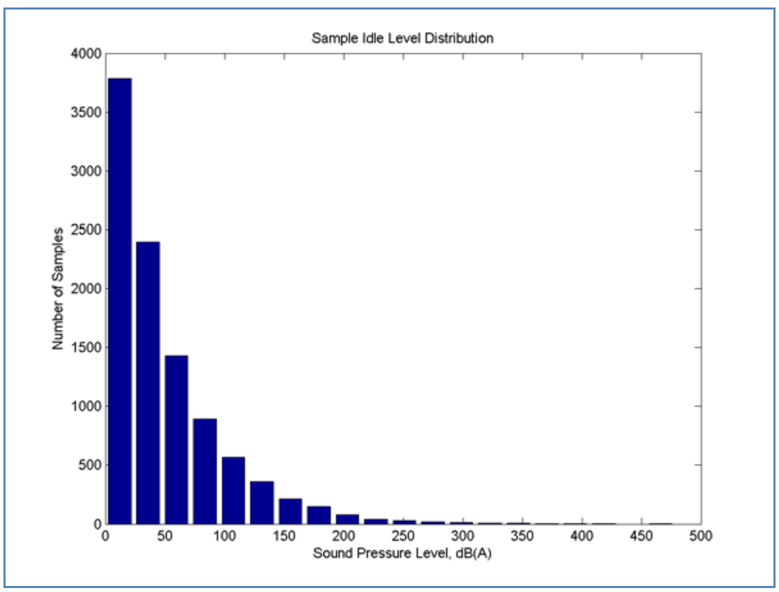

Figure 6: Sample Data Distribution that is Strongly Skewed

* The issue of confidence intervals will be discussed in detail in Section 6.

† The t-distribution can be used to compute exact difference in the confidence interval for the 3 parameter models and 14 parameter models, however, given that the base count of 30 is a gross approximation, a detail analysis thereafter is not warranted.

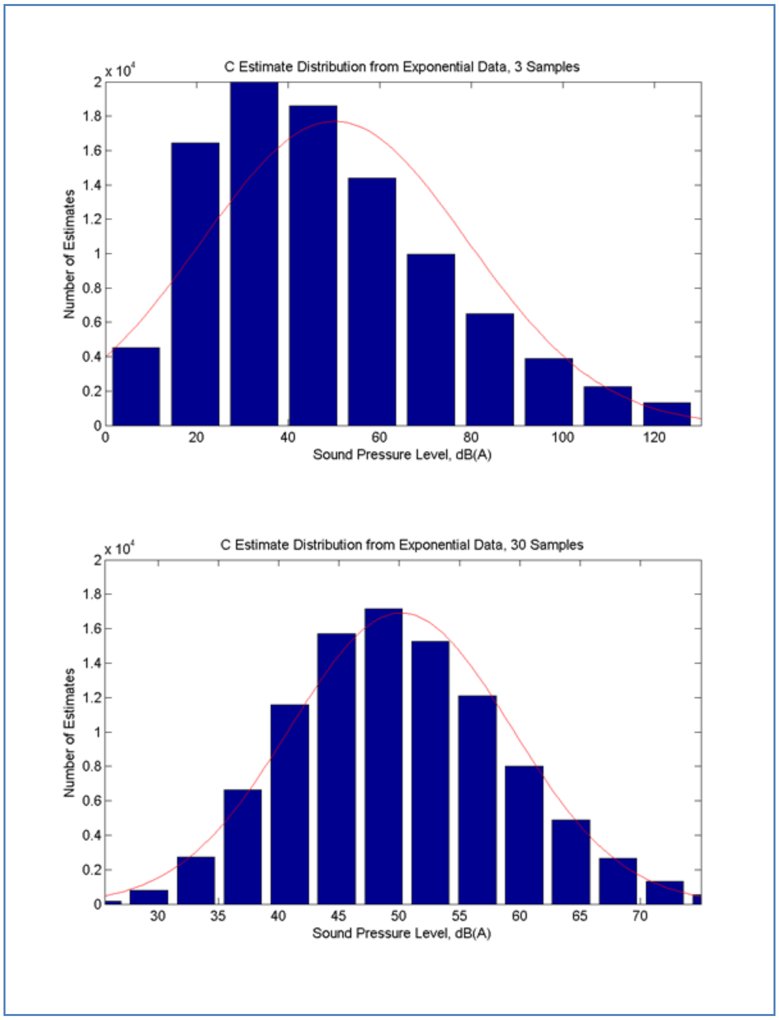

Figure 7: Distribution of Parameter Estimates for a Strongly Skewed Data Set

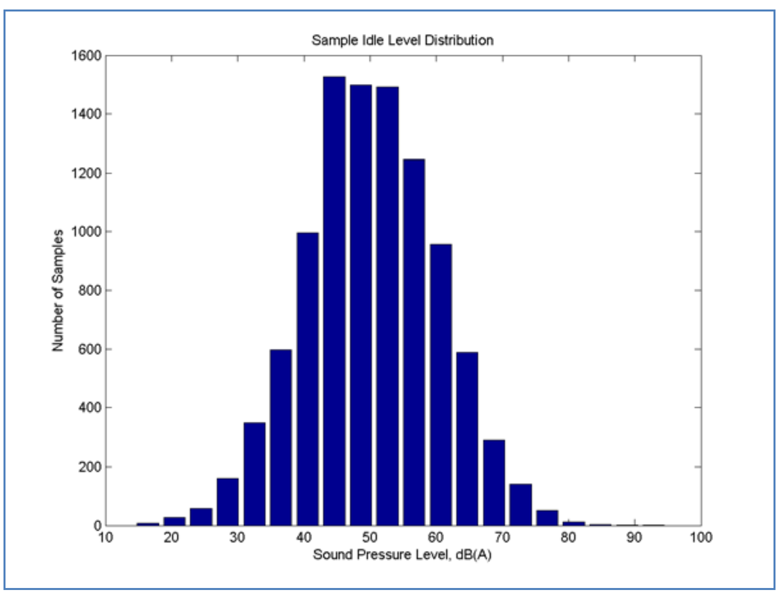

Figure 8: Sample Data Distribution that is Roughly Gaussian

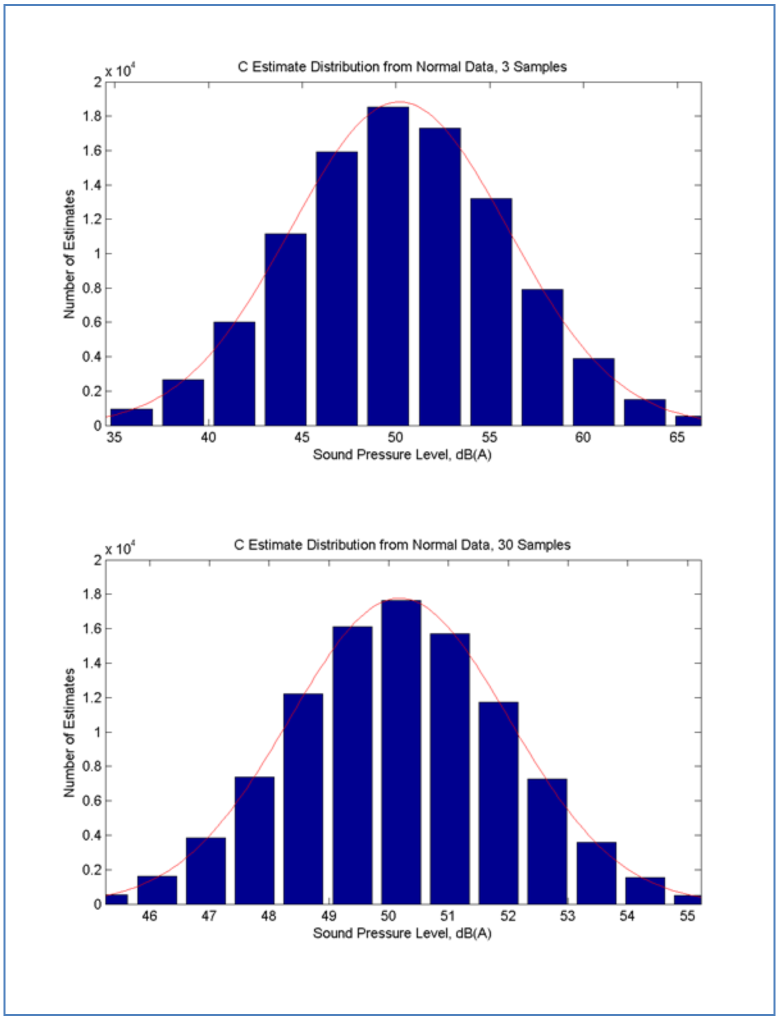

Figure 9: Distribution of Parameter Estimates for a Roughly Gaussian Data Set

Problem 2: No Low Speed Data

In the next few examples a simulated data set is used to examine how deficiencies in the sampled data affect the modeled parameters compared to the true curve. In each figure a "true" curve is computed by defining the parameters *A*, *B*, and *C* and computing $L_{A,max}$ for a set of known speeds. "Measured" data is then obtained by adding random noise to the true model. Finally, an "estimated" model is derived by using the "measured" data. If the "true" and "estimated" models are very similar, then the sampled data were sufficient. Figure 10 shows the case where a full set of data were collected and the "true" and "estimated" models match closely.

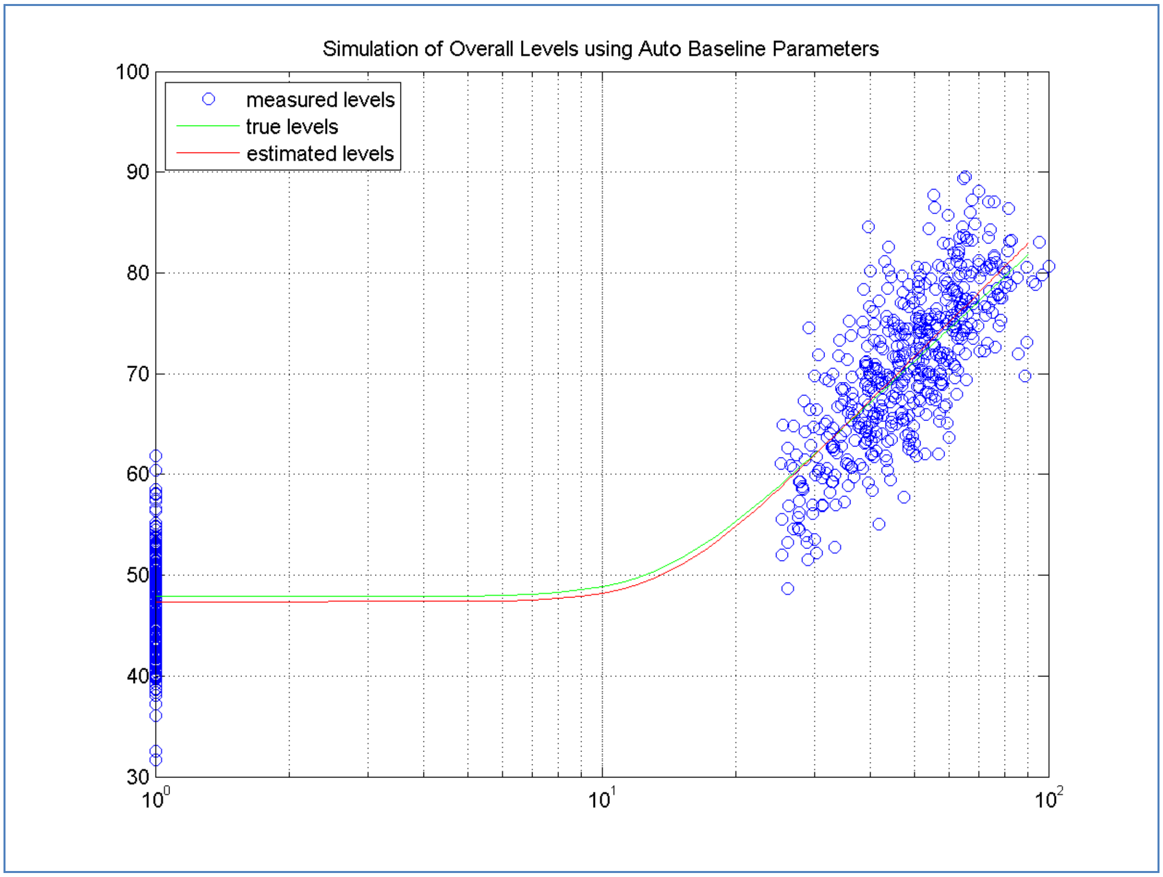

Figure 10: True and Estimated Models – Full Data Set

If no low speed data are available, as in Figure 11, then the only way to fit all three parameters: *A*, *B*, and *C* with the data set is to use the non-linear form of the model, that is, Equation 1. Even so, the estimated *C* will not likely match the true model. If a suitable replacement data set can be found, for example if a new pavement is being evaluated for a vehicle type that already has *C* computed for another pavement, then the pre-computed *C* can be used. If no equivalent idle data exists, for example a new vehicle with a completely different engine type, then low speed data must be collected to provide a reasonable chance of fitting the low speed range.

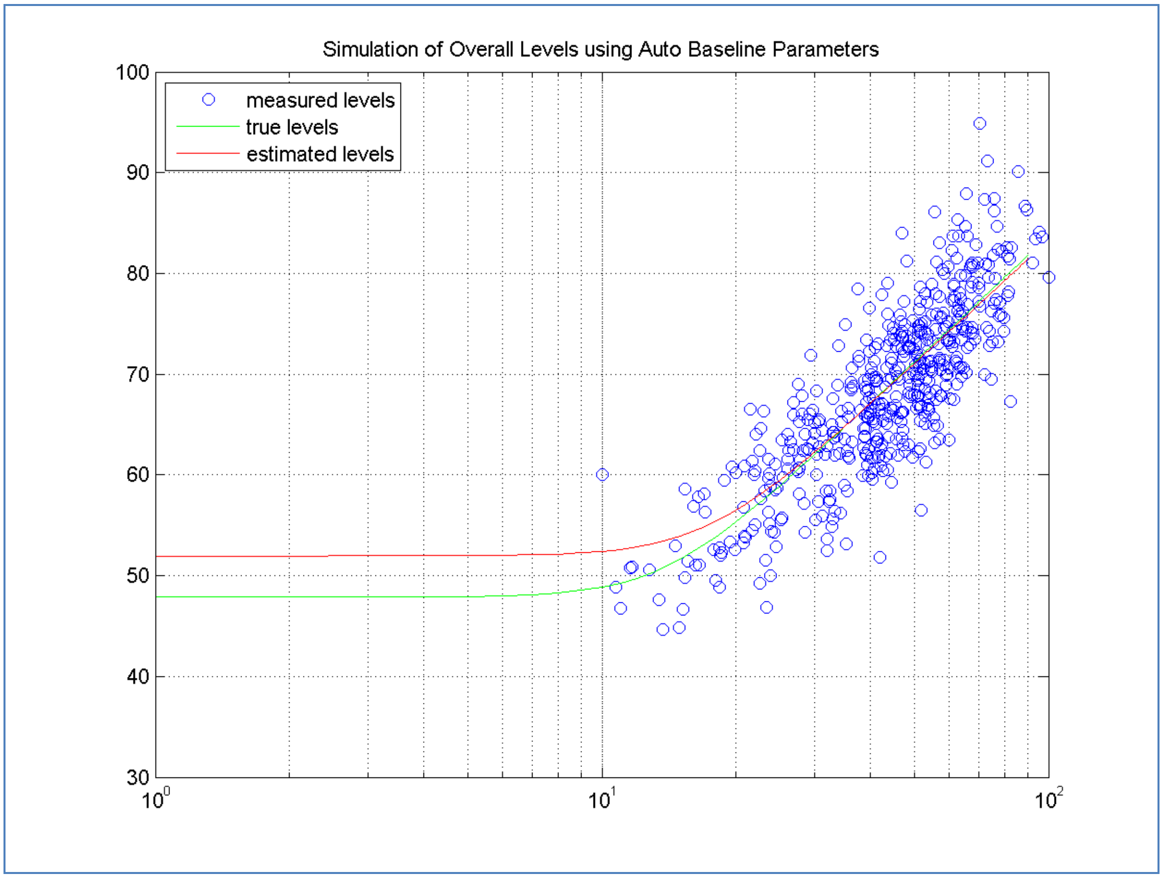

Figure 11: True and Estimated Models – No Low Speed Data

Problem 3: No High Speed Data

When plotting the data, a key indicator that the high speed data is not *high enough* is if the high speed data levels are no greater than the random distribution of the low speed data. (Note, you will not be able to evaluate this if you do not have low speed data.) In such cases both *A* and *B* coefficients can be significantly off from the true value. This can occur under two conditions: 1) the speed region sampled was not high enough, as in Figure 12, or 2) the vehicle / pavement emissions do not fit the REMEL model. The former will be addressed here, and the latter later. When examining the data, it should become clear if the speeds are not high enough. Since modeling high speed emissions is the primary reason for computing REMELs, higher speed data should be collected until a roughly straight line can be fit through the high speed range. Provided that data can be collected at highway speeds, this problem should not evince itself.

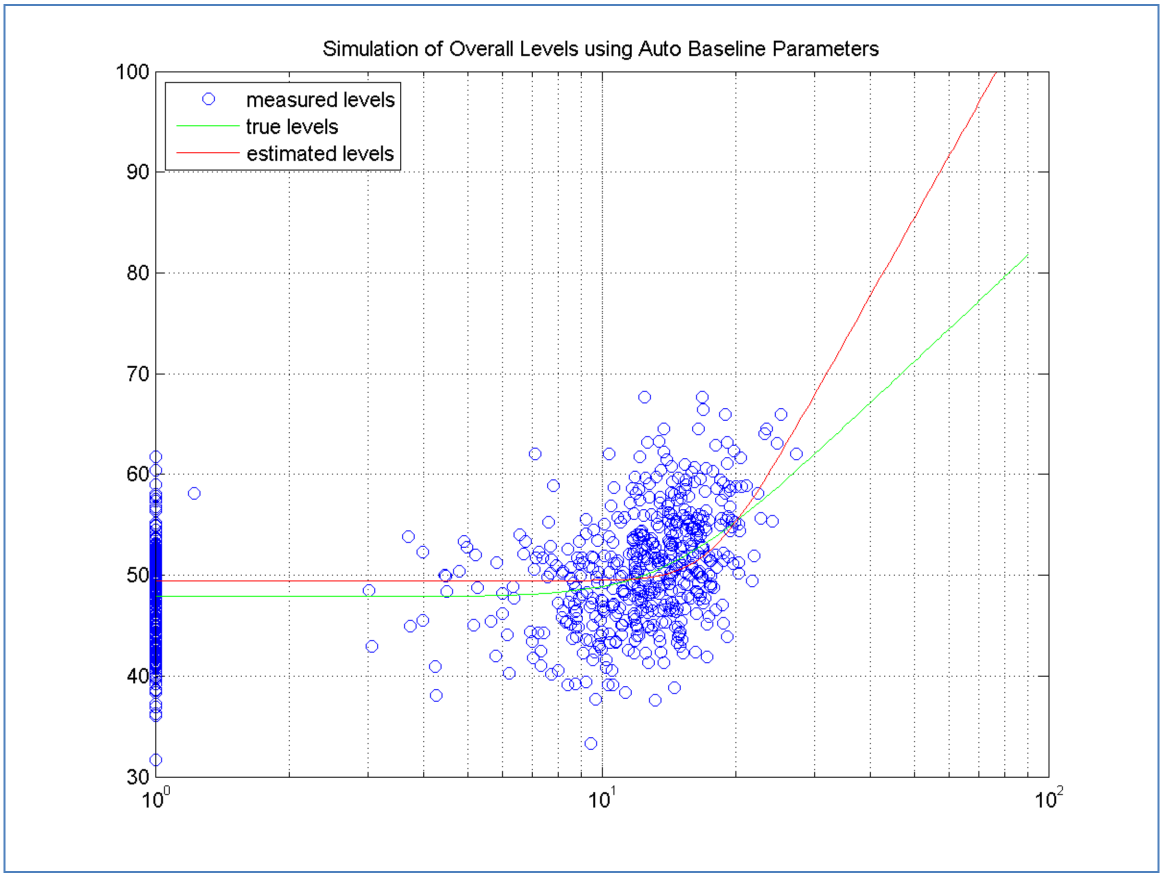

Figure 12: True and Estimated Models – No High Speed Data

Problem 4: Insufficient Speed Range to Compute High Speed Slope

Another problem that can occur with the high speed data is that there may not be enough range to accurately compute the slope (coefficient *A*) of the high speed portion of the model. This problem is more likely than not having high enough speeds, since it is possible to measure at one location where all of the vehicles travel at almost the same speed. In such cases, the best solution to this problem is to acquire more data, for example, at other locations along the same highway, at different times of the day or week, on other highways with the same pavement. However, if collecting additional data is not possible, then a substitute *A* coefficient can be used if it is expected that the *level difference* between the two REMEL curves is independent of speed in the high speed range. However, it is important to note, that without additional data, it is not possible to check this assumption.

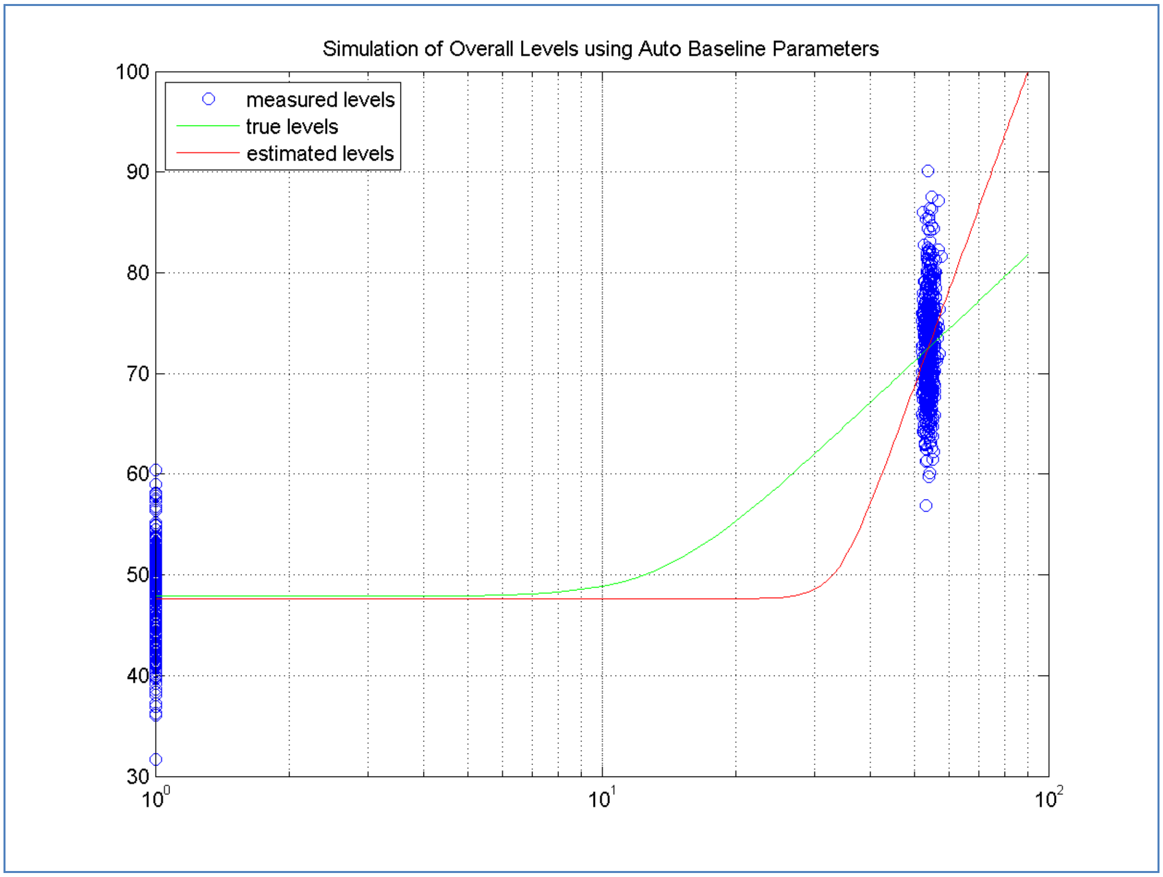

Figure 13: True and Estimated Models – Not Enough Range on High Speed Data

Problem 5: Data that do not Fit the Model: High Speed Data Extends below Idle

In some cases, the lower end of the high speed data may appear to have lower levels than the low speed data. This can be caused by: 1) using an inappropriate substitute *C* coefficient, for example using a heavy truck *C* coefficient when modeling new automobile data; 2) by having insufficient data to accurately model *A*, *B*, and *C* coefficients; or 3) because the underlying data cannot be accurately fit using the REMEL model. There are no known cases in which the model is not appropriate for typical vehicles. Therefore the main recommendations are to make sure that there is enough data to accurately model all parameters.

Problem 6: Data that do not Fit the Model: High Speed Data have No Slope or have Negative Slope

In some cases, there can appear to be a wide enough high speed range but the slope comes out to be either zero or negative. These results, although not mathematically impossible, are not consistent with the expected performance of REMEL modeling. In such cases it is recommended to gather more data, either in the same speed range or over a wider speed range if possible to improve the accuracy of the parameter estimation. With sufficient data it is expected that the slope will be positive.

Identifying and Handling Problematic Data Sets for One-Third Octave Bands

Provided that a sufficient number and range of data have been sampled to compute the overall A-weighted levels, many potential problems with computing spectral REMELs will have been eliminated. However, there are still a few special issues that are related only to spectral REMELs. These include an increased requirement for uniformity in the speed data, issues related to binning of speed data, and issues related to accounting for strong tonal components. An example of a good modeled fit to the spectral data is shown in Figure 14. Even for this model, the fit has some limitations; most notably at low frequencies the model tends to compress the shape of the spectrum. This is not due to deficiencies in the data but to the form of the model, which weights variance at higher frequencies more than at lower frequencies[*].

[*] The frequency weightings are powers of $\log_{10}(f)$, therefore errors in the parameter estimates for higher frequencies are weighted more than errors in the parameter estimates for lower frequencies.

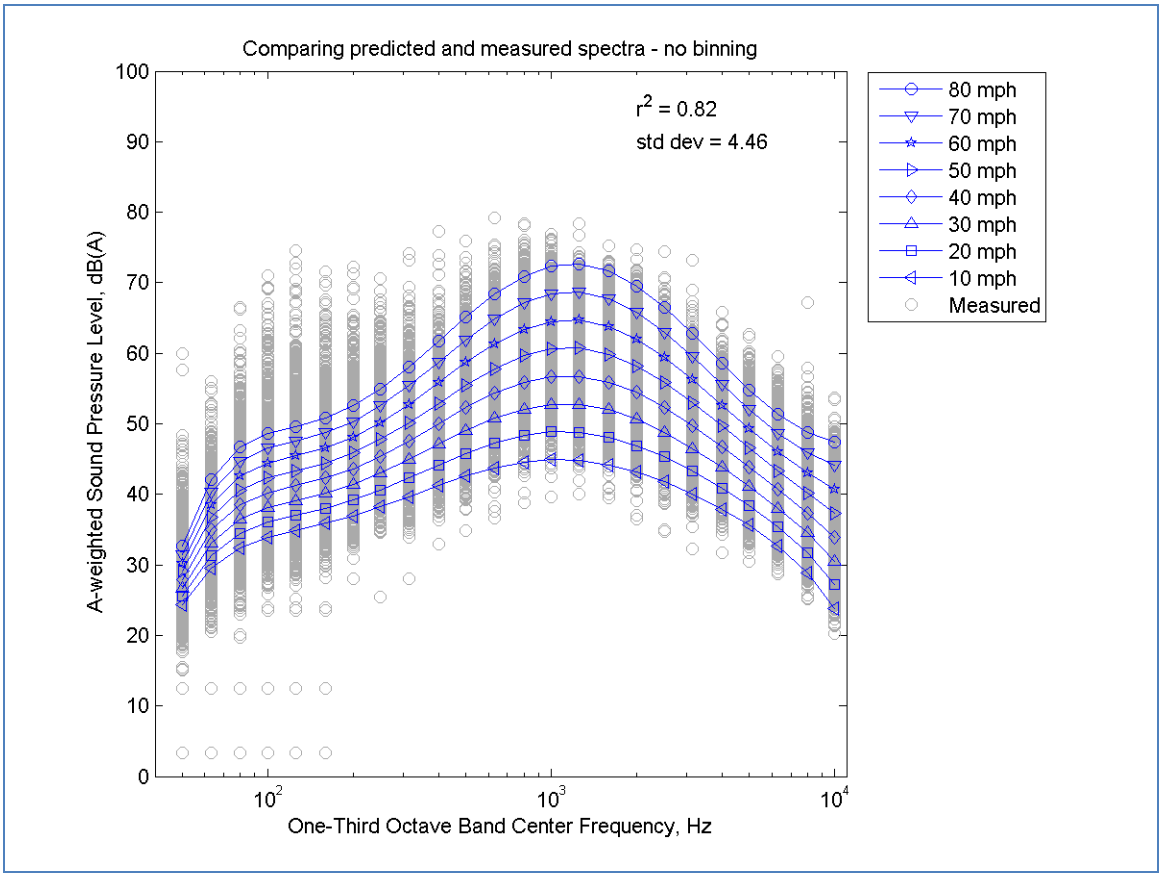

Figure 14: Example with Good Spectral Modeling

Problem 1: Insufficient Speed Range

When computing the overall A-weighted level, the REMEL model is a combination of two linear functions. Therefore, when errors are extrapolated, they tend to grow slowly. When computing REMEL spectra, the model is based on a 6^{th} order polynomial of $\log_{10}(f)$, therefore extrapolated errors tend to grow quickly. Thus the spectral model is much more sensitive to gaps in the speed distribution of the data. Several examples are shown in Figure 15 to Figure 20. In Figure 15 only low speed data less than 30 mph was used to determine parameter coefficients. When the model was used to extrapolate the spectra at higher speeds, the errors in the mid-frequencies were very large. Although, mathematically realizable, the cross-over at 125 Hz is not typical for averaged spectra. Increasing the minimum speed to 50 mph greatly improves the model, but still results in a greater spread in the spectra than expected from the full data set. The general patterns of these figures indicate that relying on low speed data tends to generate spectra that are "expanded" while relying on high speed data tends to generate spectra that are "contracted" and that the best (data reduced) models occur when the range includes at least the speed range from 30 to 65 mph. Although individual cases may vary, these general observations are expected to provide useful guidance during the evaluation of REMEL spectral results.

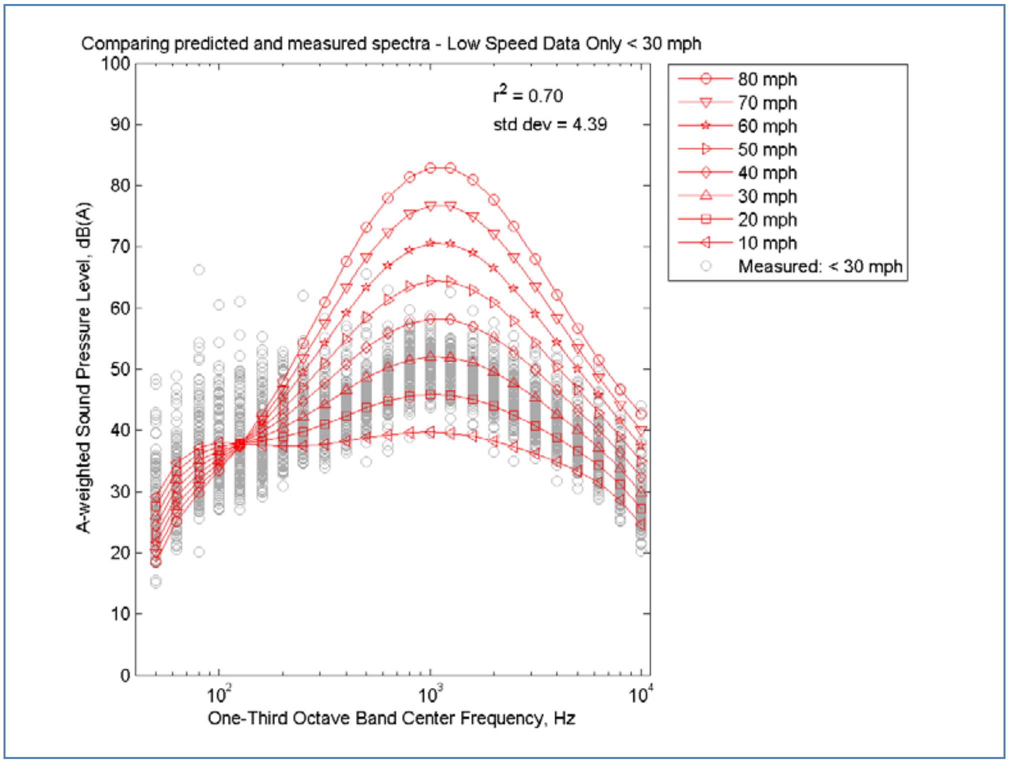

Figure 15: Example of Spectral Modeling Using only Low Speed Data < 30 mph

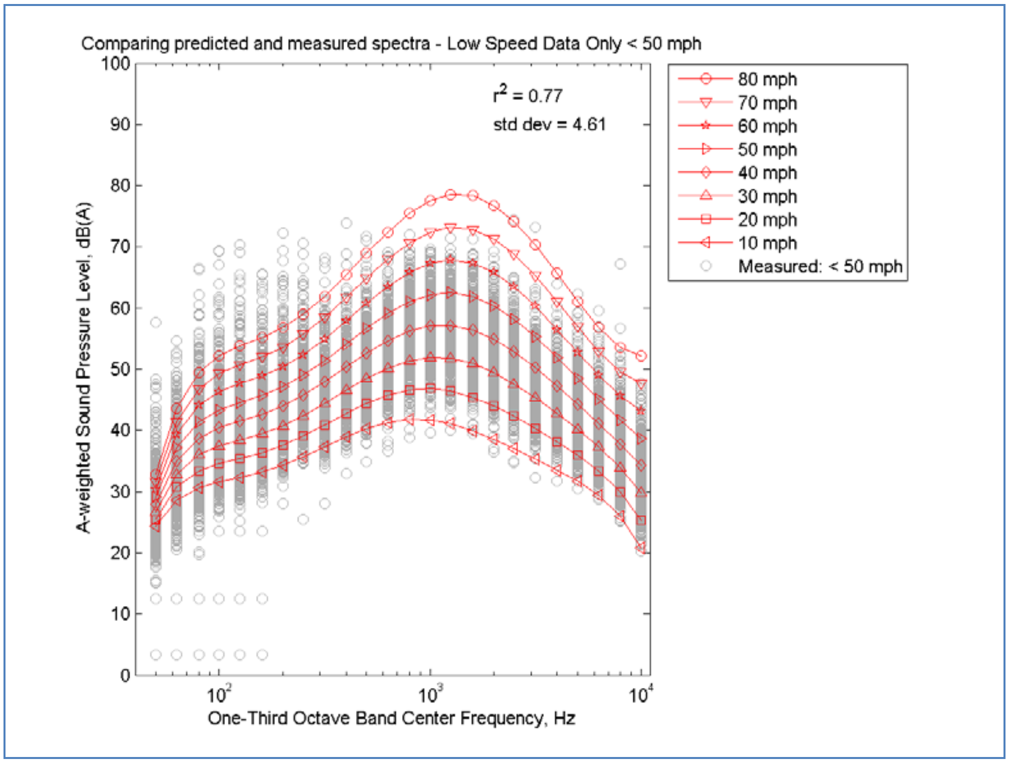

Figure 16: Example of Spectral Modeling Using only Low Speed Data < 50 mph

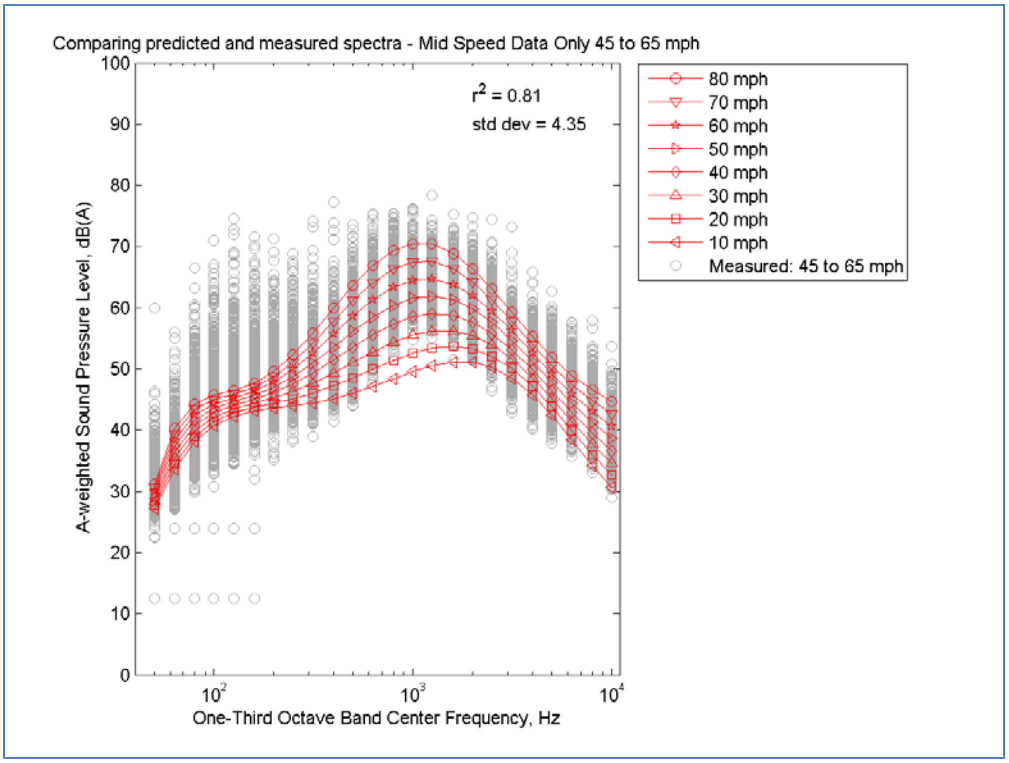

Figure 17: Example of Spectral Modeling Using only Mid Speed Data – 45 to 65 mph

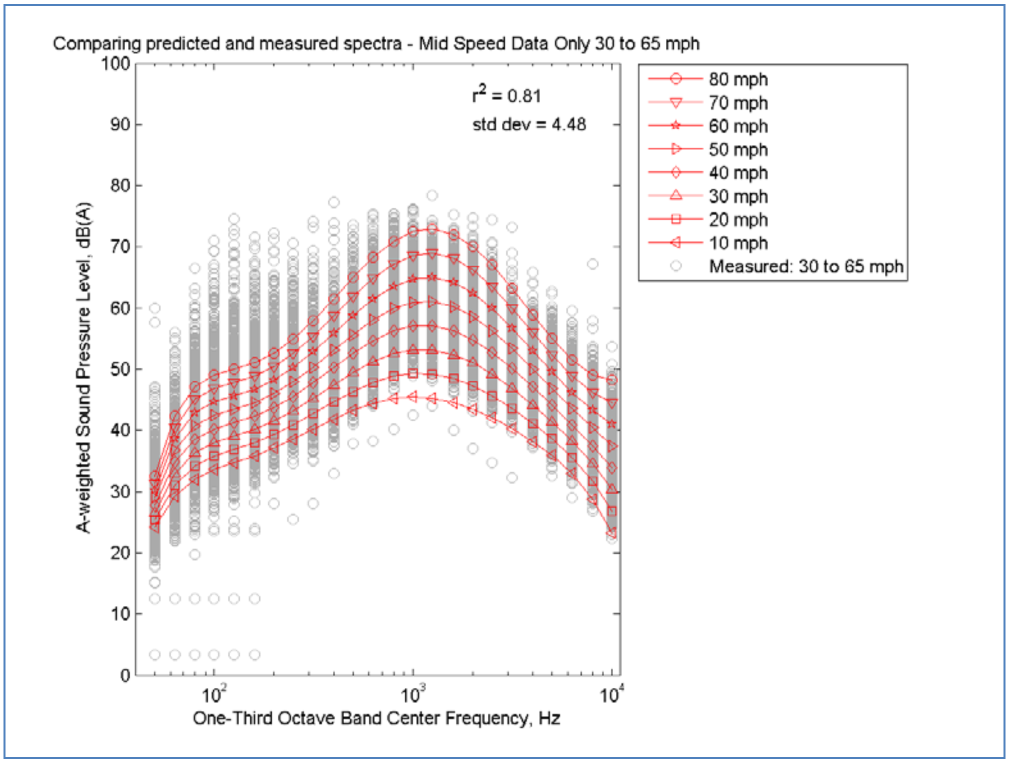

Figure 18: Example of Spectral Modeling Using only Mid Speed Data – 30 to 65 mph

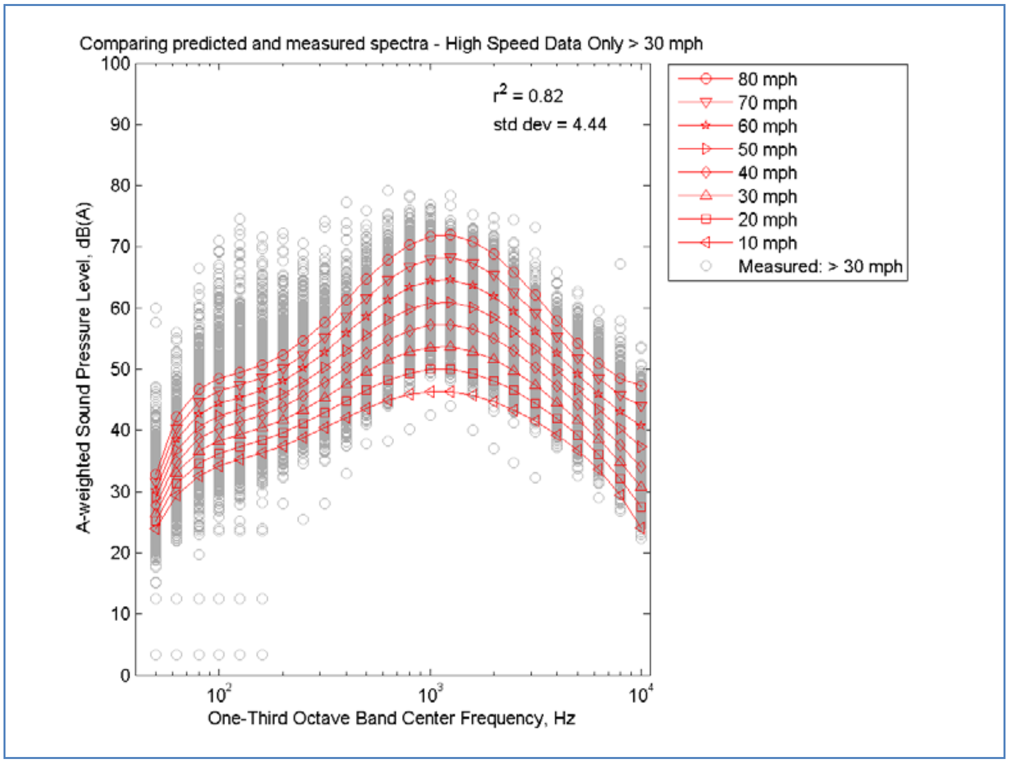

Figure 19: Example of Spectral Modeling Using only High Speed Data > 30 mph

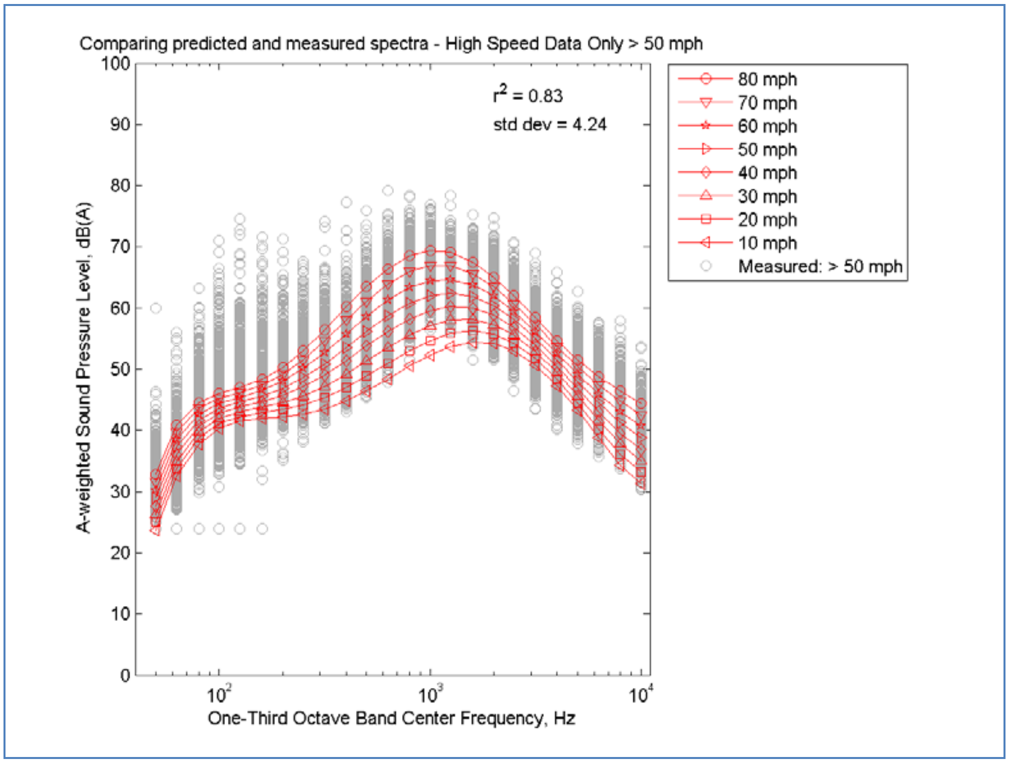

Figure 20: Example of Spectral Modeling Using only High Speed Data > 50 mph

Problem 2: Binning of Data

Although binning of data by speed is not consistent with the assumptions required for computing overall energy means, it is sometimes a practical necessity for computing spectral REMELs. Comparing the binned results from Figure 21 and Figure 22 with the original un-binned results Figure 14, it can be seen that modeling process is much less sensitive to binning than incomplete speed ranges, however, it can also be seen that low frequencies are compressed even more with binned data than with the original data. Also, the process of binning can upset the weighting of speeds based on sample size (although binning schema can be selected to weight one speed range more than others.) In general, if there is not a practical expediency to binning speed data, it is recommended to not use binning.

Note, the improved r^2 values for binned data are due to the aggregation of data, but do not provide improved confidence intervals since they decrease the effective sample size.

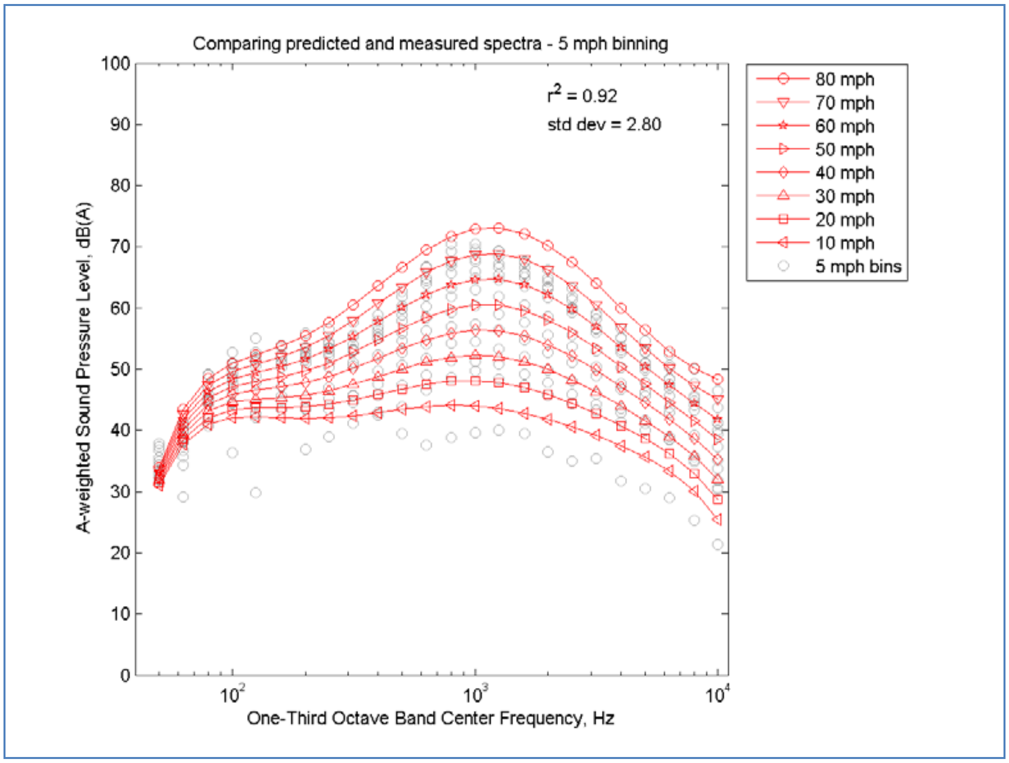

Figure 21: Spectral REMELs Derived from 5 mph Speed Bins

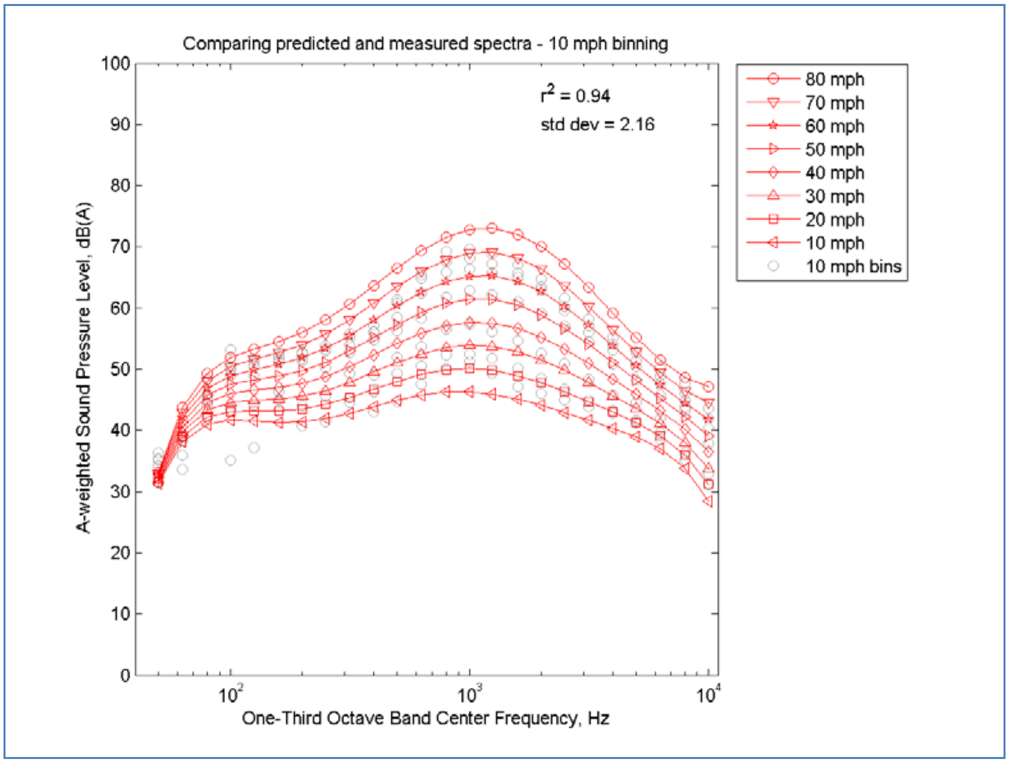

Figure 22: Spectral REMELs Derived from 10 mph Speed Bins

Problem 3: Strong Tonal Components

One final problem associated with REMEL spectral models is the handling of data with strong tonal components. These components can be present, for example, for pavements with periodic transverse patterns, such as transversely tined PCC. The problem with tones is that they generate an abrupt change in level from one band to the next; however, the spectral model does not have a high enough order to account for these abrupt changes. An example is given in Figure 23. Here a tonal component is present in the 400 Hz one-third octave band that is 10 dB above the adjacent one-third octave bands, however there is no noticeable difference in the spectra from one without the tonal component present. This illustrates that REMELs alone are not well suited for modeling tonal components. One method to handle these tones would be to provide a frequency specific correction for tonal components, such as has been done for OBSI modeling.

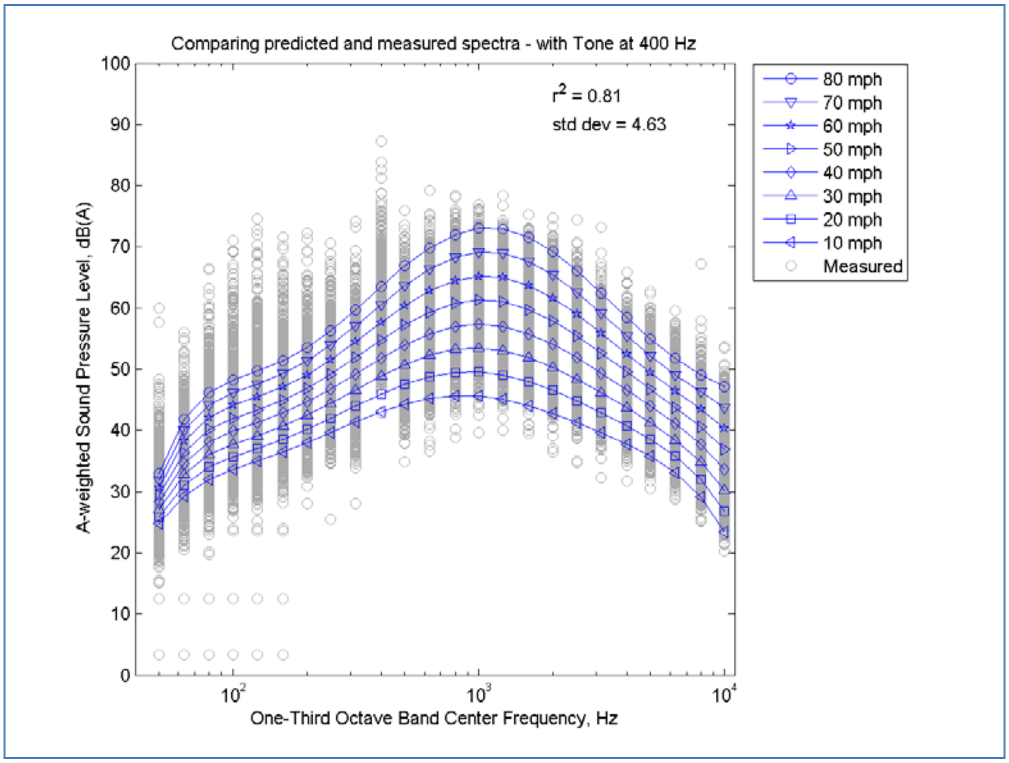

Figure 23: Example of REMEL Spectra and Underlying Data with Tonal Component

Evaluating Significance

A data set can produce results that do not show any anomalies in the shape of the curve or how it fits the data, however, unless the confidence interval for the model is evaluated, it cannot be said that enough data has been sampled in order to distinguish the new curve from existing curves, or that new curve represents the new vehicle or pavement type within a desired tolerance. The only way to assure that enough data has been sampled is to compute confidence intervals. The discussion that follows assumes that the model parameters capture the deterministic character of the data and that all variance not captured by the parameters is due to random factors associated with either measurement of the sound level or site-to-site variation. It is assumed that the parameter estimates are normally distributed. In this section, two confidence intervals will be developed. The first is useful for determining if enough data have been collected in order to provide a tolerance on the model, that is, the REMEL curve is within N dB of the true energy mean curve for the vehicle / pavement combination. The second confidence interval is useful for comparing a new curve with others to determine if the new curve is significantly different. If a new curve is not statistically different from an existing curve, then any interpretations based on the new curve that are not consistent with interpretations based on the old curve are highly questionable.

In general we can test whether sufficient data have been acquired by computing a confidence interval as follows:

1) Compute REMELs overall A-weighted model coefficients.
2) Compute model variance.
3) Choose confidence probability of interest, for example 95% or 50%.
4) Compute confidence interval for the specified probability.

Computation of the REMEL model has already been discussed. Variance is modeled by expanding Equation 5 .

Equation 5: General Equation for Variance

$$Var_F = \sum_{i=1}^{I}\left[\left(\frac{\partial F}{\partial x_i}\right)^2 Var_{x_i}\right] + 2\sum_{i=1}^{I-1}\sum_{j=i+1}^{I}\left[\left(\frac{\partial F}{\partial x_i}\right)\left(\frac{\partial F}{\partial x_j}\right)Cov_{x_i x_j}\right]$$

where, *F* is given by

$$F = 10\log_{10}\left[10^{(C+\Delta E_c)/10} + \left(s^{A/10}\right)\left(10^{(B+\Delta E_b)/10}\right)\right]$$

that is, the energy averaged overall A-weighted level. Using these two equations, the specific variance for *F* can be determined using Equation 6.

Equation 6: Total Variance

$$Var_F = M_{EmeanVar} \cdot M_{Multisite} \cdot Var_{L_{lin}}$$

where,

$$Var_{L_{lin}}(s) = \left(\log_{10}(s)\frac{s^{\frac{A}{10}} \cdot 10^{\frac{B}{10}}}{E}\right)^2 Var_A + \left(\frac{s^{\frac{A}{10}} \cdot 10^{\frac{B}{10}}}{E}\right)^2 Var_B + \left(\frac{10^{\frac{C}{10}}}{E}\right)^2 Var_C$$
$$+ 2\left\{\left(\log_{10}(s)\frac{s^{\frac{A}{10}} \cdot 10^{\frac{B}{10}}}{E}\right)\left(\frac{s^{\frac{A}{10}} \cdot 10^{\frac{B}{10}}}{E}\right)Cov_{AB}\right.$$
$$\left. + \left(\log_{10}(s)\frac{s^{\frac{A}{10}} \cdot 10^{\frac{B}{10}}}{E}\right)\left(\frac{10^{\frac{C}{10}}}{E}\right)Cov_{AC} + \left(\frac{s^{\frac{A}{10}} \cdot 10^{\frac{B}{10}}}{E}\right)\left(\frac{10^{\frac{C}{10}}}{E}\right)Cov_{BC}\right\}$$

$$E(s) = s^{\frac{A}{10}} \cdot 10^{\frac{B}{10}} + 10^{\frac{C}{10}}$$

$$M_{EmeanVar} = \frac{N\sum_{i=1}^{N} E_i^2}{\left(\sum_{i=1}^{N} E_i\right)^2}$$

$$M_{Multisite} = \frac{\left(\frac{Var[\Delta y_{site}]}{N_{sites}} + \frac{(Var[y_{resid}] - Var[\Delta y_{site}])}{N_{resid}}\right)}{\left(\frac{Var[y_{resid}]}{N_{resid}}\right)}$$

A, B, C, Var_A, Var_B, Var_C, Cov_{AB}, Cov_{AC}, and Cov_{BC} should be determined as part of the curve fitting process for the overall A-weighted level. The correction for the energy mean is simply the number of data samples multiplied by the sum of the individual data samples' energy squared divided by the square of the sum of the individual data samples' energy. The multi-site correction is a little more complicated because the variance must be separated into the portion related to sample-to-sample variation and the portion related to site-to-site variation. The site-to-site variation is estimated using the mean values for each site. The sample-to-sample variation is then computed as the total variation minus the site-to-site variation. Each component of variation is then weighted by it respective number of samples. Since the number of residuals is equal to the number of samples N_{resid} is used for both the total variance and for the sample-to-sample variance. Further details on the derivation of this specific expansion of Equation 6 can be found in References 3 and 4.

Once the variance has been determined, it is a simple matter to determine the z-score required to produce the appropriate interval. It is suggested that a 95% confidence interval be used when evaluating if the tolerance on the curve estimation is sufficiently small. Here one wants a high degree of confidence, since a false conclusion will result in an incorrect estimation. It is suggested that a 50% confidence interval be used when evaluating whether two curves are different. Using a 50% confidence interval will increase the likelihood of accepting the alternate hypothesis that the two curves are different, however, it is assumed that there is already significant evidence to indicate that there is a difference, otherwise the measurements would not have been made in the first place. (If the primary reason for conducting the measurements is not based on some anecdotal evidence that the vehicle / pavement is indeed different, then a 95% confidence interval is recommended for both types of tests.)

Figure 24 provides an example of the confidence interval computed for a large data set. Note that the interval is wider at low speeds than at high speeds. This is because there were a large number of samples at high speed, causing those parameters that control the curve at high speed to have low variance. Since the variance model is a function of speed, the change in total variance is captured. By evaluating the confidence interval over its entire range, one can determine not only if more data are needed in general, but in what speed range. Note that this is also partly a design consideration. If low speed modeling is not required, then a broader confidence interval can be tolerated at low speeds.

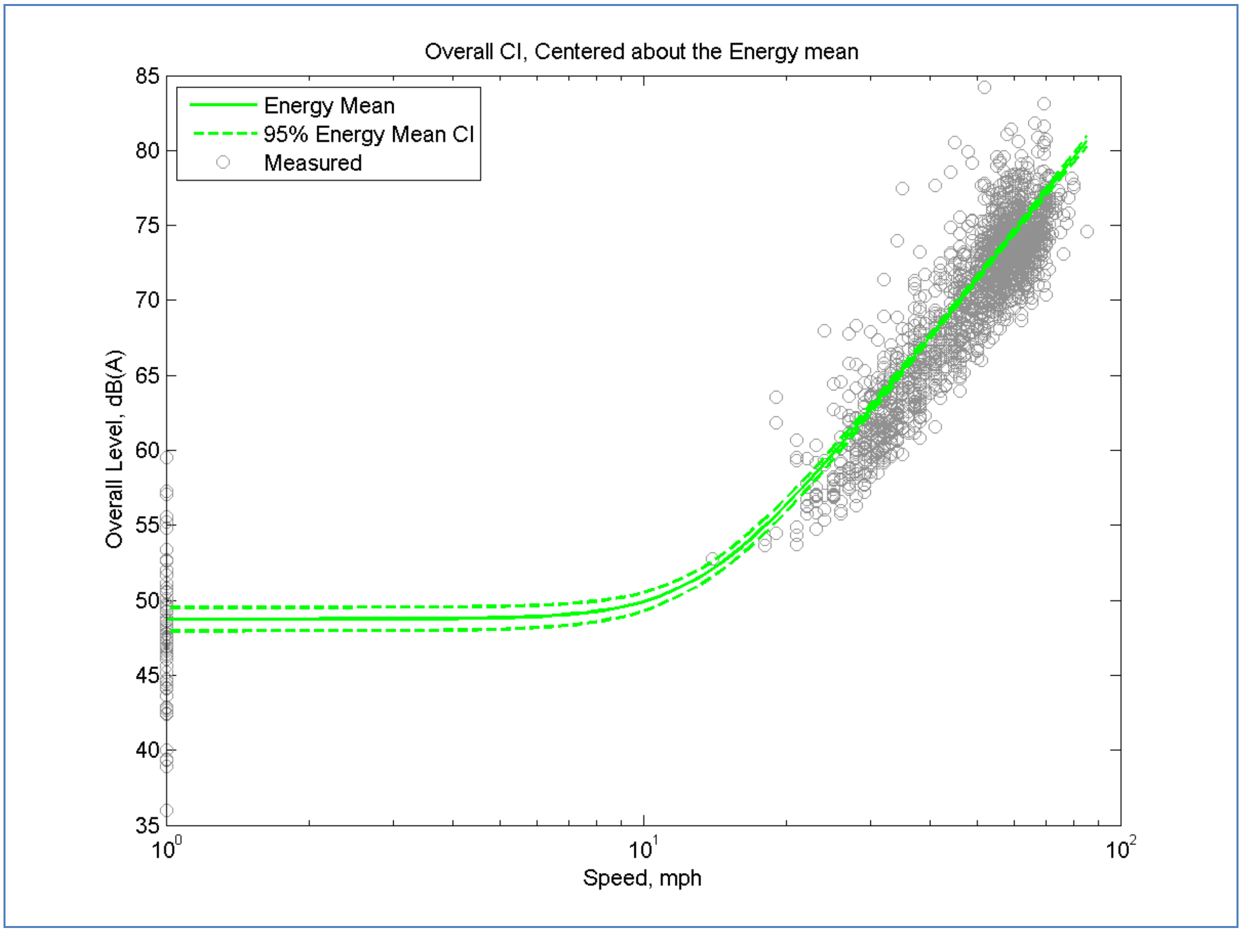

Figure 24: Measured Data, REMEL Curve, and Confidence Interval for Large Data Set (TNM Auto Baseline)

Figure 25 shows two hypothetical curves that are being compared to determine if they represent two unique curves or if they represent different samples from the same population. Even though the data have significant overlap, the curves have a level difference of 3 to 5 dB. However, even when requiring a confidence of only 50%, these data do not support the use of two curves. Assuming that the data are from different populations, gathering more data may decrease the confidence intervals such that it can be concluded that they are unique curves with sufficient confidence. Note also, that curves do not need to be unique at all speeds. In many cases, the low speed portion may be sufficiently similar that no conclusion of uniqueness can be made with confidence, however, if the high speed data are unique, then the whole curve should be considered unique.

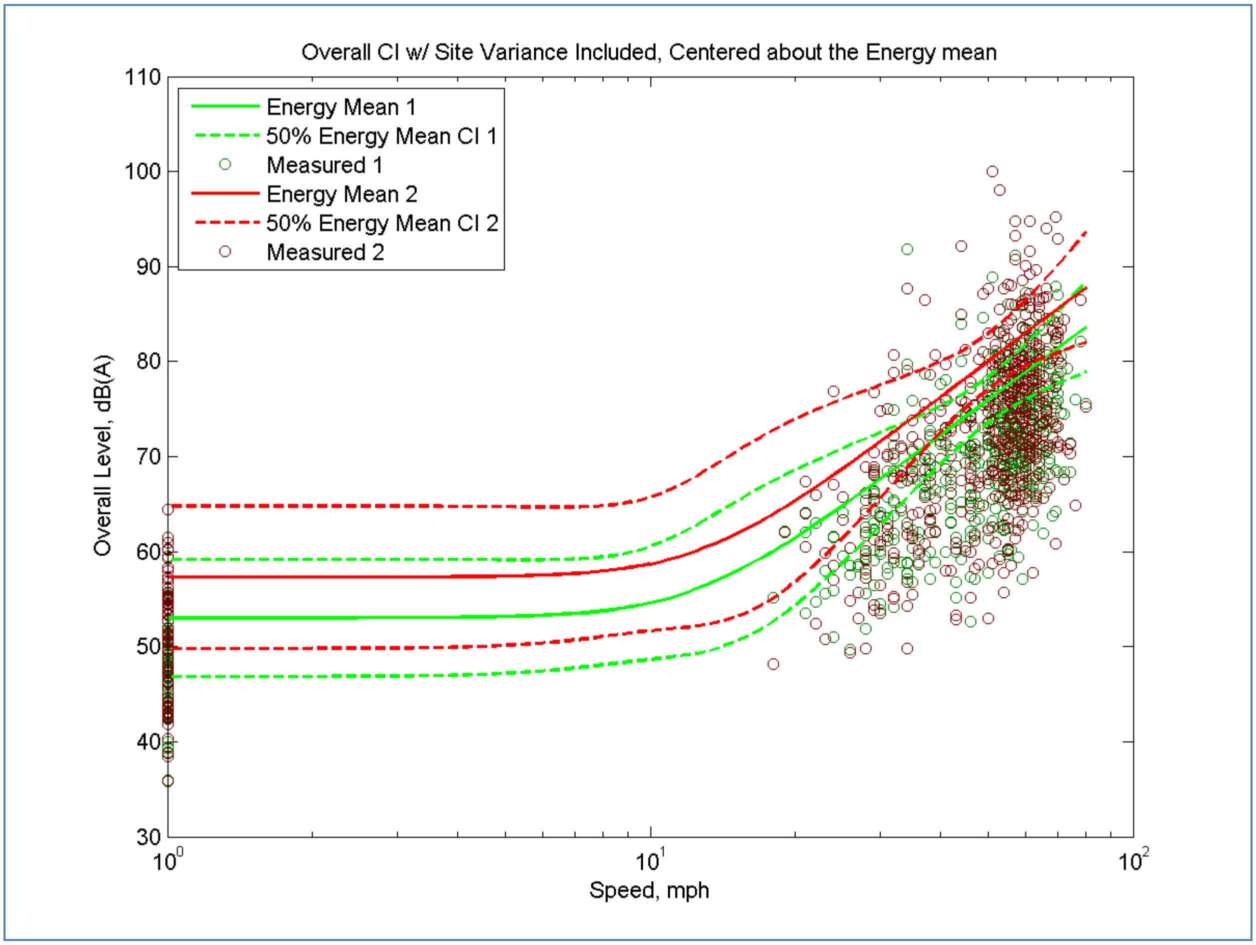

Figure 25: Confidence Intervals for Two Curves. Are they Statistically Different?

Any many cases, it will be desired to determine if a new curve is unique compared to the existing curves used by TNM. In such cases, the multipliers for the TNM curves are required. These were developed by Grant Anderson[6] and have been included here for convenience.

Table 2: Multipliers for Site-to-Site Variances for TNM REMELs According to Vehicle Type (Reference 6)

TNM Vehicle Type	$M_{Multisite}$
Automobile	31.6
Medium Truck	4.8
Heavy Truck	17.8
Bus	2.0
Motorcycle	4.8

The discussion of statistical significance has focused on the REMEL overall A-weighted level curve. Even for this simple, three-parameter model the derivation for the total variance is reasonably involved. The development of the total variance for the spectral model is beyond the scope of this document. Further, since this variance would be a function of both speed and frequency, it would require a two-dimensional model, which would be difficult to visualize and interpret consistently and meaningfully. It is suggested that the most practical statistical metrics for the spectral model are the r^2 value and the mean-squared-error. These metrics will allow one to evaluate if one model is better than another *for the same sampled data*, but not to distinguish different populations.

Summary and Sample Implementations

The steps below outline the general approach for computing REMELs using a small dataset:

A. Overall (Broadband) Levels
   1) Collect a minimum of 30 samples over the speed range of interest.
      a. If data are collected from at least 3 sites, then compute the multi-site multiplier
      b. If data are collected from less than 3 sites, then use the multi-site multipliers given in Table 2.
   2) Compute the overall level coefficients.
      a. If idle data are available, compute A, B, and C.
      b. If idle data are not available, use an appropriate C from existing REMELs and compute only A, and B.
   3) Choose a confidence probability and interval based on requirements specific to the study.
   4) Compute and compare confidence intervals. Is the confidence interval sufficiently small
      a. to compare with an existing curve to determine uniqueness?
      b. to provide sufficient accuracy for future predictions?
   5) If the answer is no, more data are required. See previous sections.

B. One-third Octave Band Spectra
   1) After determining that sufficient data are available for overall REMELs, spectral REMELs can be computed.
   2) Compute D1 to K2
   3) Plot the computed spectra and the measured spectra.
   4) The computed spectra should generally be within the measured data.
   5) The computed spectra in the frequency range from 500 Hz to 5000 Hz should match closely.
   6) An r^2 value greater than 0.9 for the entire spectral – speed region indicates good agreement.
   7) If these criteria are not me, then more data are required. See previous sections.

This approach relies on comparing the results against required levels of confidence in order to determine if enough data have been collected. Although 30 samples may be sufficient in some cases, it should be expected that in many cases several hundred samples may be required.
If a full set of data are available for a vehicle – pavement combination, then all terms can be determined. If there is no idle data, then *C* and ΔE_c cannot be determined from the data and an existing vehicle – pavement pair must be identified for use as a substitute. When determining coefficients *A*, *B*, and *C*. The resulting curve should be plotted with the data as a first analysis of

the quality of the fit. If the slope is zero or negative, or if the mid speed data seems to dip significantly below the mean low speed level, then it is likely that more data are needed. If the curve fits the data well, then confidence intervals should be developed to determine if the curve is known within a required tolerance and, if intended to replace another curve, it should also be compared against the previous curve. Spectral modleing should be done with a speed range from low to high in order to anchor the spectral coefficients. If there is insufficient spectral data, then more should be gathered. If this is not practical, replacement data may need to be generated from a suitable donor model.

Figure 26 shows confidence intervals for three sets of automobile data with similar pavement types. REMELs 1995 – Autos, DGAC is a model used by TNM 2.5, REMELs Light – Autos, DGAC is a model developed from two measurements in Massachusetts, REMELs Light – Autos, RAC is a model developed from two measurements in Arizona and one in California. Because the REMELs Light data only have data in the mid- to high-speed range, the confidence intervals at low speed are not of interest here. At high speeds, there is at least some separation, however, this figure illustrates one more "sample size issue" with which to be cautious. The site-to-site variance for the Massachusetts data was small. Because there were only two sampled sites, it is very likely that by chance the two estimated site means were very close. In order to have any useful confidence in the site-to-site variance, one should measure at the very least three sites, however, five to ten would be much more reasonable.

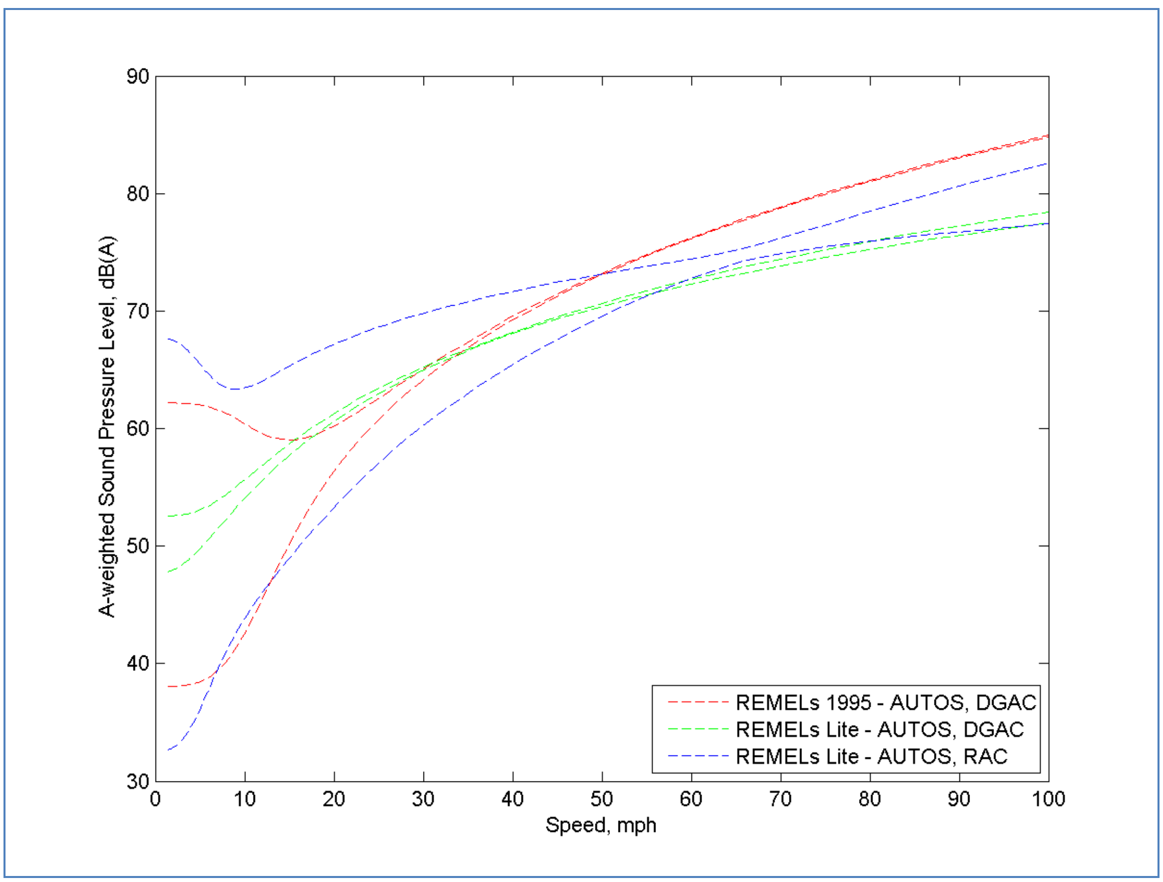

Figure 26: 50% Confidence Intervals for Three Sets of Modeled Data

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