Relationship between Tire-Pavement Interaction Noise and Surface Characteristics in 2009 Pavement Test Track Cycle

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ABSTRACT

The interest in quieter pavements has been driven largely by public awareness that altering the surface can affect traffic noise levels. The objective of this research was to utilize two methods for measuring tire-pavement noise to assess which pavement surface characteristics have the greatest influence on noise generation. The National Center for Asphalt Technology (NCAT) test track, with four different pavement surface family groups, was used to test and analyze noise from tire-pavement interaction. The tire-pavement noise was measured in a novel test approach using a surface microphone from different types of sections in the Test Track. Testing was conducted on four major family groups of superpave fine and coarse graded, open-graded friction course (OGFC) and stone matrix asphalt (SMA) mixes from 2009 NCAT Test Track research cycle to evaluate changes over time. The results show that the noise levels vary widely according to pavement surface type. The effects of pavement properties including the air void content, gradation properties, roughness, texture, pavement stiffness and age have been evaluated on one-third octave band noise levels. The evaluation confirmed that macrotexture increases the low frequency noise and higher air void content reduces the high frequency noise level, while other surface characteristics were found to have less influence on noise levels. The content of this study should be of immediate interest to pavement engineers and others concerned with pavement design and construction to determine appropriate quieter pavement surfaces.

Keywords: tire-pavement interaction noise, surface characteristics, material properties, quiet pavement
INTRODUCTION

Tire-pavement interaction noise has become an increasingly important environmental issue in densely congested urban settings near busy highways. It is also a significant consideration for the part of highway agencies that are seeking the use of quieter pavements to minimize traffic noise. Although sound walls and texturing methods have been utilized to mitigate road noise, they have some limitations as well. The need of reducing the sound at the source in some cases has led to the design of porous paving materials. In this case the carefully designed porosity introduced in the material structure of asphalt mixtures will allow sound waves to pass through and dissipate its energy (1). In the modern world, noise pollution affects more people than any other type of pollution (2). Among the many sources of noise, the one that clearly dominates is the road traffic noise. In the United States, more people are exposed to highway noise than from any other single noise source (3).

As the public consistently demands that highway traffic noise be mitigated, sound walls may provide a competitive way to reduce highway noise. However, there are no widely accepted procedures for measuring solely tire-pavement noise under in-service conditions (4). The interest in quieter pavements has been driven largely by the cost and, at times, the public’s resistance to the traditional sound wall approach (5) along with increased public demand of highway traffic noise reduction. In addition, there is more public awareness that pavement selection can affect traffic noise levels (4).

Therefore, research is needed to evaluate potential noise-measuring procedures for different surfaces. NCAT has been contributing to the understanding of the acoustics and performance of quieter pavements during the last few years. Each two-year research cycle of the Test Track has featured different types of pavement sections using a variety of design methodologies. The test results have shown that open-graded friction course (OGFC) surfaces, also referred to as porous friction courses, are successful candidates to eliminate water spray, improve skid resistance and significantly mitigate tire-pavement interaction noise (6). The use of OGFC pavement surfaces are found to be helpful in reducing the generated tire-pavement noise in a few states as well (7). In this study, the pavement surfaces that affect the portion of freeway noise generated from tires as they roll across asphalt pavements have been evaluated. The pavement classification summarized in TABLE 1 has been considered in order to evaluate different surface types in 2009 NCAT Pavement Test Track cycle.

<table>
<thead>
<tr>
<th>Design Methodology</th>
<th>Gradation Classification</th>
<th>No. of Sections</th>
<th>Test Track Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superpave</td>
<td>Fine-graded</td>
<td>23</td>
<td>E5, E6, E7, E8, E9, N3, N4, N5, N6, N7, N8, N10, N11, W2, W3, W4, W5, W6, W7, S9, S10, S11, S12</td>
</tr>
<tr>
<td></td>
<td>Coarse-graded</td>
<td>5</td>
<td>E4, W10, S2, S6, S7</td>
</tr>
<tr>
<td>Open-graded Friction Course (OGFC)</td>
<td>6</td>
<td>N1, N2, N13, S3, S4*, S8</td>
<td></td>
</tr>
<tr>
<td>Stone Matrix Asphalt (SMA)</td>
<td>5</td>
<td></td>
<td>E1, N9, N12, W1, S1</td>
</tr>
<tr>
<td>Other asphalt pavements **</td>
<td>7</td>
<td></td>
<td>E2, E3, E10, W8, W9, S5, S13</td>
</tr>
</tbody>
</table>

Note: *S4 was not considered in this study because of the poor data.  
** The remaining sections were not included in this study because of the change of surface types.
RESEARCH OBJECTIVE

The objective of this research was to utilize two methods for measuring tire-pavement noise to assess which pavement surface characteristics have the greatest influence on noise generation. Testing was conducted on NCAT test track sections using the close proximity (CPX) and on-board sound intensity (OBSI) methods to evaluate noise changes over time. The content of this study should be of immediate interest to pavement engineers and others concerned with pavement design and construction as well as the noise impacts on nearby communities.

Overview of Evaluation Testing

This study was based on two methods for measuring tire-pavement noise at the source. The first method used the NCAT close-proximity noise (CPX) trailer that utilizes a small trailer pulled by a vehicle. The trailer contains an anechoic chamber with the test tire and two free-field microphones to isolate the tire-pavement noise and the sound pressure. The second method, known as the OBSI method uses a pair of microphones mounted on the right rear tire of a vehicle, three inches above the pavement surface, to ensure that only the tire/pavement noise is being measured. This procedure has been found to be the preferred approach for measuring tire-pavement noise at the source, both in the U.S. and internationally. The test measurements provided in this report are based on the Standard Test Method for the Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method (8). Repeated sound measurements (at least 3 runs) were performed on each test section. Testing was done with a Michelin standard reference test tire (SRTT) at a speed of 45 mph and tire pressure of 30 psi. Sound-intensity testing with an NCAT triple trailer truck was also completed by attaching a frame around the rear wheels on the rear trailer. Sound-intensity microphones could be mounted to record leading-edge and trailing-edge measurements. Details of the configurations are given elsewhere (9).

An analysis was also conducted to compare CPX data against the corresponding OBSI data for all test sections, as shown in FIGURE 1. This data shows that CPX and OBSI levels are not numerically equivalent, but are strongly correlated at given frequencies. It should be noted that the two methods react differently with porous pavements. For practical consideration, the OBSI method was selected for further analysis of at-the-source tire-pavement noise in this study.

FIGURE 1 On-board sound intensity (OBSI) versus close-proximity (CPX) level at 1/3 octave band for all asphalt pavements at different ages
The results of the OBSI measurements over a wide range of frequencies on sections with various surface mixes at different pavement ages are illustrated in FIGURE 2. The first observation is that pavement age does not appear to influence tire-pavement noise for any of the surface types at any frequency within the range of data available. The one exception may be the Superpave fine-gradation section, which shows an increase in the sound-intensity level at 500 Hz. Although this increase in noise could be due to raveling of the fine-graded layer, it is clear that the trend is strongly influenced by the one data point at about 4 years. Another observation is that the OGFC section is much quieter than all of the other surface types at the mid-range frequencies between 1,000 and 2,500 Hz. It should be noted that noise experts agree that sound levels must differ by at least three decibels to be noticeable to the human ear (audibly quieter) (4).

OGFCs are designed to have small voids throughout the layer. These air voids are believed to absorb and dissipate the sound generated by the tires on the pavement surface. Overall, conventional asphalt mixtures have smaller and fewer voids, which may give them better durability than OGFC pavements but do not allow much absorption of noise. Although OGFC mixtures are found to be the quietest pavement over time among the investigated surface mixtures, climate is one of the big challenges when using OGFC pavements in some states (e.g., Washington) (7). Most states successfully using OGFC pavements are located in the southern U.S. and have relatively warm climates (e.g., Alabama, Arizona, California, Georgia, Florida, and Texas).
FIGURE 2. Sound-intensity level for different mixture types versus pavement age at different frequencies of (a) 500, (b) 1000, (c) 1600, (d) 2000, (e) 2500 and (f) 3150 Hz.

Macrotexture

Although macrotexture significantly influences the sound measured at the tire-pavement interface, the relationship between macrotexture and noise is not well defined. This might be because macrotexture is marked by other influence factors such as the porosity and stiffness of the pavement mixture. Similar studies propose that the surface profile be used to differentiate the positive and negative texture on the road surface (9). However, for the purpose of this study mean profile depth has been adopted to categorize the test track sections.

Furthermore, roughness and pavement texture are the two most commonly assessed pavement properties that influence both rolling resistance and tire-pavement noise. These two components combined effectively quantify the geometry of the profile of the pavement surface. The road surface texture and smoothness affect rolling resistance by creating vibration inputs in the tire and suspension system and potentially makes noise. Therefore, making a smoother road will reduce these vibrations and noise and subsequently decrease fuel consumption as well. Large-scale roughness may cause gross deformation in both the tire and shocks, which causes energy losses. Small-scale roughness causes smaller deformation that will be less influential on the rolling resistance but will influence tire traction and friction (10). Therefore, a detailed evaluation of OBSI versus mean profile depth of different surface mixtures at different low and high frequency octave bands has been investigated. Despite expectations, for some types of pavement surfaces the sound levels on mixtures with smoother surface texture are higher than those on a coarser surface texture. An observation made when examining these smooth surface mixtures in the field was that they would “squeak” or generate a high pitch noise if the rubber soles of one’s shoes were dragged across the surface. Although this is not an objective test, it indicates possible noise effects under rolling tires. A possible consequence of this phenomenon is the unusual peak sometimes observed in the data. In this study, surface texture of the test track sections was quantified by mean profile depth using the high-frequency laser on the ARAN van. Pavement surface layer types were categorized by mean texture depth into three texture family groups summarized in TABLE 2.
<table>
<thead>
<tr>
<th>Group</th>
<th>Mean Profile Depth (MPD) Magnitude</th>
<th>Pavement Type</th>
<th>Noise Test Section</th>
<th>No. of Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>&lt; 1.0 (mm)</td>
<td>Superpave (Fine-Graded)</td>
<td>E5, E6, E7, E8, E9, N3, N4, N5, N6, N7, N8, N10, N11, W2, W3, W4, W5, W6, W7, S9, S10, S11, S12</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Superpave (Coarse-Graded)</td>
<td>E4, S2, S6, S7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SMA</td>
<td>E1, N9, S1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Other Pavements</td>
<td>E2, E3</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1.0 &lt; MPD &lt; 1.5 (mm)</td>
<td>OGFC</td>
<td>N1, N2, N13, S3, S8</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SMA</td>
<td>N12, W1</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>&gt; 1.5 (mm)</td>
<td>Severely raveled Superpave (Coarse-graded)</td>
<td>W10</td>
<td>1</td>
</tr>
</tbody>
</table>

Based on the surface type and texture classification the results of the on-board sound intensity (OBSI) measurements are summarized in FIGURE 3 (a) and (b) for different Test Track sections. The noise data have been measured over time and are compared for pre-traffic (initial traffic) and post traffic (the end of 2009 Test Track research cycle) on different family groups.
FIGURE 3 Pre-traffic and post traffic noise data on the 2009 NCAT Test Track for (a) fine-graded and (b) coarse-graded, OGFC, SMA and other pavement family groups.

FIGURE 4 shows the OBSI level at 1/3 octave bands for characteristic mixes from the three groups. For the sake of brevity, only A-weighted global sound-intensity levels calculated by logarithmic addition of the sound levels between the third octave band frequencies of 315 and 4,000 Hz are reported. At 1/3 octave band levels below 1,000 Hz, the sound-intensity level for the section from group A is 5 to 6 dBA lower than relative group B, which is 2 to 5 dBA lower than the section with the highest macrotexture. At 1/3 octave band frequencies above 1,585, group B, which included OGFC and some SMA surfaces, are the quietest surfaces, and group A includes the loudest. The higher OBSIs at the higher frequency indicate a tonal noise generated on these smoother surfaces.
Results of Parameter Investigation

The influence of other mix characteristics on tire-pavement noise was also analyzed. Sensitivity of the sound-intensity levels to variations of each mix characteristic was evaluated at two levels of frequency for the three texture groups.

Pavement Texture and Smoothness: It is believed that the noise generated from tire-pavement interaction is substantially influenced by the macrotexture and porosity of the surface layer. Tire-pavement noise testing on the track indicates that the degree to which these factors influence noise levels is related to the weight of the vehicle and tire pressures (9). For lighter passenger vehicles, the porosity of the surface, which relates to the degree of the noise attenuation, is the dominant factor. For heavier vehicles (with higher tire pressures), the macrotexture of the surface and the positive texture presented at the tire-pavement interface has a greater influence. Sound-intensity level versus mean profile depth in FIGURE 5(a) indicates that the smoother surface mixtures generate lower sound levels at the lower frequencies (<1,000 Hz), but higher noise levels at the higher frequencies (>1,600 Hz) compared to the coarser surface mixtures. This partly explains why mixtures with low texture seem noisier, as the human ear is more sensitive to higher frequency sound levels, and the A-weighting factors effectively filter out the lower-frequency sound levels. The OGFC mix on S3 and the micro-surfacing on section S9 are also among the better performance mixtures in terms of sound intensity level at the higher frequency (1600 Hz).

Air Voids: By comparing the sound-intensity level sensitivity with in-place pavement air voids for different groups, shown in FIGURE 5 (b), group B was within the same OBSI level range as group A in the low frequency band (1,000 Hz). However, in the higher frequency band (1,600 Hz), the OGFC mixtures were audibly quieter, and the SMA mixtures were grouped with the other dense-graded mixtures despite their higher macrotexture. It is important to note that one of the OGFC sections has significant raveling at the beginning of the section, which certainly influences the results for that section. Therefore significant OBSI level difference of up to 6 dBA

FIGURE 4. 1/3 Octave band levels for pavement groups A, B, and C
was identified at higher frequency levels with the change of percent of air voids through available data. The sensitivity analysis of air void measurements show that this mixture property results in an audible difference in the OBSI level especially in the high frequencies which are more sensitive to human ears.

**Stiffness:** Pavements deform and are subjected to stresses and strains as vehicle travel on highways. Therefore, some energy dissipation might also occur during this process due to the pavement-tire interaction. It has been theorized by some researchers that flexible pavement structures will deform more than rigid pavements, thus increasing the amount of energy necessary for vehicles to remain at a constant velocity. However, research shows that when smoothness, pavement substructure, and texture are consistent; little correlation can be developed between pavement stiffness and rolling resistance. In reality, the pavement is much stiffer and its deformation is relatively small in comparison to the tire’s deformation. Therefore, the relative stiffness of the pavement-tire interaction is dominated by the stiffness of the tire, not that of the pavement. Almost all research findings have shown that pavement deflection and stiffness have little to no effect on pavement rolling resistance (10). Since rolling resistance does not have a 1:1 relationship with tire-pavement noise, this reduces the impact of pavement deflection and stiffness on noise even more drastically. This study as illustrated in **FIGURE 5** (c), suggests that pavement stiffness has a poor correlation with the OBSI level especially at lower frequency band (1000 Hz). While these estimates are based on theoretical calculations, they highlight the true disconnect between pavement stiffness and tire-pavement noise.

**Nominal Maximum Aggregate Size:** Having evaluated the texture present at the tire-pavement interface, the findings have led to further investigation of other properties influencing texture separately. As it is shown in **FIGURE 5** (d) the larger nominal maximum aggregate size affords a degree of stiffness representing the obstacle in the tires path that would generate more noise (possibly related to the forces applied at the surface) and higher OBSI level change at low frequency (1000 Hz). The smaller nominal aggregate size would serve to attenuate noise levels here. Both of these differences at low and high frequencies in sound intensity levels made by the range of evaluated nominal maximum aggregate size are audible to the human ear.

![Graphs showing the relationship between OBSI level and mean profile depth for different groups.](image-url)
Correlation Analysis of Investigated Parameters

In statistics, correlation and dependence constitute any type of statistical relationship between two or more random variables or observed data values. Different correlation coefficients are used to measure the degree of correlation, of which the Pearson correlation coefficient is the most common. This type of correlation is highly sensitive to a linear relationship between two variables and may also exist even if one is a nonlinear function of the other. The Pearson correlation is calculated by dividing the covariance of the two variables by the product of their standard deviations.
standard deviations (11). In this study explanatory analysis of the different variables is performed
using multivariate correlation analysis to determine which parameters correlate most strongly
with the sound intensity level at different frequencies as well as the overall condition. Therefore,
the most common correlation analysis (the Pearson correlation) is used for this purpose.

The results of the correlation analysis between the sound intensity level and different
variables such as mean profile depth (MPD), air void (Vv), stiffness ($|E^*|)$, international
roughness index (IRI) and nominal maximum aggregate size (NMAS) are plotted in FIGURE 6
for different frequencies as well as overall condition. Two different levels of confidence interval
(95% and 98%) are considered to identify the dominant parameters in each frequency. The IRI
has the least correlation with sound intensity level in all the frequency bands. The MPD was
identified as the dominant factor in all the frequencies and overall conditions that also
strengthens the basis adopted earlier for classifying the Test Track sections into different texture
family groups based on the range of this variable. The results indicate that the sound intensity
level is correlated with the variables listed below assuming a 95% confidence interval at different
frequency bands:

- @ Fr = 315 Hz: MPD, Vv, stiffness ($|E^*|)$ and NMAS
- @ Fr = 500 Hz: MPD, Vv and NMAS
- @ Fr = 1000 Hz: MPD, stiffness ($|E^*|)$ and NMAS
- @ Fr = 1600 Hz: MPD and Vv
- @ Fr = 2000 Hz: MPD and Vv
- @ Fr = 2500 Hz: MPD and Vv
- Overall Condition: MPD, stiffness ($|E^*|)$ and NMAS

Statistically, regression analysis refers to a broad class of modeling techniques for
analyzing multiple variables in order to find the relationship between a dependent (or response)
variable and one or more sets of independent variables. The findings of similar analysis have
helped the development of some regression models for predicting a desired target successfully
(11 and 12). So it is believed that the results of this study can be potentially considered for
generating new models for predicting the sound intensity level using the investigated set of
variables here.
SUMMARY OF FINDINGS

The noise generated as a result of interaction between rolling tire and pavement surface can be reduced by selecting the appropriate design methodology or type of tires on vehicle or more easily by selecting the surface type on a pavement. In this study the influence of aggregate size, porosity, roughness, macrotexture and stiffness has been shown. Consequently, how these features are correlated with the OBSI level at different ranges of frequency has been discussed as well. An analysis of noise data from the test track sections provides some insight into the effects
of surface layer characteristics on long-term durability of different surface mixtures. Findings of this ongoing noise analysis conducted during the 2009 NCAT Pavement Test Track cycle include the following:

1. The on-board sound intensity (OBSI) noise correlates well with the close-proximity (CPX) noise at all third-octave bands from 315Hz through 4,000Hz, with a relatively high correlation coefficient ($R^2$) in most of the frequency bands.

2. The coarser surface mixtures (OGFC, SMA, and coarse-graded Superpave) are found to be noisier pavements at low frequency, whereas the OGFC mixes were quietest at high frequencies.

3. The noise levels generated from tire-pavement interaction are influenced significantly by macrotexture, in-place air void content, and at low frequencies by nominal maximum aggregate size.

4. Pavement surface texture (MPD) is the most significant variable that affects OBSI at lower frequencies (below 1,600Hz). Higher MPD was found to have a positive effect on OBSI below 1,600 Hz and a negative effect on OBSI above 1,600 Hz.

   Additional research is needed to better understand the nature of the factors that influence the tire-pavement noise and to define the interaction at the tire-pavement interface. More comprehensive and in-depth sensitivity analyses of influencing variables are needed to fully characterize the behavior.

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REFERENCES


