NCHRP Project 1-44:
Measuring Tire-Pavement Noise at the Source

APPENDIX B

Test Evaluation of Candidate Methods and Recommendation for Test Procedure Development

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INTRODUCTION

Tire-Pavement noise has become an increasingly important consideration for highway agencies. However, there are no widely accepted procedures for measuring solely tire-pavement noise under in-service conditions. As a result, this research is undertaken to evaluate potential noise-measuring procedures and identify or develop appropriate procedures applicable to light and heavy vehicles and all paved surfaces. Such procedures will provide highway agencies with an appropriate means for (1) measuring and rating tire-pavement noise levels on existing pavements, (2) evaluating new pavements incorporating noise-mitigating features, and (3) identifying design and construction features associated with different noise levels.

The objectives of this research are to (1) develop rational procedures for measuring tire-pavement noise at the source and (2) demonstrate applicability of the procedures through testing of in-service pavements. To achieve these objectives, a literature search was conducted to gain understanding of the approaches that have been used in the past to quantify tire-pavement noise source levels (Appendix B). The purpose of this Appendix is to communicate the results of the evaluation testing completed for CPX, OBSI and the document a recommendation of an at-the-source tire-pavement noise measurement approach.

TEST EVALUATION OF CANDIDATE METHODS

Based on the results of the literature search (see Appendix B), testing was undertaken to evaluate two candidate on-board, tire-pavement noise source measurement methods. This testing consisted of measuring CPX and OBSI noise levels on the same tires and then conducting controlled passby measurements using the test tires along with three other tires of the same design mounted on the test vehicle. The details of the testing and discussions of the results are presented in this section of the report

Test Description

Testing was conducted at and around the National Center for Asphalt Technology (NCAT) test track facility in Opelika, Alabama during the week of February 13, 2006. This site was chosen for several reasons. The test track has 45 different asphalt concrete (AC) surfaces. These pavements provide a range of surface roughness, construction type, and porosity. One pavement has a transversely textured AC surface that produces sounds similar to transversely tined Portland cement concrete (PCC). Another AC pavement is known to have a high degree of porosity. As this is a test track, measurements could be made readily over a range of speeds with no concerns of conflicts or noise from other traffic. The track is also sufficiently wide that passby measurements could be made with the sound propagating over AC at a distance of 25 ft. Another advantage of this facility is that the noise performance of the surfaces has been measured previously allowing the selection of surfaces known to produce a range in level. Finally, NCAT has one of the only actively used CPX trailers in the country and it is based at the nearby NCAT laboratory complex in Auburn. The primary drawbacks to this facility were the inability to measure passby levels at 50 ft and the fact that all of the surfaces are AC. In regard to microphone distance, the difference in level at 25 ft and 50 ft for car passbys was thought to be sufficiently well documented in the literature so as not to be a significant issue. To address the issue of PCC, a public road site was used in a nearby town.

The overall plan for the evaluation generally followed that outlined in the project Working Plan. Passby measurements were made under both cruise and coast conditions. On-board tire-pavement noise source levels were measured using the two candidate methods, CPX and OBSI. CPX sound pressure levels of tire/pavement noise at the source were measured in a manner following the ISO test procedure[1]. Sound intensity levels were measured using the OBSI methodology employed in previous California Department of Transportation (Caltrans) studies[2]. In addition to these measurements, testing was done to examine potential propagation differences between sites. Altogether, measurements were made using 3 tire designs at 5 sites, 4 AC pavements at the NCAT test track and 1 PCC pavement in the town of Waverly, Alabama.

Test Methods

The CPX measurements were conducted using the NCAT trailer (Fig. 1)[3]. Two microphones were positioned 100mm above the ground, 200mm from the face of the tire, with one at 200mm in front of the centerline of the tire and the other at 200mm to the rear of the centerline in the standardized CPX positions (Fig. 2). Free-field ICP microphones were used pointed toward the center of the tire contact patch each fitted with a spherical foam windscreen. The signals from the microphones were input to PCB Model 480E09 signal conditioners which were in turn input to a Larson Davis 2900 dual-channel real time analyzer. The 1/3 octave band spectra levels of the CPX sound pressures were largely processed in real-time. The output of the LD 2900 was also recorded on a Sony LCD-100 two-channel Digital Audio Tape (DAT) recorder for backup and any further analysis deemed necessary. The microphones were calibrated using a Larson Davis Model CAL200 acoustic calibrator set for 94 dB at the beginning and end of each set of measurements. After the data was acquired, the sound pressure levels for the front and rear microphones were averaged to yield a single spectrum to represent the test condition. Typically, three runs for each configuration/condition were acquired and used for the average.

The OBSI measurements were conducted both on the CPX trailer (Fig. 3) and directly on the test vehicle (Fig. 4) for each of the 3 test tires. The OBSI probe consisted of two ½" G.R.A.S. phased matched condenser microphones installed on Larson Davis ½" Model PRM900C microphone preamplifiers. These attached to a plastic probe holder which provided a 16mm spacing of the microphones which were used in a "side-by-side" configuration. The microphones were fitted with Brüel and Kjaer Type UA 0386 ½" nose cones. The probe was oriented such that its sensitive axis (a line perpendicular to the length of microphones/pre-amplifiers and determined by the line through the microphones) was pointed toward the tire sidewall (Fig. 4). Prior to the measurements, the microphones were protected from airflow using a spherical foam windscreen as shown in Fig. 5. Measurements were made with the probe 75mm above the pavement, 100mm out from the tire sidewall, and at two locations, opposite the leading edge of the tire contact patch and opposite the trailing edge. These positions were measured separately with the probe re-positioned as necessary. The sound pressure signals from the two microphones went directly into the LD 2900 analyzer and the sound intensity level was in analyzed in 1/3 octave bands in real time. The signals were also captured on the DAT recorder. Sound intensity levels from each probe position were averaged for typically three repeat runs and then the levels for the two positions were averaged to yield a single spectrum for each test condition. Identical methods were used in both the vehicle and trailer based OBSI measurements.

Controlled vehicle passby measurements were done generally following the procedures provide by FHWA in the “Measurement of Highway-Related Noise” Report[4]. Notable exceptions were that a distance between the centerline of travel and the microphone was 25ft instead of 50ft. As noted above, this was dictated by the geometry of the test track. The microphone height was set to be 5ft above the height of the pavement. The passby sound pressure levels were measured using Larson Davis Model 820 sound level meters (SLM). These were set to “fast” response (⅛ second exponential average) and the maximum overall A-weighted sound pressure level occurring in one second intervals was logged by the SLM during the passby. The maximum level for each passby was then determined from the printout of the SLM. The acoustic signal from the SLM was also captured on DAT recordings which were used later to determine maximum passby level in 1/3 octave bands using the LD 2900 analyzer. Multiple runs were made for each test condition and those falling within a ±1 mph window about the nominal test speed were averaged together. Vehicle speed was measured with a calibrated radar gun during the passbys. A photograph showing a typical passby test set-up on the NCAT track is provided in Fig. 6.

Figure 1: Photograph of the NCAT CPX tire-pavement noise measurement trailer with access door open

Figure 2: Photograph of microphones positioned at the CPX measurement locations on NCAT trailer

Figure 3: Photograph of OBSI fixture installed on the NCAT CPX trailer

Figure 4: Photograph of OBSI fixture and probe installed on the test car (windscreen not installed)

Figure 5: *Photograph of OBSI probe position opposite the leading edge of the tire contact patch (windscreen installed as used in testing)*

Figure 6: *Photograph of a typical passby test with sound level meter and DAT recorder at 25ft*

Measurements were also made at each test site to investigate the relationship between a source essentially on the pavement and the passby microphone 25 ft away. For these measurements a small loudspeaker was placed on the pavement and centered in the test lane. The resultant noise level was measured at the 25 ft microphone position used for the passby testing. The 4 in. loudspeaker broadcast random "pink" noise and its sound power output was monitored by performing sound intensity measurements averaged over the plane of the speaker cone very near to its surface (less than 1 in.). The DAT recording of the sound captured by the 25 ft microphone was later analyzed into 1/3 octave bands using the LD 2900 in "linear average" mode averaging over several 20 second segments. The data were processed into "noise reduction" by subtracting the 25 ft sound pressure levels from the average sound intensity levels. A photograph showing a typical test set-up for these propagation tests on the NCAT track is provided in Fig. 7. Although this procedure is strictly experimental at this time, its use has been reported previously[5].

Test Sites

The measurements described above were completed on five different test sites of varying pavement characteristics. Included in these were 4 AC pavements at the NCAT test track and 1 PCC pavement in the town of Waverly, Alabama. Three of the sites at NCAT were essentially identical in geometry with different pavements. These are identified as test section S1, S4, and S5. These sections were flat and level, with the passby microphone located just off the edge of asphalt (see Fig. 6). The lanes between the test pavement and the microphone were acoustically hard AC surfaces which had been ground in preparation of future re-paving. The pavement in section S1 was a medium texture stone mastic asphalt (SMA), 1.8 in. thick and effectively non-porous. Section 4 was an open graded asphalt concrete (OGAC) pavement of coarse texture, 1.0 in. thick and some porosity. Section S5 was asphalt "Superpave" construction of fine texture, 1.5 in. thick, and effectively non-porous. The geometry of the fourth NCAT test site (section W3) was somewhat more complex. This test section was located on a banked corner of the track. At this location, although the surface is sloped, it remains visually flat across its width (Fig. 8). This section was chosen especially for its unique surface. The pavement is a Superpave construction with relatively fine aggregate. However, the surface contains transverse grooves which have been cut into the pavement. This traverse texture generates sounds which are similar to its PCC counterparts with aggressive transverse texturing. For the fifth site, a PCC surface was desired. However, the choices were quite limited due of the lack of PCC roadways in Alabama. A historic section of old PCC highway was found in the town of Waverly, Alabama. On the outskirts of town, a relatively flat and level section was found which was clear of any vertical reflecting surfaces. The roadway at this point is shoulderless and the propagation from the pavement to the passby microphone was over an acoustically softer ground (Fig. 9). The surrounding ground was 2.5 in. above the pavement and the transition was provided by an 8 in. segment of concrete producing about an 18º angle from horizontal. The pavement itself was worn PCC with exposed, smooth aggregate of varying size and large slab joints every 30 ft. Each of the five test sites and pavement are more fully documented at the end of this Appendix.

Figure 7: Photograph of instrumentation and loud speaker placement for sound propagation tests

Figure 8: Photograph of banked roadway at NCAT track section W3

It was intended in the testing to conduct measurements at several different vehicle speeds that would be common throughout the data set. However, some site specific restrictions made this not possible. To cover a range of speed in which tire-pavement noise is expected to dominate over other vehicle noises, speeds of 35, 45, and 60 mph were selected. For NCAT sections S1, S4, and S5, these speeds presented no problem. For NCAT section W3, it was found that 60 mph could not be safely maintained through the banked corner without putting additional side force on the tires. As a result, the upper speed at this site was limited to 55 mph. At the Waverly site, the local speed limit was 45 mph allowing testing only at the two lower speeds. As the main intent of the testing was to compare passby measurements to tire-pavement noise source levels, these deviations in the one test speed of 60 mph were deemed not sufficient to warrant the use of less desirable sites.

Test Tires

Three sets of tires were used for the testing. One of the tires was the Standard Reference Test Tire (SRTT). This tire was originally manufactured by Uniroyal and carries a Uniroyal Tiger Paw brand name. The tire is now available through Michelin and is distinguishable by a "SRTT" marking on the sidewall. The tire resembles the Uniroyal Tiger Paw AWP, but has a slightly different tread pattern. New SRTT tires of this design are planned to be available for at least 10 years from Michelin. The SRTT is also under study by the ISO Working Group 33 as a possible new standard test tire for the ISO CPX procedure. A second tire was a Dunlop SP Winter Sport M3. This tire is one of those intended to be tested as part of tire manufacturer and vehicle manufacturer round-robin tests to begin in the spring of 2006. The purpose of this round robin testing is to address issues concerning the ISO 10844 standard vehicle test pavement. The Dunlop tire was chosen by ISO working group as a replacement for a light truck tire due to its more aggressive tread pattern. The size of both tire types was P225/60R16 because it is the only size for the SRTT. The third tire design was the Goodyear Aquatred 3 in a P205/70R15 size. This tire design has been extensively used over the last 3 years by a number of different researchers, including Caltrans, as their primary test tire. Because of incompatibility of the sizes of the tires and wheels on which they were mounted, passby measurements for the Aquatred were not made. However, a significant amount of passby to sound intensity comparative data for this tire is available in the literature. There is also some limited comparative passby to CPX data for the Aquatred[7,6]. The relationship between OBSI and CPX data is also very well documented for this tire[2]. CPX and OBSI measurements were made at all of the test sites to provide a linkage to the historical Aquatred data. Photographs of the tread designs of the three test tires are compared in Fig. 10. Table 1 summarizes the details of the test tires. All three tires were tested at a cold inflation pressure of 30 psi. Test tires were assigned to each of the four-wheel positions on the test car and these were not altered during testing. The on-board source measurements were conducted using the right rear wheel/tire. It will be noted that two of the test tires, the Goodyear and Dunlop tires are unidirectional and care was taken that these tires were mounted and operated in the design direction.

Figure 9: Photograph of the Waverly PCC test site

TABLE 1 Test Tires

Des.	Type	Manufacturer	Trade Name	Size
Aqua3	All Seasons	Goodyear	Aquatred 3	P205/70R15
M3	Winter	Dunlop	SP Winter Sport M3	P225/60R16
SRTT	All Seasons	Michelin	Uniroyal Tiger Paw	P225/60R16

Figure 10: Photograph of the test tires

Test Matrix

The resultant combination of test types, test tires, test sites/pavements, and test speeds are documented in Tables 2 and 3.

TABLE 2: Test Surfaces and Test Speeds

Designation	Description	Test Speeds (mph)
NCAT S1	AC, SMA, 1.8" thick, medium texture, non-porous	35, 45, 60
NCAT S4	AC, OGFC, 1.0" thick, coarse, porous	35, 45, 60
NCAT S5	AC, Superpave, 1.5" thick, fine texture, non-porous	35, 45, 60
NCAT W5	AC, Superpave, 1.3" thick, transverse grooves, np	35, 45, 55
Waverly	PCC, aged, slab joints, no transverse texturing	35, 45

TABLE 3: Test Sites and Test Conditions

Test Condition	Site	Tires	Speeds
OBSI on Car	S1, S4, S5, W5, Waverly	M3, SRTT	All for site
OBSI on Trailer	S1, S4, S5, W5, Waverly	M3, SRTT, Aqua3	All for site
CPX	S1, S4, S5, W5, Waverly	M3, SRTT, Aqua3	All for site
Cruise	S1, S4, S5, W5, Waverly	M3, SRTT	All for site
Coast	S1, S4, S5, W5, Waverly	M3, SRTT	All for site
Propagation	S1, S4, S5, W5, Waverly	(n/a)	(n/a)

Test Results

As indicated by the test matrix information, the testing generated a large amount data that could be considered in many different ways at varying levels of detail. For the purpose of evaluating the OBSI and CPX methods, several types of comparisons were chosen. These focused on A-weighted correlations of CPX, OBSI, and passby levels, comparison of spectral shapes for the three methods, and rank ordering of tires and pavements by each method.

Comparison of Overall Levels

Prior to examining a comparison of overall levels between the different measurements, it is instructive to consider each data set in some detail.

Passby Data: The cruise and coast passby levels for each speed, the two test tires, and each site are presented in Figs. 11 through 15. Considering all of these cases, some scatter in both speed and noise level is seen at any one test condition. In general, there is less speed scatter for the cruise data relative to the coast. Also, in most cases, there is little distinction between coast and cruise particularly when the scatter in level is considered. It is also seen that the distinction between tires is greater on some pavements than on others. The greatest separation of the tire types occurs on the porous S4 section followed by the Waverly site. The least amount of distinction between tires is on W3 with the transverse texturing. This is not surprising because the coarse texture is presumed to dominate over differences in tread pattern. Also as expected, this coarse texture produces distinctly higher noise levels than the other pavements. Another aspect of W3 which contributes to the data scatter is that the texture and resultant sound varies in and out of the wheel path. In the wheel path, the grooving is less accentuated due to wear thereby producing lower levels. As this section is banked, it also more difficult to maintain the vehicle in a consistent wheel path. As a result, the variation in passby level is greater for this section.

The cruise passby data were used to derive a single level for each condition. This was done for two reasons: 1) the speed has less variation allowing more data averaging for a single speed, and 2) the levels for cruise and coast are virtually identical. For the cruise levels, if the speed was 1 mph greater or less than the nominal test speed, these data points were not included in the average for that condition. Even with this precaution, the range in level for any one condition was 1 to 2 dB. As a result, the accuracy of the passby data is on order of ±½ dB for all sites except for W3 where it is more on the order of ±1 dB.

On-Board Data: Analysis of the variation in the on-board data is somewhat different than the passby data. Both the OBSI and the CPX reported levels are averages of more than just one run with another. For these data, the levels from the forward measurement positions were averaged together arithmetically as were those from the rear position. These averages were then averaged on a logarithmic (mean-squared) basis to yield the corresponding level for that condition. As a result, variation from run-to-run can only be assessed on the data for one measurement, and not the total reported noise level. For CPX measurements, the average total range of the individual front and rear microphone levels was 0.4 dB. This was reduced by 0.1 dB when the more variable data of section W3 was removed. For OBSI measurements, the average total range of the individual leading edge and trailing edge intensity levels was 0.6 dB. These were also reduced by 0.1 dB

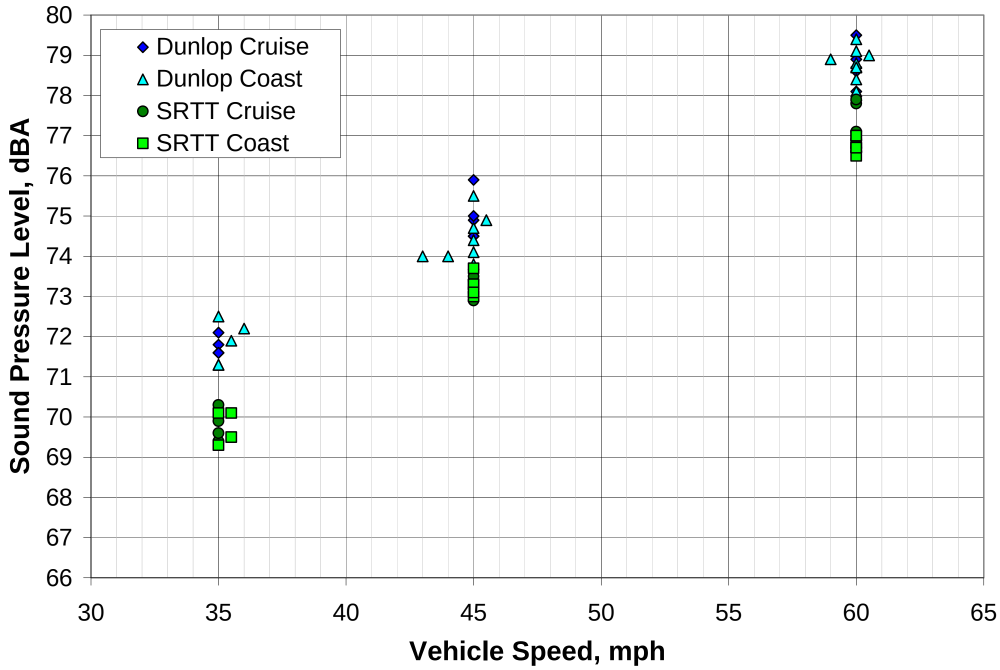

Figure 11: Coast and cruise 25 ft. passby levels at NCAT pavement section S1

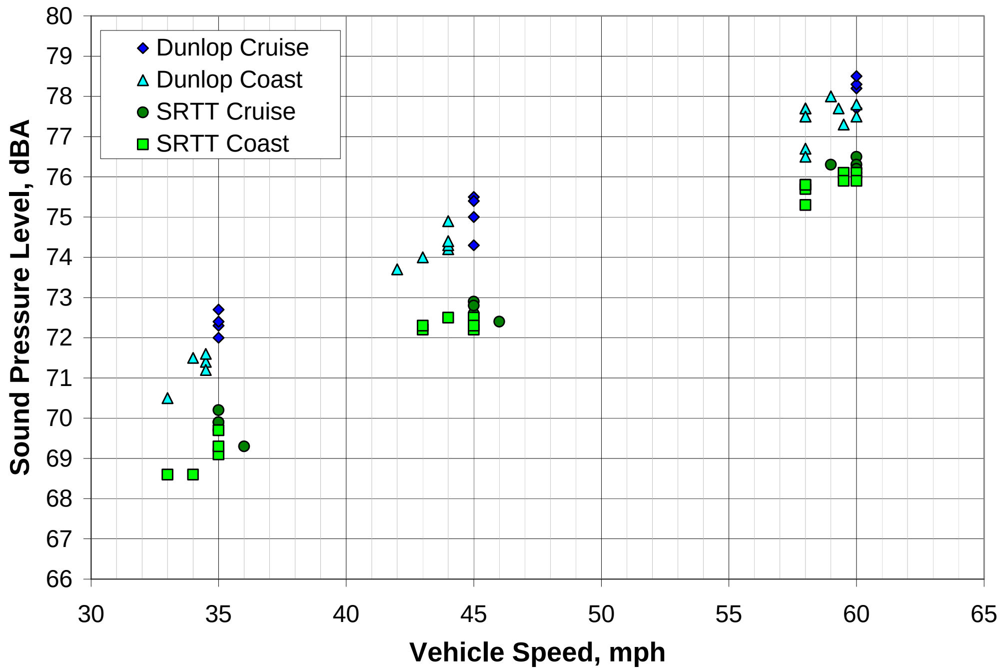

Figure 12: Coast and cruise 25 ft. passby levels at NCAT pavement section S4

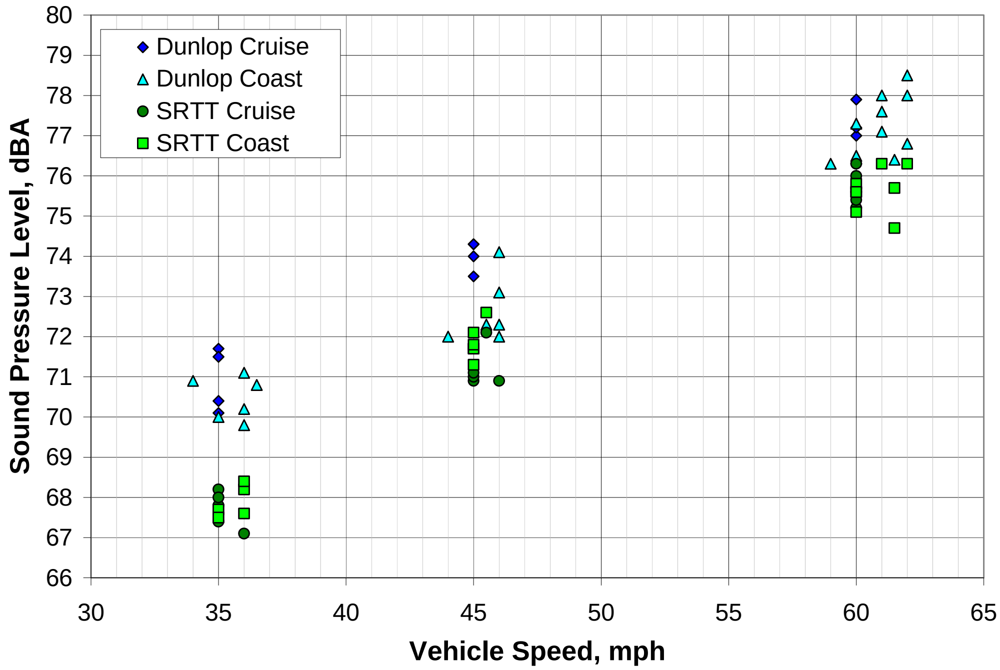

Figure 13: Coast and cruise 25 ft. passby levels at NCAT pavement section S5

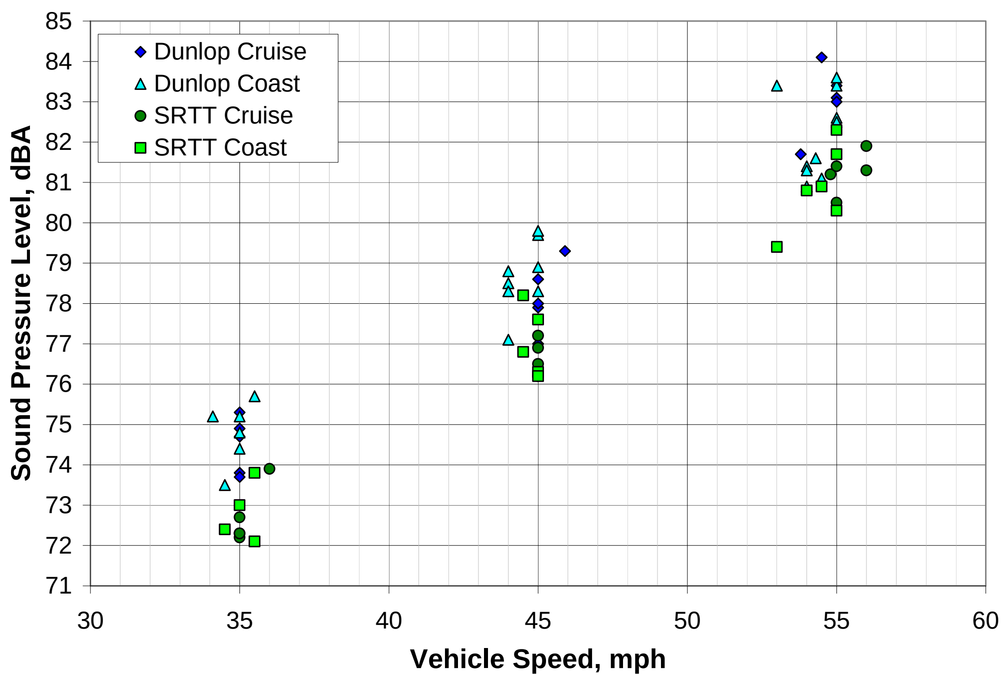

Figure 14: Coast and cruise 25 ft. passby levels at NCAT pavement section W3

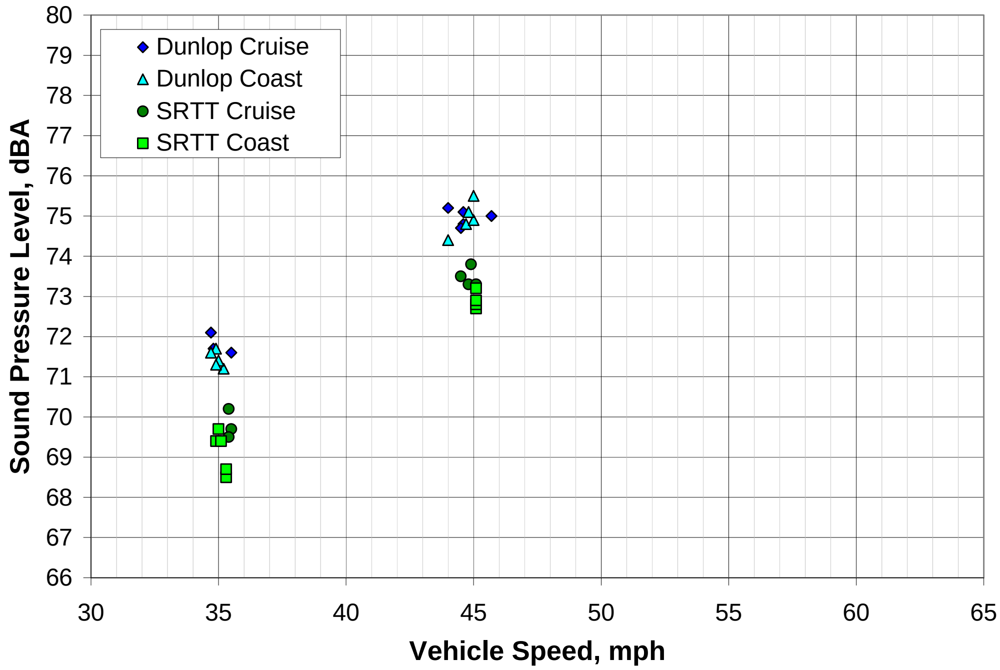

Figure 15: Coast and cruise 25 ft. passby levels at the Waverly test site

when the W3 data was removed. Given the averaging involved in the reported levels for a given condition, the expected range in level for both the CPX and OBSI data is expected to be about half of the range of the individual measurement positions. As a result, the accuracy of the CPX data is estimated to be about ±0.2 dB while the OBSI data is estimated at ±0.3 dB.

Passby and On-Board Data: The primary comparison of overall levels is between the passby and the on-board data. The overall levels for all of the tests, speeds, and two type tires are plotted in Figs. 16 and 17 for passby to CPX and passby to OBSI, respectively. For the passby to CPX comparison, the average offset between the data is 22.4 dB that falls in the range of those in the literature ranging from 20 to 23 dB (see Appendix A). The standard deviation (σ) of the data points from the best 1-to-1 fit of the data is 1.8 dB while the average deviation is 1.4 dB. These values as well as the coefficient of determination (r^2) of 0.79 are somewhat lower than those reported previously in CPX studies[7] where the average deviation was about 1 dB and the r^2 was 0.89. Also, the slope of the regression indicates a less than 1-to-1 relationship. Reviewing the individual data points, those from the Waverly site are noticeably and consistently low compared to the others. For the OBSI data, similar trends are seen. The standard deviation for the best 1-to-1 fit of the data was 1.7 dB and average deviation, 1.3 dB compared to 0.8 dB and 0.4 dB, respectively, as reported in the literature[6]. The r^2 values are also smaller, 0.80 compared to 0.98. Also for these data, the points from Waverly are noticeably lower than the others. As might be expected from Figs. 16 and 17, the correlation between the CPX and OBSI data is somewhat better (Fig. 18). For these data, the linear regression indicates a 1-to-1 relationship and an r^2 value of 0.93. The offset is smaller than that

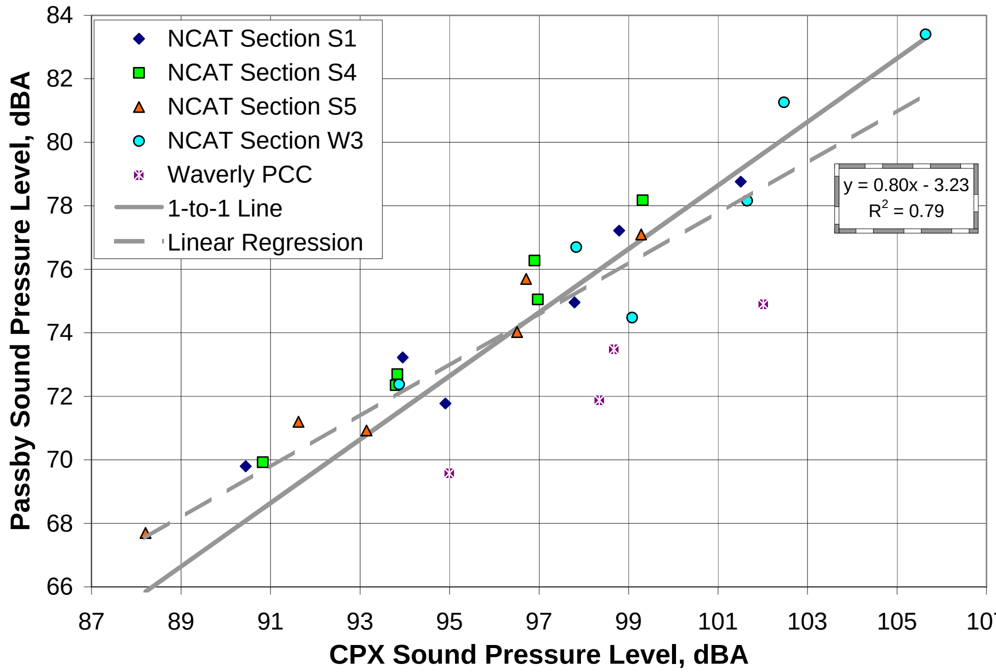

Figure 16: Relationship between CPX and passby noise levels for all sites, SRTT and Dunlop tires, and all speeds

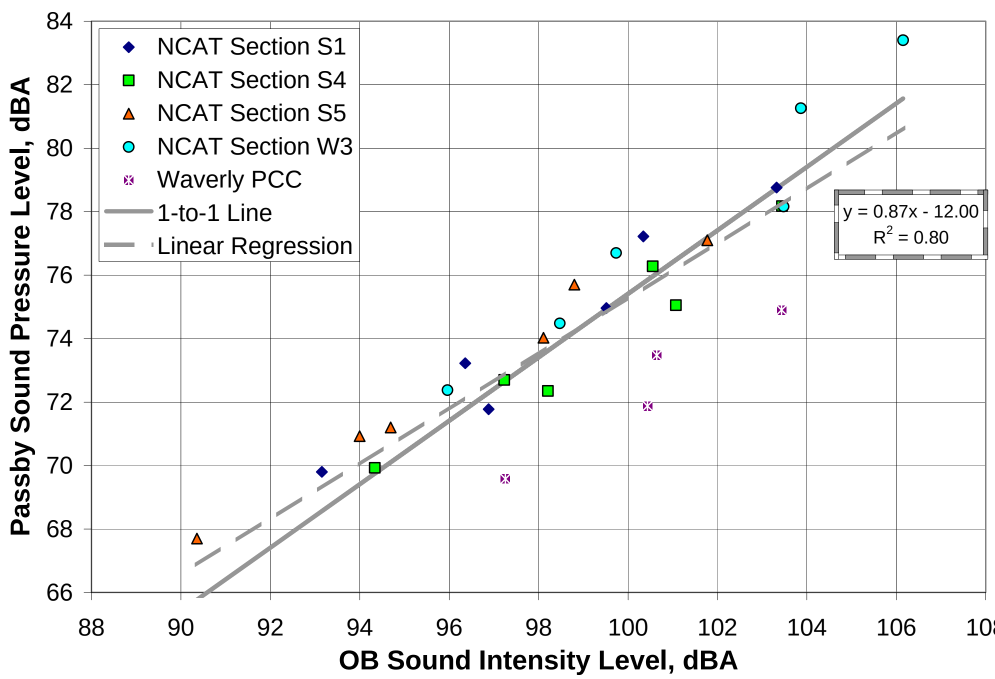

Figure 17: Relationship between OBSI and passby noise levels for all sites, SRTT and Dunlop tires, and all speeds

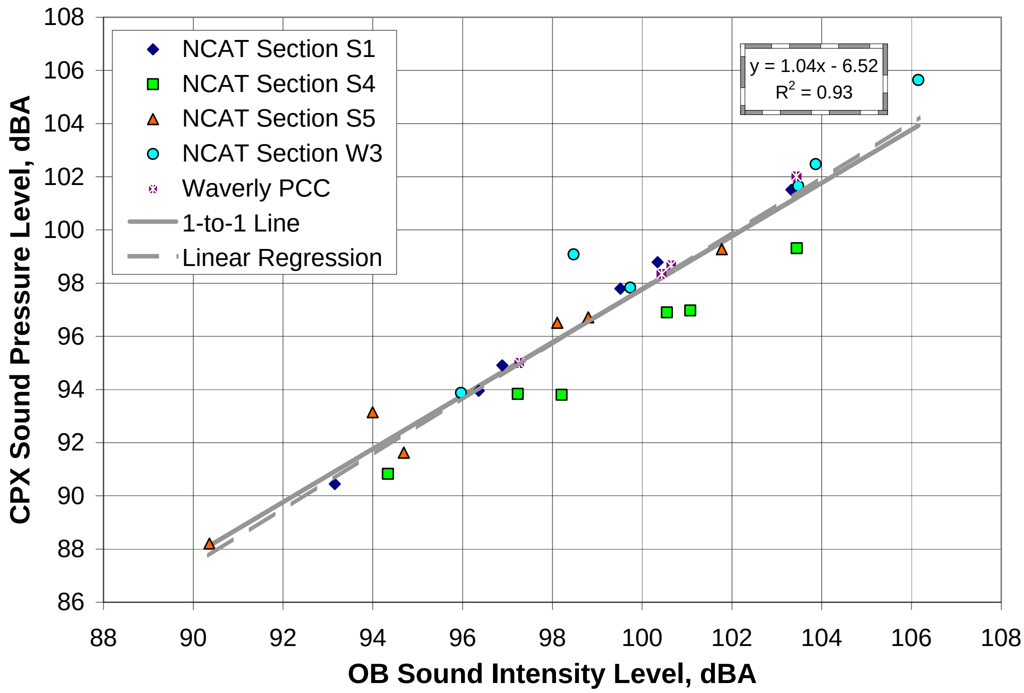

Figure 18: Relationship between OBSI and CPX noise levels for all sites, SRTT and Dunlop tires, and all speeds

reported in the literature[8], 2.2 versus 3.0 to 3.3 dB and the average deviation from a 1-to-1 fit is larger, 0.8 dB compared to 0.7 dB. In these data, the points for the porous section S4 are consistently lower than the 1-to-1 fit.

Some insight to these comparisons can be gained by reviewing the propagation measurements made at each site. The 1/3 octave band difference in levels between the sound intensity of the loudspeaker on the ground and the 25ft passby microphone is presented in Fig 19 for the five sites. In this plot, higher level indicates higher rates of attenuation between the source and receiver. These data indicate that three sites, S1, S5 and W3, are virtually identical in terms of propagation under this test method. These would be classified as typical acoustical “hard” sites as the propagation is over non-porous pavement. Sites S4 and Waverly are markedly different. For Waverly, about 3 dB of additional attenuation is apparent through the entire frequency range. Unlike all of the other sites, this could be considered an acoustical soft site because of the grass between the edge of the roadway the microphone location. Additionally, the angled curbing with slightly recessed roadway may be a factor. Either or both of these features could result in the observed attenuation. For S4, increased levels of attenuation are apparent starting at 1000 Hz. These are maximum in the 1250 Hz band with a difference of about 6 dB relative to S1, S5, and W3. Increased attenuation continues in higher frequencies with level of 1 to 3 dB higher than S1, S5, and W3. The S4 data is typical of for sound propagating over porous pavement[9].

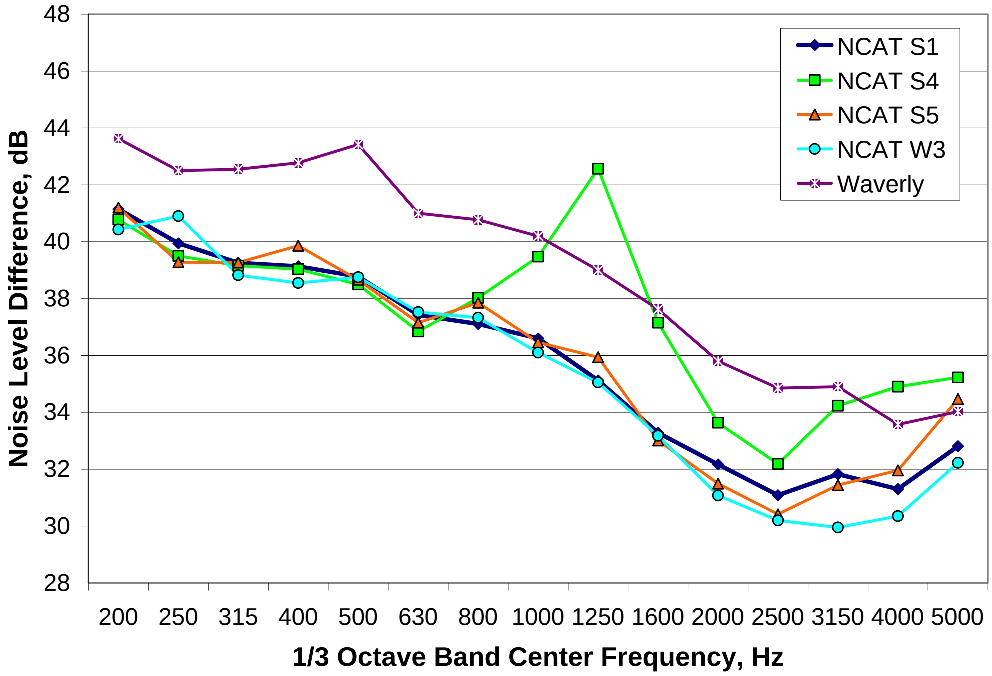

Figure 19: Difference in level between loudspeaker sound intensity and sound pressure measured at the passby microphone location

Although the attenuations produced with the loudspeaker test method are not expected to exactly match that seen for tire noise propagation, it is expected that the behaviors noted from Fig. 19 will be present in the relationships between the on-board and passby measurements. To examine this, the passby levels can be subtracted from the OBSI data and from the CPX data. These were averaged over both tires and all speeds at each site to compare to the loudspeaker tests (Figs. 20 and 21). Although the overall shape of these curves are different than that of Fig. 19, some of same trends are apparent. In both cases, there is more broadband attenuation for the Waverly site. Both types of on-board data display increased attenuation around 1250 Hz for the porous section S4. For the OBSI data, the noise difference between S1, S5, and W3 remain almost identical between 500 and 5000 Hz as does the loudspeaker data. For the CPX results; however, there is a rather dramatic drop in the attenuation below 1000 Hz which is not seen in either the loudspeaker or OBSI results. Although there are some of these specific differences, the overall trend seen in the propagation tests is also apparent in the both the CPX and OBSI results.

Given the propagation influences at NCAT section S4 and at the Waverly site, the passby data were plotted against the CPX and OBSI data for just measurements on section S1, S5, W3. These were the acoustically hard sites with non-porous pavements. As can be seen in Fig. 22, segregating the sites in this manner reduced the scatter in the passby versus CPX data considerably. The linear regression becomes closer to 1-to-1 and the r^2 value increases from 0.79 to 0.94. The offset of the best 1-to-1 fit drops to 21.9 dB with

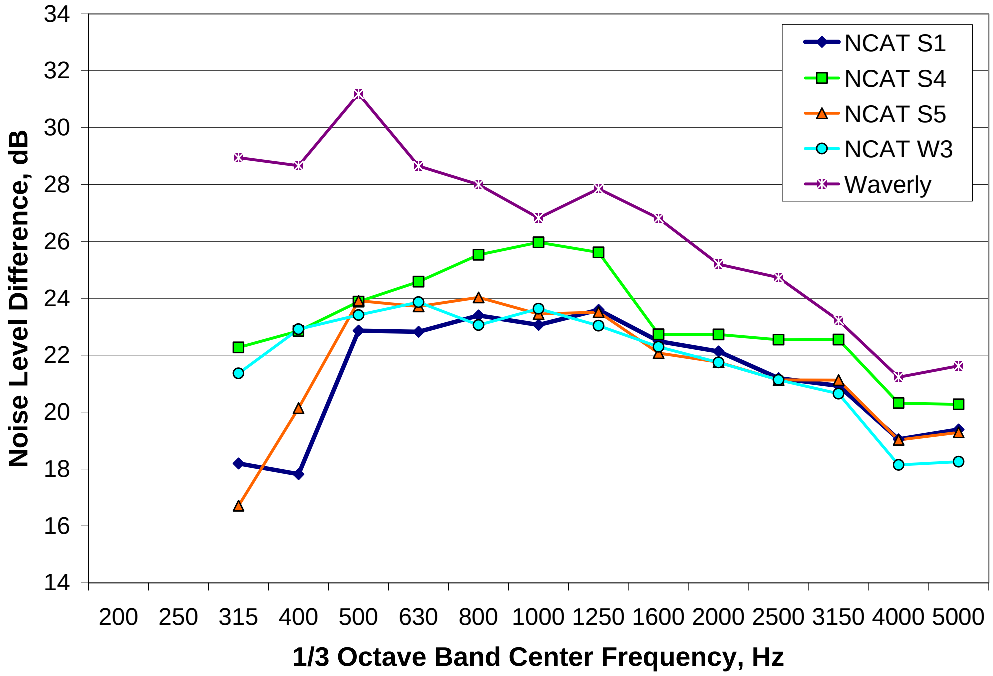

Figure 20: Difference in level between OBSI sound intensity and passby levels for each site averaged over SRTT and Dunlop tires and all speeds

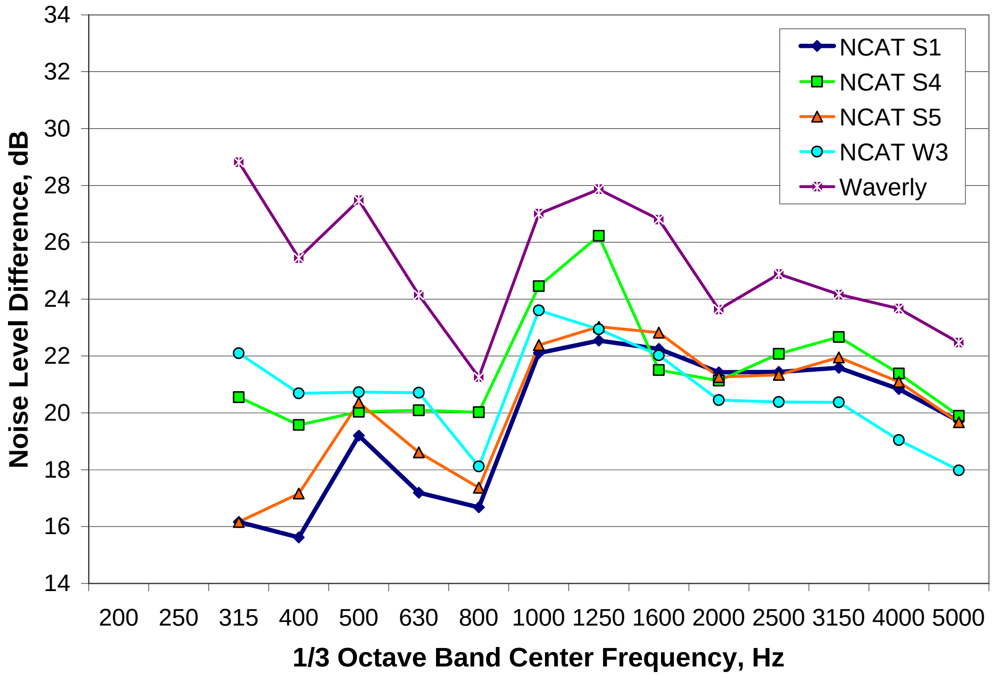

Figure 21: Difference in level between CPX sound pressure and passby levels for each site averaged over SRTT and Dunlop tires and all speeds

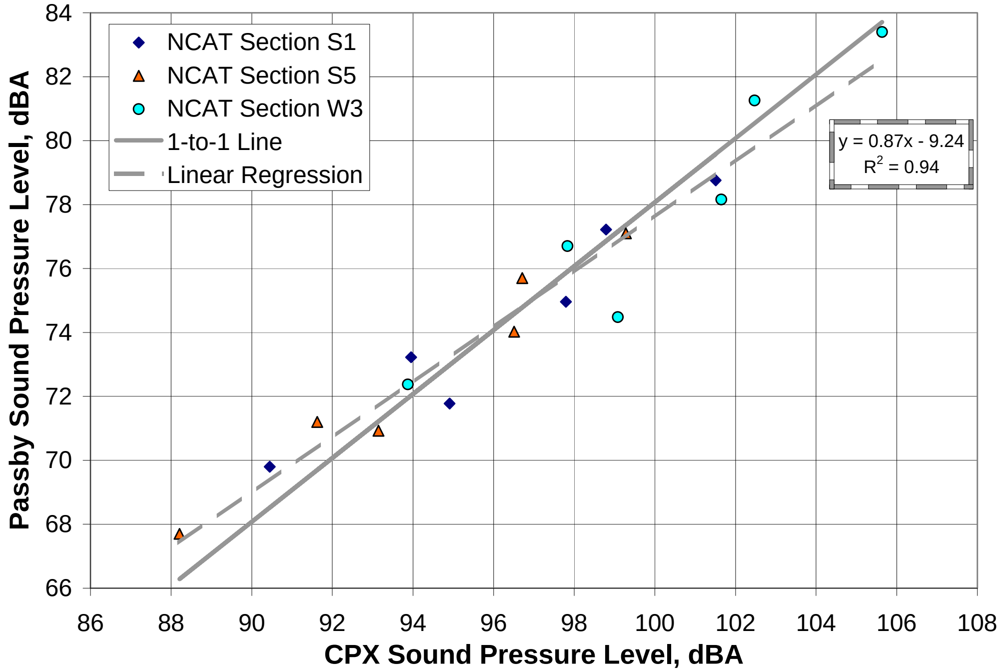

Figure 22: Relationship between CPX and passby noise levels for NCAT pavement sections S1, S5, and W3 for SRTT and Dunlop tires and all speeds

a standard deviation of 1.2 instead of 1.8 dB and an average deviation of 1.0 versus 1.4. This is more in line with that reported in the literature[11] as discussed earlier in this section. The scatter in the passby versus OBSI data was even more reduced (Fig. 23). In this case, r^2 value improved to 0.96 from 0.87, while the standard deviation improved to 0.9 dB from 1.7 dB, and the average deviation to 0.7dB from 1.3 dB. Not only are these values similar to that reported in the literature[6], the offset between the passby levels and OBSI is now 23.7 dB which matches that reported previously. There is also some smaller improvement in the scatter of the CPX versus OBSI data (Fig. 24). However, the offset between these data is reduced to 1.8 dB which is now 1.2 to 1.5 dB less than that found previously using a different CPX trailer[13].

As a final comparison of the passby and on-board data, results from all of the NCAT pavements were cross-plotted. This grouping includes both porous and non-porous pavements but, unlike the Waverly site, the propagation is entirely over pavements. In this case, the scatter in the CPX and OBSI data are quite similar as indicated in Table 4 which compares the slope of linear regression, the r^2 of the regression, the offset to a best fit 1-to-1 line, and the standard and average deviations about that line. In the first two groupings of Table 4, OBSI performs consistently better than CPX in that the slopes are closer to 1-to-1, the r^2 values are higher, as are the both the standard and average deviations. On the final grouping, except for the slope of the CPX versus that of the OBSI data, the two methods perform virtually identically. Although the OBSI has the advantage in some cases, there is still no clear “winner” in deciding which on-board method correlates better to passby measurements. Based on the results of the final grouping, it could be said that both methods correlate well to controlled vehicle passby data, particularly when the scatter in the passby results is considered.

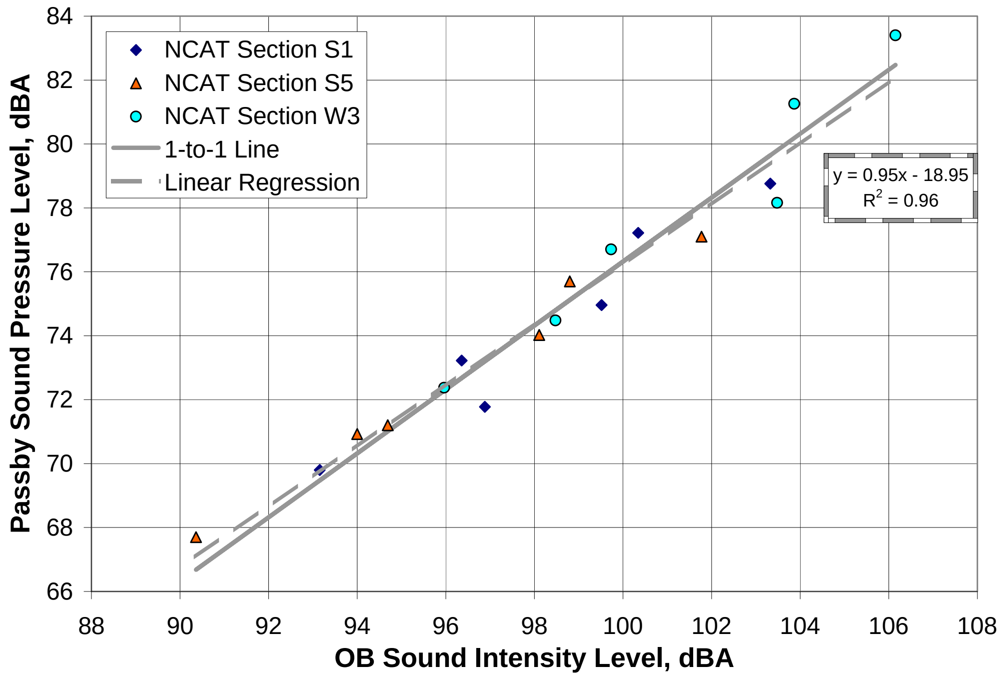

Figure 23: Relationship between OBSI and passby noise levels for NCAT Pavement sections S1, S5, and W3 for SRTT and Dunlop tires and all speeds

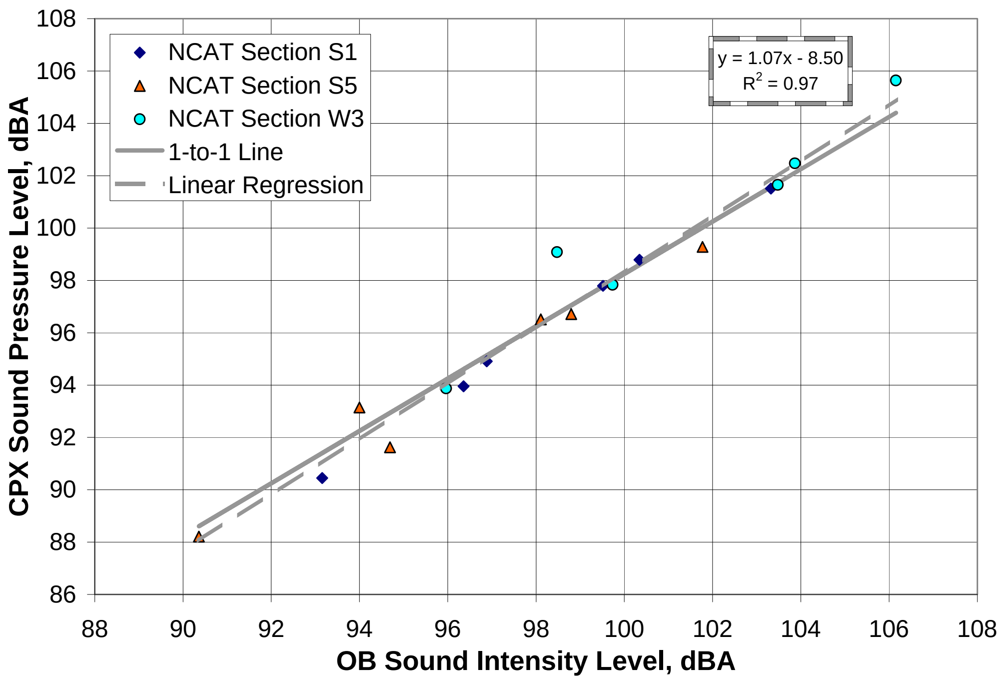

Figure 24: Relationship between OBSI and CPX noise levels for NCAT pavement sections S1, S5, and W3 for SRTT and Dunlop tires and all speeds

Table 4: Comparison of Correlation Indicators for CPX and OBSI Methods to Passby

Metric	All Sites		Sections S1, S5, W3		Sections S1, S4, S5, W3	
	CPX	OBSI	CPX	OBSI	CPX	OBSI
Slope	0.80	0.87	0.94	0.96	0.87	0.94
r^2	0.79	0.87	0.94	0.95	0.94	0.93
Offset	22.4	24.6	21.9	23.7	21.7	24.0
Std Dev	1.8	1.7	1.2	0.9	1.1	1.1
Avg Dev	1.4	1.3	1.0	0.7	0.8	0.9

Sound Intensity Measured on Car and on Trailer: Overall A-weighted OBSI levels obtained on the test vehicle were compared to those obtained on the CPX trailer. For this comparison (Fig. 25), the same tire was used for both sets of data, only the test environment was different. For the OBSI measurements on the CPX trailer, the test space was enclosed within the trailer (see Fig. 3). For OBSI on the test car (Fig. 4 and 5), the sound can propagate freely away from the tire. In comparing these data, it was found that on average, the OBSI measured on the trailer was about 0.5 dB lower in level. The trend of the data was however a 1-to-1 line with an r^2 of 0.97. The standard deviation was 0.7 dB and average deviation, 0.5 dB.

To understand the difference between the OBSI measured on the car and on the trailer, it is useful to examine the difference between the sound intensity and sound pressure levels as measured in both situations. For the special case of sound intensity measurement in the far field of a point source in a non-reflecting environment, the difference between the sound intensity and sound pressure level would be very close to 0. When measuring sound intensity using the finite difference method, a systematic error is introduced at higher frequencies which leads to increasingly larger, but totally predictable, differences between the two measures. For measurements made in the nearfield of a real noise source, the propagating energy measured by sound intensity becomes less than the total amount of fluctuating pressure which includes both propagating and non-propagating (nearfield) energy. For measurements in flow, the sound intensity also decreases relative to sound pressure in the lower frequencies as flow-induced, non-propagating noise on the microphones become greater.

All of these behaviors described above are indicated for the on-car data of Fig. 26. In the middle frequencies, the sound intensity levels are typically about 1 dB lower than the sound pressure due to the proximity of the nearfield and/or the effects of flow noise on the microphones. At higher frequencies, the curve trends lower due to the finite difference error, while in the lower frequencies, the curve also trends lower due to in-flow, turbulent noise on the microphones[10]. The trends on the CPX trailer are somewhat different. At 630 and 800 Hz, the difference between sound intensity and sound pressure is reduced an additional 2 dB lower than it is for the on car measurements. This suggests that either the sound intensity on the trailer is lower in these frequencies or that the sound pressure is higher, or both. At frequencies above 1000 Hz, the difference between sound intensity and sound pressure levels are also lower than those measured on the car.

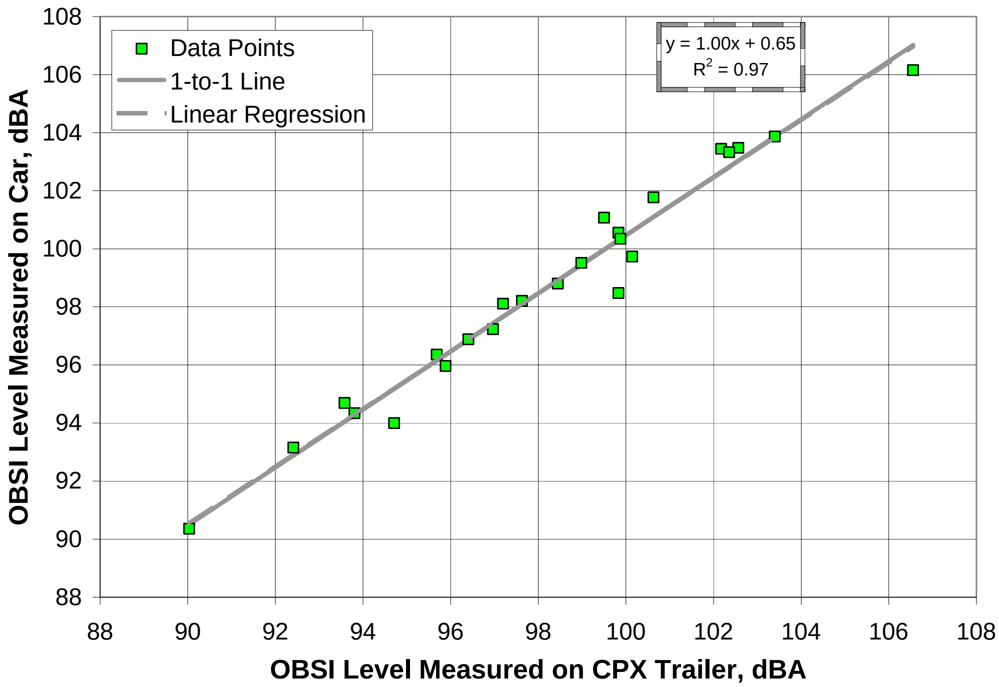

Figure 25: Relationship between OBSI levels measured on the CPX trailer and on the test car for the noise levels for all sites, SRTT and Dunlop tires, and all speeds

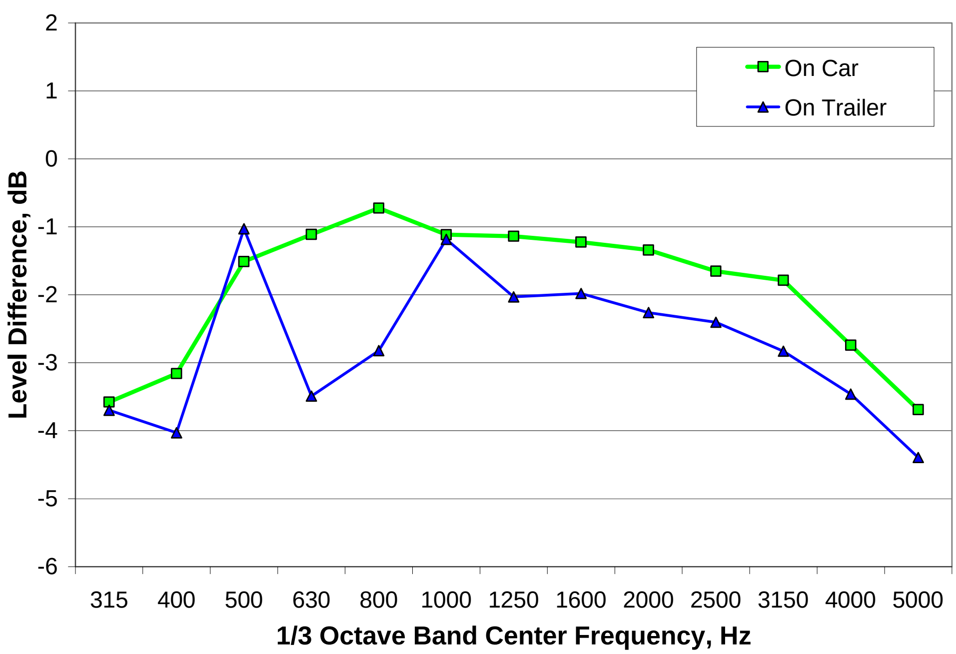

Figure 26: Sound intensity level subtracted from mean sound pressure level measured by the OBSI probe mounted on the test car and CPX trailer for all conditions

To determine if these differences on the trailer are due to increased sound pressure or decreased sound intensity, the average difference of sound intensity measured on the car and that measured on the trailer is shown in Fig. 27. At frequencies above 1000 Hz, the sound intensities are not different from each other indicating that the sound pressure on the microphones is greater in the trailer than on the car. This could potentially be due to the enclosed sound field being weakly reverberant adding in more background noise sound pressure relative to the sound intensity measurement. Such a uniform sound field would introduce higher sound pressures without affecting the sound intensity measurement. For problem frequencies of 630 and 800 Hz noted for the trailer in Fig. 26, the on-trailer sound intensity levels are almost 2 dB lower than the on-car levels. At these frequencies, it is possible that standing waves within the enclosure are affecting the sound field and alter how the sound propagates away from the tire. This in turn influences both the sound intensity and sound pressure measurements.

The results of Fig. 27 also have implications for the CPX measurements. Above 1000 Hz, the higher sound pressure levels on the intensity microphones would be expected to translate into higher levels on the CPX microphones relative to an unenclosed measurement. In the frequencies below 1000 Hz, standing waves in the enclosure could produce varying effects depending on microphone location relative to the standing waves. At antinodes of the standing waves, sound pressures would be somewhat higher than the average throughout the enclosure. These would occur near the walls of the enclosure and at various points throughout. Around the nodes, the sound pressure levels can be significantly reduced due to cancellation effects. The cancellation effects are typically more significant than the addition effects as the sound pressure level theoretically goes to zero at the nodes while the antinodes provide only a doubling of pressure. Conceptually, these conclusions for the frequencies below 1000 Hz are born out in spectral comparison of passby and CPX data in Fig. 21. For these data, rather than the difference remaining relatively flat with frequency, there is a 3 to 4 dB drop in the difference between CPX and passby at 800 Hz and below. This relative reduction in the CPX sound pressure level is likely due to standing wave effects in the enclosure. It should be noted that the effects of enclosures are well documented in the European literature (see Appendix A) and considerable attention has been given to quantifying and correcting for these effects[11]. In the ISO Draft CPX Standard, the use of sound intensity as a means of identifying reflections within an enclosure is recommended and apparently appropriate in this case.

Comparison of Spectral Shapes

There are a large number of 1/3 octave band spectral comparisons that could be considered given all the test conditions and the parameters to be evaluated. However, after some inspection of these, the relative trends and observations do not change much with either test speed or tire. As a start on these comparisons, attention here is focused on the passby, CPX, and OBSI data for the Dunlop tire operating at 45 mph on each of the five test pavements. In order to make a comparison on the plot, 23 dB was added to the passby data. This represents the average of all CPX and OBSI offsets identified in Table 4. From these plots, Figs. 28 through 32, several of the observations from the previous section are re-enforced. In an overall sense, it is seen that OBSI and passby spectral shapes are quite similar for NCAT test sections. For 1000 Hz and above, the CPX and

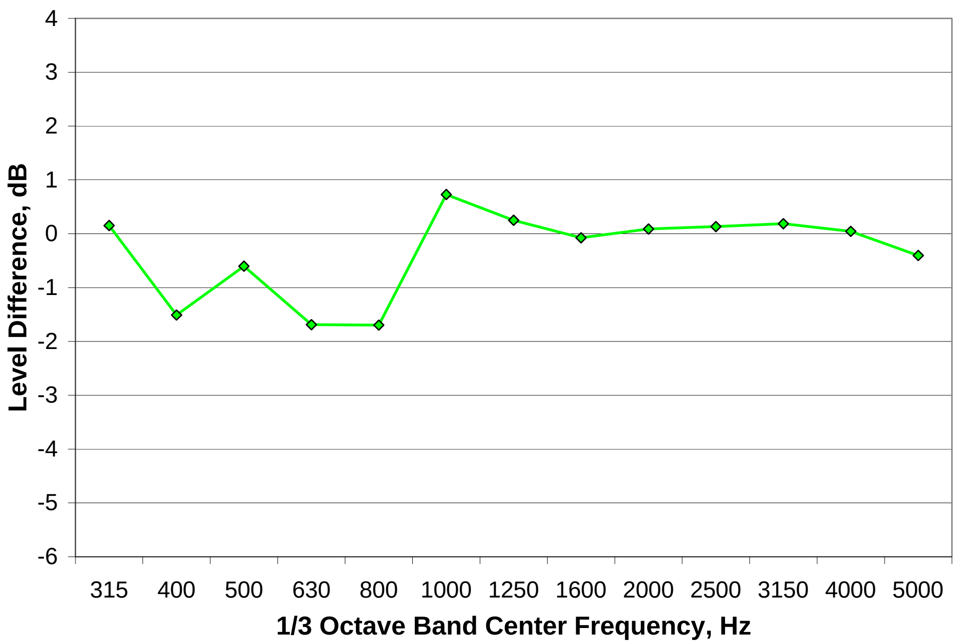

Figure 27: Difference in OBSI levels measured on the test car and CPX trailer for all conditions CPX (trailer minus test car)

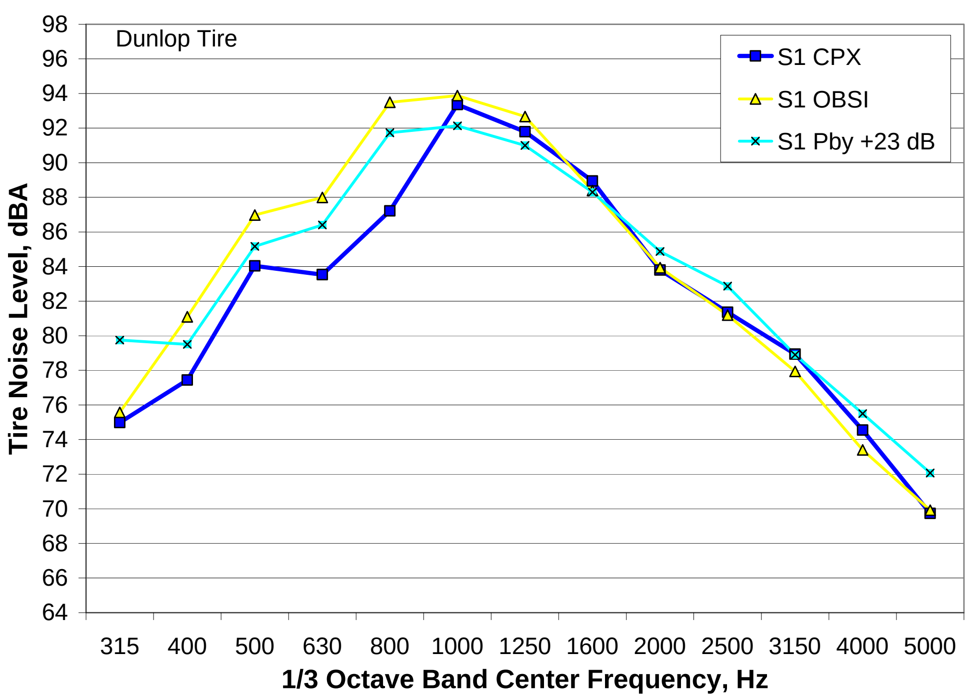

Figure 28: CPX, OBSI and passby 1/3 octave band levels for the Dunlop test tire on NCAT pavement section S1 at 45 mph (23 dB added to passby levels)

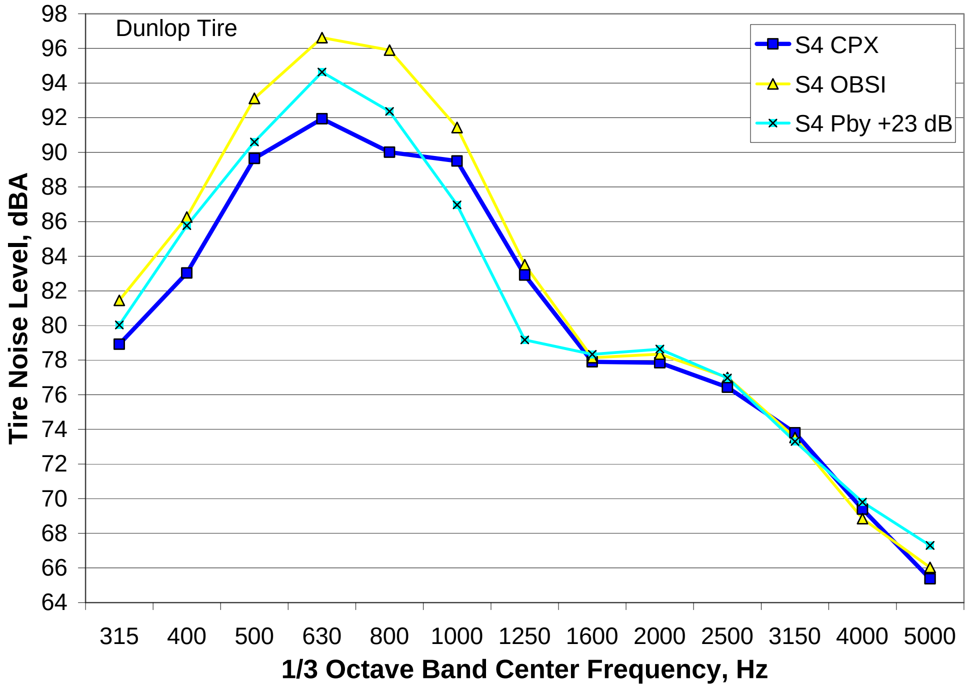

Figure 29: CPX, OBSI and passby 1/3 octave band levels for the Dunlop test tire on NCAT pavement section S4 at 45 mph (23 dB added to passby levels)

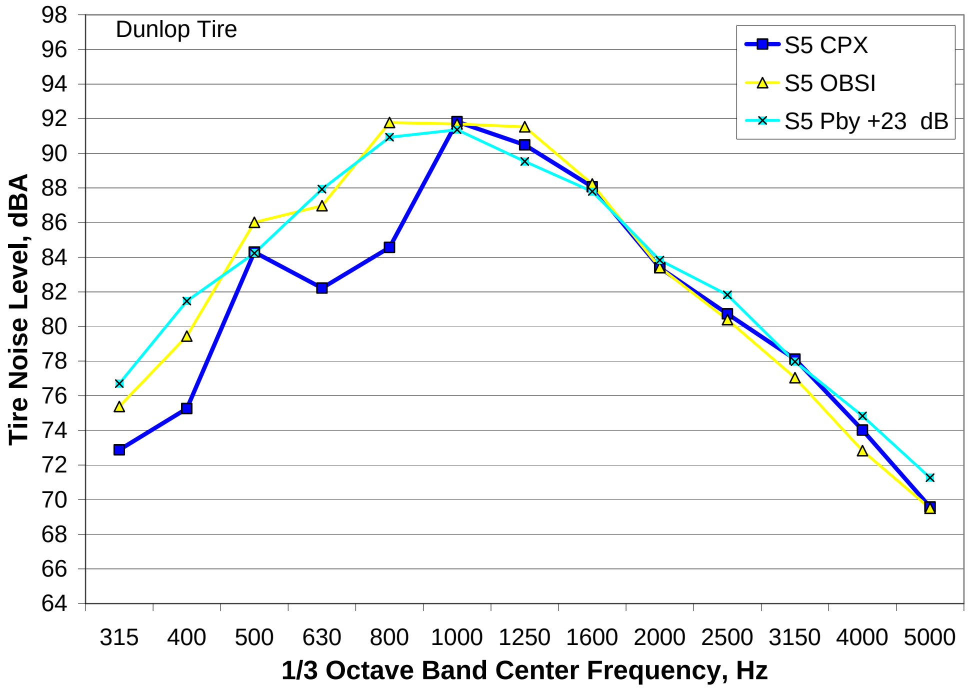

Figure 30: CPX, OBSI and passby 1/3 octave band levels for the Dunlop test tire on NCAT pavement section S5 at 45 mph (23 dB added to passby levels)

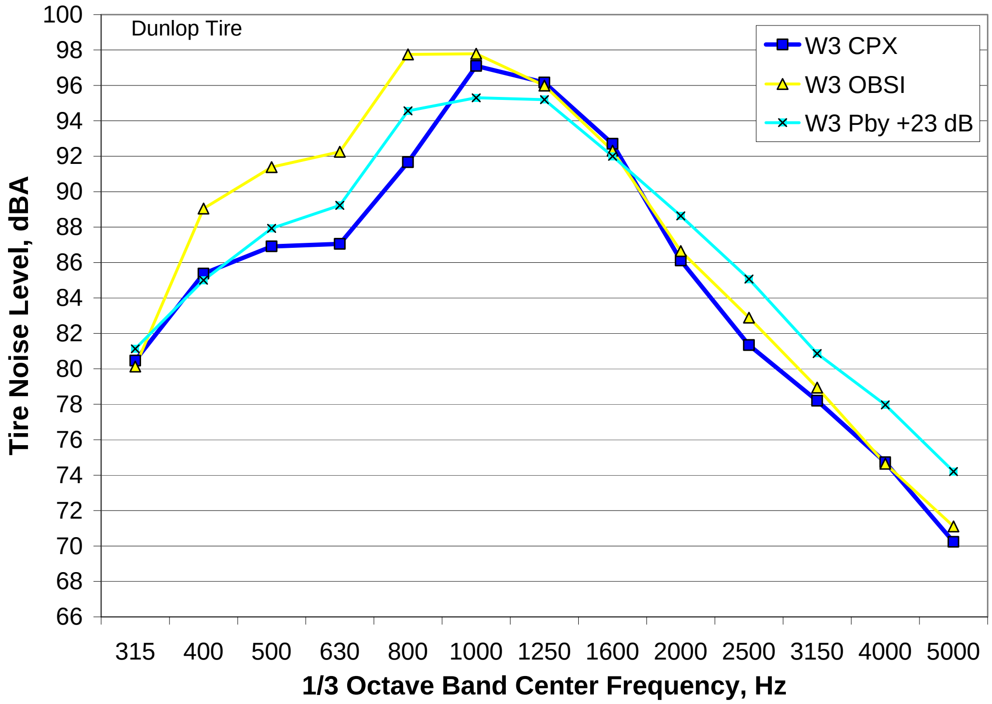

Figure 31: CPX, OBSI and passby 1/3 octave band levels for the Dunlop test tire on NCAT pavement section W3 at 45 mph (23 dB added to passby levels)

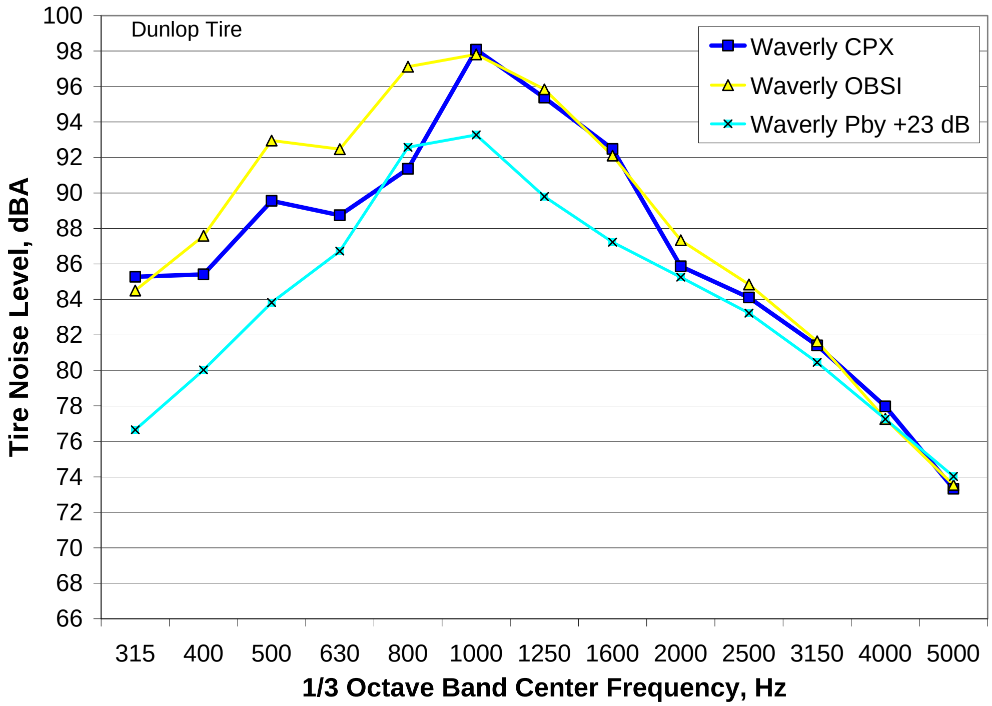

Figure 32: CPX, OBSI and passby 1/3 octave band levels for the Dunlop test tire at the Waverly test site at 45 mph (23 dB added to passby levels)

OBSI virtually overlay in terms of both amplitude and frequency content for each of the pavements. Below 1000 Hz, there is a clear deficit in the CPX spectra compared to the passby and OBSI spectra. Depending on the specific frequency, this runs from about 2 dB to as much as 6 dB. This truncation is consistent with the standing wave effects described in the previous section. Another consistent trend throughout the NCAT sections is the passby levels tend to be relatively higher than the on-board data in the broad higher frequency range above 1600 Hz. For frequency bands below 800, the OBSI and passby levels compare very well on NCAT sections S1, S4, and S5. For the W3 section, although the shape of the passby and OBSI data are similar in these lower frequencies, there is an offset which might be due to the test variability associated with maintaining the same wheel path. For the SRTT tire, there was a similar offset, except the passby data was higher (Fig. 33). Finally, as expected from the propagation data, the passby levels for the Waverly site are shifted downward relative to the comparisons for the other sites.

For comparison to Fig. 28, the 1/3 octave band spectra for section S1 are presented in Figs. 34 and 35 for test speeds of 35 and 60 mph, respectively. From these data, the trends between the passby, CPX, and OBSI are seen to be similar regardless of vehicle speed. For 45 and 60 mph, elevated level in the passby data is apparent in the 315 Hz 1/3 octave band. For the passby measurements, the level at this frequency is thought to be influenced by an exhaust note from the test vehicle.

Comparison of Tire and Pavement Rank Ordering

One key issue for an on-board measurement method is that it rank order the parameters of tire design and pavement type in the same manner as passby data. For the case of tires, since there are only two tire designs for which full sets of data are available, the comparison of the tire rank ordering is limited. For the pavement rank ordering, the four NCAT test sections were used, as the site characteristics of the Waverly measurements limit its usefulness.

Rank Ordering of Tires: Overall, the rank ordering of the tires was consistent for all of the test methods and all of the test conditions. The Dunlop tires consistently produced higher levels than the SRTT. However, there was some variation in the magnitude of difference between tires with the measurement method, speed, and pavement (Fig. 36). In general, the on-board methods detected larger differences between the tires. The average difference for all conditions was 1.9 dB for the passby data, 3.6 dB for the CPX data, and 3.2 dB for the OBSI data with standard deviations of 0.5, 0.8, and 0.4 dB, respectively. From one speed group to another in Fig. 36, there does not appear to be any consistency in which pavement produced the largest or smallest difference between tires. In the 60/55 mph bracket, all three measurement methods produced smaller differences between tires than at 35 and 45 mph.

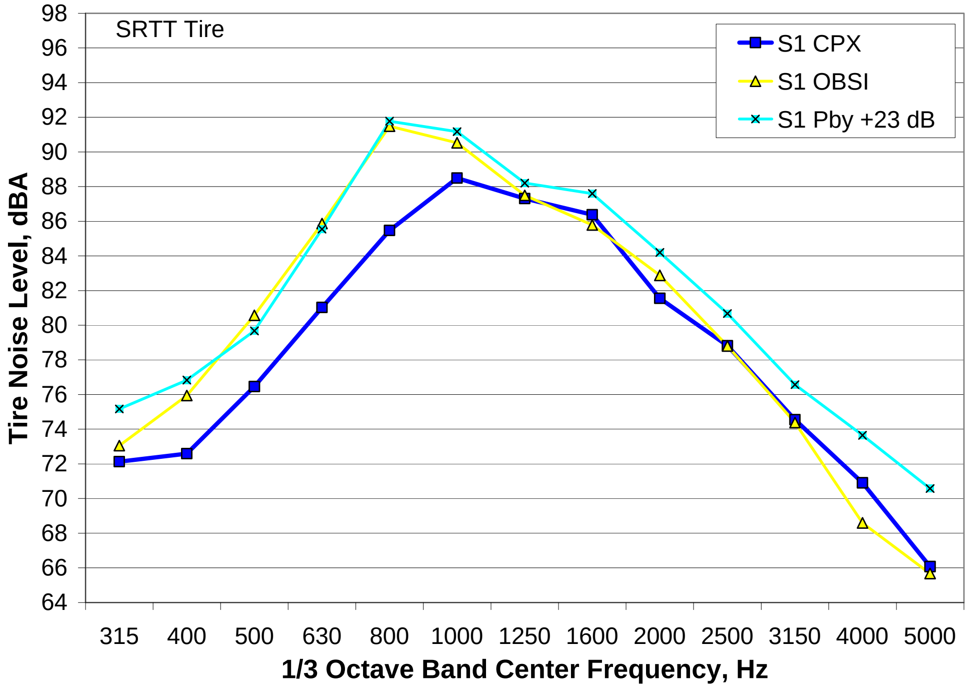

Figure 33: CPX, OBSI and passby 1/3 octave band levels for the SRTT test tire on NCAT pavement section W3 at 45 mph (23 dB added to passby levels)

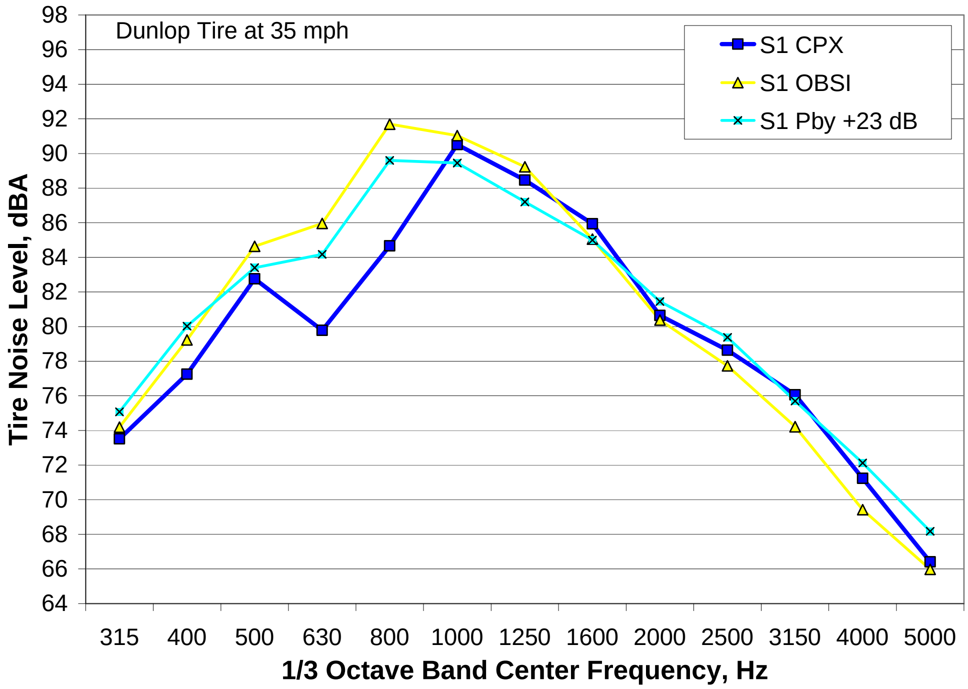

Figure 34: CPX, OBSI and passby 1/3 octave band levels for the Dunlop test tire on NCAT pavement section S1 at 35 mph (23 dB added to passby levels)

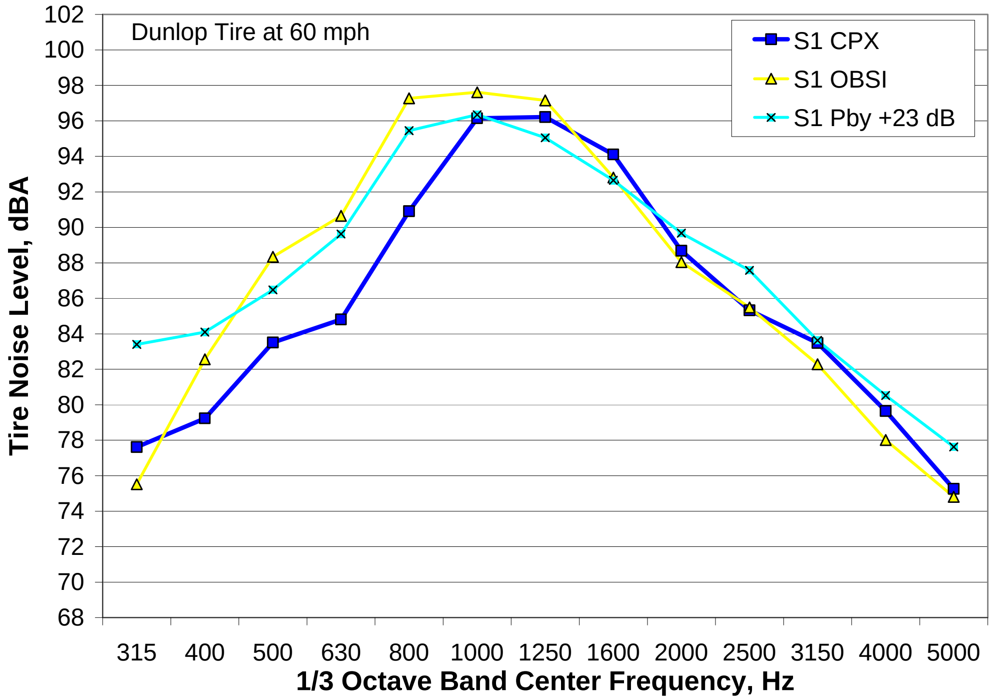

Figure 35: CPX, OBSI and passby 1/3 octave band levels for the Dunlop test tire on NCAT pavement section S1 at 60 mph (23 dB added to passby levels)

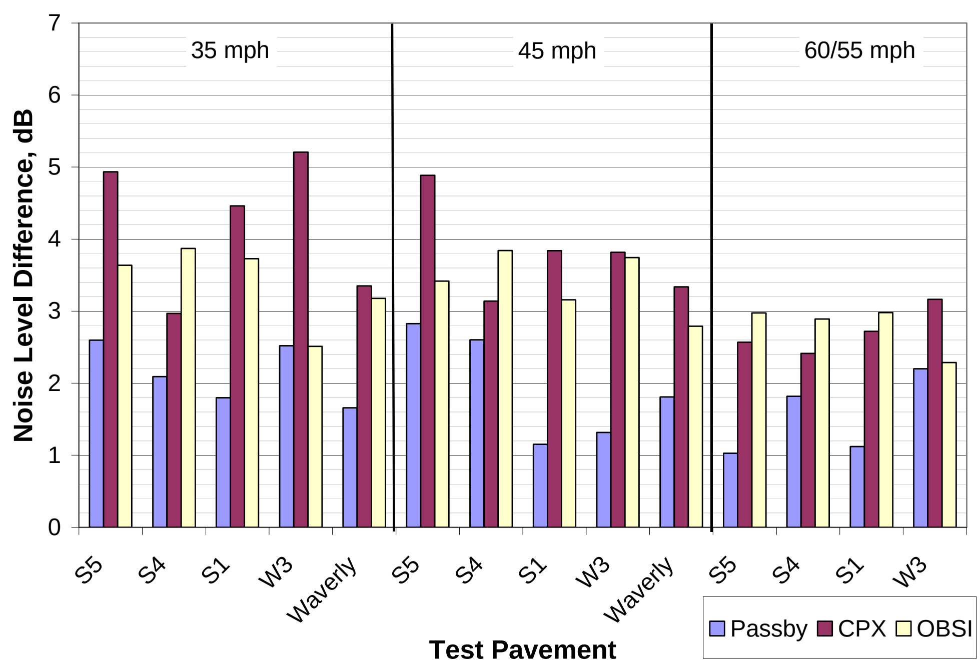

Figure 36: Difference in level measured between the Dunlop and SRTT test tires for passby, CPX, OBSI data (Dunlop minus SRTT)

The 1/3 octave band spectrum levels provide additional insight to the comparison of tires with the different measurement methods. Typical of the results for the other pavements, passby, CPX, and OBSI spectra for the two tires are compared in Figs. 37, 38, and 39 for 35, 45, and 60 mph. As indicated by the overall level differences, these spectra show a smaller difference between tires for the passby data than the on board data. Although the same spectral trends in the difference between tires are seen in all three sets of data for each speed, the offset for the on board measures are consistently greater. As expected from the earlier discussion of spectral shape, distortion of the CPX spectra is apparent below 1000 Hz relative to the OBSI and passby spectra. This does produce some effect on the overall level differences of Fig. 36. At 35 mph, the band with the highest level is 800 Hz in both the OBSI and passby data. For the CPX data, this band is attenuated and the maximum is in the 1000 Hz band. As a result, the overall CPX A-weighted level is influenced more by the 1000 and 1250 Hz bands than by the 800 and 1000 Hz bands which is the case for the OBSI and passby. As a result, the CPX overall levels are biased to exaggerating the difference between the two tires. A similar effect is seen in the 45 mph data (Fig. 38) and a lesser effect in the 60 mph data (Fig. 39).

Rank Ordering of Pavements: The overall A-weighted levels measured by each method are shown in Fig. 40 for the SRTT tire for each pavement as grouped by test speed. For ease of plotting, 23 dB was added to the passby levels for this presentation. Within each speed group, the pavements are rank ordered in level from lowest (left) to highest (right) based on the passby results. The data for the Waverly site are excluded in this figure as it is clear from the discussion of sound propagation that these results would not properly rank order with the data from the NCAT sites. With a few minor exceptions, the data of Fig. 40 indicate that the three methods generate the same rank ordering of the test pavements. These exceptions occur for pavements S4 and S1 where the difference between pavements is typically small (1 dB or less) and in fact the rank ordering changes with test speed. For 35 mph, the ordering is the same for each method. For 45 mph, they are same except for the OBSI data between S4 and S1. Here, difference for pavements from the passby and CPX data are a few tenths of a decibel, with S1 being higher, while for OBSI, S1 is almost 1 dB lower. For the 60/55 speed grouping, the OBSI also gives a different rank ordering of S4 and S1 by a few tenths of a decibel. The results for the Dunlop tire are generally similar, within about 1 dB, the pavements rank order the same with any of the methods. In this case, the exceptions are with the CPX data and section S4 and S1 at 35 and 45 mph. In these cases, the CPX results show S4 being 1 dB lower in level than S1, while the passby and OBSI data show S4 being 1 dB higher than S1.

To provide understanding of the results of Figs. 40 and 41, it is again useful to examine some of the spectral data. Results for the five pavements at 45 mph with the Dunlop tire are shown in Figs. 42, 43, and 44 for the passby, CPX, and OBSI methods, respectively. Similar to the spectral comparison of tires, the difference between pavements as measured in individual 1/3 octave bands is generally consistent between the three methods when the Waverly data is excluded. For the passby and OBSI data, not only are the band differences similar, the overall spectral shapes are also similar. For the CPX, the spectra are distorted again below 1000 Hz as discussed previously. This does have some effect on the overall levels and their difference. For the S4 pavement, the highest

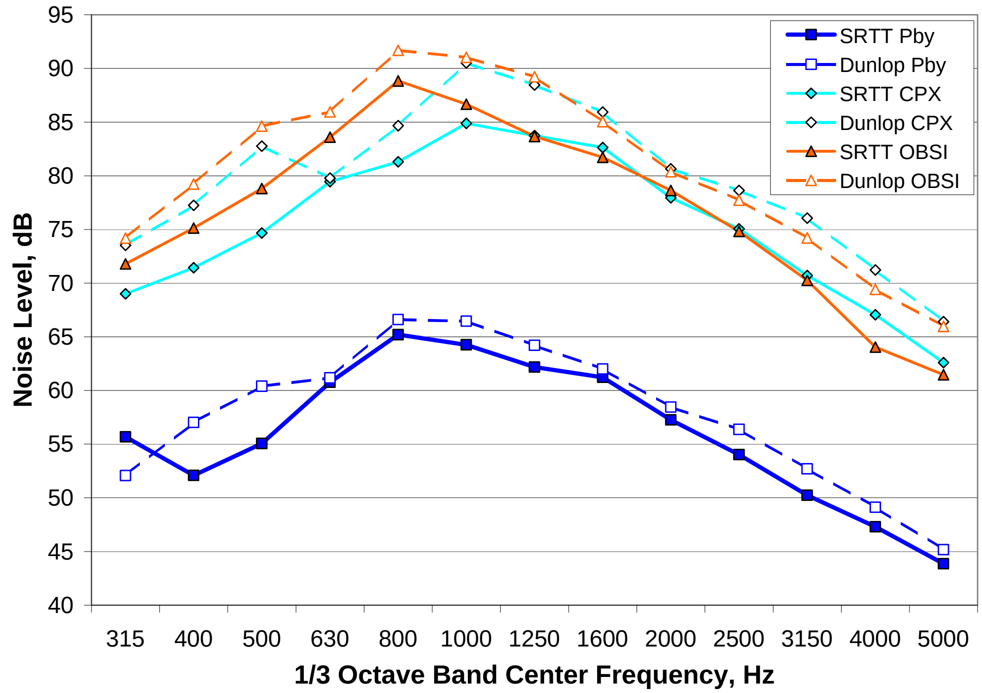

Figure 37: 1/3 octave band levels for Dunlop and SRTT test tires for passby, CPX, OBSI Data at 35 mph on NCAT Pavement Section S1

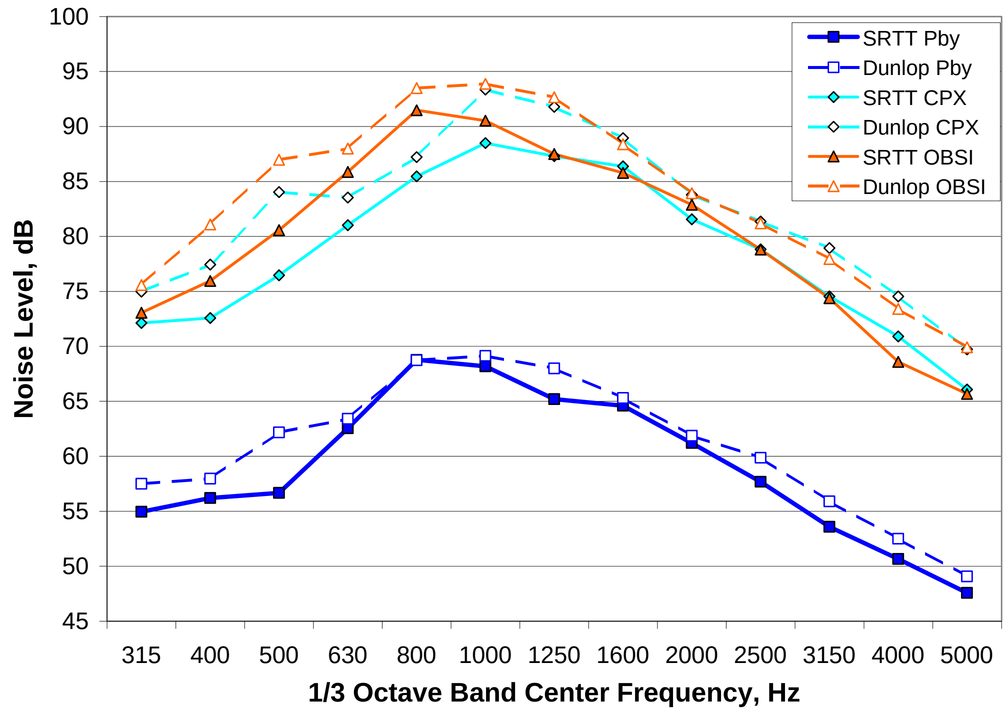

Figure 38: 1/3 octave band levels for Dunlop and SRTT test tires for passby, CPX, OBSI data at 45 mph on NCAT pavement section S1

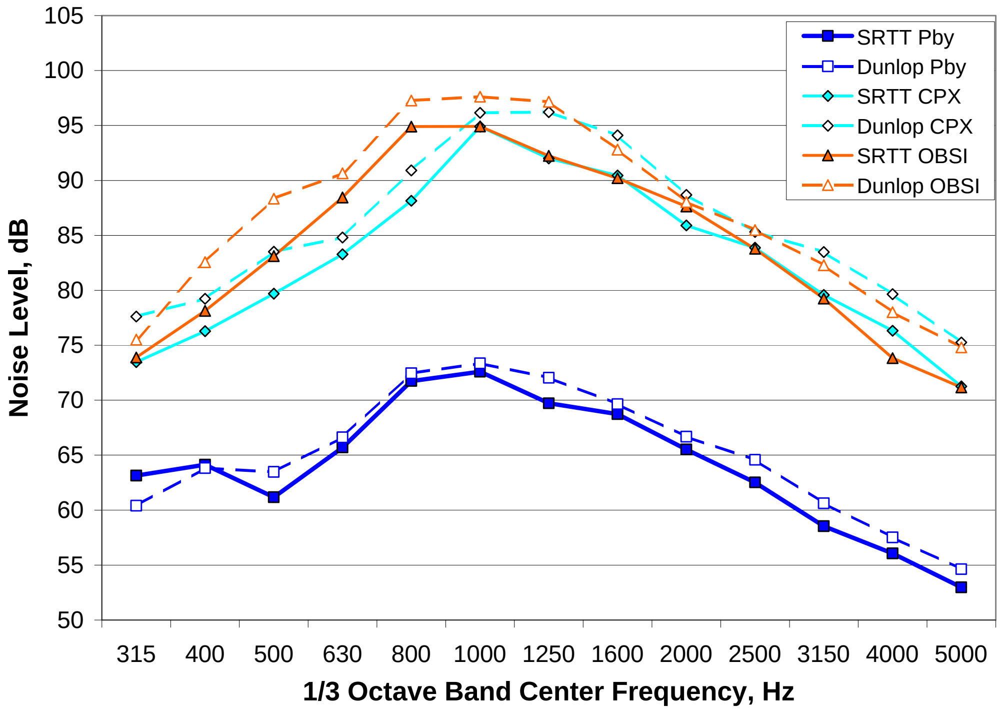

Figure 39: 1/3 octave band levels for Dunlop and SRTT test tires for passby, CPX, OBSI data at 60 mph on NCAT pavement section S1

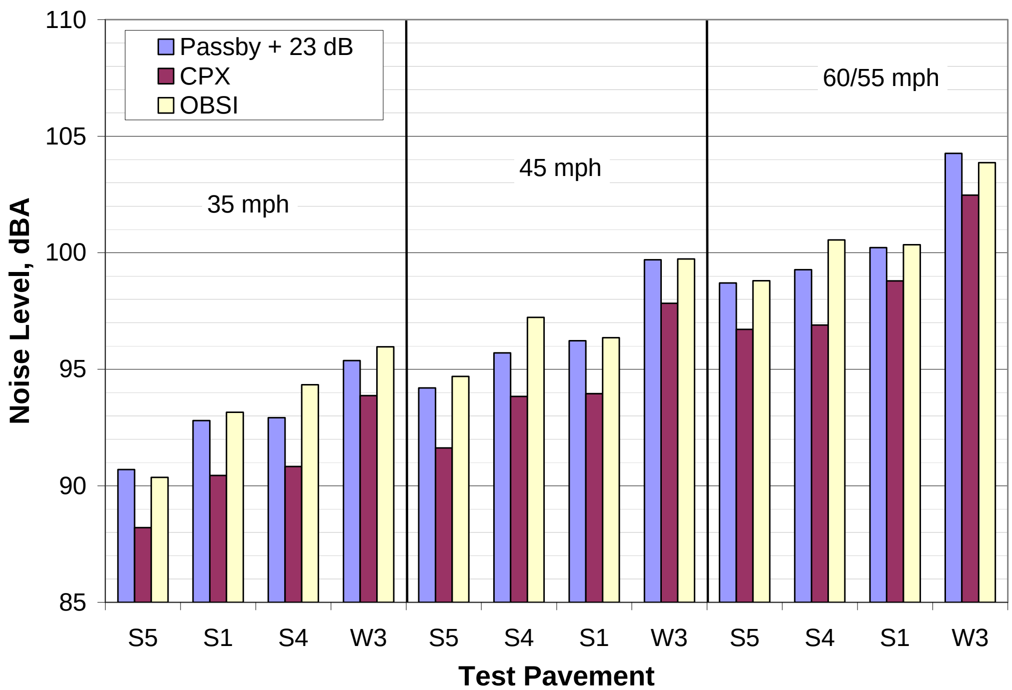

Figure 40: Rank ordering of pavements based on passby levels (with 23 dB added)

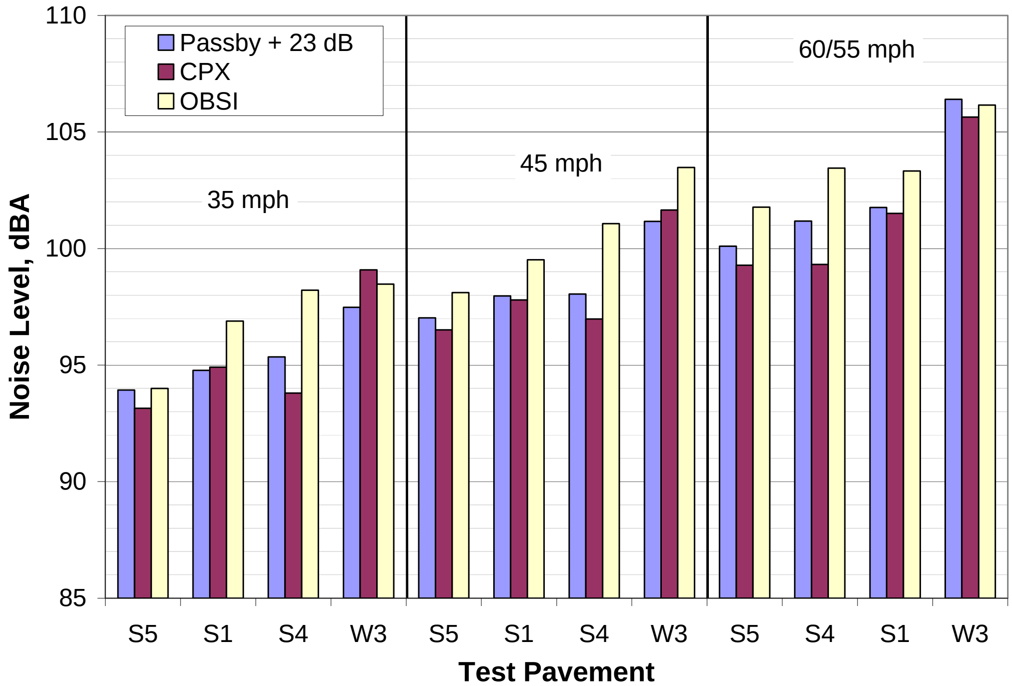

Figure 41: Rank ordering of pavements based on passby levels (with 23 dB added) with corresponding CPX and OBSI levels for the Dunlop test tire

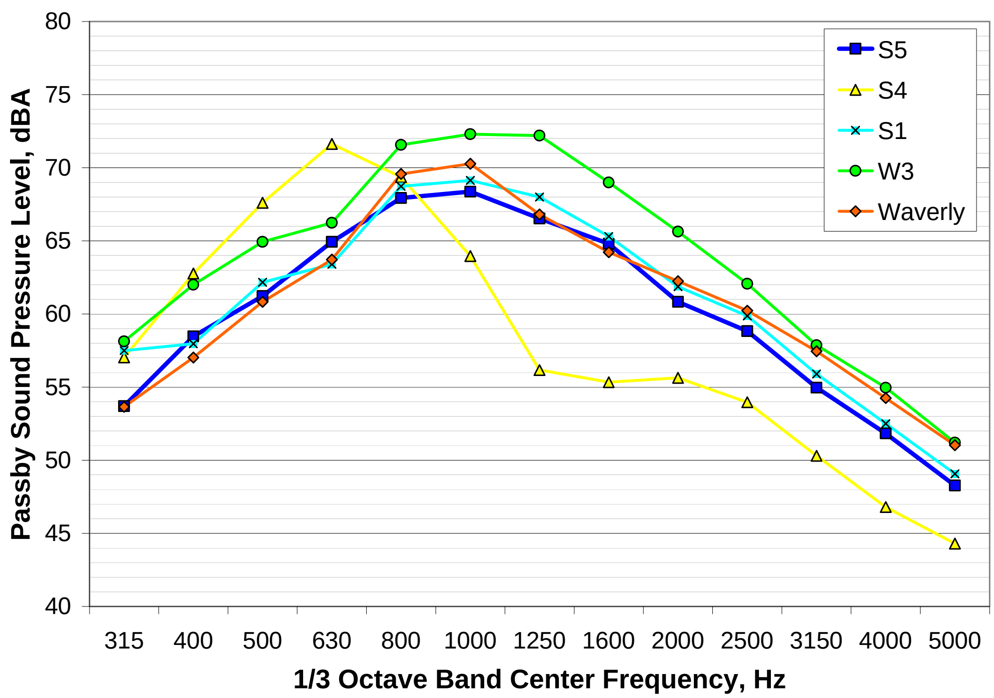

Figure 42: 1/3 octave band passby levels for the Dunlop test tire at 45 mph on each pavement

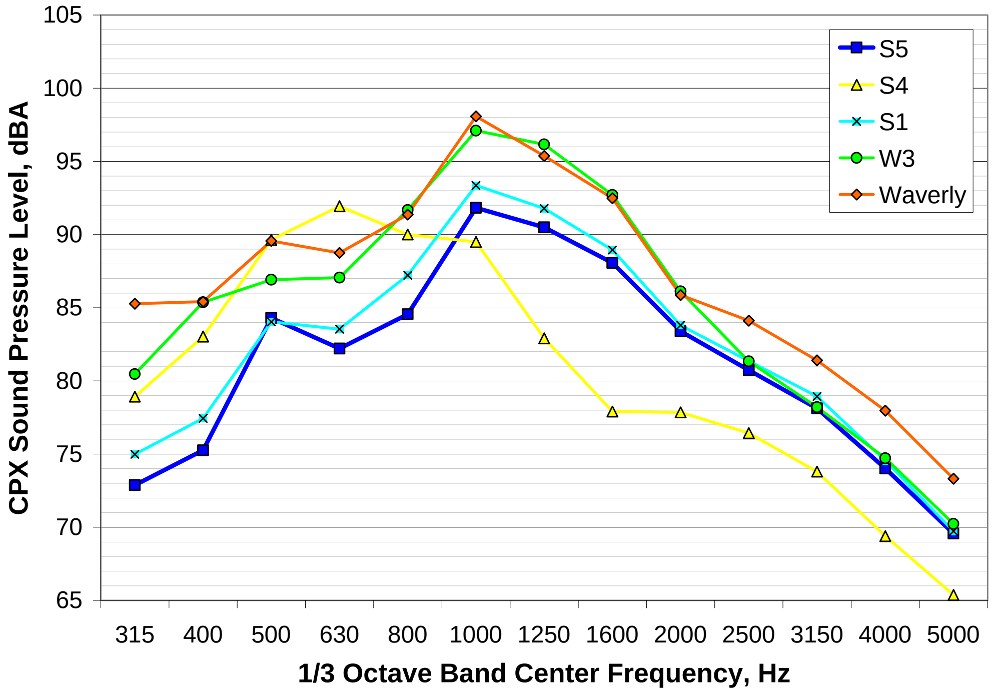

Figure 43: 1/3 octave band CPX levels for the Dunlop test tire at 45 mph on each pavement

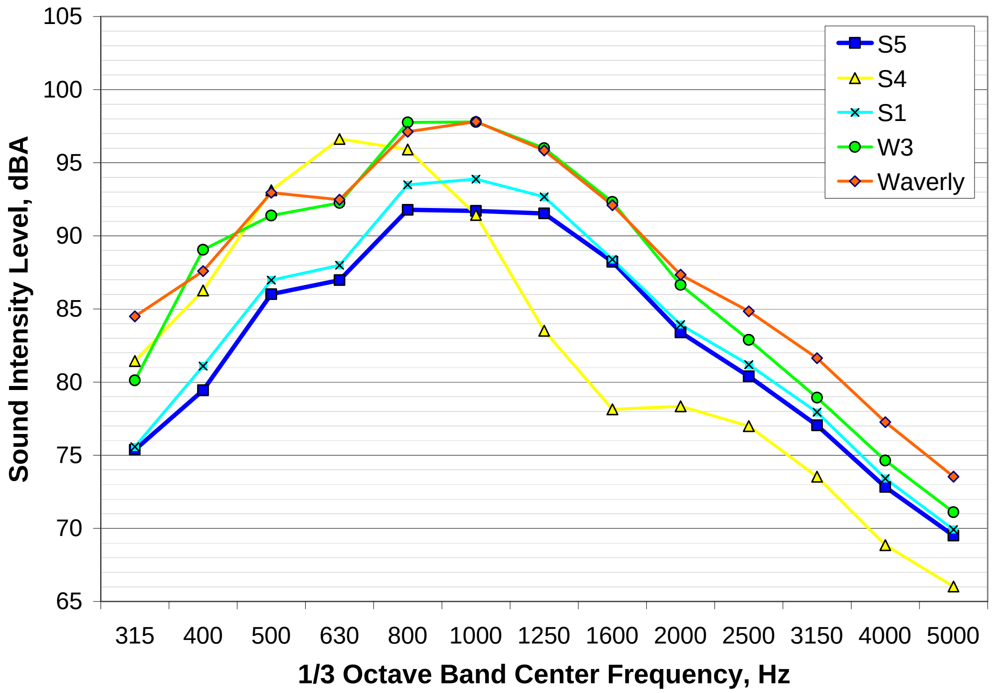

Figure 44: 1/3 octave band OBSI levels for the Dunlop test tire at 45 mph on each pavement

levels occur in the 630 Hz band for all three methods. For the passby and OBSI data the level in this band is within about 1 dB of the highest level in bands for the W3 section. As a result, the difference in A-weighted level between S4 and W3 is about 2½ to 3 dB for the passby and OBSI methods. For the CPX method, because of the relatively attenuated levels in the 630 and 800 Hz bands, the highest 1/3 octave band level for S4 at 630 Hz is about 5 dB lower than the highest of W3. As a result, the difference in overall A-weighted level is about 4½ dB instead of 2½ to 3 dB. Spectral data at 60/55 mph for the SRTT tire are presented in Figs. 45, 46, and 47 for the passby, CPX, and OBSI methods, respectively. The observations for the SRTT tire data are essentially the same as for Dunlop tire, the spectral differences between pavements are quite similar between each of the methods and distortion in the CPX spectra accounts for some variations in overall A-weighted level differences seen in Fig. 40.

Comparison of Test Tire Candidates

A key aspect of developing an on board procedure for the measurement of tire-pavement noise at the source is the selection of the test tire. In the US, most of the recently reported on board data have been for the P205/70R15 Goodyear Aqutratred 3 using both the CPX and OBSI methods. Originally, one of the reasons this design was selected was its apparent similarity to “Tyre A” specified in the ISO CPX draft standard. However, this particular tire is no longer being produced and hence is not available to those wanting to do comparable on board testing. This test program provided data on two additional tires. The SRTT, as discussed previously, is to be available for a longer period time and is attractive to testing groups for that reason. The Dunlop tire is a winter tire particularly designed for enhanced snow traction. Although the tread design is different, this tire was chosen as a substitute for “Tyre D” of the ISO CPX draft standard which is also a more aggressive tread winter tire. This tire is intended to represent the upper end of aggressiveness (and noise) for passenger car tires. It is, however, expected to be less noisy than even more aggressive “all terrain” tires used on some light trucks.

Overall CPX and OBSI A-weighted levels for the SRTT and Dunlop tires are plotted against those for the Aquatred 3 tire for NCAT pavement sections and all three test speeds in Figs. 48 and 49. The OBSI data in this case is that taken on the CPX trailer rather than on the car. For both sets of data, the SRTT tire produces generally lower levels than the Aquatred 3 averaging 1.7 dB lower with the CPX data and 0.5 dB lower for the OBSI. In both cases, the linear regression indicates a slope of nearly 1-to-1. The Dunlop tire produces higher levels, 2.0 dB on average with CPX data, and 2.6 dB with the OBSI. For the Dunlop tire, the slope of regression line is somewhat less than 1. Although there are some differences between the CPX and OBSI results, they both indicate the use of the SRTT tire would produce slightly lower noise levels than the Aquatred 3 while the Dunlop would produce consistently higher levels of 2 dB or more.

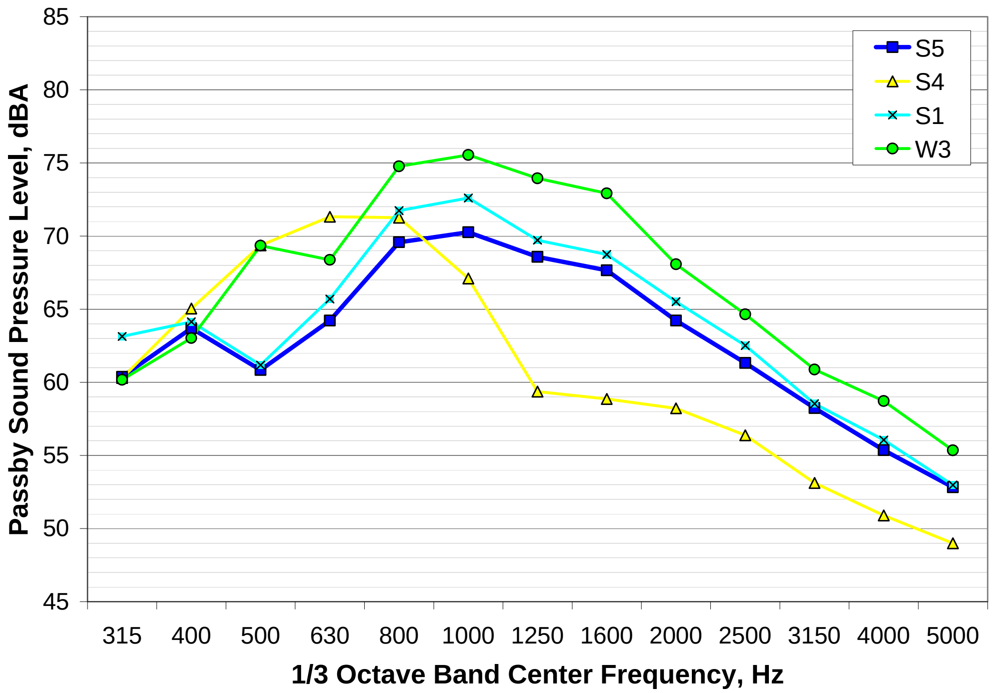

Figure 45: 1/3 octave band passby levels for the SRTT test tire at 60/55 mph on each NCAT pavement section

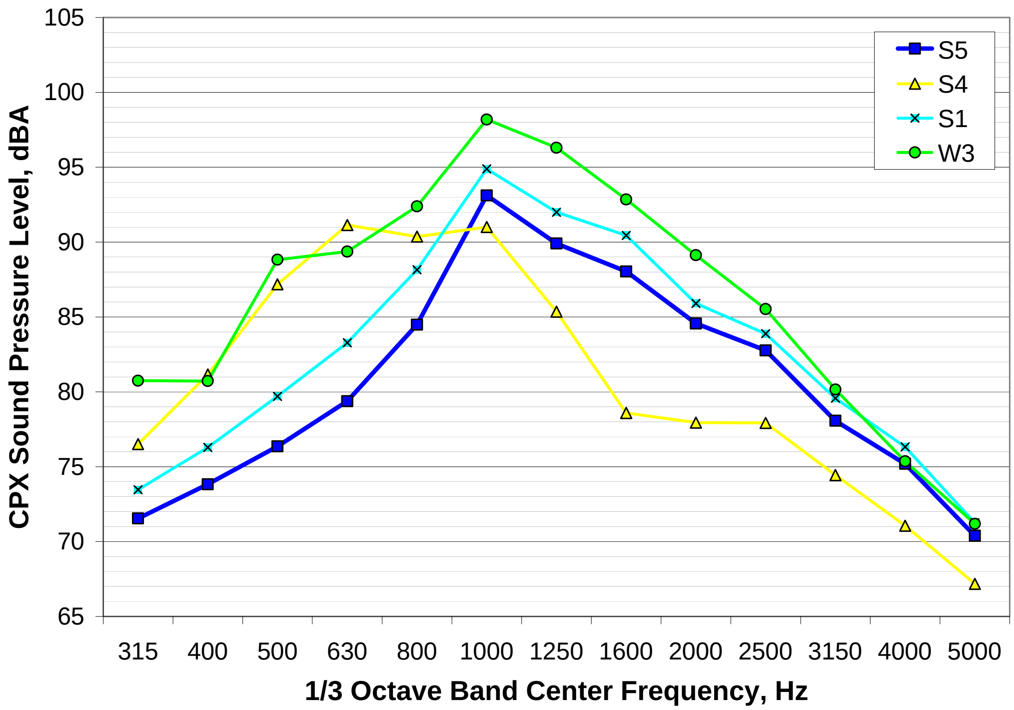

Figure 46: 1/3 octave band CPX levels for the SRTT test tire at 60/55 mph on each NCAT pavement section

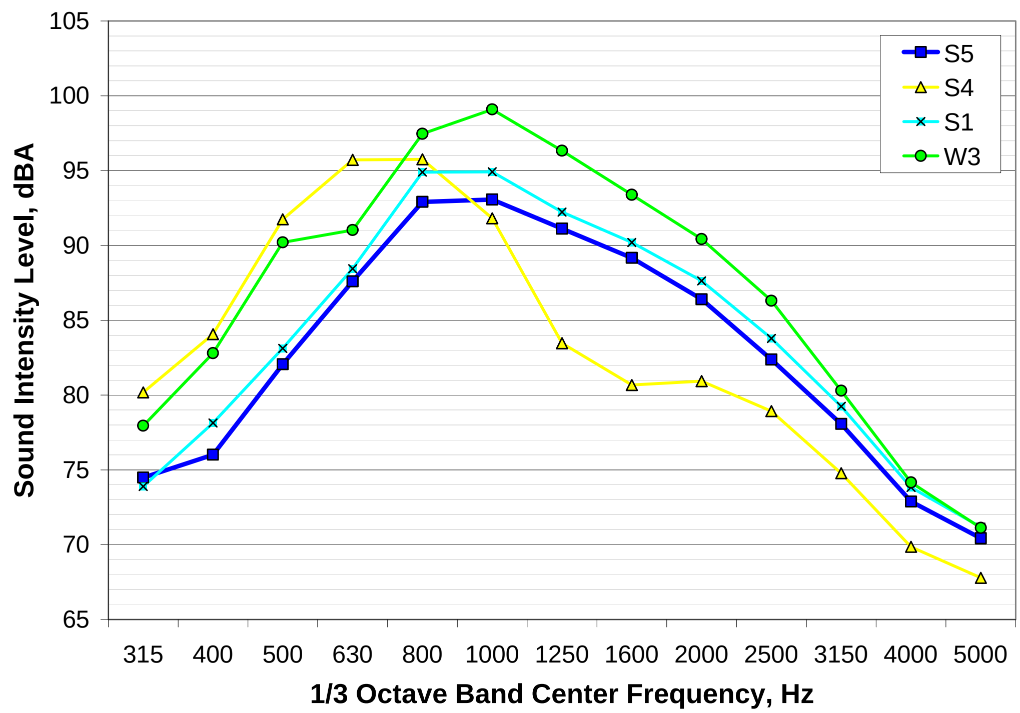

Figure 47: 1/3 octave band OBSI levels for the SRTT test tire at 60/55 mph on each NCAT pavement section

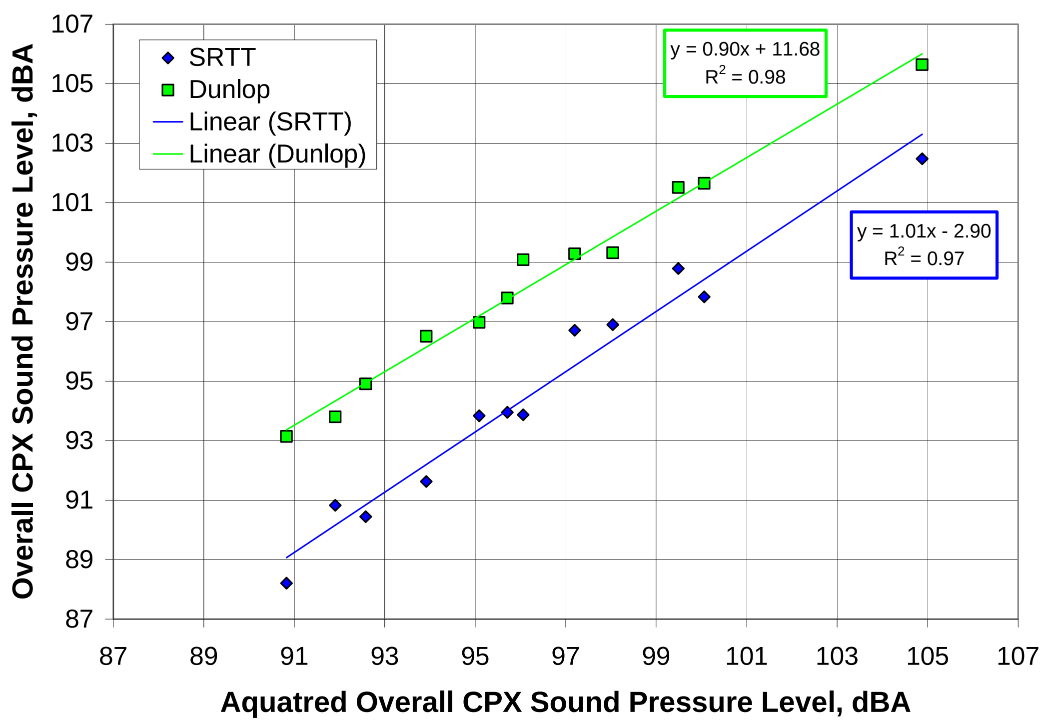

Figure 48: Noise relationship between the Goodyear Aquatred 3 test tire and the SRTT and Dunlop tires for all speeds on the NCAT pavement sections based on CPX data

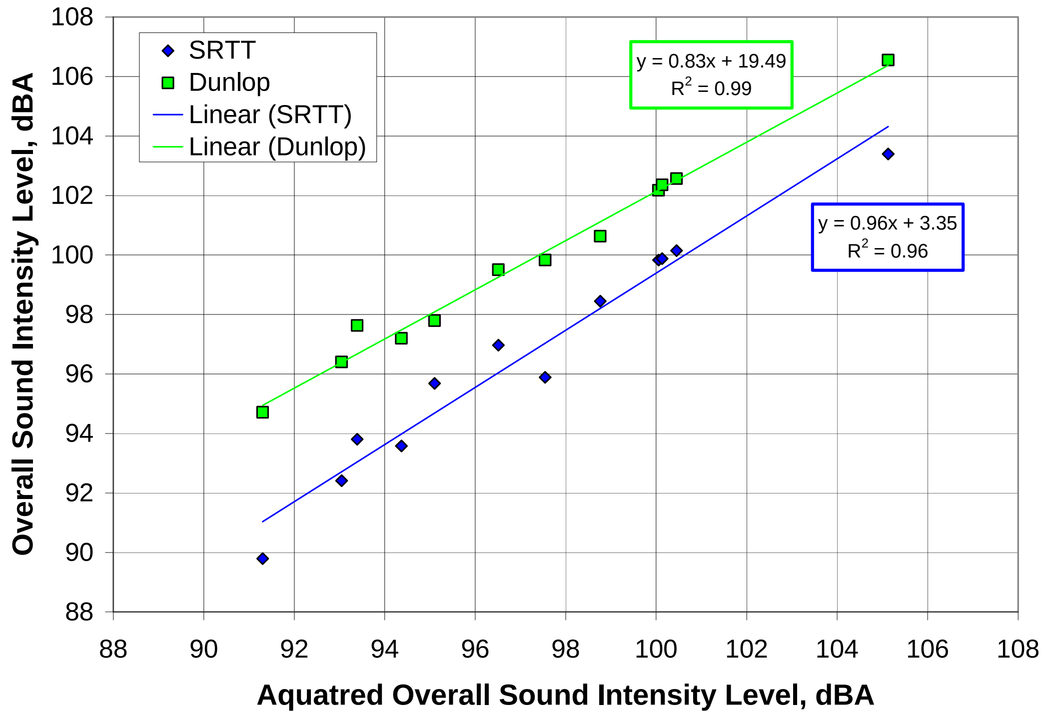

Figure 49: Noise relationship between the Goodyear Aquatred 3 test tire and the SRTT and Dunlop tires for all speeds on the NCAT pavement sections based on OBSI data

The other issue with tire type is the consistency of rank ordering of pavements. In Figs. 50 and 51, the overall A-weighted levels for all of the test conditions at the NCAT sections are shown for the CPX and OBSI, respectively. These data are presented for the pavements rank ordered based on the Aquatred 3 levels in each speed grouping. With one exception, the tires all rank order the pavements the same although the differences between pavements vary consistent with the scatter seen in Figs. 48 and 49. The one exception is in the CPX data (Fig. 50) at 35 mph where the SRTT measured slightly lower on S1 than S4 while both the Aquatred 3 and Dunlop tires measured 0.7 to 1.1 dB higher. Overall, consistent with other studies, rank ordering of pavements for tire noise generation was found to be independent of tire design to within about 1 dB or less[12,13,14]. As a result, any of these three tires could be used as the test tire and selection can be based on other factors.

RECOMMENDATION FOR TIRE-PAVEMENT TEST METHOD

Based on the literature of at-the-source, on-board tire-pavement noise measurement methods, the possibilities were narrowed to the CPX and OBSI methods. These were subsequently evaluated in the testing program conducted at NCAT and nearby Waverly, Alabama. Besides the technical merits of each approach, consideration was given to each in the areas of expense/practicality, and training/expertise to conduct the testing. All three of these aspects are reviewed in this section and final recommendation stated.

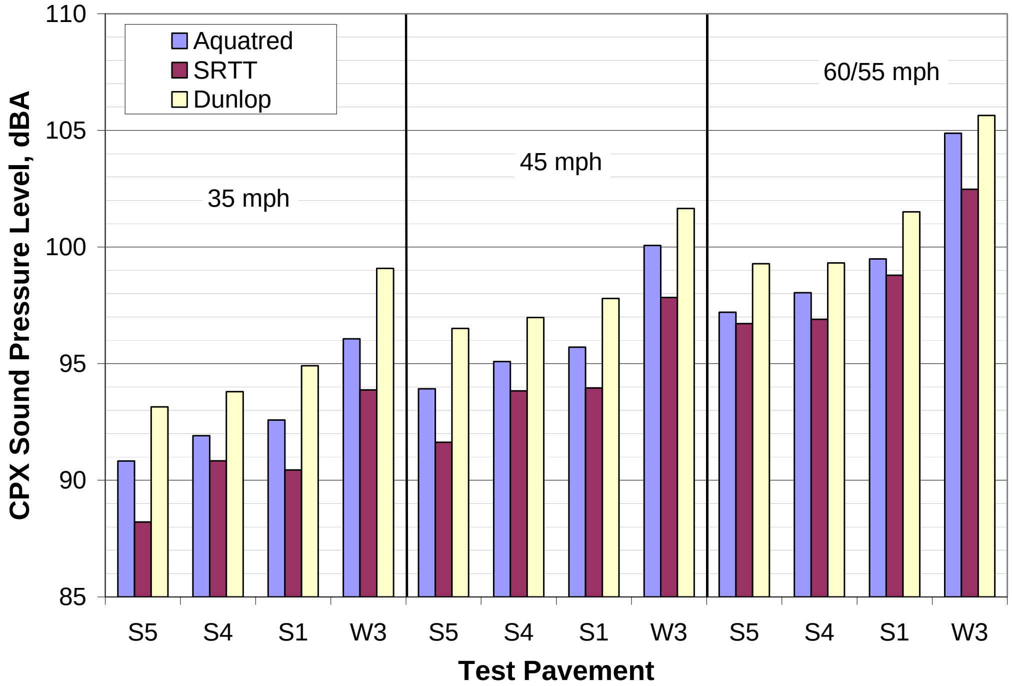

Figure 50: Rank ordering of pavements based on CPX levels of the Aquatred test tire with corresponding levels for the SRTT and Dunlop test tires

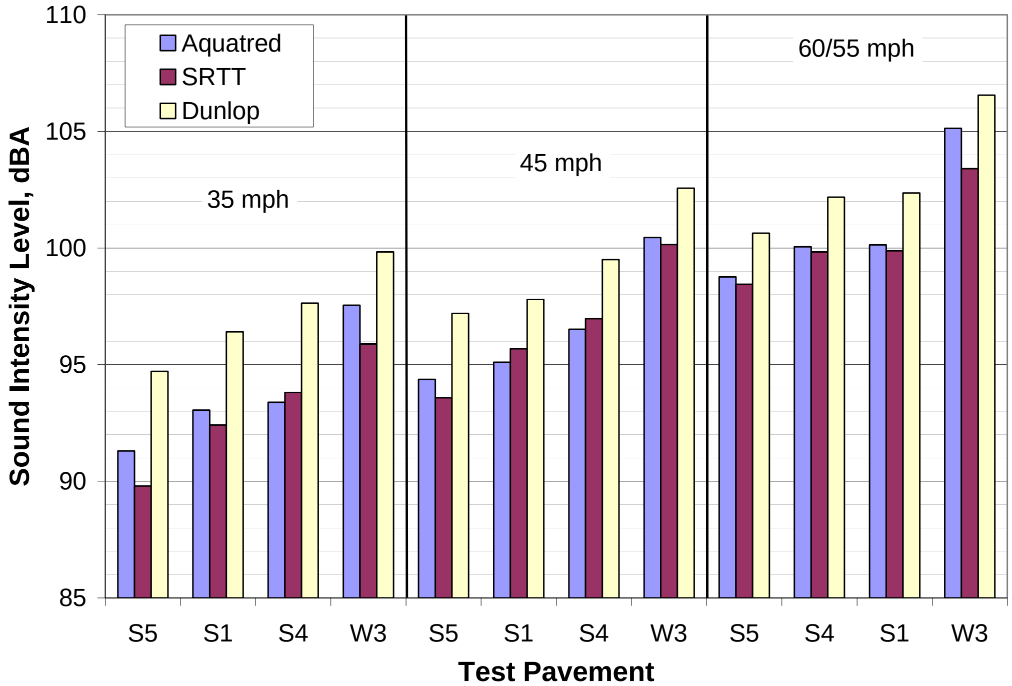

Figure 51: Rank ordering of pavements based on OBSI levels of the Aquatred test tire with corresponding levels for the SRTT and Dunlop test tires

Technical Aspects

In the area of technical aspects of a recommended test method, the overriding issue is: how well do the at-the-source measures correlate to passby data? Before tackling this issue, it is necessary to define the limits of this correlation. In this work, comparison is taken to be between tire-pavement noise measured at the source and *tire-pavement noise* measured at the wayside. As a result, measurements at the wayside are designed to minimize those source contributions that are not from the tire-pavement interface. A separate issue, which cannot be addressed by tire-pavement noise measurement at the source alone, is *overall* vehicle noise emission for arbitrary passby conditions and vehicles. The relationship(s) between tire-pavement noise as measured at the source methods or tire-pavement noise as measured at the wayside and overall vehicle noise emission can only be addressed by statistical methods. However, an extremely valuable tool in (statistically) determining how pavements effect overall vehicle noise emissions is having a method in which the contribution of tire-pavement noise to wayside levels can be identified. As a result, the question at hand is how well do the two alternative, at the source measures compare with passby data in which the vehicle is highly dominated by tire-pavement noise and the tires are same.

In terms of correlating overall levels for the CPX and OBSI measurements to the passby data, the results of Table 4 provide the simplest overview. For the nonporous pavement and excepting the Waverly site (center columns in Table 4), there may be a slight edge in favor of the OBSI measurements as the standard deviation about a 1-to-1 fit of the data is smaller than that of the CPX measurements. When the porous pavement, Section S4 is included (right columns), the standard deviations become identical with the only deviation of the linear regression of the CPX results from a slope of 1 being more of an issue than it is for the OBSI results. It should be noted that both source measures correlate well to passby even with the porous pavement included as indicated by the r^2 values and standard and average deviations. Given the scatter of the passby data (Figs. 11 through 15) is it not apparent that any better correlation could be expected. When the Waverly site is included (left columns), this can no longer be said. Although the OBSI results hold some small advantage over the CPX, the r^2 and standard deviations for both are not very acceptable. The Waverly site also re-enforces that an at-the-source measurement cannot account for an arbitrary range of site characteristics.

In terms of overall level, another indicator that there is no clear "winner" for the at-the-source measurement is the finding that the methods themselves correlate well to each other. These data suggest that within a standard deviation of 1.1 dB, CPX or OBSI source levels could be predicted from the other (Fig. 18). This is reduced to a standard deviation of 0.8 dB when the porous AC, Section S4, is excluded. It should be noted that the two methods do handle porous pavements differently. For the CPX method, the actual passby levels are consistently higher than what would be predicted from the CPX to passby correlation curve. For the OBSI method, the passby levels are consistently lower than what would be predicted. In other words, the CPX levels over predict the effect of porosity on the passby levels while the OBSI level under predict it. This is likely due to the CPX sound pressure measurements being effected by pavement sound absorption, while the sound intensity measurement is not (as much). Arguments could be made both ways as to which of these is more desirable for dealing with absorptive pavements.

One of the largest drawbacks for the CPX method is spectral distortion which occurs in comparison to passby and OBSI results. As noted in considering Fig. 21, the 1/3 octave band levels below 1000 Hz are consistently reduced by 3 to 4 dB relative to what would be expected from the passby spectra or the OBSI spectra. Although this spectral distortion has only subtle influence on the correlation of overall levels, some evidence of its effect was seen in the rank ordering of tires (Fig. 36). The effect of this distortion was also observed in comparing the SRTT and Dunlop test tires. In this case, although the differences between individual 1/3 band levels were similar for the on-board measures, some of the overall level differences were exaggerated for the lower speeds due the lower frequency content (800 Hz and below) particularly apparent for the Dunlop tire. It should be noted that although the spectral distortion apparent in the CPX results is a concern, it is not a "show-stopper". Using the techniques currently under review by ISO Working Group 33 which deals with CPX draft standard, corrections can be developed to account for the effects of the enclosure on the CPX measurements[15]. Also, spectral corrections can be developed using OBSI measurements[12] or controlled vehicle passbys. However, unless trailers were totally identical, these correction spectra should be done for each CPX trailer.

Expense and Practicality

The expense of implementing either the CPX or OBSI tire-pavement noise methods can be considered in three different areas: facilities, instrumentation, and man-hours. As with any measurement apparatus, the cost of the facilities can very greatly. Unlike the Technical Aspects discussed above, the areas reviewed below are more subjective than objective due to the (still) relatively low number of users of either the CPX or OBSI in the US. The Research Team has extensive experience in both methods, and this is drawn upon in the some of the discussion below.

Facilities Expense

For the CPX method, it is most common to conduct the tests in some type of enclosure to avoid unwanted wind noise on the microphones and to isolate the microphones from unwanted noise such as other traffic. For enclosures, the most common is the use of a special trailer designed to minimize reflections within the trailer. These trailers can range from relatively simple to very sophisticated. In the most elaborate case, a cargo van was modified to house an enclosure along with other pavement parameter measuring equipment. In the past, trailers have been available from at least two suppliers with the purchase costs in the range of $30,000 to $40,000 not including instrumentation. Depending on the resources of the investigators implementing the CPX method, suitable trailers may be built "in-house" with reduced external cost. In addition to the trailer, a suitable tow vehicle would be required to implement this CPX method. Several researchers have used externally mounted microphones to apply the CPX method which avoids the cost of acquiring a trailer. However, there is considerable concern for the possibility of wind noise on the microphones creating background noise that can not be readily detected[14]. In addition, there are issues regarding other noise sources on the test vehicle and noise from other vehicles in traffic. These issues exist for trailers also[2], however, they become more of a concern for exposed microphones. Even aside from the wind noise concern, the use of an exposed CPX measurement may require more restrictive testing such as testing in the outside lane only and/or testing under very light traffic conditions where other vehicles can be avoided.

For the OBSI method, facility costs are much lower. The parts required to build a fixture to hold the OBSI probe can be purchased from a machine shop for $2000 to $2500. OBSI fixtures have also been constructed in-house depending on the resources available. Typically, OBSI has been used directly on a test vehicle so that there is, in principle, no additional facilities cost in implementing the method if a suitable vehicle is available. With some precaution, OBSI has also been on different vehicles of the same vehicle "platform"[15]. The OBSI method has also been implemented on test trailers without sound enclosures minimizing the need to have a specific test vehicle readily available.

Aside from the potential costs associated with a tow vehicle for the CPX trailer method and a vehicle test for the OBSI method, the primary additional cost in implementing the CPX method is the trailer from a facilities viewpoint.

Instrumentation Costs

As with facilities, instrumentation required to implement either the CPX or OBSI ranges from simple to elaborate. For the CPX method, the requirement is to measure sound pressure level. This is done at two locations and could, in principle, be done one at a time with repeated passes other the same pavement section. This would require only one microphone and one sound level meter (SLM) if the two locations were measured independently. In practice, investigators use two microphones to simultaneously measure at the front and rear positions and sometimes more to simultaneously measure at the optional microphone positions of the CPX draft standard. These measurements could be done with two (or more) independent SLMs, however, as a practical matter, the investigators typically use at least a two-channel analyzer to capture and process their data. Using two SLMs instead of a simple two-channel analyzer would produce a cost savings on the order of 65 to 70%.

For the OBSI method, a minimum of two microphones is required. Further, at least a simple two-channel analyzer is required. Most modern two-channel (or more) analyzers come with sound intensity as a standard measurement requiring no additional cost over the same, simple, two-channel analyzer that may be used for CPX measurements. As a result, instrumentation costs for implementing the CPX method measuring two microphones simultaneously is about the same as that required for OBSI. However, it should be noted that the test time is not equivalent. For the OBSI method, two passes over the same pavement (one with the probe at the leading edge of the contact patch and one for the trailing) are required instead of one pass for the CPX method. This test time discrepancy can be overcome by measuring with a two-probe OBSI fixture, however, this almost doubles the cost of the OBSI instrumentation.

Man-Hours

The man-hours required to implement either the CPX or OBSI methods can be considered to be divided into test and analysis time and maintenance and support time. For test time, using dual, simultaneous measurement locations at the front and rear of the tire, the two methods are the same. As noted above, if the front and rear positions are done in series, the time for operation at the test location will be double. The time required for data analysis of the either data will depend more on the specific analyzer used than on the type of data. In terms of operation, for safety reasons, it can not be recommended that any less than two people are required to conduct the test, one for operating the instrumentation and one to operate the test or tow vehicle.

For either approach, some initial time will be required to validate the measurement system. For both systems, instrumentation checks should be performed to validate the data acquisition process. Also for both, some preliminary on-road data should be acquired and checked. For the CPX method using a trailer, the ISO draft procedure recommends additional tests to examine the effects of the enclosure on the sound pressure level data and the ability to isolate the CPX microphones from outside sources including the tow vehicle. Depending on the rigor employed, this testing could be somewhat time consuming and require special facilities such as a road-wheel. In addition, there is likely to be on-going maintenance required for the CPX trailer to maintain its acoustic and mechanical performance. If the CPX method is implemented without a trailer/enclosure, validation testing needs to be conducted to examine the effects of wind noise, other noises on the test vehicle, reflections from the test vehicle, and the influence of other traffic. These tests may also require the use of special facilities such as an anechoic wind tunnel and a road-wheel in a semi-anechoic space. In general, the CPX method will probably require somewhat more man-hours for up-front validation. For a CPX trailer, additional man-hours will be required for ongoing maintenance for the acoustic properties and mechanical operation.

Practicality Issues

Many of the issues regarding the practicality of either the CPX or OBSI depend on the needs and resources of the team implementing the method. As taken here, “practicality” means the ease at which the test work can be done aside from the man-hours discussed above. The issues mentioned in this section are more thought starters and observations of users of both methods as opposed to absolutes. Practicality issues arise both for individual users and the process for implementing a nation-wide standard test procedure.

Most of the users who employ the CPX method do it with trailers. Trailers require a tow vehicle suitable for towing them. Depending on the resources of the agency or company, this may require the acquisition of a vehicle specifically for this purpose. Part of the validation testing following the ISO draft standard requires establishing that the tow vehicle be sufficiently quiet so as not to interfere with the CPX measurement. Within some reasonable limits, it may be possible to use or rent different tow vehicles eliminating the need for a dedicated vehicle. Another issue using a trailer is the availability of a vehicle operator who is comfortable with towing a vehicle. Also, there is the issue of storing the trailer when not in use. Generally, a trailer/vehicle combination will suffer from maneuverability constraints in traffic, possibly requiring more distance to accelerate to highway speed and more braking distance. If instrumentation such as long cables and preamplifiers can be dedicated to the test trailer, set-up time for individual tests can be reduced to the point of installing and calibrating the microphones and transporting the trailer to the test site. Also, trailers can be designed to accommodate a range of tire and wheel sizes.

Most users of the OBSI method apply it directly on test vehicle. This can be done with no permanent modifications to the vehicle and equipment can be readily removed allowing the vehicle to be used for other purposes. This does add set-up time, however, as instrumentation and test fixtures will need to be added back on the vehicle as well as a test tire(s) mounted. In principle, the OBSI could be applied on any vehicle that would accept the test tire size. There is some concern with other noises such brake noise and axle noise which propagate to the OBSI probe in the same direction as tire noise. Also, variation in tire alignment, particularly toe-in/out[16], can be an issue that should be considered. It is advisable that a non-driven wheel is used for the testing and that all-wheel and 4-wheel drive vehicles be avoided due to the possibility of applied torque increasing the tire noise level[17]. On-vehicle OBSI testing may also apply some restrictions on the tire and wheel sizes that can be used, or conversely, a standard test tire may limit the choice of test vehicle. Some of these issues can be overcome by the use of an open-wheel trailer, however, there are issues to consider with the use of a trailer as discussed above. The use of a trailer would also negate the portability feature of the OBSI approach.

From the perspective of implementing a common standardized test procedure, there are additional practical issues of concern. In Europe, there is quite a range in CPX trailer design and resulting acoustic performance. This tends to be one of the bigger issues faced by this user group[15]. To implement a procedure in the US that would generate consistent noise levels and be implemented in a short period of time, having a standardized trailer/enclosure design would be most advisable. However, even with essentially the same design, the two active CPX trailers in the US, both built by NCAT, were found to produce tire-pavement levels an average of 1.3 dB different from each other with a standard deviation of 0.9 dB with 5 out 12 comparison points being in the range from 1.7 to 2.4 dB[7]. Even if a common, consistent design were developed and validated, it seems unlikely that all potential users in the US would adopt it and/or purchase it from a single supplier.

There is similar concern for implementing the OBSI method as a standard procedure. To date, a number of different methods of fixturing the OBSI probes have been implemented by various users. However, the investment in hardware is quite low in comparison to a

CPX trailer and, as a result, communizing a procedure and hardware, where necessary, may not be a large issue.

Training and Expertise

The training and expertise required for measuring tire-pavement noise at the source by either the CPX or OBSI method, on the surface, seems to be very similar. In applying either method, good experimental practices must be applied to obtain good data. Basically, either method requires that two microphone channels be properly calibrated and the proper sound pressure or sound intensity measurement option selected on the analyzer. The complexity of these operations depends very much on the specific instrumentation used and how much of a test setup can be stored and retrieved for the test. To assure that the data is "good", other checks should be implemented. The most basic of these is to listen to the output signals of the microphones. This is the simplest way to detect rattles, stone pings, wind noise, or other unusual noises in the CPX or the OBSI data. The data should also be compared to previous results as a consistency check. For either measurement, some amount of training will be necessary for any user/operator who has not been involved in acoustic measurements previously.

For getting started with the OBSI measurements, there are several features which do add some complication. Conceptually, sound intensity is not as physically intuitive as sound pressure. One cannot hear sound intensity, only sound pressure. Also sound intensity is a vector quantity so that microphone orientation is more critical compared to a sound pressure measurement. In setting up a sound intensity measurement, microphone spacing needs to be specified and significant variations from standard conditions which effect air density need to be noted and possibly corrected for in the analyzer or after data collection. The two microphone channels used for the sound intensity measurement need to be phase matched which is usually done by purchasing phase-matched microphones available from a number of suppliers. Sound intensity has been a standardized measurement for twenty years[18] and is commonly available on two (or more) channel acoustic analyzers. As a result, many of the instrument suppliers provide documentation and training material on its measurement.

Another aspect of training and experience is the mechanical operation of the test equipment. Training will be required for either method. For the CPX method, training of the operation and setup of the trailer will be necessary. For the OBSI method, training will be required on installing the test fixture and setting it up for measurement.

Recommendation for Tire-Pavement Test Method

Based on the work of Phase I of this project, it is recommended that OBSI method be used as a basis for developing an on-board, at-the-source measurement procedure for tire-pavement noise. The reasons for this recommendation are summarized as follows:

- Slightly better correlation between OBSI and passby data than for CPX data

- Lack of spectral distortion seen in comparing OBSI and passby data compared to CPX
- Expense of an enclosed trailer for CPX measurements
- Practical issues of acquiring, validating, operating, maintaining and storing a CPX trailer

Two of the four issues cited above deal with the use of a CPX trailer. The option of exposed microphone CPX is attractive from a cost and ease of implementation point of view, but technical issues of wind noise, test vehicle reflections and other noise, and operation in traffic are almost certain to lead inconsistency from one user to another. On the other hand, the issues against an OBSI approach do not appear to be significant enough to preclude its use.

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