EVALUATION OF THE OBSI METHOD

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Abstract

For evaluation of the on-board sound intensity (OBSI) method, tyre-pavement noise is recorded on a variety of different hot-mix asphalt (HMA) surface mixtures including dense-graded Superpave and open-graded friction course mixtures at the National Center for Asphalt Technologies (NCAT) Test Track. Sound testing is done using the NCAT close proximity (CPX) noise trailer and the OBSI method is used to measure sound intensity levels with different vehicles and tyres. All the noise testing is done at a speed of 72 kph. An analysis of variance (ANOVA) is used to determine the significance of mixture type, vehicle and test tyre on the noise levels. It is found that each of these statistically significantly influenced the noise levels. The data suggest that the type of vehicle used to measure sound intensity is not as critical as the tyre used.

1. INTRODUCTION

The on-board sound intensity method (OBSI) used for measuring tyre-pavement noise as applied in this study follows the procedure originally developed at General Motors for research purposes in the early 1980's (Donavan and Oswald, 1980). The OBSI method has only recently been adopted for quantifying the noise performance of in-service highways but is rapidly becoming the preferred method adopted by the Federal Highway Administration (FHWA) and State Highway Agencies for evaluating noise levels of roads in the USA.

Sound intensity describes the rate of energy flow or sound power per unit area at a point in space. Sound power can be considered the strength of the source or generator that gives rise to a sound pressure in space. It is the cause of the noise; what we hear is its effect, sound pressure. In contrast to sound pressure, which is a scalar quantity, sound intensity is a vector quantity with both direction and magnitude. Theoretically, because sound intensity is a vector quantity, the measurement of sound power will not be influenced by stationary background noise outside of the control surface between the noise source and the receivers. A discussion of the theory underlying the sound intensity method is provided elsewhere as referenced (Smit and Waller, 2007), (Trinh, 1994), (Gade, 1982).

1.1 Study Objectives

The objective of this study was to evaluate the on-board sound intensity method to (1) compare the results of OBSI testing to corresponding sound pressure measurements collected using the NCAT noise trailer and (2) to determine the sensitivity of the OBSI method to (a) tyre type, (b) vehicle type, and (c) surface (asphalt mixture) type. Based on this objective, only the influence of the main effects is addressed. The focus is on identifying the significance of these effects on the *average* noise levels measured on the different sections with the different tyres and vehicles. Although evaluated as part of the study, the paper does not discuss the possible interaction of these effects nor the variation of sound levels across the frequency spectrum as observed for the sound intensity and pressure measurements. To address this objective, a controlled experiment was developed consisting on three variables (section, vehicle and tyre type) at nine, five and three levels each, respectively. In this way, potential correlations were avoided. In addition, it is hypothesized that these three main effects control the response variable (noise) and that no significant heterogeneity is present in the dataset.

1.2 Methodology and Scope

The OBSI method as applied in this study employed two closely spaced phased-matched sound pressure microphones mounted side-by-side on a bracket fixture that was attached to the wheel hub of test vehicles as shown in Figure 1. As shown in the figure the center of the OBSI microphone configuration is spaced at a distance of 100 mm from the edge of the tyre. In contrast, in the sound pressure configuration used in the NCAT noise trailer, the microphones are spaced at a distance of 200 mm from the edge of the test tyre. This difference in distance may be relevant depending on the noise attenuating properties of the materials reflecting noise between the test tyre and the microphones.

Figure 1: The OBSI Method Microphone Configuration

Nose cones and windscreens (aligned with the flow) may be used to reduce wind noise effects. Standard specifications for implementation of the OBSI method are currently under development (AASHTO TP76-10, 2009). The method as employed by NCAT as part of this study used the single probe configuration as illustrated with the microphones spaced 16 mm apart (center-to-center), 75 mm off the ground and 100 mm from the side wall of the tyre.

Separate measurement runs were done to collect sound intensity data at the leading and trailing edge of the tyre contact patch. This doubles the time required to collect data and a dual probe configuration is being deployed to measure from the leading- and trailing-edges simultaneously. Donovan (2006) reports on the successful application of the dual probe approach, in which two intensity probes are oriented vertically.

Sound intensity testing was done using three different tyres, the Michelin standard reference test tyre (SRTT), the Goodyear Aquatread (GDYR) and the Uniroyal Tigerpaw (UNIR) inflated to a pressure of 207 kPa at ambient temperature. The treads of these tyres are shown in Figure 2. From the treads it can be seen that the Uniroyal Tigerpaw and SRTT tyres are very similar although the SRTT is a slightly wider tyre. The tyres were relatively new at the time of testing. NCAT retains noise test tyres for a period of 1 year after purchase, regardless of usage and test tyres are maintained in cooled temperature controlled storage when not in use.

Figure 2: Test tyres (Left-to-right: Goodyear Aquatread, Uniroyal Tigerpaw and SRTT)

In addition to testing with the NCAT CPX trailer, OBSI testing as part of this study was done with three different passenger vehicles i.e. Pontiac Grand Prix (PTGX), Chevrolet Malibu (CYML) and the Ford Windstar (FDWS) shown in Figure 3. These vehicles range in curb weights from 1,450 to 1,750 kg, the Ford Windstar being in the order of 180 kg heavier than the Chevrolet and Pontiac vehicles that are of similar weight. The weight of the NCAT noise trailer is 700 kg distributed between two tyres.

Figure 3: OBSI test vehicles (Left to right: Grand Prix, Malibu and Windstar)

Sound measurements were collected using an OR25, OROS analyzer with GRAS 0.5 inch microphones. The OROS NVGATE software was used to analyze the sound data. Sound intensity testing was done without the use of nose cones on the microphones although a windscreen was used. The testing speed was limited to 72 kph given safety concerns due to the geometry of the Test Track. It should be noted that the standard speed for OBSI testing is 96 kph (AASHTO TP76-10, 2009), consequently it is anticipated that the sound levels as reported are an order of magnitude lower than expected; Donovan and Lodico (2009) suggest + 0.3 dBA per 1 mph increase in speed.

The right-hand wheelpath of test sections were tested in the same direction of the traffic and the tyres were warmed by driving for 20 minutes prior to testing. Sound level measurements as reported are A-weighted but were *not* corrected for temperature based on a study at NCAT (Smit and Waller, 2007a) indicating the insensitivity of these measurements to temperature variations in the range of 10 °C to 30 °C. The noise experiments with the different vehicles and tyres were not randomized i.e. testing of the sections at the Test Track were done sequentially with a single vehicle and the three tyres before testing with the next vehicle, etc. Testing of the sections with the different vehicles with each tyre was done on four different dates as shown in Table 1, which also includes the mean air temperature on the day of testing.

Table 1: Dates of Testing

Vehicle	Date	Mean Air Temperature,°C
CPX (Pressure and Intensity)	05/08/2006	21.7
PTGX	06/01/2006	26.7
CYML	06/14/2006	24.4
FDWS	06/20/2006	27.8

2. MATERIALS

All noise testing for the project was done on 61 m long sections at the NCAT Test Track. It should be noted that this length is roughly half of that as proposed in the new OBSI standard. The structures of these sections and the mixtures are shown in Table 2.

Table 2: Test Track Sections Structures

Sections	N5	N6	N7	N8	N9	S4	S5	W3	W8
Upper Lift	OGFC	OGFC	OGFC	PEM	PEM	PFC1	SP	Milled	PFC2
Lower Lift	-	OGFC	PEM	PEM	-	-	-	-	-
Base	DGA	DGA	DGA	DGA	DGA	DGA	DGA	DGA	DGA

Sections on the North tangent included double and single layer porous friction courses (PFC) paved in 32 mm lifts. In particular, sections N6, N7, and N8 were characterized by a double-layer structure whereas N5 and N9 were with a single porous layer. These sections were paved in November, 2005 on the inside untrafficked lanes at the Track and the asphalt mixtures used for the sections included two porous mixtures, one a finer open-graded friction course (OGFC) and the other a coarser Porous European Mixture (PEM), used by the Georgia Department of Transportation. The single layer courses on sections N5 and N9 were paved over existing dense-graded asphalt (DGA) that had been milled prior to paving.

The other sections tested were on the outside trafficked lanes on the Track. These sections had been reconstructed in 2003 and, at the time of noise testing, had been subjected to accelerated trafficking of 10 million equivalent single axle loads (ESALs) as part of the 2003-2006 Test Track experiment. Sections S4 and W8 comprised open-graded PFC and S5 a dense graded Superpave (SP). The mix on section W3 had been milled for rehabilitation providing a rough surface texture. Table 3 provides aggregate gradations of the section mixes.

Table 3: Section Mix Gradations

Sieve/Mix	**19**	**12.5**	**9.5**	**4.75**	**2.36**	**1.18**	**0.6**	**0.3**	**0.15**	**0.075**
OGFC	100	100	100	36	7	3	2	2	1	1
PEM	100	92	60	15	11	-	-	-	-	3
PFC1	100	97	74	18	5	2	2	2	2	2
SP	100	96	87	68	45	33	22	10	7	5
PFC2	100	100	94	37	26	19	14	11	6	4

The aggregates and binders for the different mixtures together with asphalt contents and layer thicknesses are shown in Table 4. So the mixes evaluated as part of the study consisted primarily of open-graded porous mixtures that are typically low noise. The dense-graded Superpave on S5 and the milled section W3, which was expected to be the noisiest given its very rough surface texture, provide a frame of reference for the noise properties on these PFCs.

Table 4: Section Materials

Mix	**Aggregate**	**Binder**	**AC Content, %**	**Thick, mm**
OGFC	Granite	PG 76-22 SBS	7.0	32

PEM	Granite	PG 76-22 SBS	6.0	32
PFC1	Limestone	PG 76-22 SBS	6.0	32
SP	Gravel/Limestone/Sand	PG 76-22 SBS	5.5	43
PFC2	Granite	PG 70-28 SBS	5.0	32

2.1 Surface Macrotexture Properties

The influence of surface macrotexture on noise generated at tyre-pavement interface is well documented (Sandberg and Ejsmont, 2002). Noise studies at NCAT (Smit and Waller, 2006; 2007b; 2007c) have shown a general reduction in noise levels with reduced surface macrotexture. The macrotexture of the surfacing layers were evaluated using the circular texture meter (CTM) that provides a measure of the mean profile depth (MPD) in accordance with ASTM E2157 (2004). Figure 4 shows the mean and standard deviation of 5 MPD measurements along each of the sections tested. The milled section, W3, was too rough to measure. The dense-graded Superpave mixture presented the smoothest surface texture.

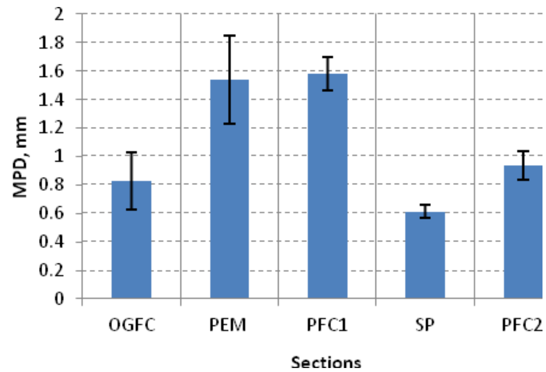


Figure 4: Section Macrotexture Measurements

Photos showing the various surfaces of the sections are given in Figure 5. The scale imposed on the photos is in 10 mm and 1 inch intervals. The photo of section W3 was taken at a greater height to illustrate the longitudinally textured milling pattern that ran parallel to the direction of travel. A USA quarter coin is visible on the surface of this section.

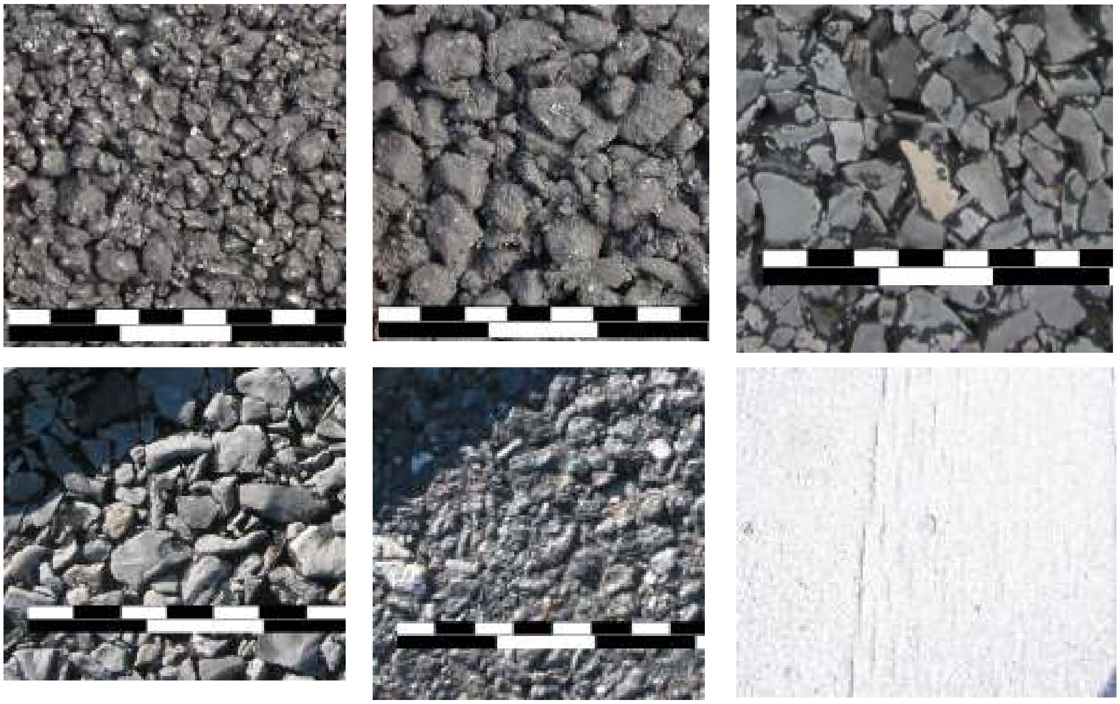
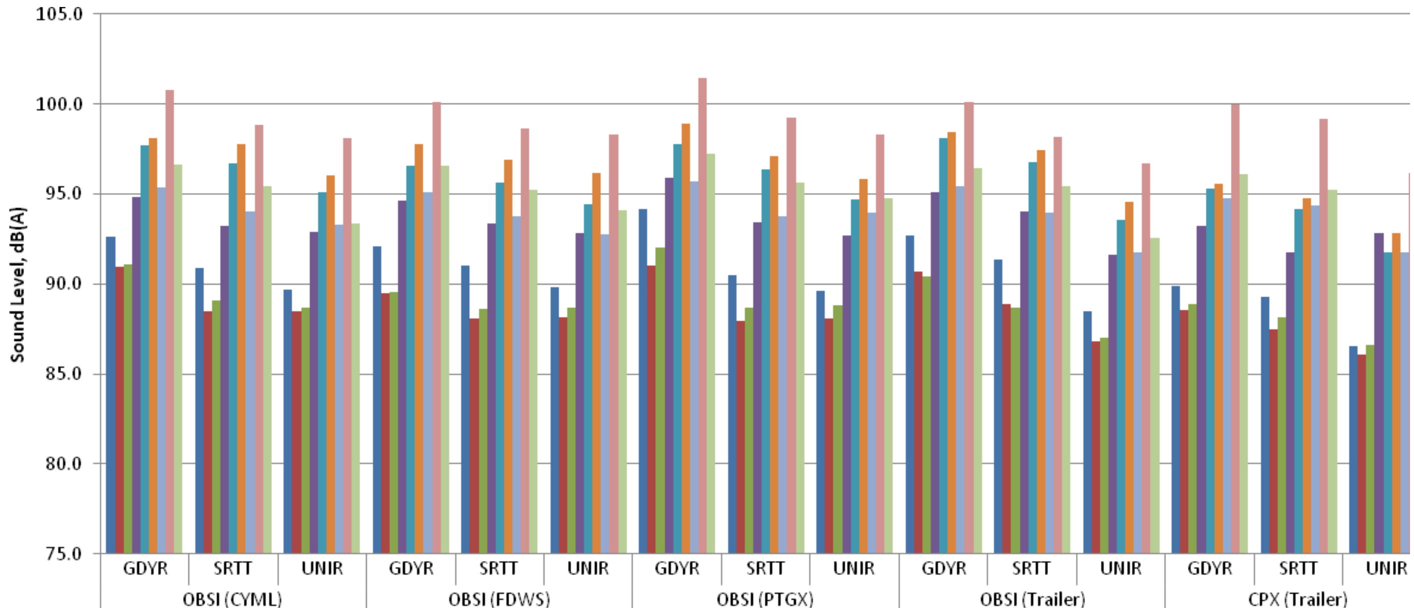


Figure 5: Photos of the Section Surfaces
left-right: OGFC, PEM, PFC1, SP, PFC2, Milled (W3)

3. SOUND MEASUREMENTS

Figure 6 summarizes the noise levels on the sections, showing the overall noise levels calculated by logarithmically adding the A-weighted noise levels at the respective third-octave band frequencies between 316 and 4,000 Hz. It should be noted that the latest OBSI standard specifies calculating overall sound levels between 400 and 5,000 Hz (AASHTO TP76-10, 2009). The average noise level for the three test runs with the different vehicles and tyres are shown. It should be noted that, typically, sound intensity is not measured inside the noise trailer but was done to compare enclosed versus exposed OBSI measurements. While both sound pressure and intensity measurements were taken within the noise trailer, to distinguish these, the acronym CPX is used to indicate the sound pressure measurements.



	OBSI (CYML)			OBSI (FDWS)			OBSI (PTGX)			OBSI (Trailer)			CPX (Trailer)		
	GDYR	SRTT	UNIR	GDYR	SRTT	UNIR	GDYR	SRTT	UNIR	GDYR	SRTT	UNIR	GDYR	SRTT	UNIR
N5	92.6	90.9	89.7	92.1	91.0	89.8	94.1	90.5	89.6	92.7	91.3	88.5	89.9	89.3	86.6
N6	90.9	88.5	88.5	89.5	88.1	88.1	91.0	87.9	88.0	90.7	88.8	86.8	88.6	87.5	86.1
N7	91.1	89.1	88.6	89.6	88.6	88.7	92.0	88.7	88.8	90.4	88.7	87.0	88.9	88.1	86.6
N8	94.8	93.2	92.9	94.6	93.4	92.8	95.9	93.4	92.7	95.1	94.0	91.6	93.2	91.7	92.8
N9	97.7	96.7	95.1	96.5	95.6	94.4	97.8	96.4	94.7	98.1	96.7	93.6	95.3	94.1	91.8
S4	98.1	97.8	96.0	97.8	96.9	96.1	98.9	97.1	95.8	98.4	97.4	94.5	95.5	94.8	92.8
S5	95.4	94.0	93.3	95.1	93.8	92.8	95.7	93.7	93.9	95.4	93.9	91.7	94.8	94.4	91.7
W3	100.8	98.9	98.1	100.1	98.6	98.3	101.4	99.2	98.3	100.1	98.2	96.7	100.0	99.2	96.2
W8	96.6	95.5	93.4	96.6	95.2	94.1	97.2	95.7	94.8	96.4	95.4	92.6	96.1	95.2	92.7

Test Tire and Vehicle

Figure 6: Mean Sound Levels at a Speed of 45 mph

From Figure 6, a similar trend or pattern in the noise levels tested using the different vehicles and tyres is apparent. The sound levels measured on section W3, the milled section, is consistently the highest, as expected. The noise levels on sections N5, N6 and N7 are significantly lower than the levels measured on the other sections. In general, the lowest noise levels are evident on section N6 with the finer double layer open-graded friction course structure.

4. STATISTICAL ANALYSIS OF NOISE LEVELS

An analysis of variance (ANOVA) was run on the overall noise level data to examine the influence of mixture type (SECTION), test vehicle (VEHICLE) and test tyre (TYRE) on the sound levels. The results of this analysis are shown in Table 5 that includes the estimated parameters with the corresponding standard errors, t-statistics and p-values. The reference variables in the model were selected as Section W3 (consistently the noisiest) for SECTION, the CPXP sound pressure noise trailer for VEHICLE and the SRTT tyre. The results of the ANOVA indicate that the model is significant. Furthermore, the high adjusted R^2 value indicates that almost 97 percent of the variation in the observed sound levels is explained by the variables evaluated! One outlier in the data set was removed, this being a faulty sound pressure measurement for one of the runs on Section N8 with the Uniroyal tyre.

Table 5: ANOVA Results for Sound Levels (at a speed of 72 kph)

Source	DF	SS	MS	F	P
Regression	14	5192.54	370.9	854.06	0.00
Residual Error	389	168.93	0.43		
Total	403	5361.47			
S =	0.66	R-Sq =	96.80%	R-Sq(adj) =	96.70%
MODEL					
Term		Coef	SE Coef	T	P
Constant		97.7	0.127	769.4	0.00
SECTION					
N6		-10.3	0.139	-74.4	0.00
N7		-9.9	0.139	-71.6	0.00
N5		-8.4	0.139	-60.2	0.00
N8		-5.6	0.140	-40.1	0.00
S5		-5.0	0.139	-35.7	0.00
W8		-3.8	0.139	-27.2	0.00
N9		-3.3	0.139	-23.7	0.00
S4		-2.4	0.139	-17.3	0.00
VEHICLE					

Trailer (OBSI)	1.2	0.104	11.9	0.00
FDWS (OBSI)	1.4	0.104	13.1	0.00
CYML (OBSI)	1.7	0.104	16.7	0.00
PTGX (OBSI)	1.9	0.104	18.5	0.00
TYRE				
UNIR	-1.4	0.080	-17.0	0.00
GDYR	1.5	0.080	18.5	0.00

From the results of the ANOVA it can be seen that each of the sections, vehicles and tyres tested, significantly influenced the measured noise levels at the 5 percent level as is indicated by all p-values smaller than 0.05. The relative ranking of the sections in terms of noise (quietest to loudest) is as shown in Table 5. Each of the sections was quieter than the reference section W3, as indicated by the negative signs of the section parameters. Section N6, the double OGFC section, was on average 10.3 dBA quieter than W3. This indicates the benefit of porous mixtures for noise attenuation purposes. The exception is the old and aged PFC on section S4 that in all likelihood had become clogged over time. The dense graded Superpave mixture on S5, although having the lowest macrotexture, falls midway in noise performance relative to the other mixtures. A comparison of the sound pressure and intensity data indicate that the sound intensity measurements are on average about 1.55 dBA higher than the sound pressure measurements. Two distinct groups can be distinguished for the vehicles: the sound intensity levels measured using the Ford Windstar and the CPX trailer are similar compared to the Chevy Malibu and Pontiac Grand Prix. It is interesting to note that between the passenger vehicles, the maximum difference in sound intensity is on average in the order of 0.5 dBA. Thus, although there appears to be a significant difference in the sound intensity levels as measured using the different passenger vehicles, the difference is not of practical significance. A very significant (statistical and practical) difference in noise levels is apparent between the different tyres. On average, the noise levels from the Michelin SRTT tyre fall between those for the quieter Uniroyal Tigerpaw and noisier Goodyear Aquatread. Coefficients in the ANOVA table indicate that the sound levels from the Uniroyal Tigerpaw tyre were on average 1.4 dBA quieter than the SRTT levels (negative sign) and the noise levels for the Goodyear Aquatread were on average 1.5 dBA louder than the SRTT levels.

Figure 7 compares the sound pressure levels to corresponding sound intensity levels measured with the different vehicles using the SRTT tyre. The figure clearly indicates a linear relationship between the two different methods with a relatively high correlation coefficient. This suggests that one of the methods may be used in lieu of the other and strongly supports the continued use of the OBSI method. For this reason the author's recommend the OBSI method as the preferred method for close proximity pavement noise assessments given the comparatively lower cost and ease of its deployment compared to the noise trailer.

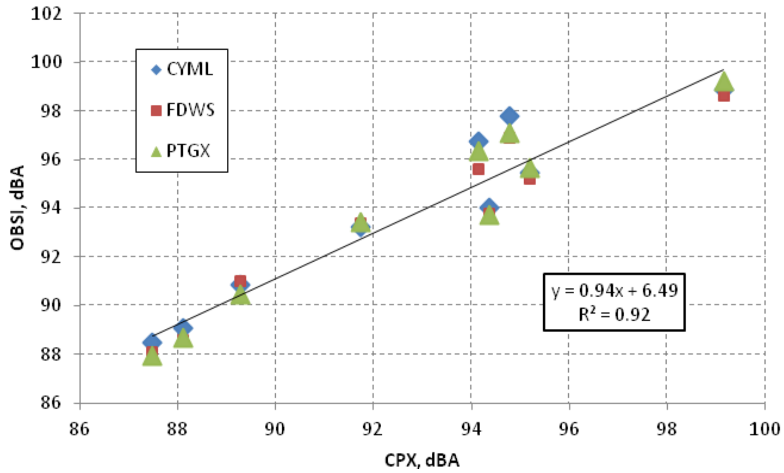


Figure 7: Comparison of CPX and OBSI Sound Levels with the SRTT Tyre (45 mph)

The ANOVA as performed was limited to an analysis of the main variables and their effect on overall tyre-pavement noise levels. Given the statistical significance of these variables it would be warranted to refine this analysis to further investigate the main variables in greater detail. An analysis of the influence of the properties of the materials tested in terms of surface macrotexture and material stiffness, the dynamics, weight and aerodynamic properties of the vehicles as well as the stiffness and tread properties of the tyres should be performed. It is further recommended that the influence of these properties on the spectral noise response be evaluated to better define the source of variability associated with tyre-pavement noise assessments.

5. CONCLUSIONS AND RECOMMENDATIONS

The paper presents the results of a statistical analysis to investigate the influence of mixture, vehicle and tyre type on sound pressure and intensity levels. Sound intensity data was collected on nine different sections at the NCAT Test Track using three different passenger vehicles and three different tyres. In addition, both sound pressure and intensity data were collected with the three different tyres using the NCAT CPX noise trailer. The testing speed was limited to 72 kph and the noise data collected were not temperature corrected.

An ANOVA indicated the statistical significance of each of the factors investigated. The noise levels on the different sections tested varied significantly. On average the difference in noise level between the quietest section, the double layer porous OGFC, and the noisiest, the milled W3 section, was in the order of 10 dBA. The new porous mixtures generally performed better than the older porous sections tested, which could indicate clogging of these older sections over time. The noise reduction benefit of mixture porosity over macrotexture was also illustrated.

The sound intensity levels measured on the sections using the passenger vehicles were on average about 1.6 dBA louder than the sound pressure levels on the sections. Although vehicle type was found to be a significant factor influencing the noise levels, the relative difference in the sound intensity levels for the different vehicles was on average about 0.6 dBA. If a difference of 1 dBA is considered significant from a practical perspective, then the measured 0.6 dBA difference suggests that the sound intensity levels with different passenger vehicles were virtually similar.

Tyre type, however, has a very significant influence on the noise measurements. The noise levels on the SRTT tyre, currently selected as the industries *de facto* reference for noise measurements, on average fall between the levels for the Uniroyal and Aquatread tyres. These latter tyres are still in use by some agencies, although these are in the process of being phased out and replaced by the SRTT. Given the significant influence of tyre type on noise levels, this replacement is strongly recommended to ensure consistency in noise measurements and allow comparison of OBSI data between agencies. Many of these agencies have extensive noise data sets based on the older tyres. The ANOVA coefficients (SRTT = UNIR + 1.4 dBA for Uniroyal tyres, and SRTT = GDYR - 1.5 dBA for Aquatread tyres) are provided as tentative estimates to convert noise levels measured using the older tyres to SRTT equivalents. These are preliminary estimates, however, specific to the mixtures tested.

The objective of this study was to addresses the influence of the main effects on noise levels and did not consider the possible interaction between mixture type, vehicle and test tyre. Although there is no reason to believe that the interactions affect noise levels one way or another, it is recommended that these interactions be investigated further to provide a more complete evaluation of the source of noise variability. It is also recommended that the influence of the test variables be investigated on the noise levels at the different frequency levels to better understand the influence of the test variables on noise development at the tyre-pavement interface.

The investigation illustrated an excellent correlation between sound pressure measurements using the NCAT noise trailer and sound intensity measurements using the OBSI method. Given the comparatively lower cost and ease of deployment, the OBSI method is recommended as the preferred method for tyre-pavement noise assessments.

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KEY WORDS

On-board sound intensity, sound pressure, tyre-pavement noise, hot mix asphalt, statistical analysis.