ACKNOWLEDGMENT OF SPONSORSHIP

This work was sponsored by the American Association of State Highway and Transportation Officials, in cooperation with the Federal Highway Administration, and was conducted in the **National Cooperative Highway Research Program**, which is administered by the Transportation Research Board of the National Academies.

DISCLAIMER

Project 1-44 (1)

Measuring Tire-Pavement Noise at the Source: Precision and Bias Statement

July 14, 2011

Prepared for:

National Cooperative Highway Research Program
Transportation Research Board of The National Academies

Prepared by:

Dr. Paul R. Donavan
Illingworth & Rodkin, Inc.
Petaluma, CA 94952

Dana M. Lodico, P.E., INCE Bd. Cert.
Lodico Acoustics LLC
Englewood, CO 80112

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

AUTHOR ACKNOWLEDGEMENTS

The research reported here in was performed under NCHRP Project 1-44(1) by Illingworth & Rodkin, Inc., Petaluma, California; Dr. Paul Donavan was the principal investigator. Lodico Acoustics, LLC, Denver, Colorado served as a subcontractor for all phases of this research and participated in data acquisition and analysis. Chris Peters and Carrie Janello, also of Illingworth & Rodkin, Inc, assisted in the test track field work and data analysis.

The authors acknowledge the assistance provided by Matt Seare and Kyle Taylor of the Hyundai·Kia America Technical Center, Inc. in the use of the Hyundai·Kia Proving Ground for the test track measurement programs. Liaison the use of these facilities was provided by Bruce Rymer of Caltrans. The authors also acknowledge the assistance provided by Alan Parrett and James Zunich of the General Motors Proving Ground in Milford, Michigan, in the use of General Motors wind tunnel and tire noise dynamometer for the laboratory test portions of this research as well as the assistance of staffs of these facilities in performing the testing.

SUMMARY

MEASURING TIRE-PAVEMENT NOISE AT THE SOURCE: PRECISION AND BIAS STATMENT

The research performed under NCHRP 1-44, "Measuring Tire-Pavement Noise at the Source", recommended a procedure for measuring tire-pavement noise using the on-board sound intensity (OBSI) method. The objectives of the research performed in the NCHRP Project 1-44 (1) "Measuring Tire-Pavement Noise at the Source: Precision and Bias Statement" were to develop and recommend modifications to the recommended method of test and to determine the precision and bias statements for this method. This was accomplished through a series of test track measurements completed in four events spanning a 10 month period and through laboratory measurements conducted on a tire noise dynamometer with replica road surfaces and in an aero-acoustic wind tunnel. The results of four comparative OBSI test "rodeos" were also analyzed to examine test team-to-team variability.

Recommendations to reduce uncertainty in the OBSI measurements were developed and incorporated in a revised Method of Test. These are enumerated in Chapter 6 and summarized here. A temperature correction of -0.04 dB/ºF is recommended to be applied to sound intensity data acquired with the analyzer set to standard conditions of 68ºF (20ºC) and 101.3 kPa atmospheric pressure effectively normalizing the reported levels to these conditions. In order to identify contamination from background noise due to other noise sources, a frequency dependent pressure to intensity (PI) index ranging from 2.5 to 5 dB was developed. A criterion of being 15 inches or more from sound reflecting surfaces was recommended. Crosswind conditions were also recommended to be no greater than 8 mph. Criteria for determining when test tires should be retired were determined. Tolerances on the data acquisition start location were defined at ±10 ft (0.23 seconds at 60 mph) and the vehicle speed tolerance was set to ±1 mph. Air temperature was restricted to a range from 40 to 100ºF. Tire loading was revised downward to 800±100 lbs from the previously recommended nominal of 850 lbs and probe fore/aft separation changed to 8¼ inches centered on the axis of rotation of the tire instead of being defined by determination of the more ambiguous tire contact patch. In addition to these changes, the existing requirements in the procedure were confirmed.

Based on the recommended revised OBSI Method of Test, uncertainties and limits on precision and bias were developed. Precision was considered in two parts. For repeatability, a single operator testing on the same pavement under the same environmental conditions within a single test session, the uncertainty was determined to be ±0.2 dB with a limit of 0.6 dB. Precision reproducibility for multiple test teams measuring under the same environmental conditions or a single test team measuring over multiple days was determined to be ±0.4 dB with a limit of 1.1 dB. Bias resulting from longer periods of time between tests or from site to site was determined to be ±0.5 dB with a limit of 1.4 dB.

CHAPTER 1

BACKGROUND

In 2008, research was completed on the NCHRP Project 1-44, entitled “Measuring Tire-Pavement Noise at the Source”. The final report was subsequently published as NCHRP Report 630[1]. The objectives of this project were to (1) develop rational procedures for measuring tire-pavement noise at the source and (2) demonstrate the applicability of the procedures through testing of in-service pavements. This work resulted in the “Proposed Method of Test for Measurement of Tire-Pavement Noise Using the On-Board Sound Intensity (OBSI) Method”[1]. The results of this research were also largely incorporated into an American Association of State Highway Transportation Officials (AASHTO) provisional Standard Method of Test entitled “Measurement of Tire/Pavement Using the On-Board Sound Intensity (OBSI) Method” TP76-11 (proposed). As the number of practitioners of the OBSI method grew and more comparative testing took place, interest developed in documenting the precision and bias of the procedure. NCHRP Project 1-44 (1), “Measuring Tire-Pavement Noise at the Source: Precision and Bias Statement” was initiated to address this need with the resultant objective of developing a precision and bias statement for the test method reported in NCHRP Report 630[1].

Findings from NCHRP 1-44 Project

In addition to developing and demonstrating rational procedures for measuring tire-pavement noise at the source, Project 1-44 research also included an initial investigation into precision repeatability, precision reproducibility and bias issues. The evaluation of test parameters included sound intensity probe configuration and orientation, variations in location of the probes, test speed, tire inflation pressure, tire loading, temperature, and the use of different test vehicles. Run-to-run repeatability was also documented for consecutive test runs or repeats, as was reproducibility from day to day. In these parameter investigations, the ranges of variable values were defined to be perturbations around a defined vehicle type, tire, and instrumentation system in a baseline condition. This testing identified OBSI probe location in the vertical direction, vehicle speed, and vehicle loading to be greatest causes of variation for the ranges and parameters evaluated. Within reasonable limits, probe distance from the tire, probe fore/aft location, and tire inflation pressure were found not to be critical. Based on these results, parameter limits were established for the OBSI procedure. Table 1 summarizes the parameter limits and criteria for the test procedure.

Based on the initial investigation into precision and bias issues, a number of recommendations for further research were identified including the effects of large temperature ranges, the effects of other environmental conditions, and the need for comparative testing between different operators and measurement systems. With the selection of the ASTM Standard Reference Test Tire (SRTT)[2], issues of tire-to-tire variation and tire performance over time were also identified as areas deserving further investigation. These are addressed in Project 1-44(1).

Table 1: Data Quality Criteria and Recommended Parameter Limits

Parameter	Data Quality Criteria
Run to Run Range, Overall A-Wtd OBSI level	Within 1 dB
Run to Run Range, ⅓ Octave Band Levels	Within 2 dB
Coherence	> 0.8 for frequencies below 4000 Hz
PI Index	< 5 dB for data reported as valid
Parameter	**Parameter Limits**
Probe Location, Vertical	75 ± 6 mm (3 ± ¼ in.) above pavement
Vehicle Test speed	97 ± 1 km/h (60 ± 1 mph)
Tire Inflation Pressure (Cold)	207 ± 14 kPa (30 ± 2 psi)
Wheel Load	385 ± 45 kg (850 ± 100 lbs)
Probe Location, Fore/Aft	200 ± 13 mm (8 ± ½ in.)
Probe Distance from Tire Sidewall	100 ± 13 mm (4 ± ½ in.)

Other Findings

Literature Review Summary

The literature review conducted as part of the NCHRP Project 1-44 included historical information regarding precision and bias for at the source tire-pavement noise measurements and are documented in NCHRP Report 630[1]. Since that time, more information has been added to the technical literature on parameters that affect tire noise generation and measurement. As described below, recent literature has focused on temperature effects, pavement variations over a test section, and test tire variables.

Previous investigations of the effects of temperature on OBSI level have generally found that tire/pavement noise decreases with increasing temperature and that this relationship depends on tire and the pavement[3,4,5]. Generally, these data were obtained for a limited range of temperature or are composite of data not necessarily taken to solely address temperature effects. Temperature affects the measurement of sound intensity due to the finite difference approximation used in its computation that includes the density of air, which is determined largely by air temperature and barometric pressure. Although theoretically a correction for air density should be made, it has not been demonstrated experimentally in the literature whether applying the correction improves or detracts from the precision of the sound intensity measurement.

In terms of the effect of pavement variation within a given test section, it is thought that significant variation in the noise of a pavement over short distances could display itself as higher than usual (greater than 1 dB) run-to-run variation due to OBSI results being sensitive to wheel path tracking and start/stop location accuracy. Variations of several dB in OBSI level have been reported to occur locally for some pavements over the standardized sampling distance of 440 ft[6,7,8]. Some researchers have also noted that variations of several dB can also occur in and out of a worn wheel path.

It has become increasingly clear through the literature that test tire differences introduce variability[9]. Generally, tires exhibiting more wear and aging, as measured by tire durometer hardness and tread depth, produced higher OBSI levels. The results of one in-depth study that measured OBSI levels with simulated increases in durometer hardness and with variations in tread depth[10] was largely inconclusive as the effects varied with tire type and test methods and test facilities used. This research indicated that the development of any such wear relationships should cover a wide range of pavements and be specific to a given test tire design (the SRTT was not included)[10]. Research specific to the SRTT tire found no consistent difference in OBSI level between new tires and those with up to about 1,200 miles and 2½ years of age[11]. Further, no consistent difference was found for tires ranging in durometer hardness from 62 to 66. The tire-to-tire variation was about 0.5 dB on average for four new tires measured on six AC and PCC pavements with a range as high as 1.1 dB for one of the pavements. In one study, conducted on a road-wheel simulator with a smooth asphalt replica surface, new SRTT tires with minimal break in were 1 dB higher in level on average than one-year old tires with about 300 miles accumulated[12]. However, tire durometer hardness was not measured as part of this experiment.

OBSI Comparative Testing

Concurrent with the research in NCHRP 1-44 (1), the Tire/Pavement Noise Research Consortium Pooled Fund TPF-5(135) sponsored four sets of comparative testing (rodeos) between OBSI users[13,14,15,16]. The first set of testing was conducted at the test track of the National Center for Asphalt Technology (NCAT), the second at the General Motors Desert Proving Ground in Yuma, AZ, the third on in-service roads in the vicinity of Austin, TX, and the fourth on in-service roads near the town of Elkin, NC. Detailed results of the comparative tests are described in the individual project reports[13,14,15,16]. This section gives a brief summary of the overall results of the comparative tests relevant to this current project (see Appendix F for further details).

The measurements for all four rodeos were performed within the limits of the recommended method of test from the NCHRP Report 630[1]. For the comparative testing near Austin, the results from three test teams fell within a maximum range of 2.0 dB for all of the test sections with an average range of 1.3 dB. The initial comparison among the four test teams in Elkin, NC resulted in an average difference from test section to section across the teams of 1.3 dB, with a standard deviation of 0.5 dB, and a maximum difference for any one pavement of 2.3 dB. A similar rodeo conducted in Mesa, AZ[9] produced a maximum range of 2.2 dB with an average range of 1.3 dB for four test teams on nine pavement surfaces. These average differences are consistent with the Yuma, AZ and NCAT comparisons, although a larger (1.1 dB) standard deviation was encountered at NCAT due to discrete tire/pavement interactions[13]. Earlier research found a range of 0.8 dB with a standard deviation of 0.3 dB for ten consecutive runs with the same equipment configuration and test tire/vehicle combination on a stud damaged concrete and smooth asphalt pavement[1]. The differences seen in the rodeos are likely due to a combination of environmental, tire, loading, and vehicle/operator variables.

The largest source of variation was found to be due to tires. However, from these limited data sets of the rodeos, no clear correlation between tire hardness, tread depth, age and tire-pavement level were identified. In the comparative testing, test tire loading ranged from about 700 lbs to 930 lbs for different vehicles under baseline conditions; however no clear trend with loading could be established. As a group, the results suggest that this variable may not be independent of other vehicle and/or tire parameters. Applying increasing load to a single vehicle typically results in increases in tire/pavement noise as demonstrated in the Yuma, AZ rodeo, NCHRP Project 1-44[1], and the results for this research reported in Chapter 4.

In the comparative testing, as well as previous research[1] and results from the literature[3,4,5], small but fairly consistent effects of temperature were observed over relatively small temperature ranges. These effects generally display the expected trend of decreased noise level with increasing temperature. Because of the relatively small temperature gradients involved compared to the uncertainties in other factors, temperature effects for the SRTT tire could not be thoroughly analyzed from the comparative tests. In the comparative testing, two instances of damp pavement were encountered. In the Texas testing, damp pavement was suspected to be a cause of some variation, but not conclusively demonstrated. In the NCAT testing, visible dampness was of no consequence even for porous pavements.

"Precision" and "Bias"

The purpose of this research was to develop a precision and bias statement for the "Proposed Method of Test for Measurement of Tire-Pavement Noise Using the On-Board Sound Intensity (OBSI) Method", included in the NCHRP Report 630. Based on the definitions provided in the ASTM Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials[17], "precision" is defined as variation for a single operator (repeatability) and variation between laboratories when testing the same material (reproducibility), in this case pavement. "Bias" is defined as the systemic error inherent in the test method. For purposes of application to this research project, precision is considered as uncertainty that occurs for a pavement measured under the same conditions made in a short time interval, two hours for instance. Bias is defined as the uncertainty that occurs over a longer time interval or from one site to another and is not accounted for in the test procedure either by limits or corrections. Precision and bias statements are developed in Chapter 5 and further details are provided in Appendix A.

CHAPTER 2

RESEARCH APPROACH

Research Objectives and Scope

The objective of this research was to develop a precision and bias statement for the OBSI test method that was developed and demonstrated in the NCHRP Project 1-44[1]. Supporting objectives were to identify any further parameter controls that would reduce the uncertainty in results obtained with the procedure and to update the proposed method of test accordingly. The research was to experimentally and analytically assess variables that could decrease measurement uncertainty. These included the environmental effects of temperature over a large range, pavement moisture, and ambient wind conditions, tire parameters including tire-to-tire variation, loading, and aging effects, variation across users, roadway geometries, and noise contamination from other sources and reflective surfaces.

Approach

The research included the following tasks:

Task 1: Collect and Evaluate Information

Although much of the historical information regarding precision and bias for at the source tire-pavement noise measurements was collected during the NCHRP Project 1-44, additional findings had been reported and were available in the literature. This material was reviewed for consistency in this project. This information was used to define gaps in the existing knowledge, identify the most critical needs for additional research, and to define the test plans described in Task 2.

Task 2: Plan and Conduct Initial Test Studies

Planning and conducting tests to evaluate the precision repeatability issues identified in Task 1 and to determine the precision reproducibility and bias limits was split into two tasks, Task 2 and 4. The initial testing in Task 2 included OBSI measurements conducted in test track and laboratory environments. All test track measurements were performed at the Hyundai-Kia Proving Ground in California City, CA, in the Mojave Desert. This location was chosen because of the extremes of temperature under which testing could be conducted over a yearly seasonal cycle and the availability of large number of special surfaces designed to represent in pavements in common use. The laboratory measurements were conducted at General Motors facilities in Michigan which included a tire noise dynamometer with smooth and coarse replica road surfaces and an aero-acoustic wind tunnel. The initial test track measurements of Task 2 focused on measuring eleven new SRTT test tires to examine new tire variability and to serve a baselines for follow-up testing, measuring a range of older, in-service tire tires, measuring OBSI under a range of cooler temperatures (February and March), and examining run-to-run repeatability and team-to-team reproducibility. Tests on the road-wheel simulator were conducted to examine run-to-run repeatability under very controlled conditions, tire warm-up, small variations in speed, the effect of reflecting objects, the effect of nearby background noise sources, and the increase in noise for drive tires under level and up-grade cruise conditions. Wind tunnel tests were conducted to determine limits on crosswind conditions for the OBSI measurement procedure and to examine wind-induced vehicle background noise levels.

Task 3: Evaluate Comparative Testing among OBSI Users

Over the course of the project, four OBSI rodeos were held as sponsored by the Pooled Fund TPF-5(135) [13,14,15,16]. The research team participated in each of these events and analyzed the results for use in this project. These rodeos occurred in four different locations in the country and involved a total of seven different measurement teams. The data produced by these events provided additional information on variability due to instrumentation, operators, vehicles, tires, and procedures. Based on results of Tasks 1 through 3, a work plan for the remaining research was developed and executed.

Task 4: Conduct Further Testing to Address Reproducibility and Bias

Tests were conducted on the test track facilities of the Hyundai-Kia Proving Ground. The tested was conducted in two sessions; one under warm to hot conditions in late September and one under cool to cold conditions in mid December. The hot weather testing concentrated primarily on the effects of temperature on the OBSI measurements. The cool weather testing included continuation of the temperature variation study, re-testing of the 11 tires evaluating the effects of accelerated ageing, in-use service, test reproducibility over a one year span, and the effect of the wheel width.
In the both the hot and cool weather test sessions, limited pass-by testing for the different temperatures was also conducted to form a more complete understanding of the effect of temperature on tire noise generation independent of the OBSI method. On-highway testing was also conducted to evaluate horizontal curvature effects.

Task 5: Investigate Methods for Calibration of OBSI Measurement Systems

To enable OBSI users to validate their sound intensity measurement system, methods of performing complete end-to-end checks or calibrations were explored. There are currently no commercially available devices to do this task. The existing standards for sound intensity measurement only address the probe components in terms of sound pressure measurement and residual indicated sound intensity. Under this task, the feasibility of using a device(s) to perform at least relative comparisons between OBSI systems was investigated and recommendations were developed.

Task 6: Develop Proposed Revisions to OBSI Procedure

Revisions to the current proposed OBSI procedure were developed based on the research performed in this project and were incorporated into a revised proposed method of test provided in Attachment 1. This report documents the research conducted, the proposed revised OBSI procedure, and precision and bias statements.

Report Organization

The remainder of this report consists of five additional chapters, references, an attached proposed revised standard method of test for OBSI, and five appendices. In Chapter 3, the test track and laboratory test programs are described with the results of this testing presented throughout Chapter 4 under the topics of the effects temperature, test tires, test parameters, environmental conditions, instrumentation, and vehicle/operator differences on the OBSI repeatability and reproducibility. In Chapter 5, precision and bias statements are developed based on the findings of Chapter 4. To enable these precision and bias statements, revisions to the proposed standard method of test are presented in Chapter 6. Recommendations and suggested research resulting from this project are discussed in Chapter 7 in regard to implementing the test procedure, coordination with other tire-pavement noise measurement procedures, and additional related research. The proposed revised standard method of test is also included as Attachment 1 at the end of the main body of the report. Appendix A provides reviews of earlier NCHRP research and the relevant literature and a definition of precision and bias as it applies to OBSI. Appendix B describes the effect of air density on OBSI measurements theoretically and empirically. Appendix C provides a detailed description of the test track measurements and the results of the tests conducted in February and March while Appendix D and E provide similar information of the tire noise dynamometer and wind tunnel testing, respectively. Appendix F includes descriptions and summaries of the OBSI comparative testing that occurred during the time of this research.

CHAPTER 3

TEST PROGRAMS

The test program included measurements made on-road using a test track and in laboratories under more controlled conditions. The test track measurements addressed temperature effects, test repeatability, tire-to-tire variability over different parameters (e.g., hardness, age, mileage, etc), and other test parameters. Laboratory measurements, conducted in a wind tunnel environment and on a tire noise dynamometer, primarily evaluated the effects of background noise from wind and other noise sources on OBSI measurements. These measurement programs are summarized in this chapter with more thorough details provided in Appendices C, D, and E for the test track, dynamometer, and wind tunnel testing, respectively.

Test Track Measurements

OBSI measurements were conducted at the Hyundai Kia (H·K) Motors California Proving Grounds (HATCHI), near California City, California. This facility has a variety of pavement types specifically designed to replicate many of the pavement type types in use in southern California and included both asphalt and Portland cement concrete pavements. Previous testing had shown that SRTT OBSI levels range from 92.6 to 104.6 dBA for 15 of the H·K surfaces[18]. The testing was conducted on ten of these pavements in four sessions in 2010; February 9th through 12th, March 15th through 18th, September 27th through 28th, and December 13th through 16th.

Facilities and Equipment

Ten pavement surfaces were tested representing a variety of design categories and covering a range in the noise level of about 10 dB. The test sections included eight AC pavements and two PCC pavements. The AC pavements consisted of two dense-graded asphalt concrete (DGAC) pavements with maximum aggregate sizes of ⅜" and ¾" (⅜" DGAC and ¾" DGAC, respectively) , an open-graded asphalt concrete (OGAC) pavement, an AC pavement that had been sand blasted and ground (Sand Blast), a slurry-sealed surface (Slurry Seal), a chip seal pavement (Chip Seal) with a maximum aggregate size of ¾", an AC of fine aggregate producing an "ultra smooth" surface (Ultra Smooth) and an AC pavement intended to be porous, but as constructed was not porous (Porous). The PCC surfaces included one longitudinal tine texture (Long. Tine PCC) and one with diagonal broom texture (Broom PCC). For propriety reasons, further construction details of these pavements were not provided by H·K, however, photographs of the test surfaces are provided in Appendix C.

A total of 17 tires were used in the test track measurements. Eleven of these were new tires obtained in the fall of 2009. These tires are referred as test tires TT#1 through TT#11. The durometer hardness of the new tires all fell within the range specified in the ASTM International F 2493 of 64 ± 2[2]. The other tires had been in-service as test tires and were provided by several OBSI practitioners. The in-service tires all had accrued some mileage and were 1 to 3 years older than the new tires. These tires generally had higher hardness numbers, most of which were not within the range given by ASTM F 2493. More details for the test tires and their applications in the research are provided in Chapter 4. All seventeen tires were tested with a 2004 Chevrolet Malibu V6 (Car 1) that was used throughout all of the test track measurements. In the February tests, a 4 cylinder 2010 Chevrolet Malibu (Car 2) was used as part of separate "team" that used a different data acquisition system and different vehicle and analyzer operators to evaluate reproducibility between teams for the same tires. Both vehicles had right rear wheel loads of about 770 lbs, including the OBSI equipment and operators.

Test Procedures and Conditions

Test Procedures. All testing followed the measurement protocol "Proposed Method of Test for Measurement of Tire-Pavement Noise Using the On-Board Sound Intensity (OBSI) Method"[1]. Testing was conducted with a baseline load consisting of two people and the OBSI instrumentation. Measurements were made using the vertical dual probe configuration as used in earlier testing and at a test speed of 60 mph. Instrumentation systems consisted of phased-matched microphone and preamplifiers whose signals were acquired with a five-channel commercial analog to digital converter that also powered the microphones and provided signal conditioning. The unit interfaced to a laptop computer that used commercial software to produce ⅓ octave band sound levels and narrow band, Fourier transform (FFT) levels.

For the AC pavements, 5-second averages were made on each surface while, on the shorter PCC pavements, the averaging time was reduced to 4 seconds. This shorter averaging time was found not to increase the run-to-run variation over that experienced for the AC pavements and, although not in strict compliance of the Proposed Method of Test, this modification presented no evidence that it compromised the precision and bias of the results over those obtained with the longer averaging time. Vehicle speed was maintained using the vehicle cruise control and monitored throughout each test run using GPS units with 0.1 mph readouts of speed. The position of start point for acquiring data at each test section was signaled to the analyzer operator with a audible impulse produced by an optical sensor mounted on the OBSI fixture and triggered by a reflective traffic cones. During the course of the measurements, the overall level of the trailing edge probe was observed and recorded. The time signal from each microphone, the coherence, and PI index were also monitored during data acquisition.

Test Configurations. More than 750 combinations of pavements, tires, vehicle, and test temperatures were measured, with more than 2250 individual runs. The tire/vehicle test matrix including the date of testing, the temperature range, and items tested is summarized in Table 2. For each test event, all ten pavements were measured for each tire. Of the eleven new tires, TT#5 was used as the primary test tire and measurements on it were repeated after three or less intermediate measurements on other tires. This provided data on OBSI level versus time and temperature, as well as a moving reference such that the test tires always had a comparison tire measured under mostly similar conditions. Occasional repeat measurements were also conducted using the secondary

Table 2: Test configurations and conditions for on-road measurements

Test Event	Temperature Range, ºF	Items Tested
Feb 2010 – Car 1	40-61	Tires TT#1- #11 – new tire baselines TT#5 repeats & temperature variation
Feb 2010 – Car 2	43-59	Tires TT#5 & TT#9 comparisons to Car 1
Mar 2010 – Car 1	62-77	In-service tires, TT#5 repeats & load variation
Sept 2010 – Car 1	72-104	Tire TT#5 & TT#9 temperature variation
Dec 2010 – Car 1	41-69	Tires TT#1- #11 – aged tires, wheel width TT#5 repeats & temperature variation

test tire, Tire TT#9. In addition to the range of new and in-service tires, cases of added weight and altered speed were also included in the matrix.

Laboratory Measurements

Laboratory measurements were conducted in a wind tunnel environment and on a road-wheel simulator. The wind tunnel tests were conducted to evaluate of the effects of wind-induced noise on the OBSI measurement as generated by the probe, fixture, test tire and vehicle. The road-wheel testing was conducted to evaluate run-to-run variation, the effect of added background noise, the effect of reflections, and vehicle operating parameters.

Wind Tunnel Testing

Measurements were conducted in the General Motors Aerodynamics Laboratory (GMAL) automotive wind tunnel. This facility features low values for inflow turbulence (~ 0.6%) and the ability to accurately reproduce wind effects on full-size vehicles for yaw angles (simulated cross-wind conditions) up to ± 20 degrees at wind speeds to as much as 150 mph. GMAL is an aero-acoustic wind tunnel achieving noise levels of 58 dB or less in all individual ⅓ octave bands at 60 mph. Figure 1 shows the test vehicle placement in the wind tunnel. Measurements were conducted using the vertical dual probe OBSI fixture used throughout the project and with a special (ideal) single probe holder designed to eliminate self noise. Two test vehicles were used, a Pontiac G6 and a Chevrolet Impala. Photographs of the dual probe configuration and of the ideal fixture are shown in Figure 2.

The majority of the testing involved measuring sound intensity and sound pressure levels under a matrix of wind conditions. These included wind speeds of 35, 45, 60, and 70 mph at 0º yaw and for yaw angles varying in two-degree increments between -14 and +14 degrees for 60 mph. The convention used for defining positive and negative

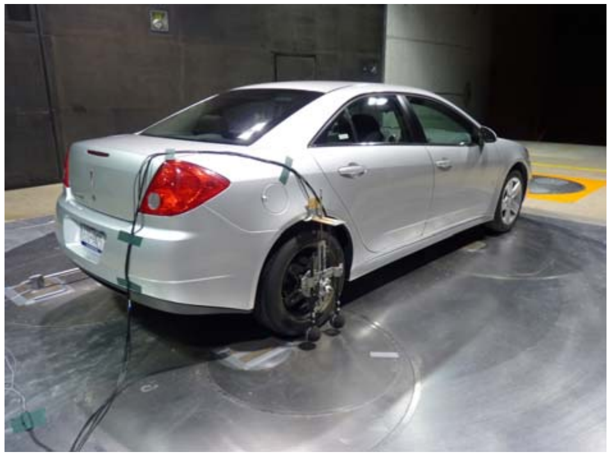


Figure 1: Pontiac G6 installed in GMAL

Figure 2: Vertical dual probe fixture installed on the Chevrolet Impala (left) and ideal fixture installed on the opposite side of the vehicle (right)

crosswind/yaw directions for the probe and test vehicle are shown in Figure 3. Noise generated by the test vehicle underbodies was isolated with the ideal probe on the opposite side of the vehicle from the OBSI fixture. Additional testing was performed to isolate and diagnose noise generated by air flow around the OBSI fixture and probes and

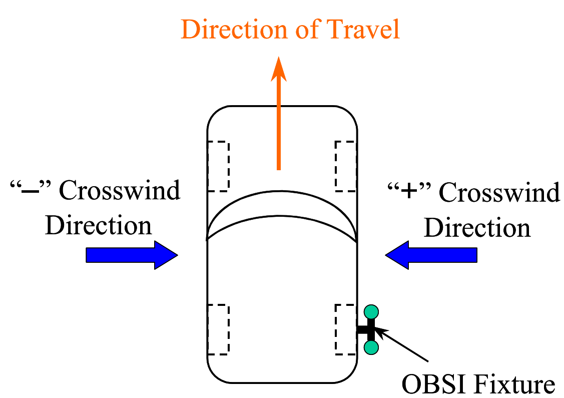


Figure 3: Plan view of the test vehicle defining negative and positive crosswind (yaw) directions

to evaluate windscreen attachment methods. The full test matrix and more details of the wind tunnel testing and results are provided in Appendix E.

Road-wheel Simulator Testing

The road-wheel simulator or tire noise chassis dynamometer is a facility at the GM Milford Proving Ground (MPG) designed specifically for tire noise testing. It consists of two independent 10-ft diameter rolls, arranged such both tires on a single automotive axle can be tested at the same time or individually. The available surfaces replicate two of the pavements currently in use at the MPG, a "smooth road" which is fine aggregate DGAC pavement and a "stud damaged concrete" (SDC) which is an exposed aggregate PCC pavement constructed to simulate wear by studded snow tires. The epoxy surfaces affixed to the dynamometer were made from castings of the actual test track surfaces. Details of this facility and test description are provided in Appendix D. The tire noise dynamometer can be operated such that it drives the tires or that the vehicle itself drives the dynamometer when the drive axle is placed on the road-wheel simulator. The road-wheel is housed in a semi-anechoic chamber (Figure 4) with a controlled environment producing air temperature consistently in the range of 64 to 66º F.

Figure 4: Test vehicle installed in on the tire noise chassis dynamometer setup for drive axis measurements

The testing was performed using a 2010 Chevrolet Malibu. On the right rear wheel position, testing on the smooth road surface was done primarily with TT#9. Limited data with TT #5 was also obtained for the baseline configuration. To test on the SDC surface, the left rear wheel position was required and the testing on the left rear wheel was done using an older SRTT tire that had been used for pass-by testing in this same wheel position. This same tire was also used on the smooth road surface in the left front wheel position for measurements made on the drive axle of the test vehicle. For most of the test conditions, speed was maintained at 60.5 mph (97.4 km/h) as set by the chassis dynamometer. Vehicle loading included only the weight of the OBSI instrumentation, providing an estimated loading of the right rear position test tire of 697 lbs based on measurements made in conjunction with test track testing completed in February. The instrumentation and installation was identical to that used in the on-road measurements.

The primary objectives of the tire noise dynamometer testing were to document the effect of background noise and reflections from nearby objects. Repeat baseline measurements were conducted to define test variability using this highly controlled facility. Additional evaluations included examining the variation in OBSI level due to small increments of test speed, the fall-off in level when the probes are moved to more outboard distances, the effect of the microphone windscreens and methods of securing them, and the differences in level when the tire is driven by vehicle versus free rolling.

CHAPTER 4

RESEARCH FINDINGS

In this chapter, all of the sources of measurement uncertainty are discussed along with the applicable findings from the test and analytical work conducted in this project. Detailed information on the test track, wind tunnel, and tire-noise dynamometer testing and test results are provided in Appendices C, D, and E. Detailed analysis of the temperature effects on tire noise generation and OBSI measurements are presented in Appendix B and summaries of the OBSI comparative testing referred to in this chapter are presented in Appendix F.

Temperature

Prior to reviewing the results regarding other parameters, it is important to first consider the effect of temperature. As shown in Table 2, testing was conducted throughout periods in February, March, September, and December over the course of several days using two primary test tires, TT#5 and TT#9. Testing began in the very early morning and continuing to the evening in order to obtain wide temperature range. For TT#5, average temperatures ranged from 40 to 101°F. For TT#9, the temperatures ranged from 41 to 104°F, although a much smaller data set was gathered. The results of the measurements on tires TT#5 are plotted in Figure 5, against air temperature for each pavement. These data include 370 data points (37 points for each pavement) over a temperature range from 40 to 101ºF.

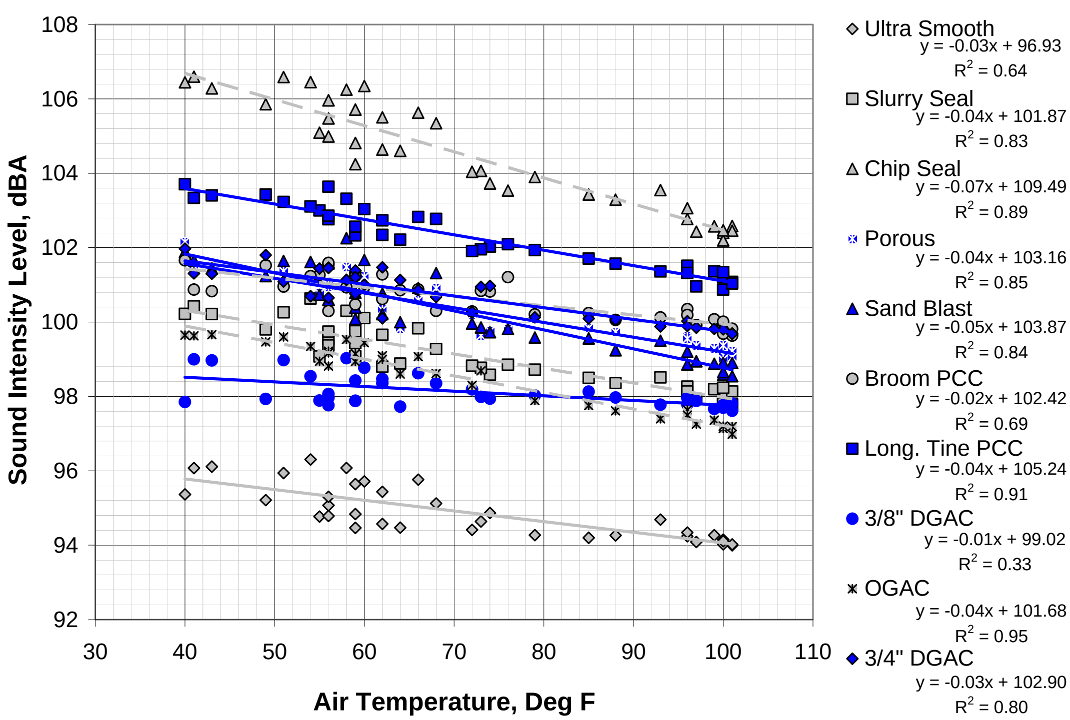


Figure 5: Overall OBSI levels for test tire TT#5 versus temperature for all test periods

Discussion of Results

Consistent with data in the literature[3,4,5] and the results from NCHRP Project 1-44[1], downward trends with increasing temperature were found for both tires for all pavements, with slopes varying by pavement type. On average for all pavements, the OBSI level decreased at a slope of 0.039 dB/°F for TT#5 using the typical assumption of linear relationships between tire noise level and temperature. Although it can be considered that a logarithmic relationship between tire noise and temperature may be more appropriate (see Appendix B for details), a linear assumption was used as a logarithmic regression did not appear to further improve the fit of data and the differences in the coefficient of determination (R^2) values were small.

For TT#5, the slopes for each pavement surface were typically in the range of 0.025 to 0.052 dB/°F with the exception of the chip seal and 3/8" DGAC pavements, which resulted in slopes of 0.068 and 0.015 dB/°F, respectively. The PCC rates fell within the AC pavements range, with one on the higher end and one on the lower end. Similar rates (with low R^2 values) were found for the SRTT tire at much higher air temperatures in the earlier research[1]. The earlier research also found that the spectra for temperature changes increased or decreased with temperature in a uniform manner so that it was not considered in the analysis.

Validation of Temperature Correction Results

As seen from Figure 5, the temperature gradients vary with pavement. These data do not indicate the applicability of multiple adjustments based on specific pavement groupings. For the purposes of the test procedure, it is also not tenable to have specific temperature gradient adjustments for individual pavements. Realizing this, the issue is whether a single, average correction will be beneficial when applied to a full range of pavement types. To assess the validity of the calculated air temperature correction, a linear rate of 0.039 dB/°F (which was calculated using the TT#5 data only) was applied in order to normalize all of the TT#5 and TT#9 data to a common temperature of 70°F. For the TT#9 data (including data from both vehicles), pavement specific temperature corrections, as calculated for each pavement based on the TT#5 results, were also applied and the results were compared to those for the more generalized correction factor.

For each pavement, the range and standard deviation of the measured OBSI levels for all test temperatures was calculated separately for the data of TT#5 and TT#9. These pavement ranges and averages were then averaged for all pavements for each tire. The performance of the temperature correction was then tested by comparing these pavement averages for range and standard deviation with and without the correction applied. The average of ranges and standard deviations of the uncorrected and corrected data for both tires is shown in Table 3. As expected, the temperature adjustment reduced the average of ranges and standard deviations for both data sets. Use of the pavement specific corrections further reduced the average range slightly, from 1.6 dB to 1.4 dB for TT#9, with the standard deviation dropping slightly from 0.5 dB to 0.4 dB. As would be expected, the pavements with specific slopes differing most from the general 0.039 dB/°F

Table 3: Average of ranges and standard deviations of uncorrected and corrected OBSI data

Test Tire	Uncorrected for Air Temperature		Corrected for Air Temperature	
	Average of Ranges, dB	Average of Standard Deviations, dB	Average of Ranges, dB	Average of Standard Deviations, dB
TT#5	2.9	0.9	1.7	0.4
TT#9	2.3	0.7	1.6	0.5

slope (e.g., the chip seal and 3/8" DGAC) resulted in the largest difference between the use of the pavement specific and general corrections.

These results indicate that even though the rates are different for each pavement, applying the general adjustment helps to reduce the variations between measurements almost as much as the pavement specific adjustment. Also, the temperature normalization improved the TT#9 data, even though the data set originated from measurements made on another test tire. Based on this analysis, the 0.039 dB/º F rate will be used in the analysis of the remainder of the test results when the influence of temperature is evaluated.

Assessment of Air Density Correction

Unlike sound pressure, sound intensity is not a directly measured acoustic quantity. It is determined using a finite difference calculation and is based on the sound pressures at two closely spaced points. Fundamentally, there is no inherent dependence of sound intensity on air density or air acoustic impedance as it is only related to the sound power output of a noise source. In implementing the finite difference approximation for determining ("measuring") sound intensity, a term of 1/ρ is introduced where ρ is the density of air. To properly account for air density at the time of the measurement, values of ambient temperature and atmospheric pressure can be input directly into the analyzer (or calculation of sound intensity) as specified in the proposed method of test[1] or the sound intensity levels output from the analyzer can be corrected during post processing using the following relationship:

$$\mathrm{IL} = 10\bullet\mathrm{Log}\,(I_i/I_{ref}) - 10\bullet\mathrm{Log}\,(\mathrm{T_m}/\mathrm{T_o}) + 10\bullet\mathrm{Log}\,(\mathrm{P_m}/\mathrm{P_o})$$

where IL is actual sound intensity level, $10\bullet\mathrm{Log}\,(I_i/I_{ref})$ is the sound intensity level indicated by the analyzer (without temperature and pressure inputs), $\mathrm{T_m}$ is the temperature at the time of the measurement, $\mathrm{T_o}$ is the temperature used by the analyzer for its standard condition, $\mathrm{P_m}$ is the atmospheric pressure at the time of the measurement, and $\mathrm{P_o}$ is the atmospheric pressure used by the analyzer for its standard condition. For further derivation, explanations, and validation of this correction, see Appendix B.

The sound power output for mechanisms associated with tire noise also has some dependence on ρ and *c*, the speed of sound (discussion provided in Appendix B). Taking these into account, the effect of ρ in the measurement of tire noise using OBSI becomes even less than indicated above. As a result, although theoretically a correction for air density should be made, it is not clear whether applying the correction improves the precision of the sound intensity measurement and whether any density corrections are necessary.

Because of the uncertainty of the application of an air density correction, OBSI data was collected in this research without adjusting to ambient temperature and pressure at the time of the data acquisition. Density correction factors were later determined relative to analyzer reference conditions of 68º F and 101.325 kPa and were found to average -0.14 dB with a range from -0.45 to +0.24 dB. In consideration of the use of the air density adjustments, the uncorrected and temperature corrected OBSI results for TT#5 and TT#9 were assessed both with and without the addition of the air density adjustment. In the case of the temperature corrected data with the air density adjustment, the resulting temperature corrections were slightly different from those calculated without the air density correction (0.043 dB/ºF as opposed to the 0.039 dB/ºF slope noted previously). In this case, the data was first corrected to (air density) conditions of 68º F and 101.325 kPa, and then the 0.043 dB/ºF temperature correction was applied to the data to normalize it to 68ºF.

The average of ranges and standard deviations for the uncorrected and corrected data for TT#5 is shown in Table 4. Unlike the temperature adjustment, the air density "correction" did not improve the average of ranges or standard deviations of the data. Similar trends were seen with TT#9, with the average range and standard deviations increasing with the use of the air density "correction". This suggests that more consistent OBSI levels will be achieved if all data were taken using a standardized analyzer reference condition, such as 68º F and 101.325 kPa, and then applying the temperature adjustment of 0.040 dB/ºF (rounded from 0.039 dB/ºF) developed in this research. In this case, it would be required to ultimately report OBSI levels relative to this reference condition along with uncorrected data referenced to the conditions under which the measurement was made.

Table 4: Average of ranges and standard deviations of uncorrected and corrected OBSI data using the air density correction for TT#5

	Uncorrected for Air Temperature		Corrected for Air Temperature	
	Average of Ranges, dB	Average of Standard Deviations, dB	Average of Range, dB	Average of Standard Deviations, dB
Without Air Density Correction	2.9	0.9	1.7	0.4
With Air Density Correction	3.2	1.0	2.0	0.5

Pass-by Measurements and Air Temperature

Pass-by measurements were made in conjunction with the OBSI measurements during the September and December testing (as time allowed) providing additional support for the temperature corrections discussed previously. Pass-by measurements were made on three of the pavements surfaces, the Chip Seal, Porous, and Broom PCC pavements over a temperature range of 50 to 102ºF. For the PCC pavement, measurements were made with the test vehicle traveling in both directions across the section. The results of the measurements are plotted in Figure 6, against air temperature for each pavement.

Consistent with the OBSI measurements and data in the literature, downward trends with increasing temperatures were found for all pavements, with slopes varying by pavement type. For Broom PCC, the pass-by slopes were very similar to the OBSI slope; 0.024 and 0.028 dB/ºF for the pass-by data as compared to 0.025 dB/ºF for the OBSI data. However, the two AC pavements resulted in lower slopes for the pass-by data; 0.043 versus 0.068 dB/ºF for Chip Seal and 0.024 versus 0.040 dB/ºF for Porous.

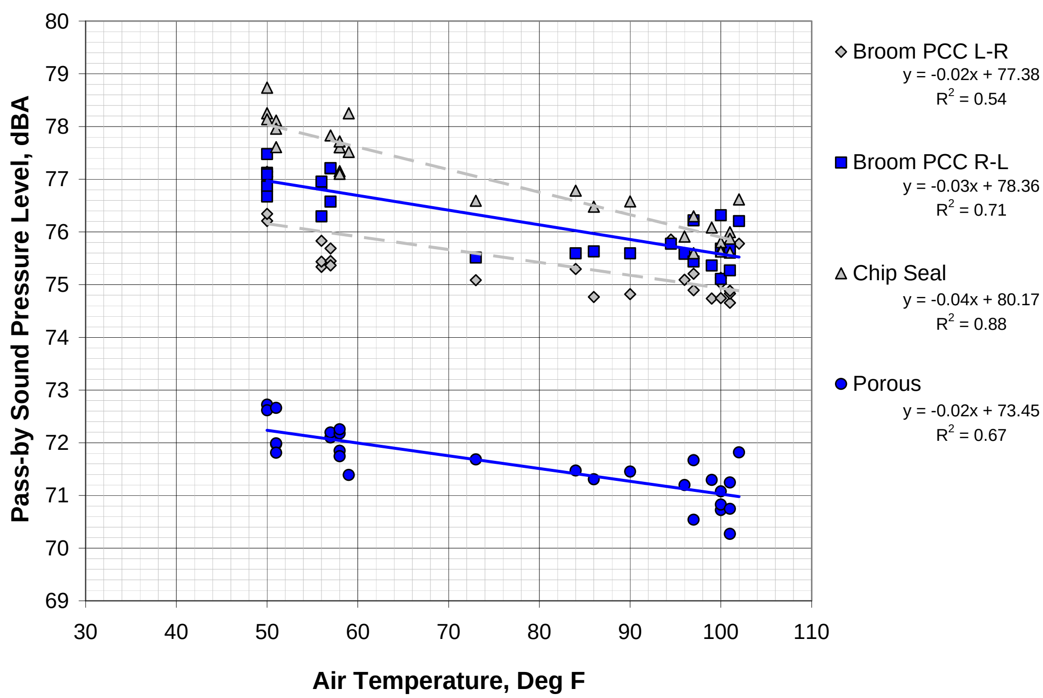


Figure 6: Overall Passby levels at 25 feet versus air temperature for September and December test periods

Consistent with the AC pavement results, analysis regarding the sound power output of tire noise sources as a function of temperature suggests that pass-by sound pressure should have less of a dependence on temperature than does OBSI data. Similar differences between OBSI and wayside variations with temperature are consistent with the results of the 10-year long I-80 Davis pavement aging study[19], which also found OBSI results to have a higher variation with temperature than wayside results for an AC pavement.

These results indicate: 1) the downward trend of noise level with increasing temperature is not limited to at-the-source tire/pavement noise measurement techniques consistent with previous literature[4]; 2) temperature corrections for OBSI should not be applied to measurements made using other techniques such as wayside/pass-by or sound pressure based Close Proximity data; 3) these limited data do not support separate temperature gradients for AC and PCC.

Pavement Temperature

During the course of the test track measurements, the surface temperature of each test pavement was measured along with OBSI levels. In general, the pavement temperatures followed the air temperature as shown in Figure 7 for the test events in all four months.

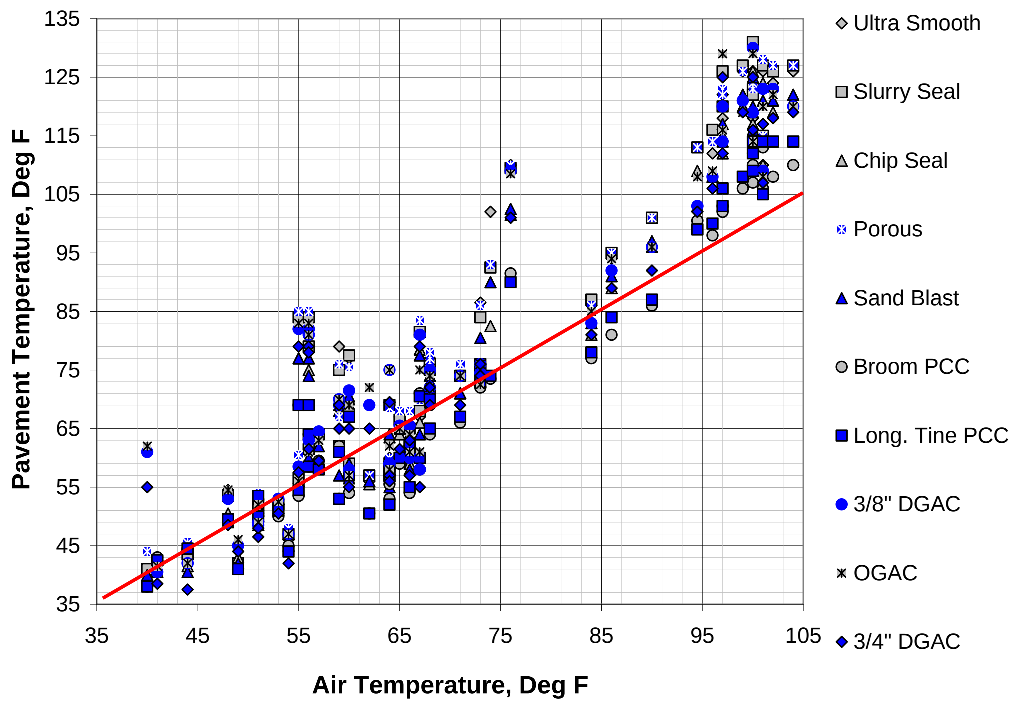


Figure 7: Pavement temperature versus of air pavements during the February, March, September, and December tests of tire TT#5

Over a day's cycle, the pavement temperatures increased fairly uniformly with air temperature early in the day. However, the pavement temperatures tended to increase at higher rate as the day progressed, apparently due to heating by the sun. Later in the day, the pavement temperatures decreased at a faster rate than the air temperature as the sun was less directly overhead. Late in the day, the pavement temperatures often dropped below those of the air. On overcast days, the difference between air and pavement temperature was less. Because of these different air and pavement temperature cycles, considerable scatter was seen in the pavement versus air temperature plot of Figure 7. In some cases due to the solar effects, range in the pavement temperatures was 20 to 30ºF for the same air temperature.

With the scatter in the air versus pavement temperatures, it is unclear whether adjusting OBSI data for air or pavement temperature data would provide the greater reduction in uncertainty. In Figure 8, OBSI levels are plotted against the pavement temperatures

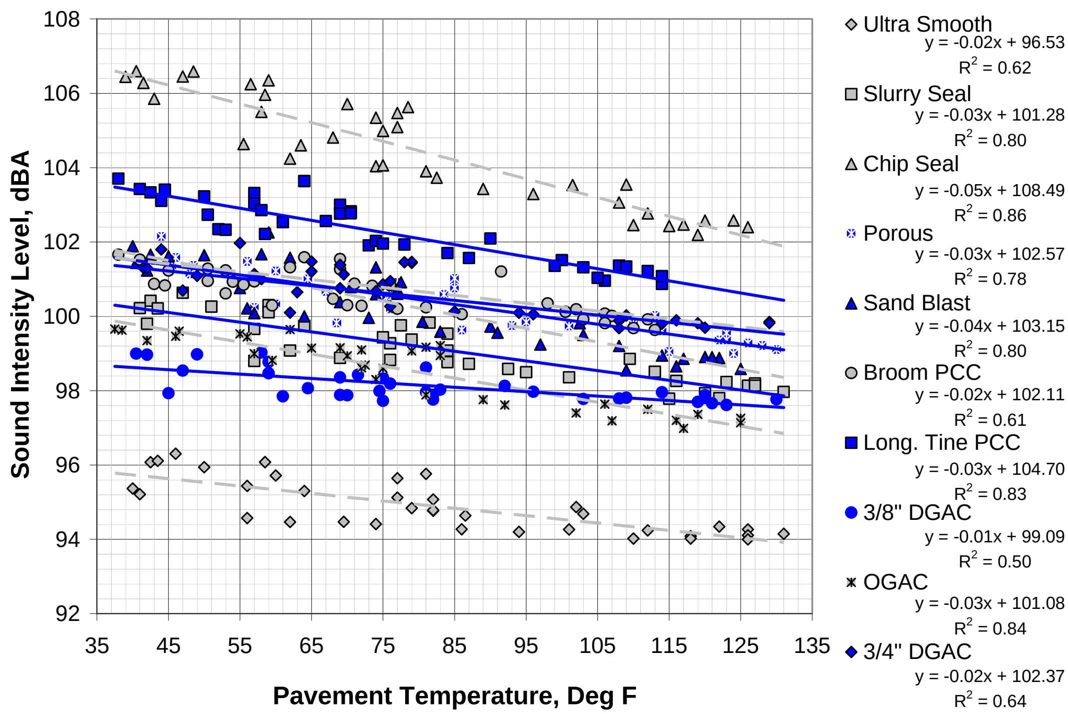


Figure 8: Overall OBSI levels for test tire TT#5 versus pavement temperature for all test periods

measured at the time of each test conducted in the four test months with no adjustments applied to the OBSI data. As with air temperature, these results show OBSI levels decreasing with increasing pavement temperature which is also consistent with the literature[3,4]. Other than including a wider temperature range, these results appear similar to those for air temperature (shown in Figure 5). The trends between pavements are similar although the slopes of the linear regression lines tend to be lower than for the air temperature data. Also the coefficients of determination (R^2) values are generally lower for the pavement temperature results. Similar to the air temperature correction discussed in the earlier section, use of individual gradients as corrections for each pavement or pavement grouping would be problematic for application to generally unknown pavements. For pavement temperature, the average gradient was 0.028 dB/ºF with a standard deviation of 0.011 dB/ºF.

The average pavement temperature gradient was applied to the OBSI data on a pavement-by-pavement basis. The average of ranges and standard deviations of OBSI levels was determined as done for Table 3 with and without the pavement temperature correction applied. These values are reported in Table 5 along with the results for no temperature correction and the average air temperature corrected results. These results show that correcting the OBSI levels for pavement temperature reduced the uncertainty in the levels as indicated by a reduction in the average of ranges from 2.9 dB to 2.1 dB and a reduction in the average of standard deviations by 0.4 dB. However, these improvements were not as much as those resulting from the air temperature correction shown in Table 5.

Table 5: Average of Ranges and Standard Deviations of Uncorrected and Corrected OBSI Data for Air and Pavement Temperature

Uncorrected for Temperature		Corrected for Air Temperature Only		Corrected for Pavement Temperature Only	
Average of Ranges	Average of Standard Deviations	Average of Ranges	Average of Standard Deviations	Average of Ranges	Average of Standard Deviations
2.9 dB	0.9 dB	1.7 dB	0.4 dB	2.1 dB	0.5 dB

These findings indicate that a pavement temperature correction is less desirable than an air temperature correction. Further, acquiring air temperature data in field situations is safer than stopping alongside a busy highway to measure pavement temperature.

Test Tires

The tires included in the test sessions are listed in Table 6 with their designation, build date, average durometer hardness at the start and completion of the 2010 testing, and application. Tires TT#1 through TT#11 are those acquired for this research and all

Table 6: Tires used in test track OBSI measurements

Tire Designation	Build Date	Avg Durometer February 2010	Avg Durometer January 2011	Application
TT#1	4608	64	68	IR mileage tire - right rear
TT#2	4608	65	70	IR mileage tire - right front
TT#3	4608	62	64	Accelerating aging test tire
TT#4	4608	65	66	Accelerating aging test tire
TT#5	4608	63	65	Primary 1-44-1 test tire
TT#6	4608	63	68	IR mileage tire - left front
TT#7	4608	64	65	Reference tire (low use)
TT#8	4608	64	64	Wheel width (7.0 inches)
TT#9	4608	64	65	Secondary 1-44-1 test tire
TT#10	4608	63	64	Wheel width (7.0 inches)
TT#11	4608	64	69	IR mileage tire - left rear
SRTT #1	4305	68		Caltrans primary test tire
SRTT #2	4305	70		Pooled Fund primary test tire
SRTT #3	4307	64		IR Secondary test tire
ACPA	0806	68		ACPA current test tire
Transtec	4206	70		Transtec current test tire
Passby RR	2906	68		Caltrans passby test tire (right rear)

have a build date of November 2008 (i.e. week 46, year 08). This group of tires enabled the evaluation of the range in OBSI performance from tires built in at similar times. The hardness of these all fell within the range specified in the ASTM International F 2493 of 64 ± 2 when measured with an ambient temperature of 74 to 77º F, within the allowed range of 73.4 ± 3.6º F. When the tires were first received, they were tested in a temperature range from 68 to 69º F slightly below the specified range. In those measurements, the initial hardness numbers were 1.7 higher than those reported in Table 6 indicating some sensitivity to measurement temperature. At the completion of testing, the hardness of 7 of the 11 tires (measured in January 2011) remained within the ASTM F 2493 range. However, the four accumulated mileage tires had higher hardness numbers that no longer fell within the ASTM F 2493 range. The six in-service tires were 1 to 3 years older than the new tires and five out of six of these tires had higher hardness numbers than the new tires and were not within the range allowed in ASTM F 2493.

Tire Comparisons

New Tires. The OBSI levels of 11 new tires were all measured in the February test session. These levels are all normalized to 58º F (the average temperature occurring over the measurements) and are presented in Figure 9. Considering each pavement

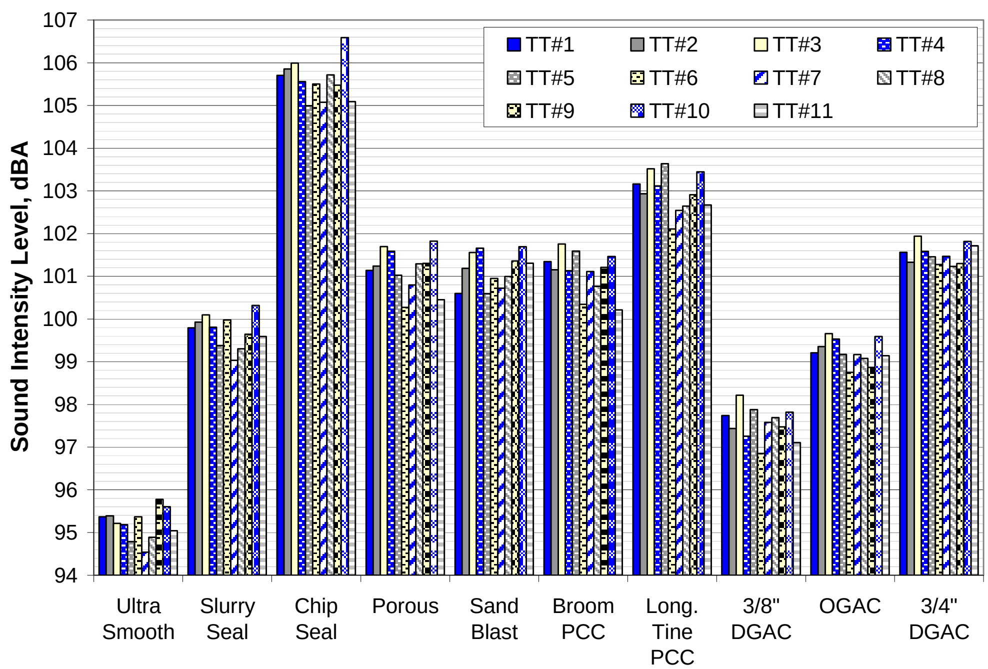


Figure 9: Overall OBSI levels for the eleven new test tires

individually, the range in OBSI levels produced by the eleven tires was from 0.7 to 1.6 dB. The average of the ranges for all pavements was 1.1 dB with a standard deviation of 0.3 dB. However, when considering only tests done with tire TT#5 in the February and March periods, the range for each pavement was from 0.2 to 1.4 dB with an average of ranges across pavements of 0.7 dB and a standard deviation of 0.3 dB. This indicates that test reproducibility is improved on average by 0.4 dB by using the same tire.

Figure 9 shows inconsistency between the relative performance of individual tires across the different pavements. That is, no tire consistently results in the lowest or highest levels from pavement to pavement and rank ordering of tires is somewhat different from one pavement to the next. To examine this further, the performance of all of the other new tires were compared against those of TT#5, as shown in Figure 10 for all of the test

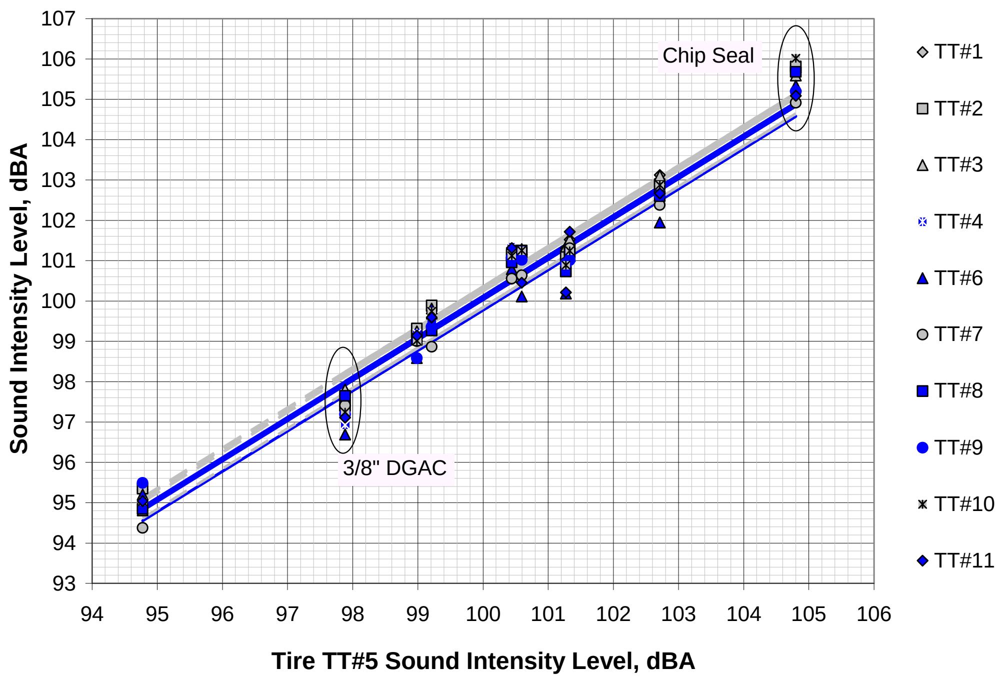


Figure 10: Overall OBSI levels for new SRTT tires versus TT#5 (with lines of average offset)

surfaces. Lines defining the average offset between the tires are also shown. These offsets range from 0.2 dB lower than TT#5 for TT#6 and TT#7 to 0.4 dB higher. These are small compared to the variation seen for individual pavements. For the 3/8" DGAC pavement, the levels for TT#5 are consistently higher than all the other pavements by 0.1 to 1.2 dB. For Chip Seal, this is reversed with the levels for TT#5 being consistently lower than all the other pavements by 0.1 to 1.2 dB. This indicates that the difference between tires is a function of the combination of tire and pavement and not just the tire. Therefore, making "corrections" based on average differences between tires on some set of pavements will not necessarily reduce the uncertainty due to tire variation.

Old and New Tires. The overall levels for the 6 older (used) tires are shown in Figure 11 along with TT#5, all normalized to 58º F. As a group, the levels for the older tires are on average 0.4 dB higher than for the new tires when averaged across all pavements. However, the average range in level for the smaller set of old tires is lower than that of the new tires, 0.9 dB versus 1.1 dB even though the standard deviations are essentially equal with calculated values of 0.35 and 0.34 dB, respectively. When the old and new tires are considered together as a group, the ranges and standard deviations increase notably as shown in Table 7 in part, due to the difference of averages between the groupings. Therefore when newer and older tires are used in comparative testing, the

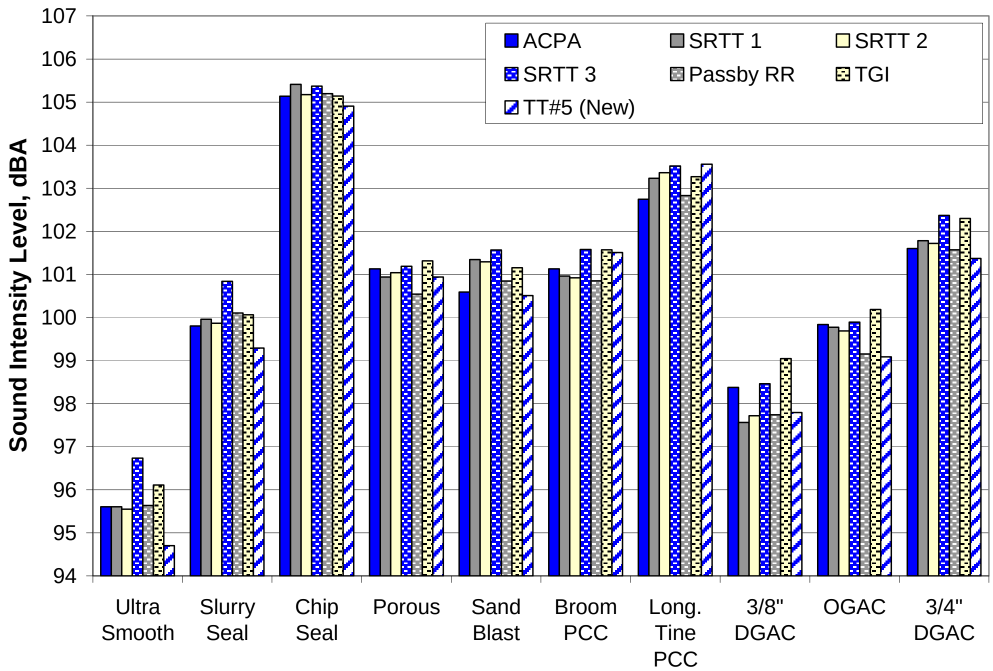


Figure 11: Overall OBSI levels for the six older test tires and new tire TT#5

expected difference increases by 0.4 to 0.7 dB. Given the average range of about 1.6 dB for the combined

Table 7: Ranges in OBSI level across all pavements, averaged over all pavements, and standard deviations for different tire groupings

Group	Range for All Pavements, dB	Average Range, dB	Standard Deviation, dB
All Tires	1.1 to 2.2	1.6	0.43
New Tires	0.7 to 1.6	1.1	0.30
Old Tires	0.3 to 1.5	0.9	0.35

tires, differences of almost 2 dB could occur due to tire differences alone for mixed old and new tires. The overall OBSI levels normalized to 58°F are plotted for the all of the old tires against the TT#5 average levels in Figure 12 and lines defining the average offset between the tires are also shown. These offsets are all positive with the range from 0.2 dB for the Passby RR tires to 1.0 dB for SRTT 3 and average offset being 0.5 dB. For the older tires, the range in offset is slightly greater than the new tires, 0.8 dB for the older tires versus 0.6 dB for the newer ones. For the older tires, the scatter for the different pavements is slightly smaller than the new tires (1.2 dB versus 1.4 dB) which could be due the smaller sample of older tires. As with the new tires, the rank ordering of tires changes with pavement although there is more consistency for some tires. For example, SRTT 3 generally produced higher levels and Passby RR generally produced lower levels. The newer tire TT#5 generally produced the lowest level of all seven tires except on the two PCC pavements. From the data of Figure 12, it appears introducing a tire correction based on all of the pavements would reduce some of the differences measured between tires from pavement to pavement. This reduction was demonstrated in

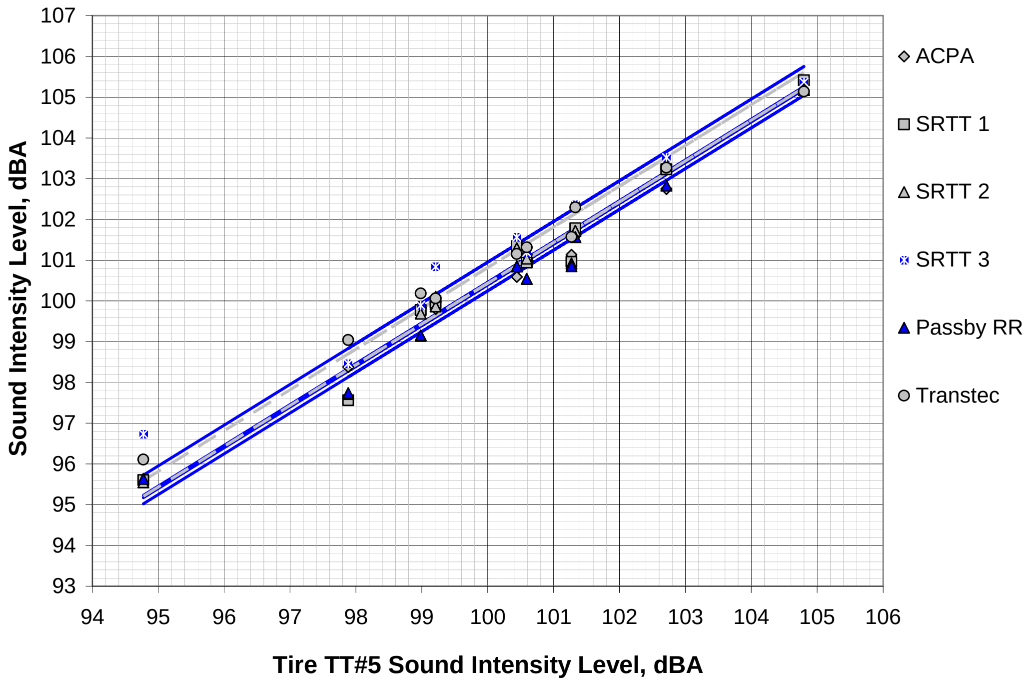


Figure 12: Overall OBSI levels for older SRTT tires versus TT#5 (with lines of average offset)

the NC Rodeo results in which the average team to team variation was reduced from 1.2 dB to 0.9 dB by adjusting levels for tire differences based on their rank ordering across the test pavements.

The linear regression lines shown in Figure 13 for all of the old and new tires generally follow the 1-to-1 slope with individual slopes ranging from 0.88 to 1.08. The spread generally increases with decreasing level and is fairly large, up to 2.3 dB for the Ultra Smooth AC pavement. This is consistent with the comparative testing results discussed in Chapter 3 and with the observation that tire differences tend to dominate the generation of tire noise on pavements producing lower levels while the pavement roughness characteristics dominate for those producing higher levels[20]. Closer examination of Figure 13 reveals that the tires with the small slopes defining the “fan-out” at lower levels are from the group of older tires. Conversely, the new tires tend to have slopes more nearly equal to 1 and do not demonstrate this fanning out behavior. Similar behavior was also noted in the results of the Mesa Rodeo conducted in 2008[9].

Figures 10 and 12 show that the range in tire age resulted in a total difference in average offset of 1.2 dB. Considering the new tires only or the old tires only, this range is 0.6 dB and 0.8 dB, respectively, with the offset between groups being 0.4 dB with the older tires producing higher levels. Also Figure 11 shows that the older tires tend to have a larger range amongst themselves for quieter pavements and are more consistently louder than new tires for these pavements. These observations suggest that using new tires may be preferred to eliminate some of these uncertainties. However, a working definition for “new” tire as well as a suggested replacement cycle needs to be developed.

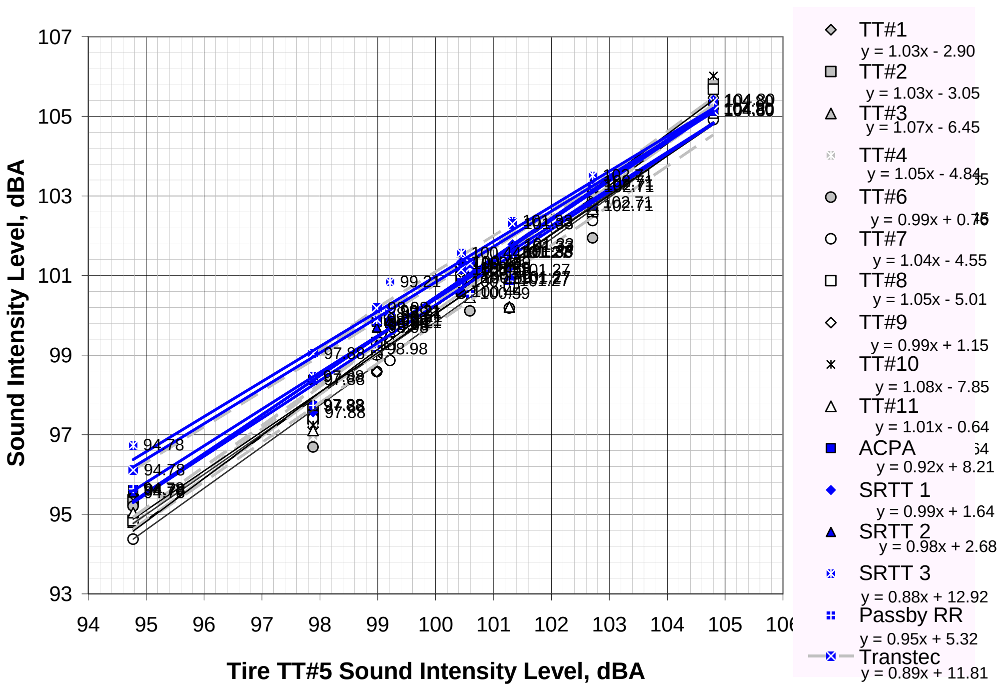


Figure 13: Overall OBSI levels for all 16 test tires versus tire TT#5 (with linear regressions)

Tire Hardness

The method of test[1] does not explicitly set limits on tire hardness or tread depth. However, it is assumed that the ASTM specification for the P225/60R16 SRTT (F 2493)[2] applies to the procedure. This specification states that the durometer of the tire shall be 64±2 hardness values as measured at a stable temperature in the range from 69.8 to 77.0º F. To assess the differences between tires, the OBSI levels for the tires measured during the February and March 2010 testing were plotted against the hardness durometer level, corrected to a temperature of 58°F (Figure 14). The literature indicates that OBSI levels generally increase with hardness by 0.058 dB/hardness number on average with some range in the slopes for different pavement types[9,21]. For three of the pavements, the slopes are greater than 0.10 dB/hardness number more consistent with the 0.2 dB/hardness number reported in the literature[21]. However, for some pavements, there appears to be no dependence on hardness. To further explore these data, the tires were grouped into old and new. For the new tires (ranging in hardness from 62 to 65), no increase in level with increasing hardness was found and, in fact, the levels decreased slightly on average with increasing hardness at a rate of -0.04 dB/hardness number. Given the small range of hardness number, there was a large amount of scatter and uncertainty that may have contributed to unexpected result. For the older tires (ranging in hardness from 64 to 70), the data indicated a negative slope attributed to SRTT #3. With the SRTT #3 data removed, all pavements displayed positive slopes in the range of 0.005 to 0.24 dB/hardness number except for Chip Seal that produced a negative slope of 0.06 dB/hardness number. The average for all tires on all of the pavements was 0.13 dB/hardness number, which is more consistent with other reported values and amounts

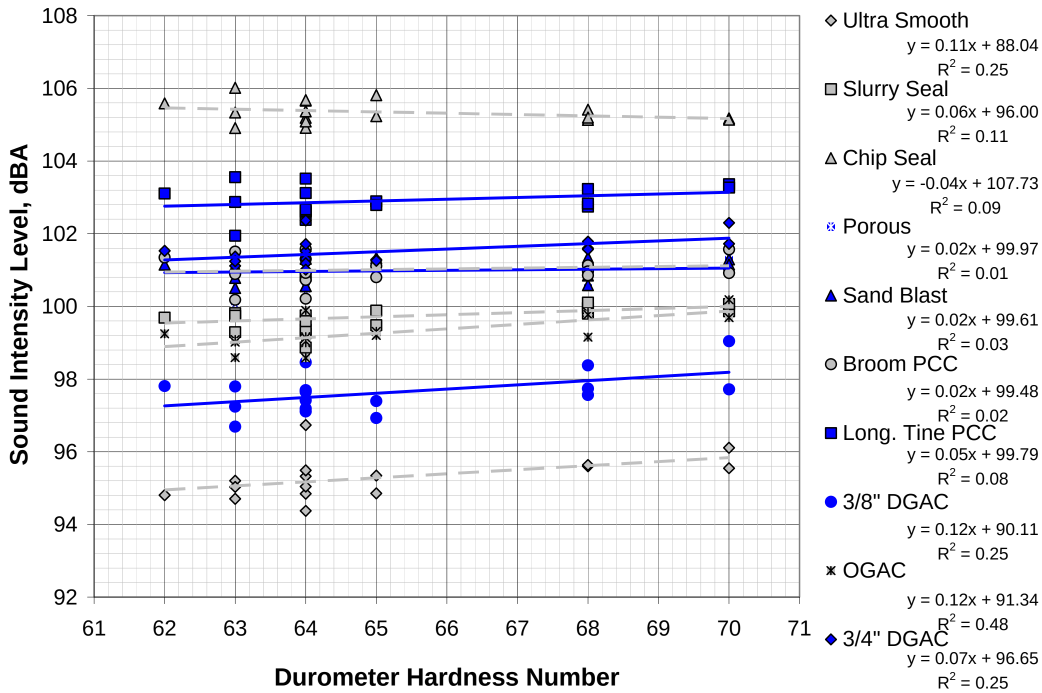


Figure 14: Overall OBSI levels for all test tires versus tire durometer hardness number

to an overall average increase of about 0.3 dB for tires with hardness numbers increasing from 68 to 70.

At the time of the December tests, the hardness of all eleven new tires had increased as shown by the January 2011 results in Table 5. The largest increases were for the in-service tires for which increases ranged from 3.9 to 5.0 durometer hardness. The hardness for these four tires then fell outside of the 66 hardness number limit specified in the ASTM specification while all of the other tires remained within the specification. As a group, the increase in OBSI levels for the in-service tires was greater than the other tires averaging 0.7 dB versus 0.4 dB. Given the average hardness number increase of 4.6 for these four tires, the average rate of increase in OBSI level with hardness is 0.15 dB/hardness number. However, the increase in level for the right side in-service tires was much lower than the left side (an average of 0.2 dB for the right versus 1.2 dB for left). Considering only right side tires, there was no trend of OBSI level increase and durometer hardness number increase.

From this research, a consistent correlation between tire hardness and tire/pavement level could not be identified. As a group, the new tires tested in February and March had lower durometer hardness numbers and produced lower OBSI levels than the older tires. However, it is not clear if restricting test tires at or below a specific hardness number would reduce variation. Hardness for all four in-service tires increased significantly (4.8), however, the trends between hardness and OBSI varied between right side and left side tires. It could be concluded that for newer SRTT tires, the rubber durometer hardness number may not be an important parameter, but as a tire ages, hardness may become an important variable. Therefore, setting some limit on hardness (and other tire aging parameters) would limit measurement uncertainty to the values obtained in this research.

Tire Loading

The AASHTO Test Method procedure (TP-76) does not limit tire loading, but the earlier research[1] recommended that loading be limited to 850 ± 100 lb. Tire loading effects on OBSI results were evaluated incrementally using the TT#5 test tire during the March test series (Table 2). Weight was added to the trunk of the vehicle to result in increased loading on the right rear wheel (where the OBSI instrumentation is attached) by 100, 150, and 200 lbs above the baseline wheel load of 770 lbs. Temperatures during these measurements ranged from 64 to 75°F. The results of these measurements, shown in Figure 15, indicate a small, but consistent increase of OBSI level with increased wheel

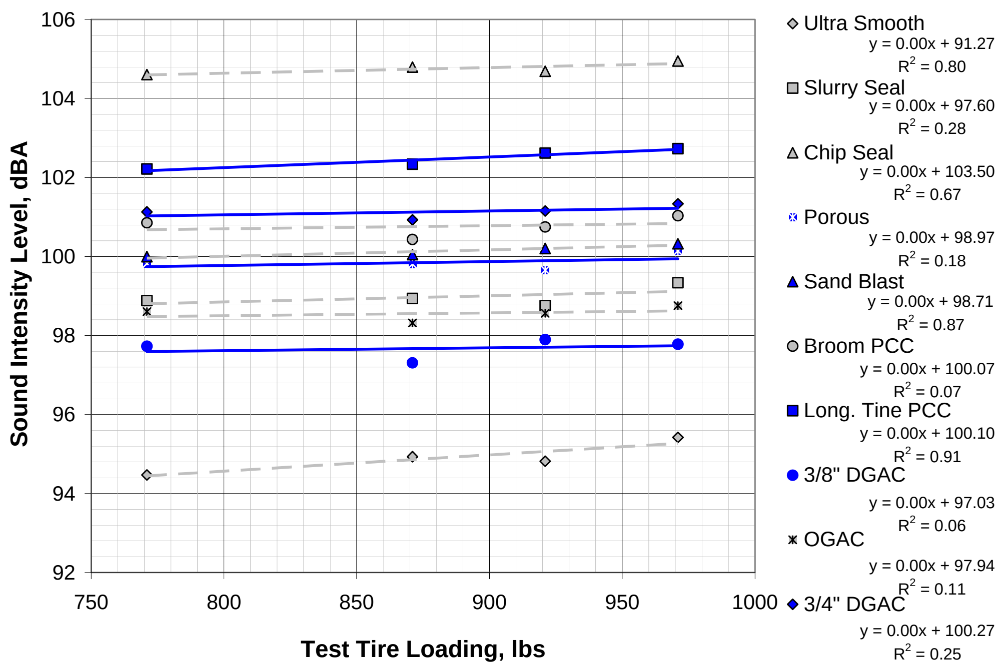


Figure 15: Overall OBSI levels for tire TT#5 with varied tire loading

load for all pavement types that averages 0.16 dB/100 lb. Using temperature corrected data, the average increase for the TT#5 data was 0.23 dB/100 lb. These results are similar to those of the earlier research, which found an increase of about 0.2 dB/100 lbs for added trunk weight (equivalent to about 60 lbs added wheel load) for the SRTT tire (without temperature corrections). The levels for each load case and pavement were also normalized to the baseline loading of 771 using the average loading rate without temperature corrections. Without the loading normalization, the average loading increase from 771 to 971 lbs resulted in a 0.40 dB increase in OBSI level. With the normalization, the average difference was reduced to 0.04 dB. This indicates that correcting for loading should reduce the variation created by loading differences.

Increased loading on tire TT#9 mounted on the Malibu rental car in February and on the TGI tire mounted on the IR Malibu in March resulted in an average increase in OBSI level of 0.09 dB/100 lbs and 0.18 dB/100 lbs, respectively. Since rates are defined by only two loadings, there is more uncertainty in these data than those defined by the incremental data shown in Figure 15. However, on average, the rates defined with the TT#9 and TGI tires are very similar to those for TT#5.

In the comparative tests, loading ranged from about 700 lbs to 930 lbs for individual test teams. In some cases, the more lightly loaded cars produced lower OBSI levels than heavier cars and in some cases not. Added weight and tire loading to baseline conditions generally increased noise level for Yuma tests, but the results displayed considerable scatter. As a group, the results suggest that this variable may not be independent of other vehicle and/or tire parameters. Further details of the comparative testing are provided in Appendix F.

Other Tire Parameters

Several other parameters were evaluated in the follow-up testing in December. The performance of the primary and secondary test tires was examined for all of the test events in test track measurements. Figure 16 presents the OBSI levels measured for each pavement averaged over the tests performed in each of the four measurement months.

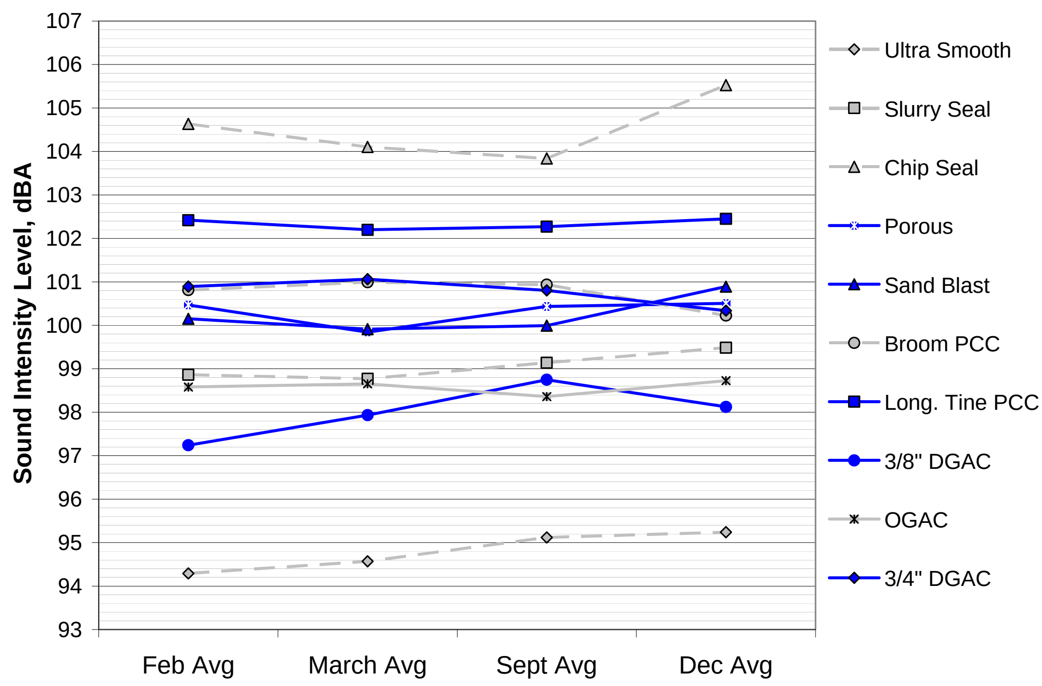


Figure 16: Average temperature adjusted OBSI levels for TT#5 for each month of testing

These values are adjusted for temperature of 68ºF. Parameters not accounted for include pavement aging, change in tire hardness/aging, and pavement temperature. For eight of the ten pavements, the OBSI levels are within a 1 dB for all of the test track measurements. For Chip Seal, an increase of 1.7 dB was measured between the September and December testing. In December, some raveling of the pavement had occurred that may have contributed to the higher level. The December levels were less than 1 dB higher than the February levels. For the ⅜ inch DGAC, variation of 1½ dB occurred with the highest level occurring in September. This pavement had a temperature gradient of 0.013 dB/ºF (see Figure 5) which is well below average so that the correction contributed to the higher variation indicated in Figure 16. On average across all pavements, the increase determined between February and December was 0.2 dB with a standard deviation of 0.25 dB. Even with fewer data points, the trends for the secondary test tire, TT#9, were similar to those for TT#5.

In addition to the parameters discussed in the previous section, several other tire parameters including tire aging and wheel width were identified as possibly influencing OBSI results. To assess these tire parameters, the 11 new tires used in this project were subject to a variety of conditions between the February and December tests as follows:

- TT#7 was used as a reference test tire and was stored under dark, no light conditions for the entire period between tests
- TT#5 and TT#9 were used as the primary and secondary test tires, respectively and used throughout the on-road and laboratory testing with the majority of the test mileage accumulated on TT#5
- TT#1, TT#2, TT#6, and TT#11 remained on the IR Malibu for the entire period between February and December accumulating about 11,000 miles of normal usage
- TT#3 and TT#4 were subjected to heat cycles of up to 139º on a daily basis throughout the summer months to increase tire hardness and were not used in any other testing
- TT#8 and TT#10 were stored under the same conditions as TT#7 but were remounted on 6.5 inch wide wheels (7 inch wide wheels used for all other tires).

The average increase in OBSI level of each tire between the February and December testing corrected to a temperature of 70ºF is shown in Figure 17.

In-Service Mileage Accumulation. The tires with accumulated mileage clearly displayed the effect of usage in terms of their physical parameters. As discussed in a previous section, these tires increased hardness numbers by 4 to 5 compared to the more typical increases of about 1 to 2. The tread depth was also reduced more on these tires than for the other tires. For the front, drive axle tires, the worn depth was 5.2 mm and 5.6 mm for the driver side tire (LF) and the passenger side tire (RF), respectively compared to the nominal new depth of 8 mm. The rear tires (RR and LR) were considerably less affected, both at about 7.2 mm, likely due to the lower loading on these tires. The OBSI results shown in Figure 17 are quite mixed. The driver side tires both displayed significant increases in level compared to all other tires. However, the increase for the passenger side tires was minimal and similar to the other tires which were also used on this side of the vehicle. The driver side tires were always tested and mounted on that

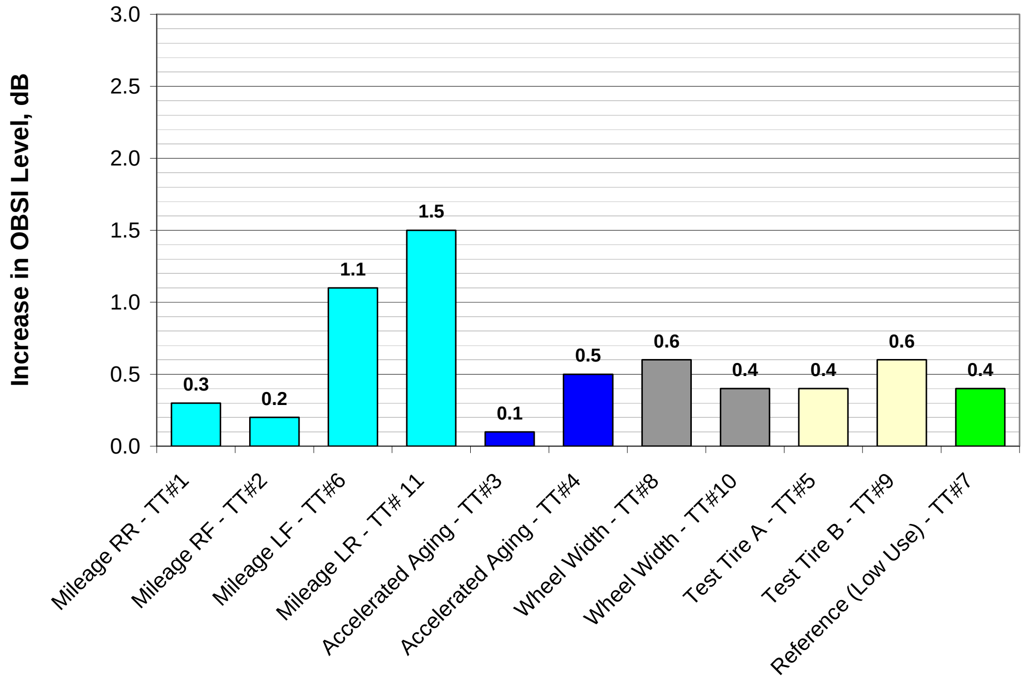


Figure 17: Overall OBSI level increase from initial(February) to final (December) testing

side of the car. Because no driver side control tire was used, the results for this side of the vehicle could not be validated. Comparison of the side-to-side data, revealed no trend to suggest that the decreased tread depth for both front tires produces measurable differences in the OBSI levels. Averaging the increase for all four tires produces an increase of 0.8 dB that may be related to the increased hardness of these tires, however, with the side-to-side differences, it is difficult validate such a conclusion. The result of this trial determined that an in-service life of about 10 months and 11,000 miles produces changes in hardness and tread depth that could affect the results if the tire is used in a test.

Wheel Width. As indicated by Figure 17, change in OBSI level produced by the two tires (TT#8 and TT#10) mounted on 6.5 inches wheels was virtually identical to the test and reference tires. In terms of OBSI level, the tires on the narrower wheel produced average levels within 0.2 dB of the of the other right side tires measured in December.

Accelerated Aging. The tires exposed to heat cycles throughout the course of summer months also produced some mixed results. The tire hardness for tires TT#3 and TT#4 increased by 2 and 1 hardness numbers, respectively. Figure 17 shows that the increase in level was actually greater for TT#4, however, both are in the range of the other right side tires. Generally, this heat exposure produced a marginal increase in hardness.

Tread Depth. At the beginning of the project, the eleven new test tires all had tread depths of nominally 8 mm (equal to or greater than the ASTM specification of 7.97 mm). After the completion of the December testing, tread depths were measured and the results are shown in Table 8. For low usage tires, TT#3, 4, 7, 8, and 10, the tread depths

Table 8: Test tire tread depth measured in January 2011

Tire	TT# 1	TT# 2	TT# 3	TT# 4	TT# 5	TT# 6	TT# 7	TT# 8	TT# 9	TT# 10	TT# 11
Depth, mm	7.2	5.2	8.1	8.0	7.8	5.6	8.0	8.1	7.8	7.9	7.2

remained at or above the ASTM specified value of 8 mm except for TT#10. The tread depths of the four in-service tires (TT#1, 2, 6, and 11) were below this specification with the front tires displaying considerable more tread loss while the loss for the lightly loaded rear tires was only about 0.8 mm after 11,000 miles of use. For TT#5, the estimated mileage of 1,300 produced a reduction in tread depth of about 0.2 mm. For TT#9, the estimated mileage of 1,000 miles also produced a reduction in tread depth of about 0.2 mm. For the other tires (other than the in-service tires), there was essentially no reduction in tread depth after an accumulated mileage of less than 75 miles.

Limits on Test Tires. February testing showed that older tires that had been in service produced 0.5 dB higher levels on average than newer tires. This suggests that some limit on tires usage and age should be considered. This research did not provide a clear quantitative definition and criterion for defining when a tire is too "old". Generally as usage increased, tread depth became less and tires became harder. The older tires used in this study were 1 to 3 years older than the eleven new tires. The older tires displayed no trend in OBSI level with build date possibly because of the sample size used. It was noted previously that relative performance of the new tires was not consistent suggesting that each tire reacts slightly differently to each pavement. As these individual tires age, such inconsistencies are expected to continue as demonstrated for the older tires tested in February and March. Also, the effect of aging variables such as hardness, tread depth, time since construction, and mileage, may not be consistent from tire-to-tire. This would make developing a single or multiple criteria for identifying when a tire should not be used quite problematic.

To avoid increased (or increasing) uncertainty with aging tires, a combination of factors could be considered based on hardness, tread depth, mileage, and years since construction or years in service. Exceeding any one criterion may not be sufficient to retire the tire, but exceeding several criteria would be sufficient. Hardness versus noise performance results for the older tires (between 68 and 70 hardness), showed an increase in OBSI level with increasing hardness. This would suggest 68 as a recommended maximum hardness number. Regarding tread depth, when the depth reached 7.2 mm, at least some tires displayed higher noise levels. For mileage, some tires displayed higher levels after 11,000 miles, but others up to 1,300 miles did not. Therefore, limiting mileage to some value between 1,300 and 11,000 these may be appropriate. SRTT#1 and SRTT#2 have both been in service since 2006 (i.e. about 4 years at the time of the February tests). Under this approach, a tire that has more than two of the attributes of 1) being in-service for more than 4 years, 2) having more than 11,000 miles, 3) having hardness number of greater 68, or 4) tread depth less than 7.2 mm would be retired.

Test Parameters

Location

The positioning of the test vehicle during a test run, including the location at which the five-second data acquisition begins and the position of the test tire in the wheel path, can be a source of variation from run-to-run of a single test team or from one measurement team to another. Because the magnitude of the effect of either of these variables depends on the pavement section being tested, it cannot be quantified without a prior knowledge of the site. However, some insight into these issues can be obtained by analyzing OBSI data that has been collected on other sites displaying variability and by evaluating some hypothetical cases.

Data Acquisition Start Location. The pavements tested at the H·K Proving Ground were constructed to be as uniform as possible. As a result, the effect of variation in start location was minimal. In order to consider the worse case, OBSI data collected for a Caltrans project on I-5 in Sacramento were considered[7]. In this project, 0.7 miles of PCC freeway were overlaid with new open graded rubber asphalt concrete (RAC[O]). Initially, the this segment was tested in three sections of 440 ft corresponding to 5 seconds of transit time at 60 mph. The difference in level between sections was measured to be 2½ dB which was greater than that measured for other pavements of the same construction project. Differences in the sounds produced inside the test vehicle as it passed over this pavement were clearly audible. Recordings of the sound pressure signals from OBSI probe were recorded for the entire length of the project and were later re-analyzed using a “fast” averaging time (1/8 second exponential average) to obtain sound intensity level as a function of time (and corresponding distance). The result of this analysis is shown in Figure 18 for a time period of 20 seconds. With this shorter analysis time, variation in OBSI level is shown to be about 7 dB excluding the slap identified in Figure 18. More typically, this type of variation is about 1 to 2 dB with maximum variations up to 4 dB.

The fast averaging time data of Figure 18 were further analyzed to produce a moving five-second energy average to simulate different start times for data acquisition. The data were summed on an energy basis into 5 second time blocks and then time was incremented by 0.1 second and the 5-second summation repeated for the length of the data from 0.6 seconds to 20 seconds (also shown in Figure 18). To evaluate the effect of start location, different points along the moving average curve were examined. As an example, if the variation in start time was 0.5 seconds (44 ft at 60 mph), the difference in OBSI level between starting at 2.0 seconds and 2.5 seconds is 0.4 dB. The largest variation occurs at near 12 seconds where audible slap is or is not included in the average and the difference in 5-second average level is 0.7 dB for a 0.5 second variation in start time. This maximum run-to-run variation that could be produced by the start variation corresponds to a standard deviation of 0.5 dB for two passes and 0.4 dB for three passes. This is within the limits required in both the NCHRP proposed procedure and the AASHTO 10-76 procedure. If a second team made measurements along this project, as along as the start position was specified to ±22 ft and the slap at the end were avoided,

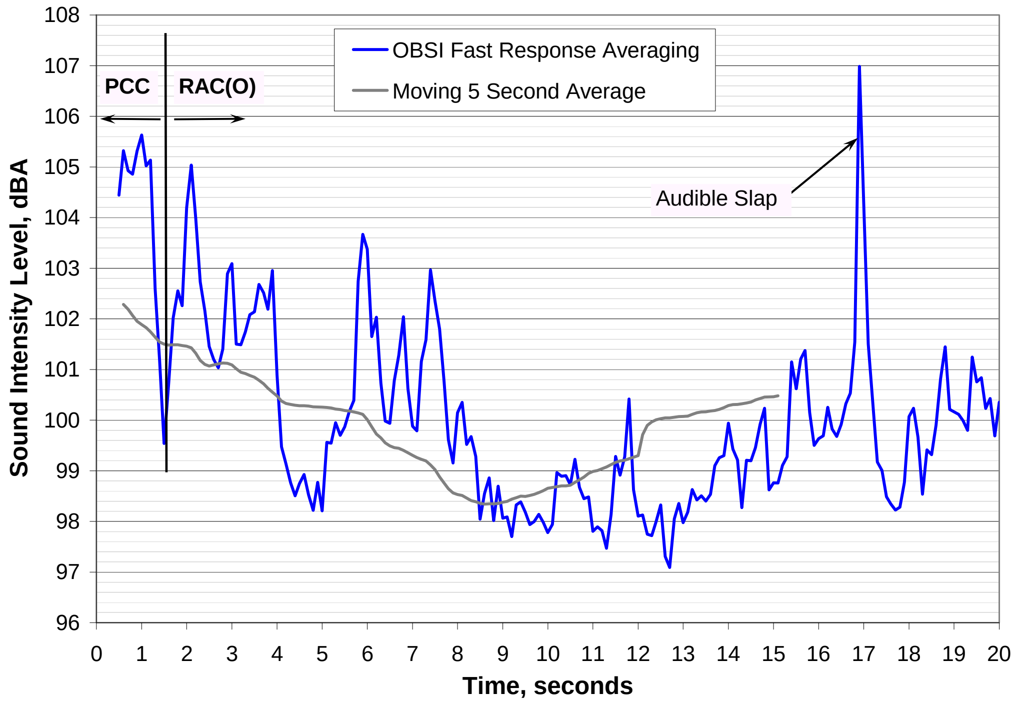


Figure 18: Example of OBSI level variation with location in a test pavement

the maximum difference between the two teams due to variation in the start location would be 0.5 dB or less.

The pavement segment included in the data shown in Figure 18 was measured in three sections over the length of the project. For each section, multiple passes were made and averaged together. The data acquisition for each start point was initiated visually based on roadside landmarks. The variation between the averages for each section was greater than 2 dB as would be expected considering sections from 2.5 to 7.5 seconds and 9.5 to 14.5 seconds. The variations between passes over these sections were typically less than 0.4 dB with one section having a maximum range of 1.0 dB with a standard deviation of 0.5 dB all within the current procedure requirements.

Start location was also evaluated analytically for different theoretical OBSI profiles including an instantaneous increase mid-way through the 5-second section, alternating levels every 0.4 seconds, steadily increasing level throughout the section, and instantaneous increases and decreases in the last 0.4 seconds of the section. The variations in 5-second average OBSI levels were found to be a function of the level difference between the different portions of the pavement and of the noise "profile". For all cases, as the difference in level within section increases, the variation increases. For the "dip" at the end case, the variation in level is the greatest of the five cases as shown in Figure 19. If the starting point for data can be maintained to a variation of about 0.2 seconds, or 17.6 ft, the variation is reduced by more than half as shown in Figure 20. With this amount of control of start location, the variation 5-second OBSI average level is 0.5 dB or less for differences in pavement of 6 dB for all noise profile scenarios. It is expected that differences of 6 dB would be clearly audible inside the test vehicle.

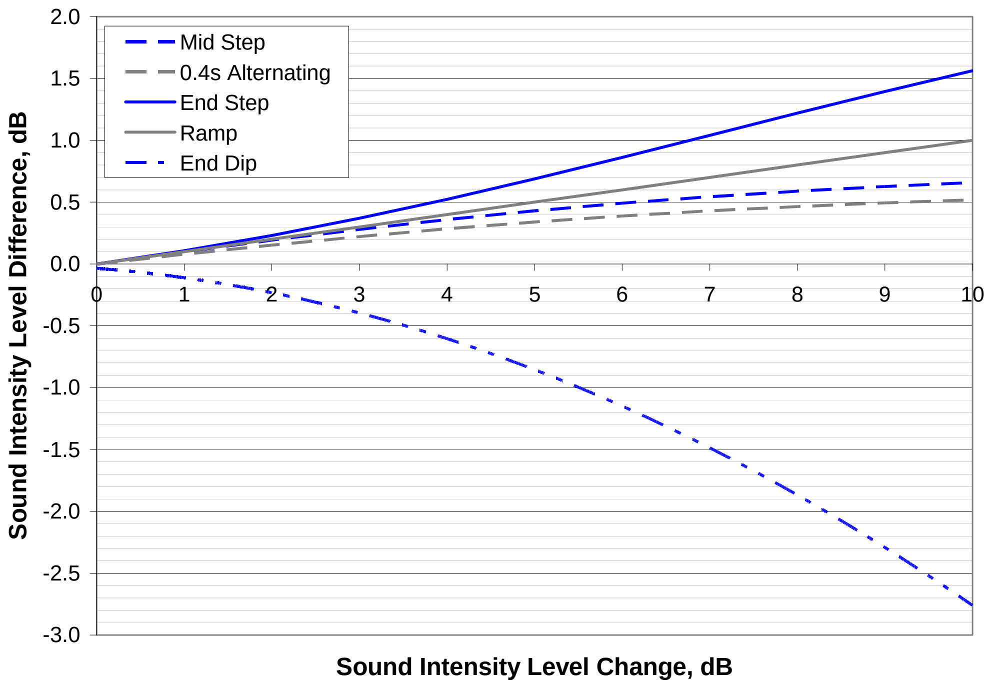


Figure 19: Difference in OBSI level created by a ½ second change in start position (44 ft) for 5 second average for different profiles of OBSI versus position as a function of the difference in OBSI level in the profile

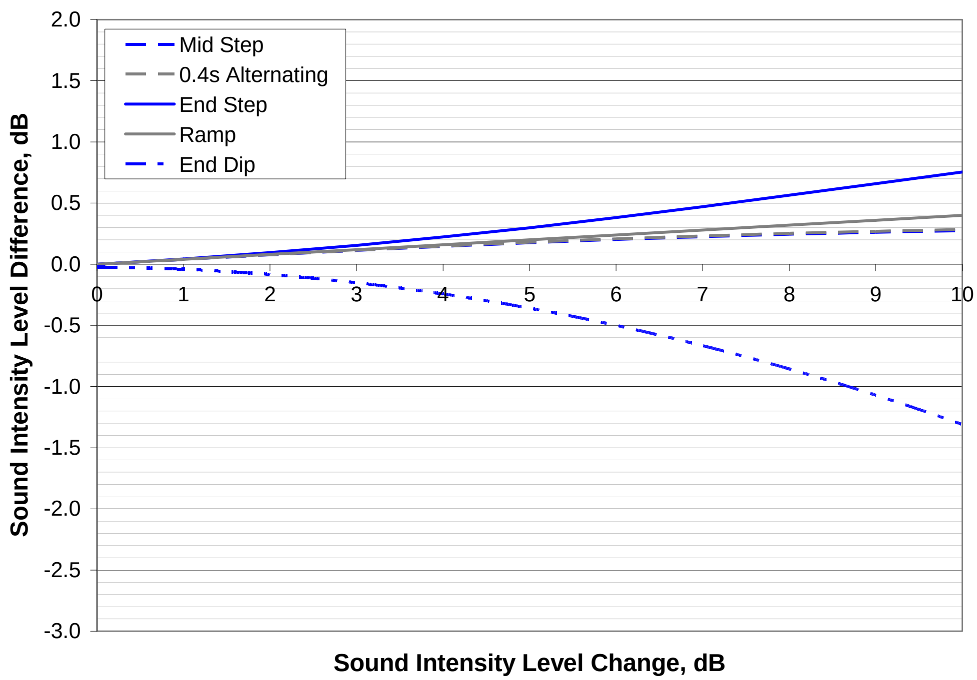


Figure 20: Difference in OBSI level created by a 0.2 second change in start position (17.6 ft) for 5 second average for different profiles of OBSI versus position as a function of the difference in OBSI level in the profile

As a field data point, in the North Carolina Comparative Testing[16] it was found that varying the position of the start of data acquisition by the length of the test cars produced variations of 0.3 dB or less which was within the variation of the repeat baselines. In regard to the OBSI procedure, for a single team testing a section of pavement, the current requirements on run-to-run variation are sufficient. However, by requiring that the start of data acquisition occur within 20 ft or 0.23 seconds relative an identified start point, the potential for variation would be further reduced.

Wheel Path. OBSI levels for tires within and outside the wheel path vary with the pavement. Differences between OBSI level for the wheel path and lane center represent the maximum differences that may be encountered for those pavements[22,23]. For ten pavements (including both HMA and PCC), the average difference between the lane center and wheel path was 1.1 dB with a standard deviation of 0.74 dB. The range was from 0 dB for a 6 month old HMA pavement to 2.4 dB for 5 year old grooved, visually damaged PCC. For run-to-run variation, if the test tire was wandering during the pass over the pavement, wheel path variation would be identified by applying the existing criteria in the OBSI test procedures. For reproducibility, it is important that the same position of the test tire relative to the wheel path be maintained in all testing. The wheel path appears to be about 2½ to 3 ft wide based on photos accompanying the wheel path/lane center data. It should be possible to maintain the test tire close enough in the wheel path to avoid the differences measured between the lane center and wheel path. Slight variation within the wheel path may be possible, however this is difficult to document. In the North Carolina Rodeo[16], two teams tested with their vehicle centered and not quite centered in the lane of travel for 12 pavements. The average differences were 0.3 and 0.2 dB which was about the same as that for repeated baseline tests. Based on these findings, tighter control of the test tire position within the wheel path does not appear to be necessary. However, tire position with respect to wheel path should be reported as part of the test results.

Background Noise

For on-road OBSI measurements, the primary background noise concern is the influence of other on-road vehicles near the test tire during data acquisition. The effects of varying levels of background noise were assessed in detail in the tire noise dynamometer testing. With increasing levels of background noise, the measured sound intensity levels decrease because the net energy coming from the test tire is cancelled by the net energy from the background source flowing toward the tire. In this situation, the PI index increases in level because the sound pressure (the sum of both the tire noise and the background noise) increases and the net sound intensity decreases. Similarly, the effect of background noise on the OBSI level is greatest when the source is directly opposite the test tire on a line perpendicular to the axis of rotation, such as when the tire or other noise source of another vehicle is directly opposite the test tire. As the tire/noise source of the adjacent vehicle moves forward or rearward of the test tire, the effect on the OBSI level diminishes rapidly due to the directivity of the sound intensity probe. The tire noise dynamometer tests showed that the sound pressure level of the background noise directly opposite of the test tire must be 10 dB or more below the sound pressure level of the tire/pavement noise source to achieve an error of less than 0.5 dB. For application to 5-second OBSI measurements, both the noise level produced by other vehicles (or noise sources) and the duration of time in which the tire/noise source is directly opposite the test tire are needed to determine the effect of background noise. As neither of these variables may be known, run-to-run variation and sound intensity direction are proposed to identify background contamination. As for all reported data, the run-to-run variation is required to be 1 dB or less. Use of this requirement should be sufficient to identify any contamination that would potentially influence the results. However, if possibility of contamination occurs during any one run of a data set, that run should be repeated in order to obtain at least two runs meeting this criterion.

In more severe cases of contamination, the direction of the sound intensity vector would be negative. Also, the effect of background noise will produce increases in the PI index. Based on the initial tire noise dynamometer testing, a tentative criterion would be to limit the PI index to about 1 dB greater than the PI index measured on the dynamometer in the absence of background noise. This criterion was explored further and the frequency dependent criteria are shown in Figure 21 along with the baseline OBSI levels measured

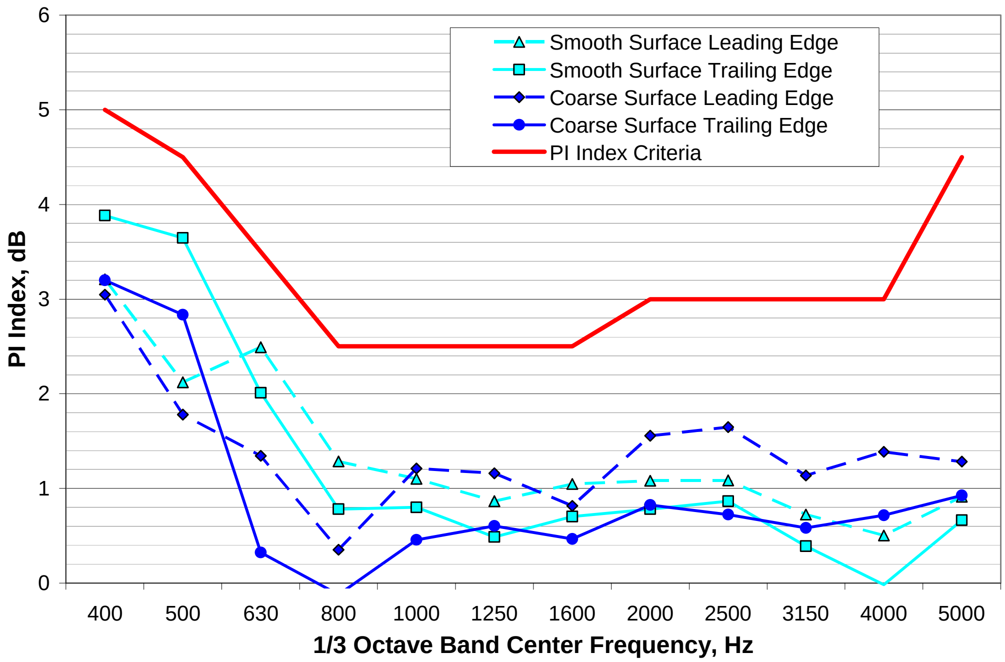


Figure 21: PI index criteria compared to baseline PI index levels on the smooth and coarse dynamometer surfaces

on the dynamometer with the smooth and coarse surfaces. By applying these criteria to the background noise data from the dynamometer, resulting errors range from about 0.8 to 1.5 dB in individual one-third octave bands which is within the limit allowed for individual bands in the current procedure. For overall A-weighted level, the error should be no greater than about 1 dB. To test their feasibility, these criteria were applied to 18 data sets containing 20 to 50 individual runs in each set for which background noise was known not to be an issue. For most of these data runs, the criteria were met for both the leading and trailing edge OBSI levels. In a few cases, the criteria were exceeded in the 400 and 5000 Hz bands. A very few runs exceeded the criteria, however, these runs were obviously outliers compared to the other runs and should be eliminated. These tighter criteria on PI index will allow an acceptable error due to background noise while not rejecting many more runs than would occur based on the current frequency independent criteria.

Reflecting Objects

The effects of reflections from nearby surfaces were also evaluated in the tire noise dynamometer testing. For these tests, a large plywood "wall" was placed opposite and parallel to the sidewall of the test tire at various distances. These tests determined that maintaining a separation of 14½ inches or greater between the tire sidewall and reflecting object provided an error of less 0.3 dB for either the smooth or coarse surface. Therefore, a separation of 15 inches appears to be an appropriate criterion.

Test Speed

During the December 2010 test track measurements, the effects of speed variation were examined by testing at 59 and 61 mph for all the test pavements. The measurements were completed within a 2½ hour time period on December 15th using the primary test tire, TT#5. During the testing, the temperature ranged from 56 to 58º F and no temperature compensation was applied to the results summarized in Table 9. On average, the increase in OBSI level due to increasing speed from 59 to 61 mph was 0.42 dB or 0.21 dB/mph consistent with the results of earlier research[1]. It is also comparable to the speed gradients of 0.22 and 0.25 dB/mph that were measured on the tire noise dynamometer under very controlled conditions. For individual pavements, the effect of speed varies considerably

Table 9: OBSI levels and level differences for test speeds of 59, 60, and 61 mph

Test Section	OBSI Level (dBA) at Nominal Test Speed (mph)			Difference in OBSI Level (dB) for Indicated Speed Differences (mph)		
	59	60	61	60-59	61-60	61-59
Ultra Smooth	95.1	95.3	95.1	0.2	-0.2	0.1
Slurry Seal	99.2	99.7	99.4	0.5	-0.4	0.1
Chip Seal	104.9	106.0	105.5	1.1	-0.4	0.6
Porous	100.6	101.0	101.3	0.4	0.2	0.7
Sand Blast	100.8	101.6	101.7	0.8	0.1	0.9
Burlap PCC	100.4	100.3	100.5	-0.1	0.2	0.1
Long. Tine PCC	102.5	102.9	103.0	0.3	0.1	0.4
3/8" DGAC	98.1	98.1	98.4	0.0	0.4	0.4
OGAC	98.8	98.8	99.1	0.1	0.3	0.3
3/4" DGAC	100.5	100.7	101.0	0.2	0.3	0.5
			Average	0.36	0.06	0.42
			Standard Deviation	0.35	0.29	0.27

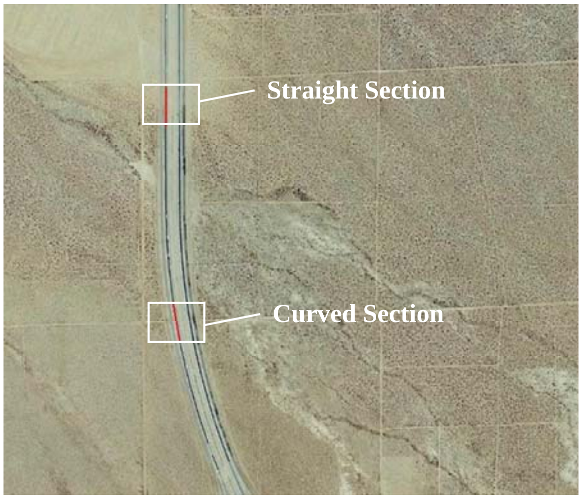
from 0.05 to 0.45 dB/mph. There appears to be no consistent trend between pavements to allow any grouping of the pavements. As a result, an adjustment for all pavements could be considered based on average gradient of 0.21 dB/mph with the knowledge that this would introduce an uncertainty of ±0.27 dB within the speed range of 59 to 60 mph.

The results shown in Table 9 indicate that the average difference in OBSI levels due to a ±1 mph change in speed are smaller than the 0.5 dB difference in sets for the same tire tested within a 4º F temperature range over a several day period (see section "On-Road Testing Reproducibility"). Therefore, maintaining the existing test speed requirement of 60 ±1 mph appears to be adequate. The standard deviations shown in Table 9 for ±1 mph speed change and variation between pavements suggest that adjustments within this range would not improve the certainty of the measurements. Adjustments to compensate for a speed change beyond ±1 mph will likely degrade measurement certainty even further given the range of speed gradients displayed for these pavements and for the twelve pavements measured in earlier research[1].

Horizontal Curves

The effect of side forces acting on tires operating in a curved path have been documented in the literature. Sandberg estimated that side forces create increases in tire noise level by 1 to 7 dB depending on the circumstance[24]. Also, increases of 2 to 10 dB have been measured for ribbed truck tires operating at low speed on a 110 ft radius circular path[25]. During comparative OBSI testing at the General Motors Proving Ground in Yuma, AZ, data on a 400 ft radius vehicle turn-around loop was collected for comparison to the same pavement on the straightaway portion of the "smooth" asphalt test track[26]. The loop was banked and had a recommended speed of 35 mph; testing was done at 30 mph. The curved/banked section produced levels that were on average 3.5 dB higher than the straightaway with the largest differences occurring in the one-third octave bands above 800 Hz. This extreme case of both curvature and banking demonstrated the potential for either of these parameters to produce higher tire/pavement noise levels in a situation where lateral force was quite apparent to the vehicle occupants.

To examine the effect of curvature under more moderate conditions, two locations on State Route 58 near the Hyundai-Kia Proving Ground were measured in conjunction with the test track measurements and are shown in Figure 22. One site was on the longitudinally tined PCC mainline and the other site was on HMA off-ramp and both were tested at 60 mph. For these cases, OBSI level increases of 0.6 dB and 0.4 dB were measured on the curved portion for the PCC and HMA sites, respectively, as shown in Figure 23. For the PCC site, the curvature was less than the HMA site, however some lateral force was experienced in the curve. The pavement was also found to be somewhat variable in OBSI level (on the order of 1 dB) and it could not be concluded that the difference is entirely due to curvature. It is suspected that the increases below 1000 Hz were more due to pavement variation than curvature. For the off-ramp site, the curvature and lateral force were greater and eight pairs of data were taken with standard deviations of 0.1 to 0.2 dB from run-to-run compared to 0.4 to 0.7 dB for the PCC site. At the ramp site, the increases in level occurred in the one-third octave bands above 800 Hz and were



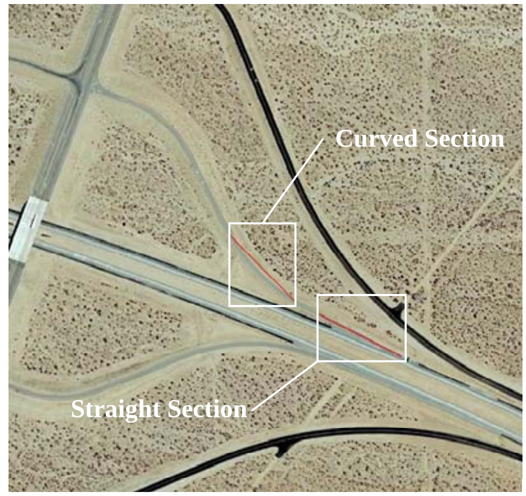


Figure 22: Sites for evaluation of horizontal curves with PCC site (left) and AC site (right)

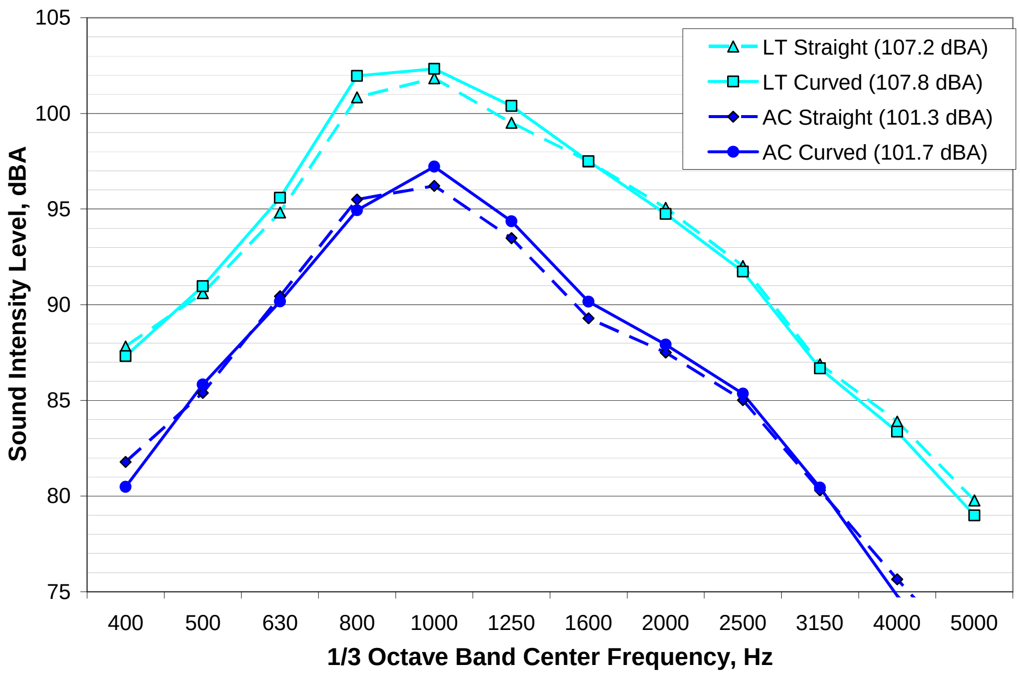


Figure 23: One-third octave band spectra comparison of straight and curved roadway sections

more consistent with the earlier results.

The results of these curvature tests were not conclusive in terms of developing strict criteria to apply to the OBSI procedure. Generally, the difference in OBSI level was on the order of test-to-test reproducibility and expected variation from site-to-site for nominally the same pavement. Further, the increase in OBSI level is likely due to increases in lateral forces acting on the tire. These forces are function of both horizontal curvature and pavement banking making a single criterion problematic. The current requirement in the procedure that the test section be “nominally straight” appears to be sufficient given the small differences measurements where lateral forces were clearly present. A possible modification to the requirement would be to add the phrase “so as not to produce any perceivable lateral force” as determined subjectively.

Vertical Curves

The effect of torque applied to the test tire by a drive axle that occurs due to over-coming road-load losses and ascending a grade was evaluated during the tire noise dynamometer testing (see details in Appendix D). In this testing, the drive axle of the front-wheel drive test vehicle was placed on the tire noise dynamometer and OBSI levels measured for this position. Testing was then done with the tire freewheeling (engine off, tires driven by the dynamometer), with the engine on supplying torque to the test tires to maintain steady cruise conditions, and with additional torque applied to the tires to overcome a 2% grade. The results indicated a 0.5 dB increase in overall OBSI level between the no-load and road-load case, and 1.1 dB between no-load and incline-load. This finding supports the requirement in the OBSI test procedure that only non-driven axles of the test vehicle should be used. Because the effects of torque would also occur under braking for a non-driven tire, measurement under free-rolling conditions should be added as part of the procedure.

Environmental Conditions

This section discusses the effects of wind and moisture on the OBSI measurements. The effect of temperature is discussed earlier in this Chapter.

Wind

One source of background noise and related inaccuracies in OBSI measurements is the noise induced by air flow passing the over and around the OBSI fixture, probes, and test vehicle. The proposed method of test using OBSI[1] does not set limits on wind conditions. To gain further understanding of possible wind noise contamination effects in isolation and to determine if and what limits on crosswind conditions are necessary for the OBSI measurement procedure, measurements were conducted in the General Motors Aeroacoustic wind tunnel. The measured wind induced background sound intensity levels (IL) and sound pressure levels (SPL) were compared to a tire/pavement noise source level calculated as an average of five of quieter pavements (labeled ‘AC Pavement’ in Figures 24 and 25, also see Appendix E). As an example, Figure 24 shows the ⅓ octave band SPL and IL levels on two test vehicles at 60 mph and 0 degrees yaw with the dual probe fixture, compared to the AC Pavement OBSI levels. These results are similar for the two vehicles. The background wind noise IL was more than 10 dB below the tire-pavement noise level in all frequency bands, which would result in increases 0.4 dB or less in the individual ⅓ octave band IL levels for AC Pavement.

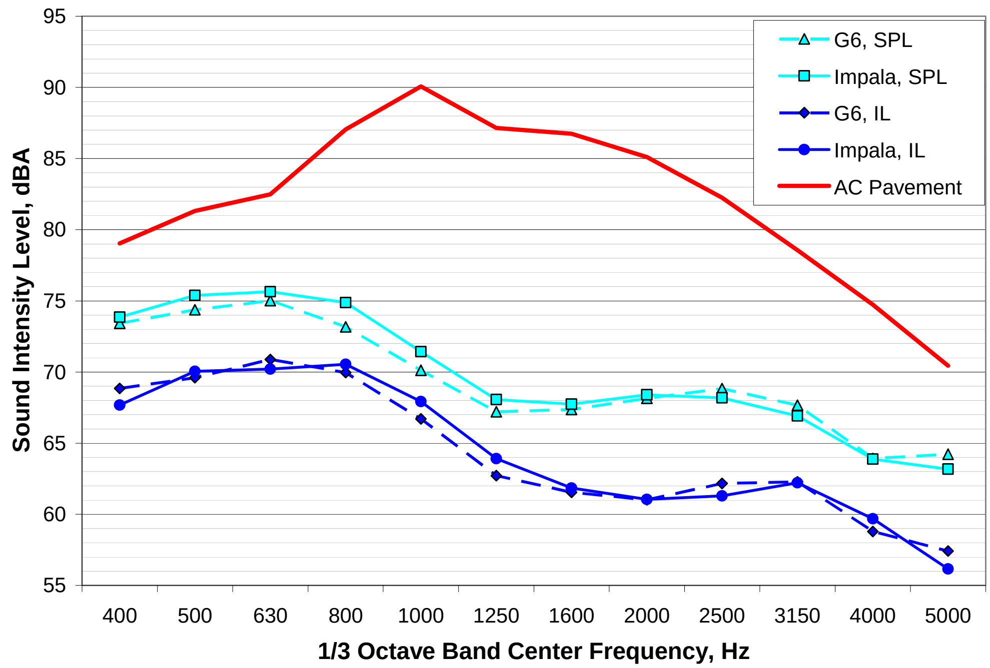


Figure 24: Sound intensity and pressure levels for test vehicles at 60 mph and 0° yaw

As shown in Figure 25, overall wind noise levels are lowest at a yaw angle of -6 degrees and highest for +14 degree yaw. For both vehicles, the overall sound intensity levels were more than 10 dB below the AC Pavement levels for all yaw angles, therefore crosswind conditions of up to 14 degrees would be acceptable for testing when considering the overall A-Weighted OBSI level.

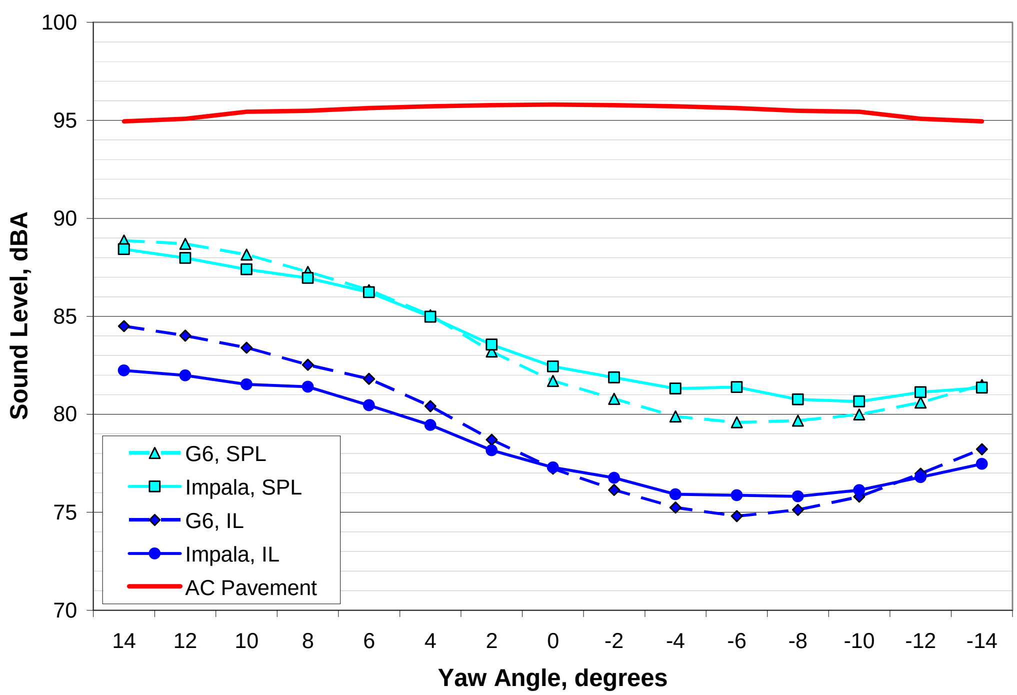


Figure 25: Overall sound intensity and pressure levels as a function of yaw angle

Wind noise levels relative to AC Pavement OBSI levels were also considered for individual ⅓ octave bands from -14 to +14 degrees yaw in 2 degree increment steps. This analysis indicated that the highest contamination occurred in the 400 and 500 Hz bands. For the bands centered at 400 and 500 Hz, wind induced background noise levels were less than 10 dB above the AC Pavement levels for yaw angles greater than 0. To quantify the error that could be expected to AC Pavement OBSI levels, the wind noise IL measured at each yaw angle for each vehicle was added to the AC Pavement level. The level due to AC Pavement alone was then subtracted from this summed level to determine the resultant error. The results of these calculations are shown in Figure 26 for the overall A-weighted levels and the 400 and 500 Hz band levels for both vehicles.

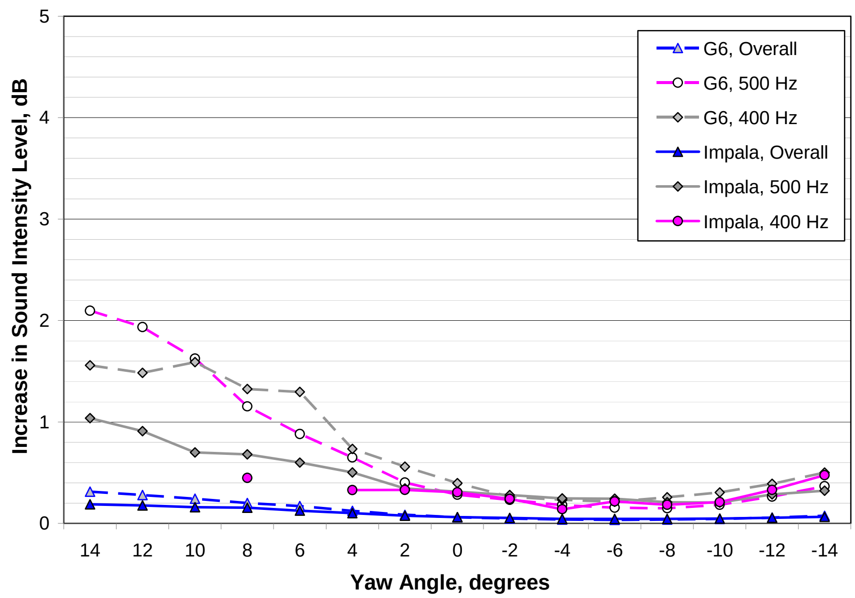


Figure 26: Increase in sound intensity levels above tire noise alone created by wind background noise effects for overall, 400, and 500 Hz bands

From Figure 26, the change in the overall OBSI for AC Pavement due to background wind noise was 0.3 dB or less in all yaw angles. In the 500 Hz band, the background noise with the Impala resulted in a 0.5 dB increase in the OBSI level starting at +4 degrees yaw and increased to 1 dB at +14 degrees yaw. In the 400 Hz band, the full range of positive yaw angle could not be evaluated due to 'drop outs' in the sound intensity level, however, up to +8 degrees, the measurement error did not exceed 0.5 dB. The errors due to the background wind noise were higher with the G6. In the 500 Hz band, the G6 background noise resulted in a 0.5 dB increase in the OBSI level starting at +4 degrees yaw, 1 dB at +8 degrees yaw, and 2 dB at +14 degrees yaw. For 400 Hz, the G6 resulted in a 0.5 dB increase OBSI level starting at +2 degrees yaw, 1 dB at +6 degrees yaw, and reaching 1.8 dB at +10 and +12 degrees yaw.

In the proposed method of test, run-to-run variability of 1 dB for the overall a-weighed OBSI level and 2 dB for the individual one-third octave band are set and extreme cases were at or below this limit for all conditions. Based on Figure 26, a conservative limit on crosswind condition could be set at +8 degrees yaw, or 8 mph, for wind in the direction from the probe to the test vehicle considering the possible accumulation of other sources of error.

Based on an analysis of the PI index with respect to the influences of wind induced background noise on OBSI measurement, it appears that tighter limits on the PI index may account for crosswind conditions in which the wind induced background noise is found to affect OBSI measurement levels. The results of the wind tunnel testing indicate that limits should be addressed on an individual 1/3-octave band case with particular attention paid to the 400, 500, and 5,000 Hz bands. Recommendations limiting the PI index which take into account the results described here as well as the results from other testing throughout the study, are discussed later in this Chapter.

Pavement Dampness

In the literature[24], persisting effect of damp porous pavement is documented up to 18 hours after rainfall even when the pavement appears to be dry. In the ISO 11819-2 standard defining the close proximity method of on-bound tire noise measurement[27], it is required to check for moisture in the porous pavement if rain has occurred within 2 days of the testing. In the proposed method of test, this requirement is also stated. For OBSI users, this requirement has been of concern as it cannot always be confirmed that a specific segment of roadway did or did not receive rainfall if rain was in the general vicinity. Further, a 2-day restriction will limit the time when a pavement can be tested. For non-porous pavements, the requirement is that the pavement appears dry. Because of these concerns, a more definitive limit on porous pavement moisture was examined.

During NCAT comparative testing, measurements were made on two porous pavements 1) when the were visually damp from rain occurring on the previous day, 2) when the pavements appeared visually dry later that day, and 3) two days later when pavements were completely dry (with no rain occurring for the previous three days). As shown in Figure 27 for the first pavement, the overall OBSI levels were essentially the same for the three conditions. In ⅓ octave bands, above 1000 Hz, differences of as much as 2 dB occur, however, the levels are higher when the pavement is completely dry. If moisture were affecting the sound absorptive properties of the pavement, it would be expected to occur in these frequencies and it would be expected that the damp levels would be higher[24]. For the second pavement shown in Figure 28, the overall levels were higher for the dry condition by 0.7 dB and the effect on higher frequencies is mixed. The change in overall level is determined by the frequency bands from 630 to 1000 Hz, which are generally controlled by pavement surface roughness and not by pavement porosity. The increase in level would be even greater if the difference in temperature were taken into account (61º and 65º F for the damp conditions, and73º F for the dry conditions). Similar behaviors were also noted at a 45 mph test speed.

Although the effect of porous pavement dampness on OBSI level was different than expected (increase with dry conditions), the results from the NCAT testing re-enforce the requirement that porous pavement should be given sufficient time to dry after rain before measurements are made. Two days for drying is specified in the current proposed method of test and this appears to be overly cautious. The requirement could be reduced to 24 hours with no appearance of dampness.

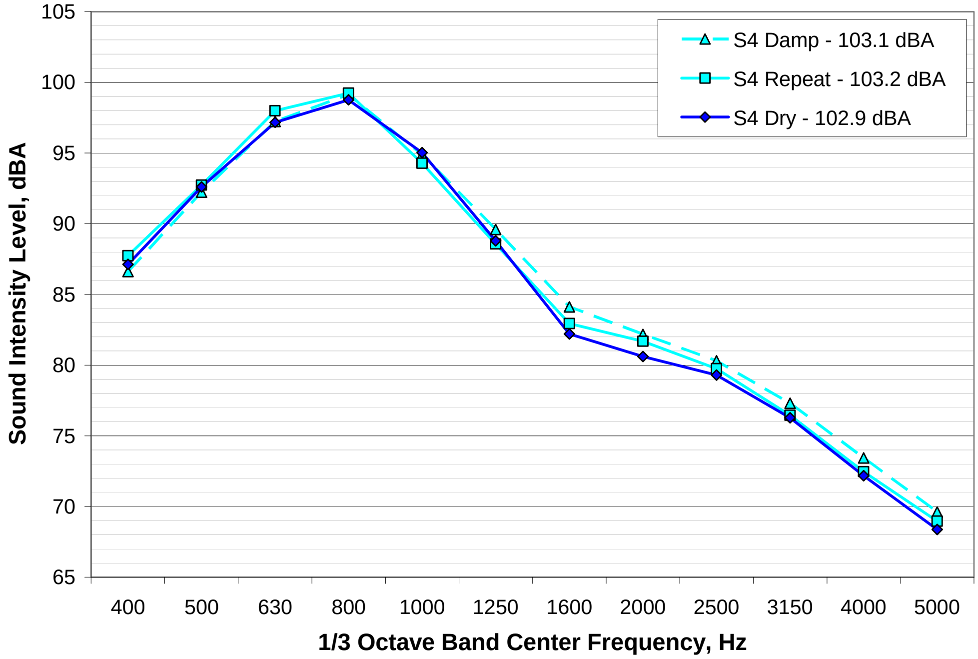


Figure 27: ⅓ octave band OBSI level on Section S4 (½" porous OGAC) for visibly damp and dry conditions

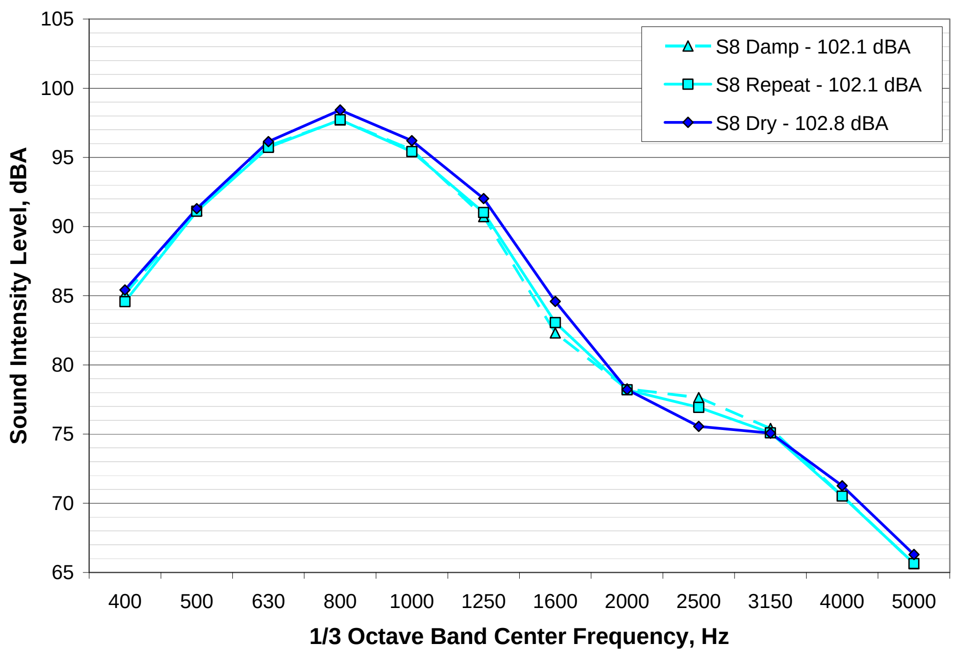


Figure 28: ⅓ octave band OBSI level on Section S8 (½" porous PFC) for visibly damp and dry conditions

Instrumentation

OBSI Measuring Equipment

The measurement of sound intensity is documented in two standards of the American National Standards Institute (ANSI) [28,29]. These cover the instruments for measuring sound intensity[28] and the methods for determining the sound power of noise sources using sound intensity[29]. Instruments are also covered in an International Electrotechnical Commission (IEC) Standard[30] which is similar to the ANSI standard. The ANSI standard for sound intensity[28] identifies a number of requirements on the instrumentation and their performance relative to sound pressure measurements and to the relationship between sound pressure and sound intensity under specific conditions. The stated operating temperature range of the measurements is 5º to 40ºC (41º to 104º F). The standard does not provide an overall uncertainty of the measurement if the standard is followed as it "depends on many factors"[31]. However, it provides tolerances on sound intensity measurements for plane waves incident on a probe at the reference direction (the line established by the two microphones of the probe for the positive direction). Under plane conditions, the tolerance for a Class 1 system is ±0.7 dB between one-third octave bands centered at 315 to 1250 Hz, ±1.0 dB for 1600 to 2000 Hz, and ±1.4 dB for 2500 to 5000 Hz. The ANSI standard for sound power determination[29] states uncertainties with standard deviations of 2.0 dB between 250 and 500 Hz, and 1.5 dB between 1000 and 4000 Hz for sound power determined with sound intensity. These values are higher than those for the sound intensity measurement alone due the added uncertainties in defining the average sound intensity on a surface enclosing the source. There are no temperature or other environmental requirements specified in the standard.

The standards provide little information on the uncertainty that could be expected in the OBSI measurement as the sound field is not ideal and does not contain only plane waves. Therefore, measurement uncertainty needs to be examined within the context of the OBSI measurements and it was addressed in the test track measurements and results of OBSI comparative testing. The elements that comprise an OBSI instrumentation system can however be considered individually for their uncertainties. Specifications provided by several suppliers of the sound intensity microphone pairs, microphone amplifiers, and calibrators were reviewed for accuracy and operating range. The operating ranges for microphones are typically between -10º and 50º C with a gradient of -0.002 dB/º C. The frequency response uncertainties are ±1.0 dB over the range of the OBSI measurement. The operating temperature ranges for preamplifiers are greater and the frequency response uncertainties range from ±0.2 dB to ±0.5 dB. This performance is valid up to 95% relative humidity. For sound pressure calibrators, the uncertainty at reference conditions (20º to 23º C temperature and 101.3 kPa atmospheric pressure) is typically ±0.2 dB. For larger ranges in temperature (-10º and 50º C) and pressure (65 kPa to 108 kPa), these uncertainties are increase by 0.1 to 0.2 dB. There is also some sensitivity to relative humidity such that most suppliers state an operating range from 10% to 90% RH with a gradient on the order of 0.001 dB/% RH.

In practice, although these uncertainties could produce a significant "stack-up" of uncertainties, effects of these uncertainties generally appear to be minor. Bench-top comparisons between different systems exposed to the same sound field showed differences consistently about 0.2 dB or less using the same calibrator and pressure and temperature settings. The Test Track measurements showed a 0.1 dB difference for the two instrumentation systems of the same model number, but different microphones, preamplifiers, and sound intensity processors. In comparison tests, sound pressure calibrators have produced differences of 0.2 dB, this falls within the range typically specified by calibrator suppliers.

To minimize uncertainties due to instrumentation, the proposed revisions test procedure set limits on temperature from 40º to 100ºF. These are at slight variance with those specified in the ANSI standard[28] of 5º to 40ºC (41º to 104ºF). The proposed lower limit is considered as a rounded number from the temperature scale conversion. Also, testing in this research was successful accomplished as low as 40ºF. The proposed high temperature was reduced due to testing in earlier research conducted in Mesa, AZ[1] and in the September 2010 testing. In both cases, problems with instrument were encountered when the air temperature exceeded about 100ºF. Under these conditions, the microphone and preamplifiers surface temperatures were measured to be about 120ºF and the signals produced by the probes generated input overloads in the sound intensity processor such that further testing was not possible. This could only be remedied by allowing the probes to cool in air-conditioned garage space.

OBSI System Calibration

As noted earlier, there is no calibration standard for sound intensity measurement. The ANSI standard for sound power determination from sound intensity measurements requires overall sound intensity measurement system verification using a reference sound source[26]. Under this procedure, the sound power of the source of known level is determined using the methods specified in the standard. This is basically an indirect method of a sound intensity calibration and the tolerances are large (± 1.5 dB for 800 to 5000 Hz) for the purposes of OBSI instrumentation validation. There is one commercially available device that does an actual sound intensity level by inserting a metal screen between two microphones making up a sound intensity probe. In this device, the same sound field is generated in the coupler with a small loudspeaker in which random noise can be input. The metal screen then induces a phase shift between the microphones and simulating a progressive sound wave between the microphones for which a sound intensity-like level is generated. Such a device was used in the bench-top temperature/pressure study (reported in Appendix B). Using a controlled voltage input to the device, stable pseudo sound intensity levels were generated over a period of months. This coupler could in principle be used a basis for a system for comparing sound intensity levels obtained by different OBSI users under bench-top conditions. However, a stable input signal would have to be verified and maintained. Also the "calibration" would only be relative among users and not absolute. Further, although the coupler appears to be stable itself, there are variations from coupler to coupler.

Vehicle/Operator Effects

Vehicle and operator effects were assessed during the on-road track testing and throughout the comparative testing events. The results of both the test track and comparative testing are within the limits of the proposed method of test and are similar to the earlier results[1], which indicated small bias for similar vehicles.

The February test track measurements were conducted by two different test teams each using their own test vehicle, test tire, instrumentation, driver, and instrumentation operator. The two instrumentation systems were similar and had been compared previously in a bench-top calibration and were found to produce overall levels within 0.1 dB of each other and differences for individual one-third octave bands ranging from 0.1 to 0.4 dB for the 400 to 5000 Hz bands. In the test track measurements, an initial comparison was conducted followed by a comparison in which the two teams swapped test tires. For the ten pavements, the maximum average difference between the team/ tire combinations was 0.2 dB as shown in Figure 29, mostly due to tire differences. The

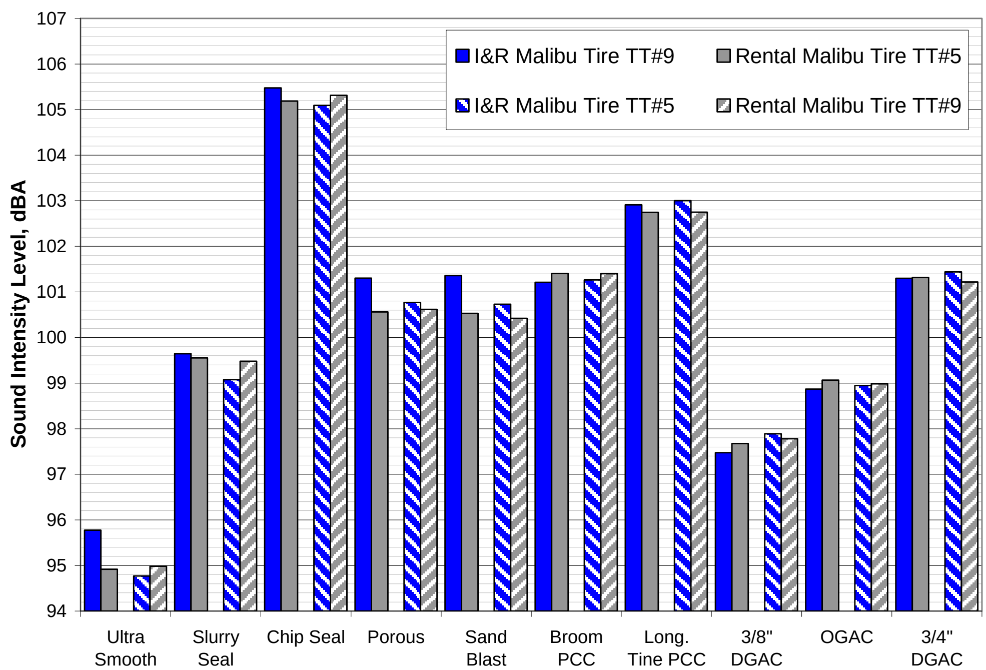


Figure 29: Overall OBSI levels for the two test teams with and without test tires switched

results of this controlled comparison with the same instrumentation (comparable to within 0.1 dB), the same tire loading for two different cars, the same section start point trigger signals, same vintage of test tires, and vehicle speed monitoring should produce less variation than would be expected in other less controlled OBSI comparative testing.

Once tire and temperature differences were taken into account in the comparative testing, differences due to measurement systems and operational issues between teams were found to be minimal. Differences between test teams were found to be attributable to tire loading, although the results were generally inconsistent and displayed considerable scatter. In the Yuma comparison testing, bench-top testing of different instrumentation was found to be within 0.2 dB. The North Carolina comparative tests could not identify consistent bias between teams using similar instrumentation and data acquisition setups, even with a variety of vehicle makes, models, and loading. The average differences between teams was found to be smaller than the differences between repeat baselines, suggesting that, on average, no significant differences between the procedures used by each team, the three different test vehicles, the instrumentation systems, or the tire loading occurred.

Repeatability and Reproducibility

The issue of repeatability was assessed under controlled laboratory conditions and for on-road conditions through analysis of consecutive passes made using the same vehicle/tire combination. Reproducibility was assessed through comparison of on-road data, using the same vehicle/tire combination over the course of the study.

Controlled Testing Repeatability

To identify the repeatability that could be expected under 'ideal' conditions, baseline measurements were repeated on the smooth and rough surfaces on the road wheel simulator. For these measurements, the tire was driven by the dyno at a constant test speed of 60.5 mph. Per the road wheel simulator protocol, measurements were made after approximately 5 minutes to allow the tire to reach a constant operating temperature. Measurements were made in three blocks with the dyno shutdown and restarted between the blocks. Within each block nine data samples were acquired in groups of three with each sample being a five second linear average as specified in the proposed method of test[1]. The overall A-weighted levels for these measurements are shown in Figure 30 for TT#5 on the smooth surface.

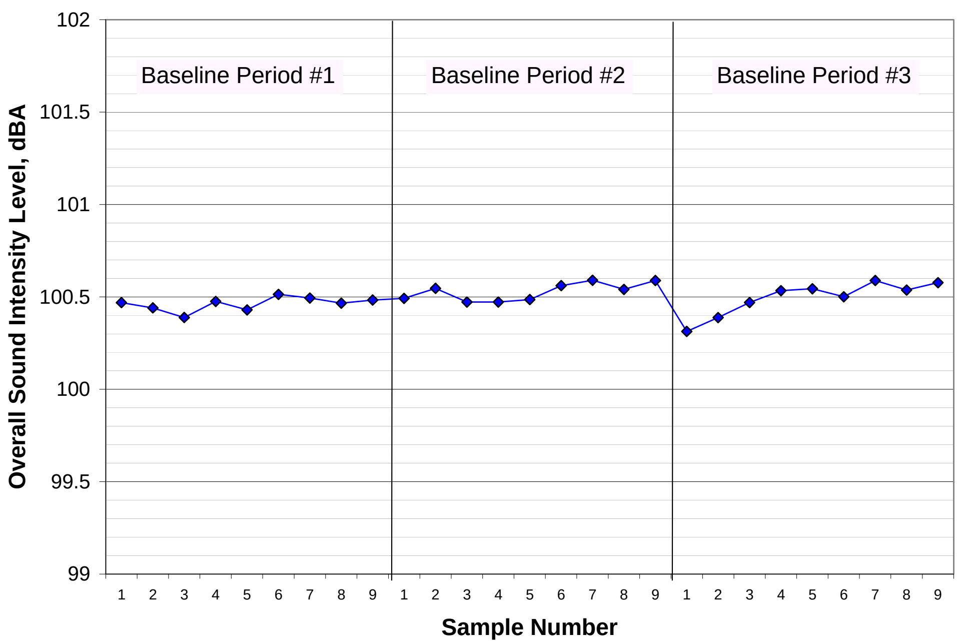


Figure 30: Overall OBSI levels for repeat runs over three baseline times

For the smooth road surface, the variation in levels for individual data points for TT#5 was found to be small with an overall range of less than 0.3 dB and a standard deviation of 0.07 dB. For TT#9 on the smooth surface, a range of 0.2 dB occurred with a standard deviation of 0.07 dB. For the individual one-third octave band levels, the average range was 0.6 dB with an average standard deviation of 0.17 dB for TT#5 and the average range was 0.5 dB with an average standard deviation of 0.13 dB for TT#9. A similar series of baseline measurements was conducted on the coarse road surface at the left rear wheel position using the passby SRTT. For these measurements, the range in baseline levels was 0.3 dB with a standard deviation of 0.1 dB.

Once stable operating parameters were achieved, the typical range in overall OBSI level was about 0.3 dB with a standard deviation less than 0.1 dB for both test surfaces. Limited variation in OBSI level occurred because test speed, environmental conditions, and wheel path were highly controlled and stop/start timing was not an issue. It would not be reasonable to expect that such low variation could be maintained for on-road conditions.

On-road Testing Repeatability

As part of the earlier research[1], ten or more consecutive passes were measured and compared to assess on-road run-to-run repeatability. Testing occurred over a period of 50 minutes and an air temperature range of 2º F. The total range in overall A-weighted OBSI levels for the SRTT tire on both the AC and PCC pavements was 0.8 dB, with standard deviations of 0.3.

The run-to-run variations of the individual passes were examined in this research in the February test track measurements and were found to be generally small. First, the range of the overall level from run-to-run for each tire and each pavement was identified resulting in 180 three run data sets. For each pavement, the average, maximum, and minimum of the ranges were determined and are presented in Table 10. These data indicate an average run-to-run variation of 0.1 to 0.3 dB and a maximum range for all pavements and tires of 0.9 dB (similar to the maximum range reported in the earlier research[1]. The maximum standard deviation for any surface and tire combination was 0.5

Table 10: Run-to-run level variation for February testing

Pavement	Average Range, dB	Maximum Range, dB	Minimum Range, dB
Ultra Smooth	0.3	0.9	0.1
Slurry Seal	0.2	0.5	0.0
Chip Seal	0.3	0.6	0.1
Porous	0.1	0.3	0.0
Sand Blast	0.2	0.4	0.0
Burlap PCC	0.2	0.4	0.1
Long. Tine PCC	0.3	0.8	0.0
3/8" DGAC	0.1	0.3	0.1
OGAC	0.1	0.3	0.0

with an average of 0.3 and standard deviation of 0.1.

The results for the range in run-to-run variation indicate that a 1 dB requirement is achievable and that a run-to-run variation of about 0.5 dB should be achievable. Results for the standard deviation of run-to-run levels support a requirement for a maximum limit of 0.6 with more typical standard deviations being about 0.3.

On-road Testing Reproducibility

To assess reproducibility, the variations between three-run data sets measured using TT#5 over three days of testing in February (temperature range of 55 to 59ºF) as well as over the course of the study were examined for TT#5. The measurements over the course of the study included a temperature range of 40 to 101º F and extended over 10 months in which mileage and aging occurred on both the test tire and the pavement surface.

Table 11 shows the maximum range and standard deviation of test-to-test variation for each pavement after temperature corrections were applied for both comparisons. The

Table 11: Test-to-test OBSI level variation for on-road testing

Pavement	February (55-59ºF)		All Testing (40-101ºF)	
	Range, dB	Standard Deviation, dB	Range, dB	Standard Deviation, dB
Ultra Smooth	0.5	0.2	1.6	0.5
Slurry Seal	0.5	0.2	1.5	0.4
Chip Seal	1.1	0.4	2.6	0.8
Porous	0.9	0.3	1.4	0.3
Sand Blast	0.5	0.2	2.1	0.5
Burlap PCC	0.4	0.2	1.7	0.4
Long. Tine PCC	1.2	0.4	1.2	0.3
3/8" DGAC	0.3	0.1	2.3	0.7
OGAC	0.4	0.2	0.9	0.2
3/4" DGAC	0.2	0.1	1.4	0.3
Average	0.5	0.2	1.7	0.4

February testing resulted in maximum test-to-test ranges of 0.2 to 1.2 dB, with standard deviations of 0.1 to 0.4. For all testing conducted, the maximum range for any pavement was 2.6 dB and maximum standard deviation for any surface was 0.8 dB.

These results indicate that about a 1 dB variation in levels may be achievable for measurements over the course of a several days conducted within a reasonable temperature range (~5ºF). However, even with application of the temperature correction, comparison testing when small differences are expected is best conducted within similar temperature ranges (~10ºF) unless temperature is the variable being tested.

CHAPTER 5

DEVELOPMENT OF PRECISION AND BIAS STATEMENTS

"Precision" is defined as variation for a single operator (repeatability) and variation between laboratories when testing the same material (reproducibility), in this case pavement, and "bias" is defined as the systemic error inherent in the test method. For this research, precision is considered as uncertainty that occurs for a pavement measured under the same conditions made in a short time interval, two hours for instance. Bias is defined as the uncertainty that occurs over a longer time interval or from one site to another and is not accounted for in the test procedure either by limits or corrections. For example, temperature differences, tire age, and pavement age are sources of bias.

The approach to assessing uncertainty in experimental data used in this analysis is based on the international standard ISO 5725[32,33]. Based on these references, the uncertainty and the limit of repeatability, reproducibility, or bias associated with observed values can be calculated with a probability of 95 percent as follows:

$U = 2 * \sigma$, where U is uncertainty and σ is the standard deviation from the mean
$l = 2.8 * \sigma$, where l is the limit of repeatability, reproducibility, or bias

Precision and bias were defined and calculated using the data sets indicated below.

1) Precision repeatability
   a. Definition - The uncertainty of the results for a single operator testing on a pavement surface under the same environmental conditions over a relatively short time interval
   b. Data - On-road test results made with TT#5 in February within 5º F temperature range.

2) Precision reproducibility
   a. Definition - The uncertainty between test tires/teams for a given pavement under the same environmental conditions made within a short time interval or for a single operator over a multi-day test period
   b. Data Set 1 - On-road test results made with TT#5 in February and March
   c. Data Set 2 - The 16 different SRTT test tires that were tested while mounted on the right rear wheel of the test vehicle during the February and March testing

3) Bias
   a. Definition - The uncertainty occurring over a longer time interval or from one site to another that is not accounted for in the test procedure
   b. Data - Test results made during all on-road testing with TT#5, including tests in February, March, September, and December with the recommended temperature adjustment.

The uncertainty and limit of repeatability, reproducibility, and bias were calculated for each of the conditions listed above. The uncertainty was used to define the precision and bias in the test procedure. The results of these calculations are shown in Table 12.

Table 12: Calculated Uncertainty and Limit of Repeatability for Test Procedure

	Uncertainty, dB	**Limit, dB**
Repeatability	± 0.2 (0.4 total)	0.6
Reproducibility	± 0.4 (0.8 total)	1.1
Bias	± 0.5 (1.0 total)	1.4

The limits of reproducibility were compared to the comparative testing results to validate the results of the calculations. The average ranges for the comparative tests were about 1.3 dB, which is slightly higher than the limit of reproducibility (1.1 dB). However, these comparative testing results do not take into account the recommended limits or corrections recommended in this research. Therefore, it seems reasonable to expect slightly lower ranges with some modification of the test procedure.

CHAPTER 6

PROPOSED REVISIONS TO THE PROCEDURE

Based on the findings of this research, several changes to the test method are recommended. The following is a summary of the recommended changes:

- Require that test tire hardness, wheel width, and groove (tread) depth fall within the specifications indicated in ASTM F 2493 P225/60R16 for new tires.
- Change the tire loading specification from 850±100 lbs to 800±100 lbs, to better align with the range of vehicles used in current OBSI testing.
- Add criteria to indicate when a test tire is considered inappropriate for use and should be replaced (with a new SRTT).
- Define the position of the leading and trailing edge probes fore/aft by a probe separation of 8¼ inches centered on the axis of rotation of the tire (to avoid ambiguity of defining the edges of the contact patch) and remove Figure 2.
- Remove the air density correction and require that standard values of 68°F (20°C) and 1 atm be entered into the analyzer for all testing.
- Require measurement of air temperatures every half hour or less to detect changes of ±2°F and that testing is further restricted to be within a temperature range from 40 to 100°F and recommend (not require) measurement of pavement temperature.
- Recommend that tests be conducted when crosswind wind speed is 8 mph or less in the wind direction from the probe to the test vehicle (see Figure 3).
- Require that atmospheric pressure be determined for the test period
- Require that reflective surfaces be located at a distance of 15 inches or greater from the tire sidewall.
- Add a new section entitled "Vehicle Operation" addressing start location, tire path, and test vehicle speed.
- Require start location to be within ±10 feet relative to the identified start point.
- Require that testing to be conducted with the test tire in the wheel path or otherwise to document and report tire position.
- Require that test vehicle speed be maintained within ±1 mph of the nominal test speed.
- Require frequency dependent PI index data quality criteria.
- Specify an air temperature correction of 0.04 dB/º F to normalize the overall A-weighted OBSI levels to a standardized air temperature of 68ºF (20ºC).
- Require only temperature corrected OBSI data to be reported along with the correction factor.
- Require that atmospheric pressure be reported.
- Require that OBSI levels uncorrected for temperature, tire hardness, tire loading, and location of the start point are recorded.
- Add revised precision and bias statements.

The test procedure revised to reflect these recommended changes is presented as Attachment 1.

CHAPTER 7

RECOMMENDATIONS AND SUGGESTED RESEARCH

Based on the findings of this research, recommendations for the implementation of the test procedure and other recommendations are provided in this section.

Test Procedure Implementation

The proposed revisions to the test procedure outlined in Chapter 6 should be reconciled with the current draft AASHTO OBSI procedure. Also, the findings of this research should be communicated to other standards organizations (ASTM and SAE) involved in developing OBSI procedures.

Continuing Test Procedure Refinement

This research has recommended changes to define and reduce the limits of the precision bias of the OBSI procedure. Because of the complexity and interactions between individual test tires, pavements, and other variables, better understanding of the influence of these items on the precision and bias is necessary. This can be accomplished through thoroughly documented comparative testing following the recommended procedure. Particular emphasis should be applied to test tires because they contribute most to uncontrolled variation. Statistical correlations between tire hardness, tread depth, age, loading, and tire/pavement noise level should be investigated. Further, the recommended criteria for test tire retirement should be assessed to determine if the recommended limits are sufficiently restrictive to reduce variability between tires or if they more strict than necessary. Further, a periodic review of the choice of the SRTT for consistency of noise generation both for single tires over time and for the population of new tires should be conducted. In addition, roadway specific issues such as the effect of roadway curvature, banking, and tire position relative to the wheel path should be investigated to determine if more quantitative controls are necessary to achieve less uncertainty.

Use of Tire Noise Road-Wheel Simulators

The majority of the testing for this project was conducted on-road. However, the OBSI testing conducted on the road-wheel simulator and on-road over the replicated pavement surfaces demonstrated sufficient correlation to consider such facilities in future work. Parameters such as test tire variation and aging, test speed, wheel load, inflation pressure, wheel alignment and temperature should be evaluated using a road-wheel simulator allowing more controlled testing.

Coordination with Other Tire/Pavement Noise Assessment Procedures

Statistical Isolated Pass-by (SIP) and Continuous-Flow Traffic Time Integrated (CTIM) methods are two procedures describing methods of determining the influence of pavements on vehicle noise at locations adjacent to a roadway (e.g., “wayside” locations, representative of communities adjacent to highways) under various in-situ highway traffic conditions. Coordinating the development of these procedures with OBSI methods is an important aspect of implementing the OBSI method and generating increasing understanding of relation of on-board and wayside techniques. To facilitate comparison of SIP and CTIM and OBSI, these wayside procedures should undergo similar analysis to that presented in this study to develop precision and bias statements.

Suggested Research

The following topics of research are suggested based on the findings of this project:

- Investigate tire variation to determine the influence of parameters that may affect noise generation and could be controlled in the test procedure.
- Verify the findings and recommendations of this research on several porous pavements.
- Conduct testing to further identify differences between test teams that might be controlled through the test procedure.
- Conduct parameter testing under a laboratory setting to further isolate variations with variables such as test speed, test tires, inflation pressure, wheel alignment, and wheel load.
- Investigate the effect of site-specific variables on CTIM and SIP measurements to identify the more important variables and set limits.
- Develop a method for relative calibration of complete sound intensity measurement systems.

REFERENCES

1. Donavan, P. and Lodico, D., “Measuring Tire-Pavement Noise at the Source”, NCHRP Report 630, Transportation Research Board, Washington, D.C., 2009.
2. F2493 Standard Specification of P225/60R16 Radial Standard Reference Test Tire, ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA.
3. Sandberg, U., “Semi-Generic Temperature Corrections for Tyre/Road Noise”, Proceedings of Inter-Noise 2004, Istanbul, Turkey, August 2004.
4. Anfosso-Lédée, F., and Pichaud, Y.. “Temperature Effect of Tyre-Road Noise”, Applied Acoustics 68 (2007) 1-6, June 2006.
5. Bendtsen, H., Lu, Q., and Kohler, E., “Temperature Influence on Road Traffic Noise: California OBSI Measurement Study”, draft report of the Danish Road Institute, the University of California Pavement Research Center, Dynatest, and Caltrans (contact Bruce Rymer, Caltrans for availability).
6. Thornton, W., Bernard, R., Hanson, D., and Scofield, L., “Acoustical Variability of Existing Pavements”, Proceedings of Noise-Con 2004, Baltimore, Maryland, July 2004.
7. Donavan, P., “Illingworth & Rodkin Updates”, Proceedings of the FHWA Tire/Pavement Noise Strategic Planning Workshop, Purdue University, Indianapolis, IN, April 2006.
8. Rasmussen, R., Mun, E., Karamihas, S., and Chang, G., “Relating Pavement Texture to Tire-Pavement Noise”, Proceedings of Inter-Noise 2006, Honolulu, Hawaii, December 2006.
9. Donavan, P., “Comparison of OBSI Measurements for Four Research Teams: the Mesa Rodeo”, California Department of Transportation, Division of Environmental Analysis, Sacramento, CA, prepared by Illingworth & Rodkin, Inc., Petaluma, CA, January 2006.
10. Sandberg, U. and Glaeser, K., Effect of Tyre Wear on Noise Emission and Rolling Resistance”, Proceedings of Inter-Noise 2008, Shanghai, China, October 2008.
11. Donavan, P., “Use of the ATSM Standard Reference Test Tire as a Benchmark for On-Board Tire/Pavement Noise Measurement”, SAE Paper 2009-01-2108, Society of Automotive Engineers Noise and Vibration Conference Proceedings, St. Charles, Illinois, May 2009.
12. Moore, D., “SRTT Noise Variability”, presentation to the ISO Working Group 33 of the ISO Procedure 11819, Acoustics – Measurement of the Influence of Road Surfaces on Traffic Noise, International Organization for Standardization, Geneva, Switzerland.
13. Donavan, P.R., “Pavement Acoustics Testing at NCAT: OBSI, Sound Propagation, and Comparative Measurements”, prepared for the Washington State Department of Transportation under Agreement Y-10704 and Tire/Pavement Noise Research Consortium Pooled Fund TPF-5(135), by Illingworth & Rodkin, Inc., Petaluma CA, August 2010.
14. Donavan, P.R., “Comparative OBSI Testing at the General Motors Proving Ground in Yuma”, prepared for the Washington State Department of Transportation under Agreement Y-10704 and Tire/Pavement Noise Research Consortium Pooled Fund TPF-5(135), by Illingworth & Rodkin, Inc., Petaluma CA, August 2010.

15. Lodico, D., “Comparison OBSI Testing near Austin, TX: TxDOT Rodeo”, Prepared for the Texas Department of Transportation, the Washington State Department of Transportation under Agreement Y-10704, and Tire/Pavement Noise Research Consortium Pooled Fund TPF-5(135), by Illingworth & Rodkin, Inc., Petaluma CA, July 2010.
16. Donavan, P.R., “Comparative OBSI Testing in North Carolina: The North Carolina Rodeo”, prepared for the Washington State Department of Transportation under Agreement Y-10704 and Tire/Pavement Noise Research Consortium Pooled Fund TPF-5(135), by Illingworth & Rodkin, Inc., Petaluma CA, March 2011.
17. ASTM International, “Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials”, ASTM C 670-03, ASTM International, West Conshohocken, Pennsylvania, 2003.
18. Donavan, P. and Lodico, D., “Tire/Pavement Noise of Test Track Surfaces Designed to Replicate California Highways”, Proceedings of Inter-Noise 2009, Ottawa, Ontario, Canada, August 2009.
19. Lodico, Dana M., and Reyff, James A., "Long-term noise performance of open graded asphalt concrete (OGAC) - Results of 10-year long study", Noise Control Engineering J., Volume 57, Issue 2, pp. 84-93 (March 2009).
20. Rasmussen, R., Bernhard, R., Sandberg, U., and Mun, E., “The Little Book of Quieter Pavements”, Report No. FHWA-IF-08-004, prepared by the Transtec Group, Inc., Austin TX, for the Federal Highway Administration, Office of Pavement Technology, Washington, DC, July 2007.
21. Sandberg, U., “Influence of Tyre Rubber Hardness on Tyre/Road Noise Emission”, Proceedings of INTERNOISE 2007, Istanbul, Turkey, August 2007.
22. Donavan, P. and Rymer, B., “Effects of Aging on Tire/Pavement Noise Generation for Concrete Pavements of Different Textures”, Compendium of Papers, TRB 90th Annual Meeting, Washington, D.C., January 2011.
23. Donavan, P., “Tire Noise Generation and Propagation over Non-Porous Asphalt Pavements”, Compendium of Papers, TRB 90th Annual Meeting, Washington, D.C., January 2011.
24. Sandberg, U., and Ejsmont, J., The Tyre/Road Noise Reference Book, INFORMEX, Ejsmont & Sandberg Handelsbolag, Harg, SE-59040 Kisa, Sweden, 2002, p.483-484.
25. Donavan, P.R., “Examination of Tire/Road Noise at Frequencies above 630 Hertz”, The Proceeding of InterNoise 2002, Dearborn, MI, USA, August 2002
26. Donavan, P.R., “Comparative OBSI Testing at the General Motors Proving Ground in Yuma”, prepared for the Washington State Department of Transportation under Agreement Y-10704 and Tire/Pavement Noise Research Consortium Pooled Fund TPF-5(135), by Illingworth & Rodkin, Inc., Petaluma CA, August 2010.
27. International Standard ISO 11819-2, “Acoustics – Measurement of the Influence of Road Surfaces on Traffic Noise – Part 2: The Close Proximity Method”, International Organization of Standardization, Geneva, Switzerland, 2000.
28. American National Standard ANSI S1.9-1996, “Instruments for the Measurement of Sound Intensity”, American National Standards Institute, Inc. administered by the Acoustical Society of America, New York, NY, 1996 (reaffirmed 2006).
29. American National Standard ANSI S12.12-1992, “Engineering Method for the Determination of Sound Power Levels of Noise Sources Using Sound Intensity”,

30. International Electrotechnical Commission Standard IEC 61043, "Instruments for the Measurement of Sound Intensity", IEC, Geneva Switzerland, 1993.
31. Jacobsen, F., "On the Uncertainty in Measurement of Sound Power Using Sound Intensity", Noise Control Eng. J. 55(1), 2007 Jan-Feb.
32. International Standard ISO 5725, "Part 1 to 6 Accuracy Trueness and Precision of Measurement Methods and Results", International Organization of Standardization, Geneva, Switzerland, 1994.
33. Ageron, T., Pardo, L., Berthou, C., Ficheux, S., and Perruchet, C., "Experimental approach for evaluating uncertainties associated with vehicle noise according to ISO 5725", Noise Control Engineering Journal, 2006.

NCHRP Project 1-44 (1):
Measuring Tire-Pavement Noise at the Source:
Precision and Bias Statement

Attachment 1

PROPOSED REVISED STANDARD METHOD OF TEST FOR

MEASUREMENT OF TIRE/PAVEMENT NOISE USING THE ON-BOARD SOUND INTENSITY METHOD (OBSI)

PROPOSED STANDARD METHOD OF TEST FOR

DISCLAIMER

The proposed revised test method is a recommendation of the staff at Illingworth & Rodkin, Inc and Lodico Acoustics, LLC. The test method has not been approved by NCHRP or by any AASHTO Committee or formally accepted for the AASHTO specifications.

MEASUREMENT OF TIRE/PAVEMENT NOISE USING THE ON-BOARD SOUND INTENSITY METHOD (OBSI)

1. Scope

1.1 This document defines the procedures for measuring tire/pavement noise using the on-board sound intensity (OBSI) method.

1.2 OBSI measurements at the source can be used to characterize the in-service noise performance of pavements.

1.3 This procedure is anticipated to change as experience increases and additional research allows for the establishment of testing variables over a larger data set.

1.4 This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards

2.1.1 F2493 Standard Specification of P225/60R16 Radial Standard Reference Test Tire

2.2 ANSI Standards

2.2.1 ANSI S1.9-1996 (R2006): Instruments for the Measurement of Sound Intensity

2.2.2 ANSI S1.40-2006: American National Standard Specifications and Verification Procedures for Sound Calibrators

2.2.3 ANSI S1.11 Specification for Octave-Band and Fractional-Octave-Band Analog and Digital Filters

3. Terminology

3.1 *Sound intensity* – the instantaneous product of acoustic pressure and acoustic particle velocity at a point with the direction of propagation defined by the particle velocity vector. It corresponds to the acoustic energy flow through a unit area and has the units of Watts per square meter.

3.2 *Sound intensity level* – ten times the logarithm of the time averaged sound intensity divided by the reference sound intensity (I_{ref}) of 1 x 10^{-12} watts per square meter ($10*Log(I/I_{ref})$).

3.3 *Coherence* – a measure of the linear dependency of two signals with a value of 0 being no dependency, and a value of 1 being prefect linear dependence. Mathematically, it is the magnitude of the cross-spectrum between two signals squared divided the product of the auto-spectrum of both signals.

3.4 PI_{index} – the sound intensity to sound pressure level index defined by subtracting the sound intensity level from the sound pressure level.

4. Summary of Method

4.1 A method is described to measure tire/pavement noise from a standard test tire using a sound intensity probe that is installed directly on a test vehicle using an appropriate fixture. Data is acquired over a 440 ft section of pavement at a steady test speed. Where possible, a test speed of 60 mph is used with alternative speeds of 35 and 45 mph depending on local conditions and regulations. Sound intensity levels are measured at the leading and trailing edge contact patch of the test tire, either simultaneously or consecutively, and a minimum of two runs for each probe location are made. Data is acquired for ⅓ octave bands centered at 400 to 5000 Hz and checked to ensure that data quality criteria are met. The results from the leading and trailing edge positions for each run are averaged together and then the tire averages for individual runs are averaged, resulting in the overall A-weighted OBSI level and ⅓ octave band levels that are reported for each pavement section.

5. Significance and Use

5.1 This test method defines procedures to quantify tire/pavement noise levels very near the noise source and in isolation from other vehicle noises.

5.2 Using the method and the specified standard test tire, measurements can be compared across different pavements and among different users of the method.

5.3 The method can also be used to compare the tire/pavement noise generation of different tires, including truck tires, if the intent of the measurements is to compare tire noise generation on some defined set of pavements.

6. Equipment

6.1 Acoustic Instrumentation

6.1.1 The sound intensity level shall be measured using a sound intensity meter or equivalent measurement system meeting the requirements of ANSI S1.9-1996 (R 2006) and requirements of ANSI S1.11.

6.1.2 The sound intensity probe shall consist of two ½" phased matched condenser microphones installed on two ½" microphone preamplifiers. These shall be attached to a plastic probe holder that provides a 16mm center-to-center spacing of the microphones as measured from the center of the microphone diaphragms resulting in a "side-by-side" SI probe configuration. The midpoint between these microphones shall be used in positioning the probe. The microphones shall be protected from airflow using a spherical foam windscreen approximately 3½" in diameter.

6.1.3 Acoustic calibration of the entire data acquisition system shall be performed with a sound calibrator that fulfils the requirements of ANSI S1.40 Class 0 or Class 1.

6.2 Non-Acoustic Instrumentation

6.2.1 Air and surface temperatures shall be measured with a device with an overall accuracy of ±1.8° F.

6.2.2 Wind speed shall be measured with a device capable with an overall accuracy of ±5%

6.2.3 Tire inflation pressure shall be measured with a device with an overall accuracy of ±1 psi.

6.2.4 Vehicle speed shall be measured with a device with an overall accuracy of ±1 mph. Vehicle speedometers may be used if independently calibrated by a device with an overall accuracy of ±1 mph.

6.3 Test Tire

6.3.1 Measurements shall be conducted using the ASTM F 2493 P225/60R16 (16 inch) Standard Reference Test Tire (SRTT). Note that in order to be in adherence with ASTM F 2493 P225/60R16, the hardness of new test tires must be 64 ± 2 when measured with an ambient temperature of 73.4 ± 3.6º F. The test tire must be mounted with a wheel width of 6.5± 0.5 inches. Once in use, tire hardness must be measured and recorded within a month of each test.

6.3.2 Test tires shall be operated in only one rotational direction for the test life of the tire. The test tire shall be mounted on the right side of the test vehicle unless special circumstance requires testing in the left wheel path. The test tire shall be mounted on a non-driven axle for free-rolling operation.

6.3.3 The test tire shall be inflated to a pressure of 30±2 psi cold.

6.3.4 The test tire shall be loaded with the existing, unloaded weight of the vehicle plus personnel and equipment to perform the testing unless specified otherwise in the test plan. Loading of the test tire shall be 800±100 lbs.

6.3.5 The test tire shall be replaced when two or more of the following conditions occur:

6.3.5.1 The test tire has been in service for more than four years
6.3.5.2 The test tire has accumulated mileage greater 7,000 miles
6.3.5.3 The durometer hardness number of the tire is greater than 68
6.3.5.4 The average tread depth is less than 7.2 mm

6.4 Test Vehicle

6.4.1 The test vehicle shall provide a non-driven, non-steering tire/wheel mounting location.

6.4.2 The tire and wheel at the test position shall rotate freely without extraneous noise of any kind.

7. Measuring Procedure

7.1 Probe Location

7.1.1 Sound intensity shall be measured at two points, one opposite the leading edge of the contact patch and one opposite the trailing edge (Figure 1)

7.1.2 The measurement point for the leading edge probe shall be 4⅛ inches forward of the centerline of tire rotation. The trailing edge probe shall be located 4⅛ inches aft of the centerline of tire rotation providing a total probe separation of 8¼ inches.

7.1.3 The measurement points shall be 3±¼ inches above the ground with the test vehicle on a flat surface

7.1.4 Measurements shall be made in a plane surface parallel to the sidewall of the tire with the measurement plane 4±½ inches from the tire sidewall at the measurement location.

7.1.5 The probe shall be supported by a fixture capable of maintaining it in the specified position for the duration of the test. The fixture shall be designed to minimize extraneous noise and wind turbulence. Measurements of the leading

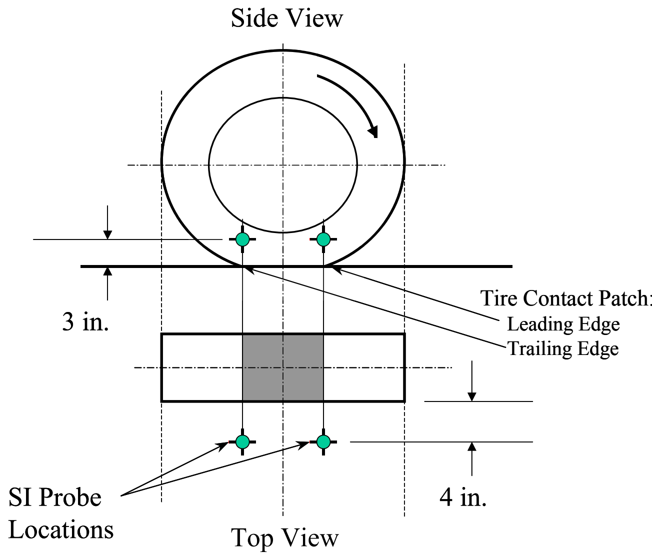


Figure 1: OBSI probe locations relative to test tire and pavement surface

7.2 Acoustic Calibration

7.2.1 Prior to each set of measurements, the sound intensity probes and measurement system shall be calibrated with the acoustic calibrator. At the end of each set measurements or after 4 hours (whichever is shorter), the calibration shall be repeated. If the second calibration differs from the first by more than ±0.2 dB, the set shall be repeated.

7.2.2 Standard values of 68ºF (20°C) air temperature and 1 atm barometric pressure shall be entered into the analyzer for proper calculation of sound intensity prior to OBSI measurement and used for all testing. (Corrections to account for actual temperature are specified in Section 8)

7.3 Environmental Conditions

7.3.1 Pavement dampness - The pavement shall be dry. For known non-porous pavements, this criterion shall be followed from visual inspection. For porous pavements, testing shall not be conducted on the pavement if it is known that rain has occurred in the vicinity of the test site within 48 hours.

7.3.2 Temperature – Air temperature shall be measured at the beginning of the OBSI measurement set and every half-hour thereafter, or sooner if environmental conditions are rapidly changing, such that changes of ±2°F are detected. Testing shall be restricted to a temperature range from 40 to 100°F unless the purpose of the testing is intended to evaluate the effects of temperature. If feasible, pavement temperature should be measured on same cycle defined for air temperature

7.3.3 Wind speed and direction - Wind speed and direction shall be monitored and noted for the test period. Crosswind speeds of 8 mph or more in the wind direction from the probe to the test vehicle should be avoided. Data validity checks shall be used to identify when wind conditions have adverse effects on the OBSI measurement.

7.3.4 Atmospheric pressure – Atmospheric pressure shall be determined for the time of test by direct measurement, by use of nearby meteorological data, or by other means.

7.4 Test Section

7.4.1 The test section shall have the same nominal material and surfacing for its length.
7.4.2 The test section shall be free of debris to the extent possible.
7.4.3 The test section shall be nominally straight so as not to produce any perceivable lateral force and free of dips and swells.
7.4.4 Any reflective surfaces shall be located at a minimum of 15 inches or greater from the location of the tire sidewall in the test section.
7.4.5 The start of data acquisition shall occur within ±10 ft relative to the identified start point.
7.4.6 Testing should be conducted with the test tire positioned in the wheel path. If testing is conducted outside of the wheel path, the location of the tire on the test section shall be documented and reported.

7.5 Acoustic Data Acquisition

7.5.1 Sound intensity shall be measured using a "linear average" (energy average) over a specific time interval. An averaging time of 5 seconds is be used for a test speed of 60 mph. For 45 mph, the averaging time is 6.7 seconds. For 35 mph, it is 8.6 seconds. If the pavement sections are too short to allow this or if it is suspected that the pavement is not consistent throughout the specified section, shorter period times are allowable as long as all Data Quality Criteria are met.

7.5.2 The mean sound pressure level of the probe microphone pair and coherence of the sound pressure signals between the microphone pair shall be measured. Microphone signals shall also be recorded for additional post-processing if required.

7.5.3 OBSI and other acoustic data shall be acquired at minimum for the ⅓ octave bands centered at 400 to 5000 Hz.

7.5.4 Microphone signals shall be filtered by the A-weighting spectrum shape at the input to the analyzer.

7.5.5 A minimum of two measurements each for the leading and trailing edge probe locations shall be made for each section of pavement tested. It is recommended that three or more measurements of each section be performed. If data quality criteria are not met for at least two of the runs, the measurements shall be repeated until they are.

7.6 Data Quality Criteria

7.6.1 Audio monitoring - The sound pressure signals shall be acoustically and/or visually monitored as they are acquired. Any unusual noises such as rattles, excessive wind noise, stones embedded in the tire tread, etc. shall be observed and the cause of such noises shall be identified and remedied.

7.6.2 The direction of the sound intensity shall be positive for all data reported as valid. Positive direction is defined as sound propagating away from the test tire.

7.6.3 The PI_{index} shall be equal to or less than the values given in Table 1 and greater than –1 dB in all ⅓ octave bands for all data reported as valid.

Table 1: Maximum allowed PI_{index} values for reported data

Freq.	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
Level	5	4.5	3.5	2.5	2.5	2.5	2.5	3.0	3.0	3.0	3.0	4.5

7.6.4 Coherence – The ordinary coherence between the two microphones comprising the probe shall be greater than 0.8 for all frequencies below 4000 Hz.

7.6.5 Overall A-weighted sound intensity levels for measurements made of the same pavement section shall be within 1 dBA. The range in sound intensity level between runs shall be less than 2 dB in all ⅓ octave bands for all data reported as valid.

8. Data Processing

8.1 OBSI data shall be processed into levels representing the combination of the noise sources at the leading and trailing edge of the contact patch. If a single probe is used, multiple runs shall be averaged together arithmetically for the leading and trailing edges separately. The leading and trailing averages shall then be averaged on an energy basis. If dual probes are used, the level of the two probes shall be averaged on an energy basis for each run. The energy averages for individual runs shall then be averaged together arithmetically.

8.2 A linear air temperature correction of 0.04 dB/º F shall be used to normalize the overall A-weighted OBSI levels to a standardized air temperature of 68ºF (20ºC) using the equation:

$$IL_{norm} = IL_{meas} + 0.04(T_{meas} - 68^{o}F)$$

Where IL_{meas} is the sound intensity measured by the analyzer set to 68ºF, T_{meas} is the temperature at the time of the test in ºF, and IL_{norm} is the OBSI level to be reported as the corrected level.

Both corrected and uncorrected data shall be documented. No attempt shall be made to correct the individual ⅓ octave band data.

9. Data Reporting

9.1 The specific acoustic data reported shall depend on the specific needs of the test as defined in the test plan and final report. As a minimum, the following tire/pavement average data shall be reported for each pavement section tested: overall A-weighted OBSI level summed over the frequency bands from 400 to 5,000 Hz corrected for temperature with correction value noted; ⅓ octave band levels for frequency bands from 400 to 5,000 Hz corrected for temperature with correction value noted.

9.2 Any exceptions to this stated OBSI procedure must be reported.

9.3 Other information that shall be reported include: air and pavement temperature range during testing, atmospheric pressure during testing, location and description of the test pavement, the location of the start point ±10 ft, the date of the measurement, period of the performance of the measurements, and test speed.

9.4 Additional information to be recorded shall include: wind conditions during the measurements, coherence, PI_{index}, probe configuration, tire hardness, tire loading, test vehicle make and model, and overall A-weighted OBSI level and ⅓ octave band levels over the frequency bands from 400 to 5,000 Hz uncorrected for temperature.

10. Precision and Bias

10.1 Precision

10.1.1 Repeatability - The uncertainty of the results of this test method for a single operator testing a given pavement under similar wind and humidity conditions, within a temperature range of 5ºF, and within a time period of 2 hours is ± 0.2 dB. The limit of repeatability is 0.6 dB.

10.1.2 Reproducibility – The uncertainty for a single operator testing over a multiple day test period is ± 0.4 dB. The limit of reproducibility is 1.1 dB.

10.1.3 Test Tire Reproducibility – The uncertainty between test tires under similar wind and humidity conditions, within a temperature range of 5ºF, and within a time period of 2 hours is ± 0.4 dB. The limit of test tire reproducibility is 1.1 dB.

10.2 Bias – The uncertainty occurring over a longer time interval or from one site to another that is not accounted for in the test procedure is ± 0.5 dB. The limit of bias is 1.4 dB.