Modeling Tire-Pavement Noise Using MnROAD Data

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ABSTRACT
Tire-pavement noise is the result of a complex system of noise generation mechanisms and is affected by several different pavement and atmospheric parameters. Accurately predicting tire-pavement noise from given a set of parameters has proven difficult for researchers. The purpose of this research was to explore a wealth of pavement, atmospheric, and noise data taken at the MnROAD pavement test facility and to develop a model to predict tire-pavement noise on asphalt pavements. Using a series of sub-models, variables significant to noise generation were identified. Finally, two distinct models of noise generation were developed, each capable of predicting one-third octave band on-board sound intensity (OBSI) spectra. The models were developed using a hybrid statistical-experimental approach and were able to predict overall OBSI levels to within 1.5 dB for 80–90% of the pavements tested.

INTRODUCTION

A significant amount of transportation-related noise is generated and amplified by the interaction of the tires and the pavement surface under varied climatic conditions. While the composition and structure of the tires are beyond the control of pavement designers, many properties of the pavement surface can be controlled to help to mitigate tire-pavement noise. The ability to predict tire-pavement noise for various pavement surfaces based on properties of those surfaces would allow evaluation of changing pavement surface properties prior to implementation.

The model summarized in this paper was developed using the extensive database of pavement material and noise data available at the MnROAD pavement test facility. The overall objective was to develop a model to predict on-board sound intensity (OBSI) levels on asphalt pavements taking the pavement surface properties into account. Ultimately, two nonlinear statistical models were developed using data from MnROAD test cells. The models predict one-third octave band and overall sound intensity levels using the pavement and climatic parameters that were found to have the most significant effects on tire-pavement noise generation. Further details on both models and their development are available in the final report (*1*).

Scope

The models were developed based on noise and physical property data collected on 25 asphalt-surfaced roadway test sections at the MnROAD pavement testing facility (15 on the Mainline and 10 on the Low Volume Road), as summarized in Table 1. These test sections were mostly constructed in 2007 and 2008 using a variety of materials, mixtures and layer thicknesses.

An extensive database containing a wide range of information has been amassed since the time of construction, including measurements of noise, friction, surface texture, ride quality, temperature, distress and structural capacity, among other properties. One complication for the modeling is that complementary data about different parameters at about the same time is not always available.

The On-Board Sound Intensity (OBSI) method AASHTO TP 76 (*2*) is used here, because that is the method used routinely at MnROAD to collect tire-pavement noise data. In this method, sound intensity probes placed near the leading and trailing edges of the tire-pavement interface detect only sound radiating from the tire. Since noise is measured near the source, the impacts of climatic conditions on the propagation of sound are reduced, though effects of the climate on the generation mechanisms will still exist.

The models were developed for the types of asphalt surfaces tested at MnROAD and based on the types of test data available. Applying these models to other surface types or with different input variables would require validation and perhaps revision of the models. However, the models were formulated and implemented in such a way that future revisions can be readily accommodated.

TABLE 1 Cells Used in Model Analysis and Development

Cell	Surface Type	Binder	Spec/Designation
1	75-Blow Marshall Mix Mill & Inlay	PG52-34	SPWEB340A
2	Ultrathin Bonded Wearing Course	Novachip	--
3	Ultrathin Bonded Wearing Course	Novachip	--
4	Hot Mix Asphalt	PG64-34	SPWEB440F
6	4.75mm Taconite Mix	PG64-34	2360
15	Warm Mix Asphalt	PG58-34	SPWEB440C
16	Warm Mix Asphalt	PG58-34	SPWEB440C
17	Warm Mix Asphalt	PG58-34	SPWEB440C
18	Warm Mix Asphalt	PG58-34	SPWEB440C
19	Warm Mix Asphalt	PG58-34	SPWEB440C
20	Hot Mix Asphalt with RAP	PG58-28	SPWEB440B
21	Hot Mix Asphalt with Fractionated RAP	PG58-28	SPWEB440B
22	Hot Mix Asphalt with Fractionated RAP	PG58-28	SPWEB440B
23	Warm Mix Asphalt	PG58-34	SPWEB440C
24*	Warm Mix Asphalt – Aging Study	PG58-34	SPWEB440C
27*	Hot Mix Asphalt (Chip Seal in 2009)	PG58-34	SPWEB340C
28*	Hot Mix Asphalt (Double Chip Seal in 2011)	PG58-34	SPWEB340C 2356
31*	Hot Mix Asphalt – Taconite Aggregate	PG64-34	SPWEB240F
33*	Hot Mix Asphalt	PG58-34 PPA	SPWEB340C
34*	Hot Mix Asphalt	PG58-34 SBS+PPA	SPWEB340C
35*	Hot Mix Asphalt	PG58-34 SBS	SPWEB340C
70	Hot Mix Asphalt	PG64-34	SPWEB440F
77*	Hot Mix Asphalt	PG58-34 Elvaloy+PPA	SPWEB340C
86*	Pervious HMA	PG70-28	2360
88*	Pervious HMA	PG70-28	2360

*Cells on Low Volume Road; all others on Mainline.

Approach

The development of models to predict OBSI levels required identifying those pavement characteristics and environmental effects that impact noise generation and amplification, as well as the availability of MnROAD data to support the models

Tire-pavement noise is generated and amplified through a variety of mechanisms, including tire carcass vibration, slip-stick, air pumping, adhesion and others (*3*). A number of pavement surface characteristics may affect the generation and propagation of tire-pavement noise. Different pavement parameters affect different mechanisms, and some are more important than others. Characteristics that are strongly related to tire-pavement noise include the surface texture, surface condition, friction, air voids, sound absorption, mechanical impedance (stiffness) and others. Pavement surface characteristics also depend on some mixture characteristics, such as aggregate gradation, volumetrics and binder type. These characteristics may vary to some extent with daily or seasonal changes in temperature and moisture conditions. Factors of somewhat lesser importance include airflow resistance, roughness and surface rating.

Controlling tire-pavement noise involves interfering with or disrupting these mechanisms. For example, air movement (pumping) can be reduced by using a porous asphalt surface where the air can be dissipated through the open pores in the pavement.

Texture

Pavement texture is one of the surface characteristics with the greatest impact on tire-pavement noise, therefore it is included in virtually all tire-pavement noise models (e.g., *4–6*). There are, however, different aspects of texture that must be considered. Consequently, texture is generally broken into different ranges of texture wavelength.

Microtexture is defined as the fine-scale texture of the surface with a wavelength less than 0.5 mm (*7, 8*) and is a function of the surface texture of the aggregate particles. Microtexture is related to friction; hence it affects noise generated by tire vibrations induced by friction and by the adhesion between the tire and the pavement surface, especially at frequencies above 1000 Hz (*9*, *10*). Sandberg and Ejsmont suggest that higher microtexture typically causes increased friction, which increases the stick-slip noise generation mechanism. On the other hand, increased microtexture also leads to a decrease in adhesion, which results in a lowering of the stick-snap mechanism. These conflicting changes may explain why clear relations between microtexture and tire-pavement noise are not always observed (*11*). Inclusion of a microtexture term was explored during model development but was not found to have a significant impact for the pavements tested in this study.

Macrotexture, with wavelengths between 0.5 mm and 50 mm, is determined by the overall properties of the pavement surface. It is related to the type of asphalt surface (e.g., dense versus porous), the gradation of the aggregates in the mixture, and presence of air voids at the surface. Macrotexture of the pavement is a major factor affecting air pumping, impact-induced vibrations, friction-induced vibrations, adhesion, pipe resonance and Helmholtz resonance and has been shown to affect OBSI levels in the 630–1000 Hz range (*12–14*).

Macrotexture can be measured by several methods, two of which have been used at MnROAD. Measurement with a laser profiler or Circular Track (or Texture) Meter (CTM) can be used to separate the effects of different texture wavelengths within the macrotexture range. Both types of measurements have been made at MnROAD. A RoboTex laser profiler, meeting the requirements of ISO 13473-4 (*15*), was used one time over three days in 2011. The CTM, standardized in ASTM E2157 (*16*), has been used periodically since 2008.

Friction

Pavement friction is closely related to texture. Changes in friction primarily affect the slip-stick mechanism, and so affect OBSI levels at high frequencies (*17*). Friction is most commonly measured in the U.S. using an ASTM towed friction trailer (*18*). Another standard test of wet friction is described in ASTM E1911 (*19*), using the dynamic friction tester (DFT). Both types of data are available at MnROAD; the DFT has been used periodically on some cells since 2008 and the towed friction trailer has been used one to three times annually. Because friction and texture are so closely related, the need to include both terms in the model was explored during model development; macrotexture measurements were found to be sufficient to predict noise on the surfaces tested in this study.

Seasonal and short-term variations in friction are widely recognized (e.g., *20–22*) . Typically friction levels are lowest towards the end of summer and highest during the winter or spring.

Temperature

Changes in the air and pavement temperatures can affect tire-pavement noise generation mechanisms. Increased temperatures are generally associated with increases in high-frequency noise, likely due to changes in adhesion or friction properties, and decreases in low-frequency noise, through changes in the mechanical impedance of the pavement (*1*).

Mechanical Impedance

The mechanical impedance of the pavement is related to the flexibility and energy dissipation properties of the pavement surface. In an asphalt mixture, the mechanical impedance is related to the stiffness, or modulus, of the mixture. The modulus of the pavement materials has an unknown effect on tire-pavement noise, but it is potentially a fairly important factor affecting impact-generated vibrations (*11*).

Mixture stiffness is affected by many factors, including the mixture type, aggregate type and gradation, binder properties and mixture volumetrics. A more elastic binder, such as a polymer modified binder, would be expected to produce a more flexible mixture. Asphalt mixture stiffness properties change as the temperature changes, so the mechanical impedance, as measured by the modulus, would also change over the course of a day or seasonally. Since asphalt binders age over time through oxidation, the mechanical impedance could also change over the life of the pavement as the mixture stiffens.

Modulus can be measured or estimated in a variety of ways. Some laboratory data on mixture stiffness, specifically dynamic modulus, is available in the MnROAD database. However, this data was only collected at the time of construction, so cannot be used to evaluate changes in stiffness seasonally or because of aging. Consequently, the best estimates of modulus over time are backcalculated layer moduli from periodic Falling Weight Deflectometer (FWD) readings. The EverCalc software program (*23*) was selected to analyze the FWD data based on work by Rao and Von Quintus (*24*).

Other parameters that have been shown in the literature to affect tire-pavement noise were considered for inclusion in the models but were dropped. These include airflow resistance, pavement condition rating, and ride quality. Porosity and sound absorption were also not included, since only two pervious HMA surfaces were available in the data set. If more permeable pavements were to be included, another parameter, such as sound absorption, might need to be added.

THE MECHANISM DECOMPOSITION APPROACH TO TIRE-PAVEMENT NOISE MODELING

Since tire-pavement noise is the result of several generation mechanisms, and each of these mechanisms is affected differently by changes in pavement parameters, an accurate noise prediction model must allow for the noise from each mechanism to vary independently. The mechanism decomposition method is one technique to accomplish this. The fundamental theory of this hybrid statistical-experimental approach is that a tire-pavement sound intensity spectrum can be decomposed into several constituent spectra, each representing the contribution from a generation mechanism (*25*). Since each mechanism is an independent noise source, the constituent spectra are added logarithmically to form the total tire-pavement noise spectrum.

A fundamental principle of the mechanism decomposition method is that although a change in pavement parameters may cause a complicated change in the shape of an OBSI spectrum, the shapes of the underlying constituent spectra do not change significantly. It is assumed that changes in pavement parameters may change the magnitudes, but not the shapes, of the constituent spectra. Statistical techniques can be used to determine the effect of pavement parameters. For example, a simple one-parameter model of tire-pavement noise may be defined using Equations 1.

$$L_{\text{low}}^*(f) = L_{\text{low}}(f) + \beta_1\alpha + \beta_2 \qquad \text{Eqn 1a}$$
$$L_{\text{mid}}^*(f) = L_{\text{mid}}(f) + \beta_3\alpha + \beta_4 \qquad \text{Eqn 1b}$$
$$L_{\text{high}}^*(f) = L_{\text{high}}(f) + \beta_5\alpha + \beta_6 \qquad \text{Eqn 1c}$$

where L_{low}, L_{mid}, and L_{high} are constituent spectra, each relating to a distinct noise generation mechanism; L_{low}^*, L_{mid}^*, and L_{high}^* are modified constituent spectra; α is a pavement or atmospheric parameter such as mean profile depth or air temperature; and $\beta_{1\text{-}6}$ are best-fit coefficients determined through nonlinear least-squares curve fitting.

A predicted total OBSI spectrum is formed from the modified spectra according to Equation 2.

$$L_{\text{total}} = 10\log_{10}\left(10^{\frac{L_{\text{low}}}{10}} + 10^{\frac{L_{\text{mid}}}{10}} + 2\sqrt{10^{\frac{L_{\text{low}}}{10}}10^{\frac{L_{\text{mid}}}{10}}}\cos\phi + 10^{\frac{L_{\text{high}}}{10}}\right) \qquad \text{Eqn 2}$$

The term involving $\cos\phi$ represents a phase relationship between the low- and mid-frequency spectra, which can constructively or destructively interfere (*26*). This predicted spectrum can then be compared to the OBSI spectrum on a given pavement. The fit coefficients, $\beta_{1\text{-}6}$, are determined by comparing measured and predicted OBSI spectra for a number of different pavements, each having a different parameter α. For this research project, the coefficients were determined by minimizing the total squared error between the measured and predicted one-third octave band levels using the `lsqnonlin` function in MATLAB.

IDENTIFICATION OF VARIABLES SIGNIFICANT TO TIRE-PAVEMENT NOISE

As shown earlier, many different parameters have been shown in the literature to affect tire-pavement noise to one extent or another. For efficient model development, however, the variables with significant effects on tire-pavement noise needed to be identified. These variables were identified by developing a series of simplified models for tire-pavement noise using MnROAD data. Each simplified model involved only one or two variables, and all of the other variables were controlled. By controlling for all other parameters, the effect of air temperature alone could be identified.

A series of one- and two-parameter models was developed to identify the pavement parameters that most affect tire-pavement noise in the different frequency ranges. The effect of temperature on OBSI levels is discussed as an example of how the reduced-parameter models were used. Air and pavement temperatures and OBSI measurements were made on 21 pavements over the course of approximately 14 hours on two different days at MnROAD. For the first test, in April 2011, atmospheric temperature varied from 0.7–11.0°C, and pavement temperature varied from 5.0–27.5°C. During the second test, in June 2011, air temperature varied from 19.9–33.9°C, and pavement temperature varied from 17.9–48.9°C. One-third octave band OBSI spectra varied about 2–5 dB with temperature for this experiment, depending on frequency. For some frequency ranges, colder temperatures consistently resulted in higher OBSI levels than warmer temperatures.

Using pavement temperature produced more consistent temperature (best-fit) coefficients across pavements and between the April and June data sets than did the air temperature measurements. The average pavement temperature coefficients for the low-, mid- and high-frequency constituent spectra were -0.016, -0.030, and -0.078 dB/°C, respectively. This shows the low- and mid-frequency spectra are affected less by temperature changes than the high-frequency spectrum. For an annual temperature variation of 50°C, these coefficients would yield OBSI variations of 0.8, 1.5, and 3.9 dB for the three constituent spectra. Therefore, temperature effects on the low- and mid-frequency spectra (0.8 and 1.5 dB annual variation) are not significant and do not need to be considered in future modeling efforts. Temperature effects on the high-frequency spectrum (3.9 dB variation) should be considered.

Similar approaches were used to control variables and evaluate one or two parameters at a time. If a parameter produced a significant impact (2 dB or greater) on noise in one or more frequency ranges, that parameter was considered in development of the final model. Details are available in the final report (*1*). The following parameters would found to have a significant impact on OBSI at some frequencies:

- Temperature was found to affect high-frequency noise.
- Texture (evaluated using RoboTex data) was found to affect low- and mid-frequency spectra positively (that is, an increase in texture causes an increase in OBSI) and to affect high-frequency spectra negatively (increased texture reduces noise).
- Mean profile depth (MPD) affected all three frequency ranges, but may be redundant with texture. As with texture, in increase in MPD led to increased low- and mid-frequency spectra but a decrease in high-frequency noise.
- Absorption may affect OBSI levels, but is likely related to other parameters, such as texture, so was considered in further modeling but would not be used as a sole parameter.
- Friction was found to impact OBSI levels in the low- and mid-frequency ranges, but again is likely correlated with other parameters, such as texture.
- Temperature and age were modeled in a two-parameter model; OBSI levels were observed to increase over time at all frequency ranges, but the increase was less above 1600 Hz.
- Temperature and modulus were also modeled jointly since asphalt is viscoelastic; both modulus and temperature were included in further development but the need to include both parameters was considered.

The model coefficients for all one-parameter models considered are shown in Table 2. For each parameter, the range of values is also shown, along with the maximum potential dB effect on each of the three constituent spectra. For each parameter, the maximum dB effect was found by multiplying the model coefficient by the range in the parameter found in the data set. For example, the leading edge, low-frequency coefficient for MPD was found to be 3.46 dB/mm. The range in MPD measured for all pavements was 1.1 mm, giving a maximum potential effect of 3.8 dB. In the table, maximum effects of greater than 4 dB are highlighted in red (with bold, italic type), indicating a significant effect on noise levels. Effects between 2 and 4 dB are shown in yellow (with bold type), indicating a moderate effect. Effects of less than 2 dB are shown in green (with italic type) to indicate that the parameter has little effect. In general, the low-frequency spectrum is affected most by macrotexture parameters (MPD, 64-mm wavelength) and is less affected by microtexture, absorption and temperature. The mid-frequency spectrum is affected by all texture parameters and absorption. The high-frequency spectrum is most affected by microtexture and air temperature. Using the two-parameter age-temperature model, it was shown that age significantly affects the low- and mid-frequency spectra but not the high-frequency spectrum. The two-parameter temperature-modulus model was used to show that modulus and temperature must both be considered for the high-frequency spectrum but not necessarily for the low-frequency spectrum. Many pairs of parameters, such as 12.5 mm texture and MPD, are highly correlated, so the need to include both in the final model was explored.

Some variables were found not to be necessary for each of the three constituent spectra. For example, air and pavement temperature do not affect low-frequency noise, so these variables were not included in later models.

TABLE 2 One-parameter model coefficients, parameter ranges, and maximum dB effects.

		MPD (mm)		skew		$\lambda_{1.25\ mm}$ (dB)		$\lambda_{12.5\ mm}$ (dB)		$\lambda_{64\ mm}$ (dB)	
		Lead	Trail	Lead	Trail	Lead	Trail	Lead	Trail	Lead	Trail
Model coefficient (dB/EU)	Low-freq.	3.46	4.97	-0.42	-0.13	0.24	0.97	0.30	0.40	0.25	0.37
	Mid-freq.	7.35	7.70	-0.84	-0.98	2.02	1.77	0.59	0.58	0.56	0.56
	High-freq.	-1.44	-1.31	0.62	0.04	-0.72	-0.79	-0.12	-0.10	-0.13	-0.12
Parameter range	Maximum	1.5	1.5	0.15	0.15	41.2	41.2	50.6	50.6	49.5	49.5
	Minimum	0.4	0.4	-0.97	-0.97	36.5	36.5	38.2	38.2	35.2	35.2
	Range	1.1	1.1	1.1	1.1	4.7	4.7	12.4	12.4	14.3	14.3
Maximum effect (dB)	Low-freq.	**3.8**	***5.5***	*0.5*	*0.1*	*1.1*	***4.6***	**3.7**	*5.0*	**3.6**	***5.3***
	Mid-freq.	***8.1***	***8.5***	*0.9*	*1.1*	***9.5***	**8.3**	*7.3*	*7.2*	*8.0*	*8.0*
	High-freq.	*1.6*	*1.4*	*0.7*	*0.1*	**3.4**	***3.7***	*1.6*	*1.3*	*1.9*	*1.6*

		FN		$\alpha_{1000\ Hz}$		T_{pav} (°C)		T_{air} (°C)	
		Lead	Trail	Lead	Trail	Lead	Trail	Lead	Trail
Model coefficient (dB/EU)	Low-freq.	0.21	0.17	-2.84	1.87	-0.016	-0.010	-0.038	-0.016
	Mid-freq.	0.15	0.16	7.85	9.19	-0.030	-0.065	-0.053	-0.098
	High-freq.	0.00	0.03	-3.95	-4.77	-0.078	-0.063	-0.13	-0.109
Parameter range	Maximum	60.9	60.9	0.6	0.6	48.9	48.9	33.9	33.9
	Minimum	42.3	42.3	0.0	0.0	5.0	5.0	0.7	0.7
	Range	18.6	18.6	0.5	0.5	44.0	44.0	33.2	33.2
Maximum effect (dB)	Low-freq.	**3.9**	**3.1**	*1.5*	*1.0*	*0.7*	*0.5*	*1.3*	*0.6*
	Mid-freq.	**2.8**	**3.0**	***4.1***	***4.8***	*1.3*	**3.2**	*1.7*	**3.3**
	High-freq.	*0.1*	*0.5*	**2.1**	**2.5**	**3.4**	**3.1**	***4.5***	**3.7**

DEVELOPMENT OF THE FINAL MECHANISM DECOMPOSITION MODELS

Using the mechanism decomposition approach, the significant variables identified and the available MnROAD data, two models to predict tire-pavement noise were developed. The first method is based on using the RoboTex texture data, and the second uses CTM texture data in a similar fashion.

Statistical Models of OBSI Levels

The final version of the CTM model is shown in Equations 3a-c.

$$L^*_{\text{low}} = L_{\text{low}} + \beta_1 L_M + \beta_2 T + \beta_3 E + \beta_4 \qquad \text{Eqn 3a}$$
$$L^*_{\text{mid}} = L_{\text{mid}} + \beta_5 L_M + \beta_6 E + \beta_7 \qquad \text{Eqn 3b}$$
$$L^*_{\text{high}} = L_{\text{high}} + \beta_8 L_M + \beta_9 T + \beta_{10} \qquad \text{Eqn 3c}$$

where L^*_{low}, L^*_{mid}, and L^*_{high} are modified constituent spectra, the macrotexture term L_M (dB at 12.5 mm wavelength) is determined based on CTM data, T is pavement surface temperature (°C), E is the pavement modulus (GPa) and β_{1-10} are best-fit coefficients determined through nonlinear least-squares curve fitting.

A predicted total OBSI spectrum is formed according to Equation 2 and compared to the OBSI spectrum on a given pavement to determine the fit coefficients, β_{1-10}. The final model, including the best-fit coefficients, is shown in Equation 4a-c for the leading edge (LE). Similar equations for the trailing edge can be found in the final report (*1*).

$$L^*_{\text{LE, low}} = L_{\text{LE, low}} + 0.11 L_M + 0.031 T + 0.098 E - 4.2\ \text{dB} \qquad \text{Eqn 4a}$$
$$L^*_{\text{LE, mid}} = L_{\text{LE, mid}} - 0.12 L_M + 0.068 E + 5.8\ \text{dB} \qquad \text{Eqn 4b}$$
$$L^*_{\text{LE, high}} = L_{\text{LE, high}} - 0.20 L_M - 0.060 T + 7.2\ \text{dB} \qquad \text{Eqn 4c}$$

The final version of the RoboTex model is shown in Equations 5a-c

$$L^*_{\text{low}} = L_{\text{low}} + \beta_1 L_M + \beta_2 T + \beta_3 Y + \beta_4 E + \beta_5 \qquad \text{Eqn 5a}$$
$$L^*_{\text{mid}} = L_{\text{mid}} + \beta_6 L_M + \beta_7 Y + \beta_8 E + \beta_9 \qquad \text{Eqn 5b}$$
$$L^*_{\text{high}} = L_{\text{high}} + \beta_{10} L_M + \beta_{11} T + \beta_{12} Y + \beta_{13} \qquad \text{Eqn 5c}$$

where Y is the number of years since the pavement texture was measured, and β_{1-13} are best-fit coefficients. The final model is shown in Equation 6a-c for the leading edge.

$$L^*_{\text{LE, low}} = L_{\text{LE, low}} + 0.50 L_M - 0.050 T + 1.29 Y + 0.073 E - 18.3\ \text{dB} \qquad \text{Eqn 6a}$$
$$L^*_{\text{LE, mid}} = L_{\text{LE, mid}} + 0.024 L_M + 1.12 Y + 0.030 E - 0.3\ \text{dB} \qquad \text{Eqn 6b}$$
$$L^*_{\text{LE, high}} = L_{\text{LE, high}} - 0.28 L_M - 0.10 T + 0.60 Y + 11.2\ \text{dB} \qquad \text{Eqn 6c}$$

The models described by Equations 4 and 6 are complex, yet their individual terms can be interpreted physically. The results of using the model with the CTM and RoboTex texture data to predict noise at the leading and trailing edges are described below.

Macrotexture – when using the CTM to measure macrotexture, the resulting model coefficients indicate that low-frequency noise would increase with increasing macrotexture (positive coefficient), the mid-frequency range would increase somewhat less, and the high-frequency content would decrease (negative coefficient). An increase of 6 dB in the macrotexture is predicted to result in an overall noise level increase of approximately 0.3 dB. Using the RoboTex model, the OBSI spectrum is predicted to increase at frequencies below 1250 Hz, but decrease at higher frequencies, as shown in Figure 1. The macrotexture terms in the mid-frequency spectra have much smaller coefficients, meaning that macrotexture is predicted to have a smaller effect in the mid-frequency range. These results match previous findings by Sandberg and Ejsmont (*4*). The overall level is predicted to increase by approximately 0.5 dB.

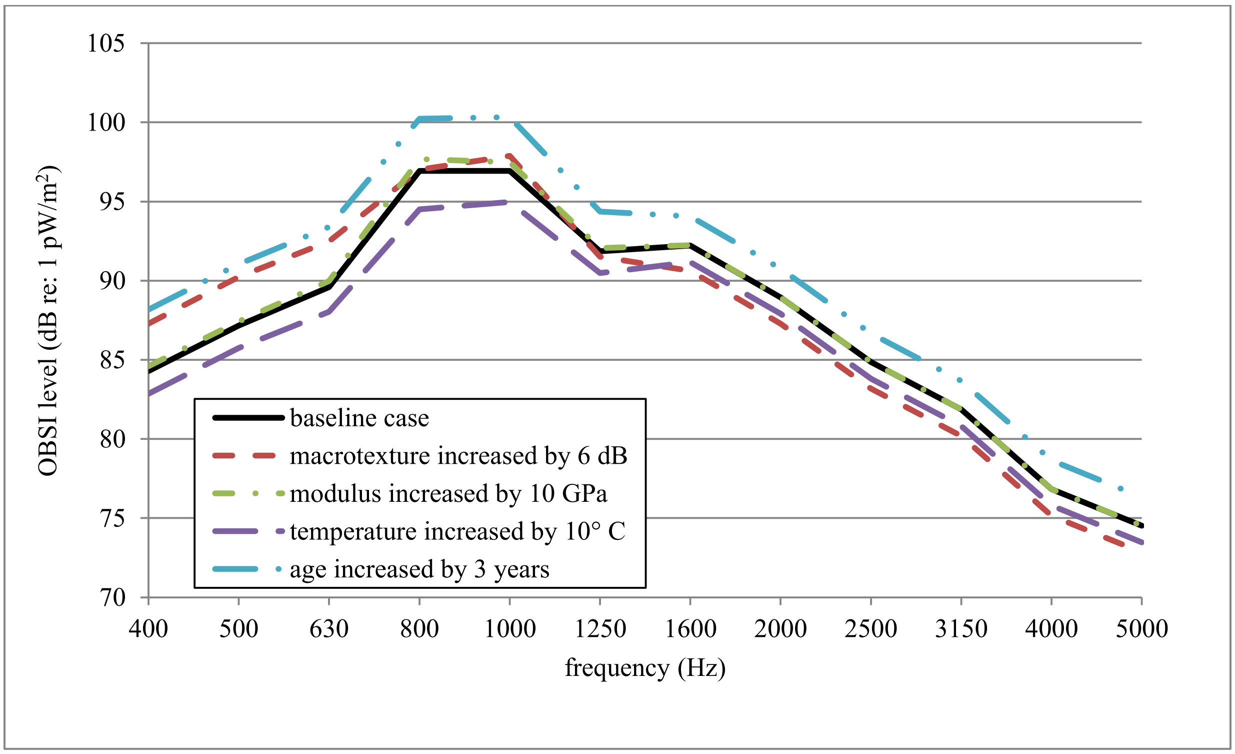

FIGURE 1 Predicted effects of pavement parameters on OBSI spectra using RoboTex model.

Modulus – for both models, an increase in the modulus of the pavement, backcalculated from FWD readings, is expected to cause an increase in noise in the low- and mid-frequency ranges, with little effect on high-frequency noise, as shown in Figure 1. An increase in modulus of 10 GPa is predicted to result in an overall increase in the noise level of approximately 0.5 dB in both models.

Pavement Temperature – both models result in negative coefficients over most frequency ranges, indicating that as pavement temperature increases, noise would decrease. This is consistent with findings by other researchers (*26*). An increase of temperature will also likely result in a change in the pavement modulus, which also needs to be considered. The combined effects of a change in temperature and a change in modulus are shown in Figure 1. The CTM model predicts an overall decrease in noise of approximately 0.7 dB with an increase in temperature of 10°C, and the RoboTex model predicts a decrease of approximately 1.8 dB. While the increased temperature alone causes a small decrease in noise, the resulting change in modulus with increased temperature results in a larger decrease.

Effect of Time – the RoboTex model (but not the CTM model) incorporates the effects of time on OBSI predictions. The time term, Y, can be thought of as a correction for the increase in macrotexture over time. The term is needed for the RoboTex model, since texture scans were only performed once, while OBSI measurements were made over the course of several years. The term is not necessary for the CTM model, since CTM measurements were made at regular intervals. The predicted result of aging a pavement three years is shown in Figure 1. The result is a broadband increase in noise, with the overall level predicted to increase by approximately 3 dB.

Model Accuracy

Several different metrics were used to judge the accuracy of the models by comparing model predictions to measured OBSI data. For the CTM model, a total of 13 different asphalt pavements had texture data measured at different times. The sound levels were measured on these cells several times over more than five years, for a total of 441 different measurements of leading and trailing OBSI noise. For the RoboTex model, 22 different asphalt pavements were were scanned with the RoboTex equipment. A total of 1421 different OBSI measurements were made on these pavements.

- The measured and predicted overall OBSI levels are shown in Figure 2 (top). The average error in overall OBSI levels is 1.0 dB for the CTM model and 0.8 dB for the RoboTex model. For comparison, the run-to-run variation in overall octave bands for the data used in this study, representing the average variations between two runs on the same pavement on the same day, was approximately 0.6 dB.
- For both models, the residual errors between the measured and predicted levels by test cell vary between about 0.5 and 1.5 dB.
- The average error by temperature range (from 0 to 60°C in 10°C) varied between about 0.5 and 1.5 dB. The worst prediction occurs during very hot temperatures when other mechanisms, such as adhesion between the pavement and the tread blocks, may become more prominent.
- Comparisons of the measured and predicted one-third octave band spectra are shown in Figure 2 (center and bottom). For the CTM model, this figure shows that for frequencies up to and including 1000 Hz, the predicted OBSI levels fall in a more narrow range than the measured values, so that the cluster of points takes on more of a horizontal shape rather than centering on the 1:1 line. This suggests that the model is not predicting the OBSI levels well in this range. For the RoboTex model, the spread within the measured and predicted values is approximately the same, and the data points are approximately symmetric about the 1:1 line.
- The average residual errors in one-third octave bands by frequency band show that the CTM model predicts the OBSI level to within 2 dB on average and the RoboTex model to within 1.5 dB on average.

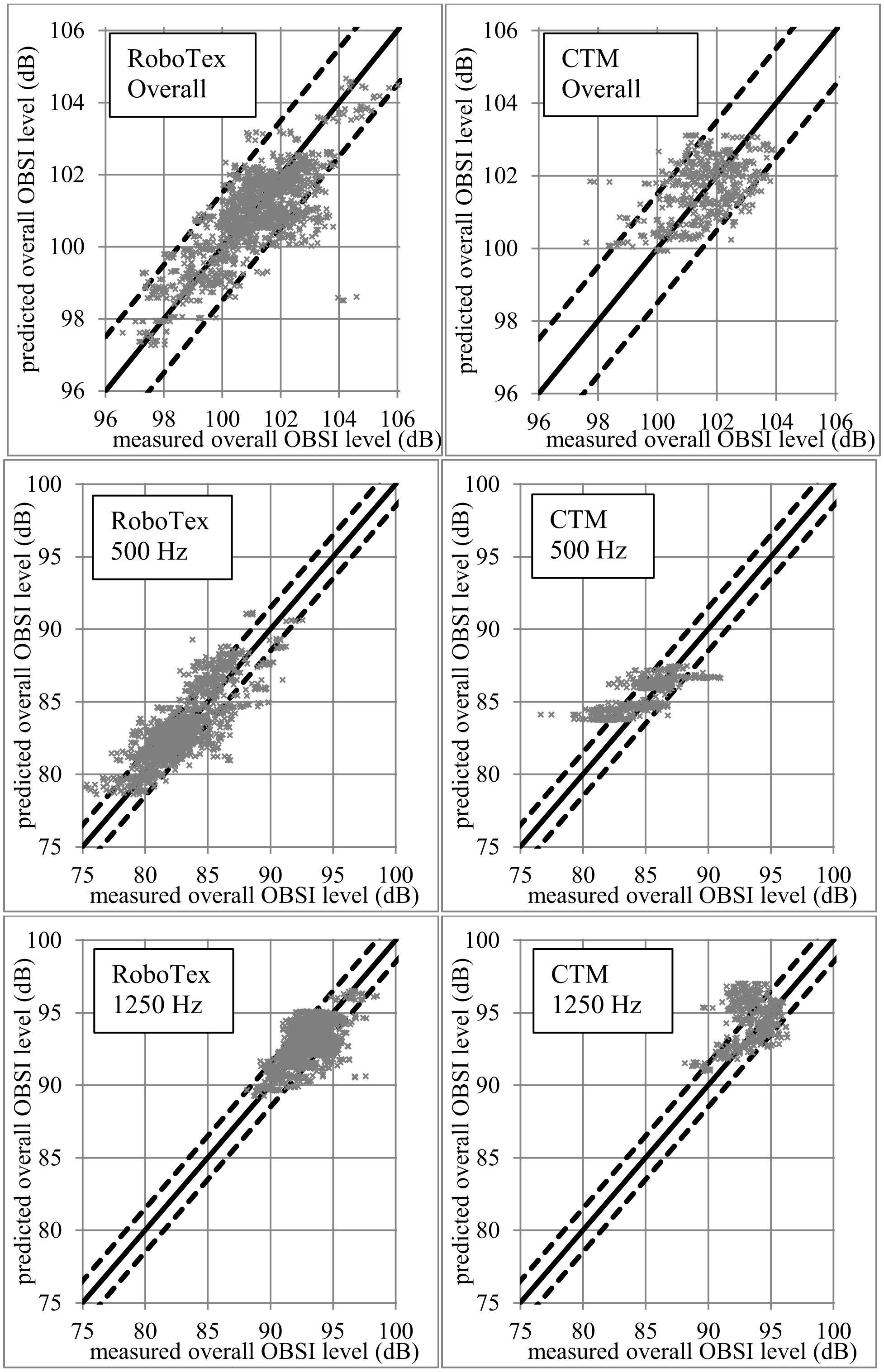

FIGURE 2 Measured and predicted one-third octave band levels. Upper left: RoboTex model, overall levels. Upper right: CTM model, overall levels. Center left: RoboTex model, 500 Hz. Center right: CTM model, 500 Hz. Lower left: RoboTex model, 1250 Hz. Lower right: CTM model, 1250 Hz. Solid line: 1:1. Dashed lines: ±1.5 dB from 1:1 line.

Discussion

In general, the model developed using RoboTex data is more accurate than the model using the CTM data. The overall level accuracy, summarized in Table 3, is better for the RoboTex model. The overall prediction errors by cell, year and temperature range are all higher for the CTM model than for the RoboTex model. The one-third octave band data (Figure 2, center and bottom) shows that the CTM model is not doing a good job of predicting the one-third octave band spectra for frequencies up to and including 1000 Hz. However, it is much easier, less expensive and more feasible for an agency to measure texture using the CTM model versus the RoboTex model.

TABLE 3 Percent of pavements with noise levels predicted to within 1.5 dB for the two models

	Percent of Pavements with Noise Levels Predicted to within 1.5 dB	
Model / Location	RoboTex Model	CTM Model
Leading Edge	87%	81%
Trailing Edge	90%	82%

The improved performance of the RoboTex method may be due to several reasons. Firstly, although RoboTex data was only collected once, it was collected on 22 test cells vs 13 cells tested with the CTM. When the number of OBSI readings taken on these pavements is considered, there was over three times as much data for the RoboTex model compared to the CTM model. Secondly, and perhaps more importantly, is the nature of the texture measurements themselves. The RoboTex collects 100 lines of data, resulting in approximately 15,000 m of data within a test cell; this resulted in error bars on the texture measurements of 0.1–0.2 dB. The CTM, on the other hand, was typically used to test eight locations within a test cell. Given the circumference of the circle scanned by the CTM, this resulted in approximately 7–8 m of data per cell. In other words, there was about 2000 times more texture data from the RoboTex as from the CTM. The error bars on the CTM texture data were 3–5 dB, leading to 2–3 dB variation in the predicted OBSI. It might be possible to improve the accuracy of the CTM model by performing more measurements in each test cell, but the time and labor required to do so is likely prohibitive and could not reasonably be expected to provide the same amount of data as was obtained with the RoboTex.

Understanding the limitations of the models, then, either can be used to predict tire-pavement noise based on differing input values. The RoboTex model provides better accuracy because of the extensive amount of texture data available; however, the model is more accurate when the texture measurements are more recent and collection of the RoboTex data is expected to be a one time, or certainly rare, event. The CTM data is much more feasible to collect frequently, however, the model is not as accurate because even with frequent measurements, there is not as much texture data available because of the much shorter path measured.

DISCUSSION AND CONCLUSIONS

The objective of this project was to develop a model to predict on-board sound intensity (OBSI) levels on asphalt pavements using field and laboratory data from MnROAD and including the effects of pavement surface and material characteristics.

Only asphalt surfaces were studied in this project. However, there was a fairly wide range of surface types. Most of these surfaces were constructed in 2007 and 2008, so the pavement age is limited. A total of 25 test cells were used in various portions of the study.

The models show that to achieve a low noise pavement, a smooth surface with a low stiffness is preferable. As the macrotexture and stiffness decrease, the peak and overall OBSI levels also decrease. Since modulus is related to temperature, increasing the temperature results in a decrease in the modulus, but some surface materials are more sensitive to changes in temperature than others. In general, stiffer materials tend to experience greater decreases in stiffness than softer materials. In this study, the ultrathin wearing courses were among the stiffer materials and produced some of the higher noise levels. The sections with chip or surface seals had higher texture and also higher noise levels. The warm mix asphalt and lower traffic volume mixtures tended to have lower stiffness values and lower noise. The models also reflect that noise tends to increase as pavements age, but none of the cells tested were approaching the end of their service life or exhibiting high levels of distress.

The following conclusions can be drawn from this study:

- Different noise generation and amplification mechanisms affect different frequency ranges. In addition, different pavement characteristics affect different mechanisms.
- The mechanism decomposition method allows the effects of changes in various pavement parameters on the low-, mid- and high-frequency noise spectra to be predicted independently. The changes in the individual constituent spectra are then logarithmically added to yield estimates of overall tire-pavement noise and one-third octave bands levels.
- Using simplified one- or two-parameter models, the factors that have the greatest impact on tire-pavement noise in low-, mid- and high-frequency ranges were identified. In general, the low-frequency spectrum was found to be affected most by macrotexture parameters and less by microtexture, absorption, and temperature. The mid-frequency spectrum was affected by all texture parameters and absorption. The high-frequency spectrum was most affected by microtexture and air temperature.
- Some variables were found not to be necessary for each of the three constituent spectra, so they were eliminated from further model development at the appropriate frequency ranges.
- Ultimately, it was found necessary for the models to consider the effects of pavement macrotexture, air temperature, modulus of the pavement surface layer, and the combined effect of temperature and modulus. Only two porous pavements were included in the data set; if more porous pavements were included, an absorption parameter might be found to be significant.
- The models were developed for the types of asphalt surfaces tested at MnROAD and based on the types of test data available. Because the models rely heavily on modulus, they would not be reliably used on other pavement types that have different stiffness values and respond differently to changes in temperature compared to asphalt mixtures. A wide range of asphalt mixtures was studied, so the models are applicable to a wide range of types of asphalt surfaces, but high levels of distress and old pavements were not tested.
- In addition, the models were developed to predict noise as measured by the OBSI method; attempts to correlate OBSI data to other types of noise data have yielded mixed results. Applying these models to other surface types, with different input variables or to predict other noise measurements would require validation and perhaps revision of the

models. However, the models were formulated and implemented (in an Excel spreadsheet) in such a way that future revisions can be readily accommodated.
- The models have been found to predict the overall OBSI sound intensity level to within 1.5 dB and the one-third octave bands to within 2 dB for most of the pavements tested. Other metrics and evaluation of the model accuracy by cell, year, temperature and other factors are also reported and are generally favorable.

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