John A. Volpe National Transportation Systems Center

On-Board Sound Intensity (OBSI) Study

Phase 2

FDOT Project No. #BDT06

Final REPORT

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Disclaimer

SI (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3

GLOSSARY OF RELEVANT ROAD TEXTURE TERMS

(As adapted from Sandberg and Ejsmont and ISO/FDIS 13473-2)[1]

Texture

Deviation of a road surface from a true planar surface, with a texture wavelength less than 0.5 m, and divided into micro-, macro- and megatexture according to the following definitions.

Texture wavelength

Quantity describing the horizontal dimension of the irregularities of a texture profile.

Spatial frequency

This is the inverse of texture wavelength. One can consider it as frequency in the space domain.

Microtexture

Deviation of a road surface from a true planar surface with the characteristics dimensions along the surface of less than 0.5 mm, corresponding to texture wavelengths with one-third-octave bands with up to 0.5 mm of center wavelengths.

Note: Peak-to-peak amplitudes normally vary in the range 0.001 mm to 0.5 mm. This type of texture is the texture that makes the surface feel more or less harsh but which is usually too small to be observed by the eye. It is produced by the surface properties (sharpness and harshness) of the individual chippings or other particles of the surface that may be in direct contact with the tires.

Macrotexture

Deviation of a road surface from a true planar surface with the characteristic dimensions along the surface ranging from 0.5 mm to 50 mm, corresponding to texture wavelengths with one-third-octave bands including the range 0.63 mm to 50 mm of center wavelengths.

Note: Peak-to-peak amplitudes may normally vary in the range 0.1 mm to 20 mm. This type of texture is the texture that has wavelengths of the same order of size as tire tread elements in the tire/pavement interface. Surfaces are normally designed with sufficient macrotexture to obtain suitable water drainage in the tire/pavement interface. The macrotexture is obtained by suitably proportioning the aggregate and mortar of the mix or by surface finishing techniques.

Megatexture

Deviation of a road surface from a true planar surface with the characteristics dimensions along the surface of 50 mm to 500 mm, corresponding to texture wavelengths with one-third-octave bands including the range 63 mm to 500 mm of center wavelengths.

Note: Peak-to-peak amplitudes normally vary in the range 0.1 mm to 50 mm. This type of texture is the texture that has wavelengths in the same order of size as a tire/pavement interface and is often created by potholes or ‘waviness’. It is usually an unwanted characteristic resulting from defects in the surface. Surface roughness with longer wavelengths than megatexture is referred to as unevenness.

Unevenness

Deviation of a road surface from a true planar surface with the characteristic dimensions along the surface ranging from 0.5 m to 50 m, corresponding to wavelengths with one-third-octave bands including the range 0.63 m to 50 m of center wavelengths.

Note: Road surface characteristics at longer wavelengths than 0.5 m are considered to be above that of texture and are referred to here as unevenness.

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16. Abstract

This is a continuation effort of previous research (Modeling of Quieter Pavement in Florida) and as such is a sister report to the previous final report. Both research efforts pertain to the noise created at the tire/pavement interface, which continues to gather considerable interest because of the potential benefits and a general desire by the public for quieter highways. A short review of important information is included from the Phase 1 report. Key findings from both reports (Phase 1 and Phase 2) are included and a detailed examination of the collected data is included. Additionally, the overall equipment is described as well as data collection procedures.

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EXECUTIVE SUMMARY

This is a continuation effort of previous research (Modeling of Quieter Pavement in Florida) and as such is a sister report to the previous final report. Both research efforts pertain to the noise created at the tire/pavement interface, which continues to gather considerable interest because of the potential benefits and a general desire by the public for quieter highways. The first report included a description of the sound generation mechanisms from tire/pavement noise and will not be included in this document except for a short review. Multiple key findings were included in the first report and led to findings and suggested action items that were included as objectives in this second research effort. These are:

1. Continue participation in the FHWA Quiet Pavements Program
2. Validation and implementation of the OBSI system
3. Develop and populate a formal acoustic inventory of pavement surfaces used in Florida
4. Develop precision statement based on research findings
5. Conduct training for FDOT personnel on the use of equipment and analysis of data

These objectives were met and included in this report. Key results included:

- Development of the final test rig and FDOT OBSI Test Trailer, field measurements at 47 new locations and 5 repeats of Phase 1 sections to measure changes in the sound created by the aging surface.
- A large ranking of the surface textures in use throughout Florida especially for rigid pavements, dense graded and open graded pavements.
- An analysis of different mix parameters and how they affect not only the sound levels but also the frequency components of the sound.
- Training of FDOT personnel on data collection including development of standard operating procedures.
- Documentation of the data and findings.

Key findings included:

- A final test rig design has been developed and thoroughly evaluated. It should provide service to the FDOT for many years.
- The FDOT Test Trailer has been greatly improved with multiple upgrades and again should provide service for many years.
- A solid methodology has been defined for collection and analysis of OBSI data. This has been turned into a guidance document attached to this report as Appendices A.1, A.2, and A.3.

- A tremendous data base of OBSI intensity levels, matched wayside sound pressure levels, meteorological data, and field notes has been established. While considerable analysis has occurred and is included in this report, much more work could be accomplished if resources were available.
- FDOT personnel have been trained on multiple occasions and should be able to collect quality data. However, much more detailed training may be necessary to start to understand the full acoustic concepts associated with this testing.
- A large number of surface textures (wear courses) have now been evaluated and ranked both at the source (tire/pavement interface) and at the wayside of the roadway.
- Flexible pavements appear to represent the quieter pavements in use in Florida.
- Three variables that seem significant in the pavement texture in terms of noise control are mean profile depth, aggregate size, and friction number. These variables were selected for analysis because of the general use in pavement design, availability, and are thought to act for surrogates of the acoustic parameters.
- Both the amplitude and frequency spectra were shown to be different based on the variables above.
- Rigid pavement (LGD), dense graded asphalt (FC125), and open graded asphalt (FC5 and FCQ) display distinctly different patterns in frequency spectra.
- The FC5 surface has a maximum (peak) at approximately 800 Hertz while the FC125 peak is about 1000 Hertz. The maximum peak is greater for the FC5, resulting in greater intensity levels at the tire/pavement interface.
- While the FC125 tend to have a linear falloff for the higher ranges, the FC5 surface has a noticeable dip over 2000 Hertz in the frequency spectra.
- The FCQ, which is essentially a FC5 surface, with different aggregate characteristics, follows the trends of the FC5 surface which would be expected.
- In Phase 1 an average difference of 32.2 dB(A) occurred when matched pairs of OBSI and wayside data were compared. The standard deviation was 2.5. This compares very favorably with results from Phase 2 where an difference of 32.5 dB(A) was measured with a standard deviation of 1.62 dB(A).
- The difference or delta consistency allows a general first order approximate method to approximate wayside sound levels if OBSI measurements are made. This general first order approximation is:

  Wayside SPL [dB(A)] = OBSI Sound Intensity Level – 32.5

  The uncertainty, considering 2.15 standard deviations in the positive and negative direction (practical limits of Gaussian distribution) is ± 3.5 dB(A) [standard deviation of 1.62 dB multiplied by 2.15 standard deviations, and rounded to nearest 1/10th dB(A)].

- The FC5 mixes resulted in the greatest decreases in the propagation path caused by the interaction with the pavement surface (the top three reductions and except for one glaring exception in the top half of rankings based on the noise difference of OBSI – Wayside). Dense graded pavements were not as effective. Rigid pavements were also not as effective.

- Similar sound levels for open and dense graded surfaces occur at the wayside even though greater intensity levels tend to occur at the tire/pavement interface for open graded surfaces. The dense graded mix (FC125) was generally in the bottom half of the rankings. LGD was surprising good and bad, being fourth and 16th out of 17 surfaces analyzed.
- Measurement of pavement surface textures over a long span allowed the aging reduction of sound qualities to be quantified (~0.2 dB/year). However, values were very small and since the new test rig and test trailer were in use this needs to be further verified.
- A transfer function was derived that should improve the estimation process but more work, especially validation, is still needed to better quantify the propagation path effects from the various pavement surface textures. The final function was:

  $$\Delta = 32.57 + 0.0349(\mathrm{FN}) + 18.094(\mathrm{MPD}) - 0.0493(\mathrm{AG4})$$

  ($R^2 = 0.7328$) with a residual standard error of 1.0 dB(A)

  As defined within the text, Δ is the difference to be subtracted from the OBSI level, FN is friction number, MPD is mean profile depth, and AG4 is an aggregate designation used in testing.
- The repeatability of the FDOT OBSI system, calculated from differences in multiple runs for the 95% confidence level, is 0.26 dB. Based on comparison to other systems during the FDOT “Rodeo”, an accuracy of approximately 1 dB can be expected.

As can be seen, the work was very successful. This has led to multiple recommendations for continuation of the work and is included in this reporting. One key recommendation is for the materials personnel to continue to work with the acoustic analysts so that not only will a better understanding occur, but quieter surfaces can be developed leading to less costly control of noise for neighbors abutting the highway.

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CHAPTER 1. INTRODUCTION

This is a continuation effort of previous research (Modeling of Quieter Pavement in Florida) and as such is a sister report to the previous final report[2]. Both research efforts pertain to the noise created at the tire/pavement interface, which continues to gather considerable interest because of the potential benefits and a general desire by the public for quieter highways. The first report included a description of the sound generation mechanisms from tire/pavement noise and will not be included in this document except for a short review. Key findings from that first report included:

- A working trailer based system was developed for on-board sound intensity (OBSI) measurements in Florida. It was recommended that the prototype design for the test rig (sound intensity probe mount) be further developed.
- A methodology and equipment for data collection using the On-Board Sound Intensity (OBSI) method was established and during the first phase, more detailed guidelines for measurement of the tire/pavement interaction occurred in the form of an AASHTO standard was completed.
- A statistical passby method was established to allow measurement and correlation wayside data with the OBSI measurements.
- An initial data base of OBSI intensity levels, matching wayside sound levels, highway information, texture characteristics, and weather observations was formed for Florida highways. It was recommended that this work continue to further develop the data base.
- Multiple pavement textures/types used in Florida were ranked by both the sound generated at the tire/pavement interface using the OBSI method as well as at the wayside.
- Two Portland Cement Concrete (PCC) pavements were measured with the longitudinally tined surface generated less noise than the burlap drag surface with the same trend at the wayside.
- FC-5 pavements were 4 of the top 5 surfaces in terms of noise reduction in the propagation path (difference between OBSI and wayside levels) but this trend did not always hold with some FC-5 pavements showing very small amounts of reduction. Understanding why this occurred is paramount to the overall goals of FDOT and included as a recommendation for further research.
- The average difference between the OBSI measurements and the common reference wayside location (50 feet from centerline of vehicle travel and 1.5 feet above the pavement surface) was determined and provided a general first approximation rule that can be used to predict the wayside noise from the OBSI measurement.
    - Wayside SPL, dB(A) = OBSI Sound Intensity Level – 32.2, dB

Where SPL is sound pressure level, dB is decibels, and dB(A) are A-weighted dB or as the human ear perceives the sound. It must be noted that this first approximation method has a possible error of ± 5.4 dB(A). Further work was recommended to refine this estimation process and include other pavement variables.

- Surfaces such as jointed PCC with a high degree of macrotexture changes (bordering on megatexture) were shown to have more energy in higher frequency bands than do smoother pavements.
- Correlation was shown with the friction number, mean profile depth, aggregate size, and to a lesser degree the sand patch test. The relationship between the textures and these key characteristics were recommended to be further explored.
- As a first step in multivariate analysis the product of the pavement characteristics for a small sample size provided a first cut overall equation form with very good correlation. This tended to indicate a strong possibility for future modeling of wayside sound levels based on OBSI testing.
- Frequency differences in the spectra between the OBSI measurements and the wayside measurements were recommended to be further explored to determine how much is caused by the road surface as compared to the intervening ground surface.
- While some correlation was shown for the propagation reduction phenomenon, more work was found to be needed.
- Comparison of the OBSI measurements made with the FDOT OBSI system and measurements made with another researcher’s (Donavan) OBSI system showed very similar results, thus validating the data and the FDOT OBSI system.
- Test with the equipment indicate that microphones and preamps must be checked often because of the potential for error. Additionally, tests show that the larger windscreens should probably be used.
- It was recommended that all future testing follow the AASHTO OBSI standard method.

These findings led to suggested action items that were included as objectives in this second research effort and have been completed to the extent possible. These are:

1. Continue participation in the FHWA Quiet Pavements Program
2. Validation and implementation of the OBSI system
3. Develop and populate a formal acoustic inventory of pavement surfaces used in Florida
4. Develop precision statement based on research findings
5. Conduct training for FDOT personnel on the use of equipment and analysis of data

To complete these objectives, eight discrete tasks were defined and have been completed. These were:

1. Prepare equipment for deployment and validation of previous sections
2. Further evaluation of data collected in Phase 1
3. Participate in a national OBSI “Rodeo”
4. Prepare reference material for FDOT personnel on OBSI System
5. Train FDOT personnel in the use of equipment and data reduction/analysis
6. Conduct up to 40 field measurements on various pavement surfaces in Florida and reported findings to form an acoustic inventory data base.
7. Evaluate, analyze, and integrate new data set and combined data set including an analysis of precision of OBSI testing and procedures to estimated wayside levels with precision in the terms of standard deviations of provided.
8. Participate in an OBSI Rodeo to estimate the precision of the FDOT OBSI system.
9. Document data, analysis, results and findings including procedures/methodologies.

Detailed training of FDOT staff has occurred in multiple session and extensive field work. All other task results are described in this report.

CHAPTER 2. PHASE 1 RESULTS

A prototype rig (see Figure 1) was developed in Phase 1 and with an adapted sound analyzer system and proved very successful in measuring the tire/pavement interface noise using the OBSI method. Table 1 provides a summary of the test locations measured in Phase 1. These locations, primarily in the Central Florida area, provided information to form the first pavement ranking for the noise generation of surface textures for the Florida Department of Transportation (FDOT). Figure 2 shows these rankings. Wayside measurements (passby measurements along the side of the road) were also accomplished in Phase 1 as a matched pair to the OBSI measurements. Figure 3 shows these rankings for the measurement location 50 feet (15 meters) from the centerline of the measured lane and 5 feet (1.5 meters) above the pavement surface. To make a direct comparison, the wayside measurements were then reordered to match the rankings from the surface texture OBSI measurements as shown in Figure 4. It can be seen in Figure 4 that the rankings are very different. Further analysis showed this to be related to the pavement surface where sound absorption and scattering could occur at different rates.

Figure 1. Prototype Test Rig With Intensity Probes, Phase 1

Table 1. General Location Details, Phase 1

Location No.	Date Measured	Location Description	Lane Tested	Test Limits MP/ Co.
1	9/14/2007	SR 417	NBTL	4.000 to 5.000 Seminole
2	9/29/2007	SR 528	WBTL	Brevard
3	11/8/2007	I 95	NBTL	6.881 to 27.147 Volusia
4	11/9/2007	SR 500 (US 192)	NBTL	0.000 to 9.687 Brevard
5	2/14/2008	SR 417	NBTL	4.000 to 5.000 Seminole
6	7/9/2008	SR 417	NBTL	4.000 to 5.000 Seminole
7	7/11/2008	I 75	SBTL	19.000 to 27.380 Columbia
8	7/13/2008	I 295	SBTL	33.965 to 34.562 Duval
9	7/13/2008	I 295	SBTL	31.910 to 32.839 Duval
10	10/27/2008	SR 40	EBTL	10.157 to 32.206 Marion
11	1/27/2008	SR 40	EBTL	10.157 to 32.206 Marion
12	10/28/2008	SR 24, Almost to Waldo	NBTL	14.380 to 15.285 Alachua
13	10/28/2008	SR 24, by Austin Cary Memorial	NBTL	12.145 to 12.540 Alachua
14	10/29/2008	SR 16	EBTL	6.943 to 7.469 Bradford
15	10/30/2008	SR 417	NBTL	4.000 to 5.000 Seminole
16	11/4/2008	SR 528	WBTL	Brevard
17	11/25/2008	SR 600 / US 92, Deland	WBTL	2.452 to 1.930 Volusia
18	11/25/2008	SR 600 / US 92, Deland	WBTL	4.807 to 4.460 Volusia
19	2/16/2009	SR 222, 39th Ave	EBTL	12.375 to 12.790 Alachua

Location No.	Date Measured	Location Description	Lane Tested	Test Limits MP/ Co.
20	1/17/009	SR 26 by Fletcher's Mill	EBTL	12.220 to 12.520 Alachua
21	4/28/2009	US 441, Paynes Prairie	SBTL	8.150 to 8.840 Alachua
22	4/29/2009	SR24	NBTL	12.145 to 12.540 Alachua

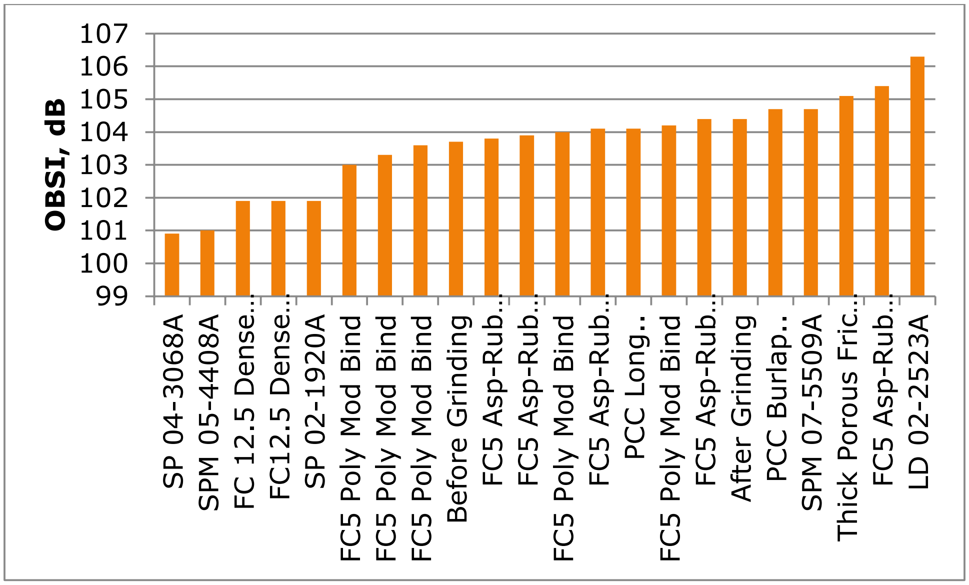


Figure 2. Ranking of OBSI By Pavement Type/Texture, Phase 1

Note: 04-3068A – FC9.5 – ARB5 – Granite; 05-4408A – FC9.5 – PG76-22 – Granite
02-1920A – FC-6 – ARB5 – Limestone; 07-5509A – FC5 – PG 76-22 - Granite
LD 02-2523A – FC5 – ARB12 – Granite

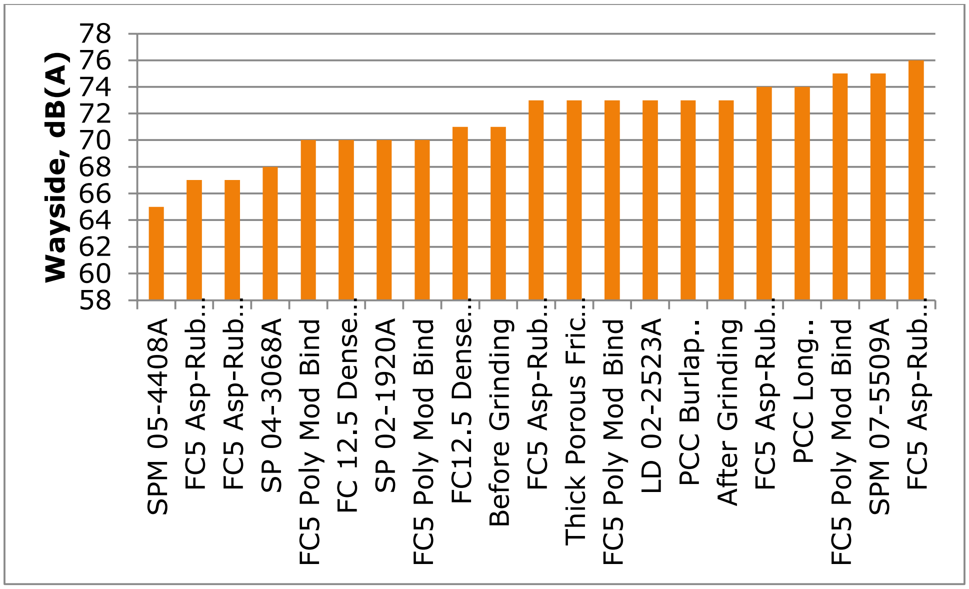


Figure 3. Ranking of Surface Textures by Wayside Sound Pressure Levels, Phase 1

Note: 04-3068A – FC9.5 – ARB5 – Granite; 05-4408A – FC9.5 – PG76-22 – Granite
02-1920A – FC-6 – ARB5 – Limestone; 07-5509A – FC5 – PG 76-22 - Granite
LD 02-2523A – FC5 – ARB12 – Granite

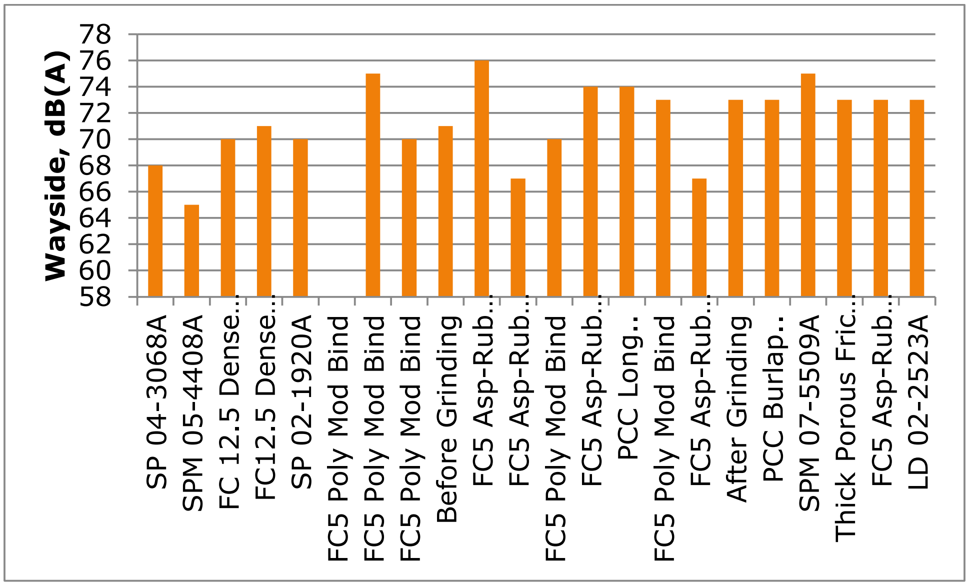


Figure 4. Ranking of Surface Textures by Wayside Sound Pressure Levels, Phase 1 [Shown in Same Order as OBSI Ranking]

Note: 04-3068A – FC9.5 – ARB5 – Granite; 05-4408A – FC9.5 – PG76-22 – Granite
02-1920A – FC-6 – ARB5 – Limestone; 07-5509A – FC5 – PG 76-22 - Granite
LD 02-2523A – FC5 – ARB12 – Granite

The frequency spectra differences between at the tire/pavement interface (OBSI) and the wayside caused by propagation effects were revisited. Figure 5 shows an example of these results. As seen in Figure 5, multiple OBSI measurements were made, as for all locations, to validate repeatability as a quality control method. It can also be seen that the trends of the two frequency patterns are very similar, although offset due to the difference in amplitude. A closer examination shows that there are changes in the lower frequencies, beginning at approximately 400 Hertz (Hz.). It can be seen that there are dips in the wayside measurements that do not occur in the OBSI. Unfortunately, OBSI measurements are limited on the lower frequency ranges because of wind noise and cannot be used. Fortunately, the human ear does not hear these frequencies well. Even with the frequency limitation of all OBSI systems, the trend is evident. These wayside dips are characteristic of ground effects or in this case the effect on the wave propagation over the pavement surface. This led to the recommendation to further review this phenomenon. Phase 2 was then based on these results, findings, and recommendations from Phase 1.

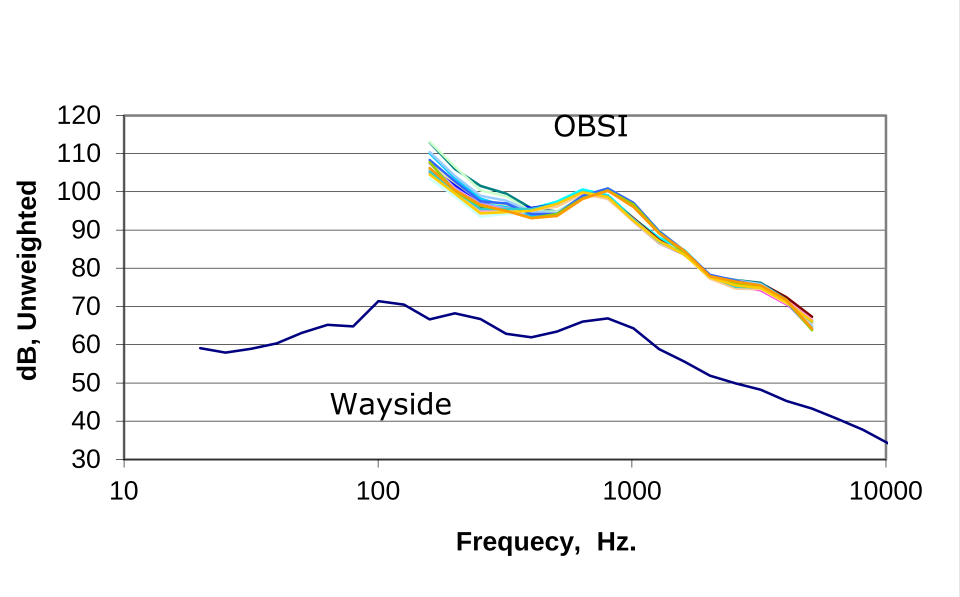


Figure 5. Example of OBSI and Wayside Spectra [un-weighted] from Phase 1

CHAPTER 3. EQUIPMENT AND METHODOLOGY

This chapter provides an overview of the equipment and procedures used. In addition to this chapter, appendices have been included pertaining to the data collection methodology to assist the FDOT State Materials Office in future measurement work.

Equipment and Procedures

Sound measurements made in close proximity to the tire continue to be an emerging measurement technique in many countries and on multiple continents. As reported in Phase 1, research in Europe led to standards for a Sound Pressure Level (SPL) type of measurement, called the close proximity method (CPX).[3,4] This methodology standardization began a new formalized series of tire/pavement interface measurements for roadway analysis. But SPL can be affected by nearby sources since it is a scalar quantity composed of the sounds from all sources arriving at the defined location at the same time from many directions. Sound intensity, I, (or acoustic intensity) is defined as the sound power P_{ac} per unit area A. For instantaneous acoustic pressure $p_{\mathrm{inst}}(t)$ and particle velocity $\boldsymbol{v}(t)$ the average acoustic intensity during time T is given by Equation 1:

$$I = \frac{1}{T}\int_0^T p_{inst}(t) \cdot v(t)\, dt \qquad [1]$$

Of note in Equation 1 is that the intensity, I, is measured at a point and represents the time-averaged rate of energy flow per unit area and has a defined direction as indicated by the velocity term. Being a vector, we can measure sound from an exact direction (the tire/pavement interface) even when other sounds such as traffic noise are nearby.

OBSI Equipment Description

This section describes the Florida OBSI system and methods used in the Phase 2 research to measure the sound intensity.

Because of the directional component associated with sound intensity, two microphones are needed to form a *sound intensity probe* for each measurement position. Using the two microphones in an intensity array permits measurements of the sound being emitted by the tire/pavement interface without the influence of other nearby sources such as traffic as previously alluded to.

The normal probe used for sound intensity measurements is not practical in the high speed, rough environment associated with a tire rolling along a normal roadway. As such many researchers have experimented with variations of intensity probes and mounting hardware which we will call the “rig”. Figure 6 shows two examples of intensity probes mounted on vehicles[5] that have been used by other researchers. As was described in the Phase 1 report, a prototype rig was designed and used with a trailer instead of direct mounting to a vehicle making the Florida system somewhat unique. The primary reason for using the trailer was to allow for continuity over a long time period since it is not practical to always use the same vehicle to mount the test probes during measurements. This prototype turned out to be very successful and was shown in Figure 1.

The Florida OBSI Trailer is a single axle vehicle and the test tire is mounted on the *passenger* side of the trailer during measurements, important in that this is the side of the vehicle that directly radiates to the highway neighbors and the one of most importance during wayside measurements. The, OBSI trailer, was originally converted from an older test trailer no longer in use during Phase 1. In Phase 2, the trailer underwent significant upgrades. The upgrades were primarily functional in nature, but also provided for a much more aesthetic appearance due to streamlining of the body and new paint. Upgrades included taking out all old mechanisms no longer in use in the trailer that were causing noise rattle, creating a vastly improved storage area for transport of the test tire and test rig, installation of an electric jack for tire mounting purposes, improving visibility for safety reasons, and allowing weights to be added or taken out for ease in changing the wheel loading. The trailer was weighed on multiple occasions and weight combinations used to approximate a typical passenger car wheel loading were established. Testing of various weight combinations were also accomplished to determine the overall effect on measured values. The official weight decided upon was 640 pounds (291 kilograms) of wheel loading to approximate the rear wheel loading of a common passenger vehicle.

In addition to the assistance by the FDOT State Materials Office in Gainesville for the Florida OBSI Trailer upgrades, a new, more refined test rig was developed. Development included critical performance evaluations and configuration changes resulting in a final more proficient design. The refinements included the ability to adjust the probe location more efficiently, a better mounting mechanism for the microphones, and greater ease of mounting/takedown of the test tire from the trailer for transport. The new system is shown in Figure 7. It can be seen in the figure that as before, the leading and trailing edge of the tire patch is measured at the same time in a vertical array with the final rig design.

a. Horizontal configuration (single probe) b. Vertical configuration (dual probe)

Figure 6. Examples of Intensity Probes for Tire/Pavement Sound Measurements[8]

Figure 7. Final Rig, Intensity Probes, and Overall Vehicle System, Phase 2

The new test rig underwent significant testing, well beyond what was envisioned at the beginning of the project. Comparisons to the prototype rig showed a general increase and bias in the data. Through multiple testing on probe distances, test tires, trailer weighting, different size wind screens, test rig modifications were made. Modifications included streamlining to reduce air turbulence, detailed measurement of trailer weight and weighting schemes to be similar to past tests with the revamped trailer, and isolation of the probe to prevent vibrational transfer to the microphones. A significant finding was that vibration was causing most of the increase. Use of nylon washers for isolation such as at the rig/trailer interface were needed to eliminate this effect. Afterwards comparison tests confirmed both test rig results were similar. This was crucial to development but a resource consuming exercise.

The overall measurement equipment remained relatively the same as in Phase 1 although microphone and preamplifier changes were made. Minor changes included the more permanent mounting of equipment such as the Pimento analyzer and use of larger windscreens.

As shown in Figure 7, the rig holds the preamplifiers and microphones in sets (test probe) which are connected via the cables shown to the analyzer.   Exact location of the microphones is crucial and follows the standard established by the American Association of State Highway and Transportation Officials (AASHTO).[6] Figure 8 shows the critical distances from the AASHTO standard.

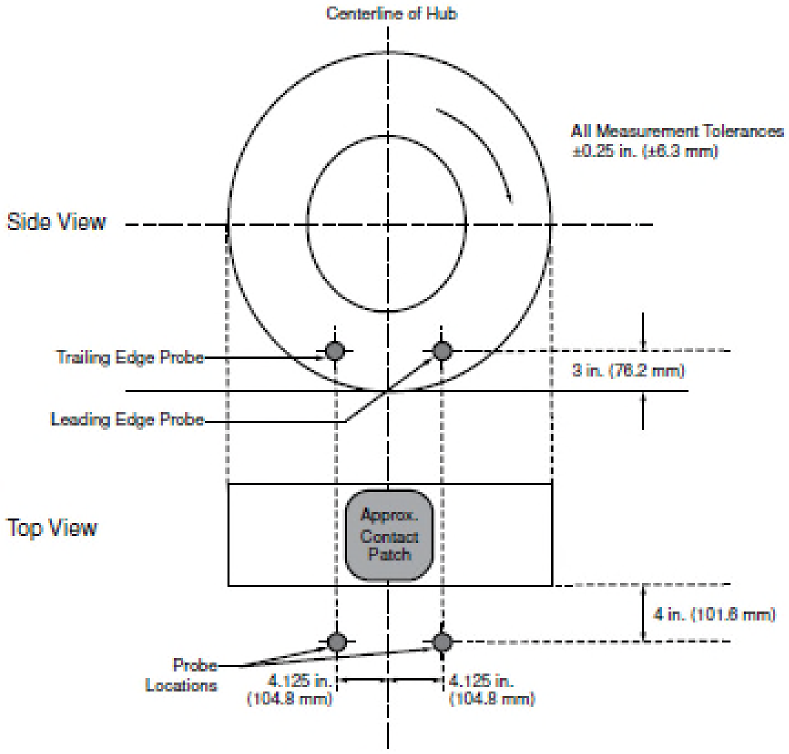


Figure 8. Sound Intensity Probe Descriptions as Promulgated in the AASHSTO Standard[6]

It should be noted that during Phase 1, the OBSI standard method in the U.S. was just beginning development and changes were still in progress. During this development, recommended microphone placement dimensions and test procedures changed. The microphone placement differences from this work are now an even 3 inches (76 mm) above the pavement surface instead of 2.76 inches (70 mm) used in Phase 1. The dimensions from the tire face are now 4 inches (102 mm) instead of 3.94 inches (100 mm) from the tire face as was used in Phase 1. However, the tolerance allowed in the standard is 0.25 inches (6.3 mm) so the testing for Phase 1 is still within the tolerance ranges. Finally, a separation distance between the microphones is now specified to be 8.25 inches (209.6 mm) based on being in line with the leading and trailing edge of the Standard Reference Test Tire (SRTT). In Phase 1, the microphones were confirmed to be in line with the leading and trailing edges of the tire so in theory, with the same standard test tire used (16 inches or 40.6 cm, SRTT standard tire size) the location for this dimension was considered to be consistent with the new standard as well. A distance of 0.59 inches (15 mm) separation between the center points of the microphone diaphragms was maintained to allow lower frequency analysis. Insulation material is used to make sure the preamp bodies do not touch which could cause electrical problems.

Sound is detected by the microphones, amplified by preamplifiers and sent via cables to the analyzer. From the analyzer the signal is sent to a laptop computer that controls the system and stores the data. A large database was then downloaded and maintained on a safe server. A raw data base was created and great efforts were taken in quality control before adding data to a final data base. This provided a needed measure of quality for all analysis by use of this final overall database. Figure 9 shows a breakdown of the overall system. Examples of the data output are shown as related to the various system components as well.

Not shown in Figure 9 is a power inverter used to change the 12 volt DC system of the truck into 120 volt, 60 cycle power for the equipment.

The major equipment consisted of the components as shown in Table 2. In addition to these major components of the OBSI trailer system, many other minor equipment needs also existed including power supplies, defined measurement blocks, ruler/scale (mm), tape measure, preamp spacer material, electrical test meters, various hand tools, and expendables (e.g., zip ties).

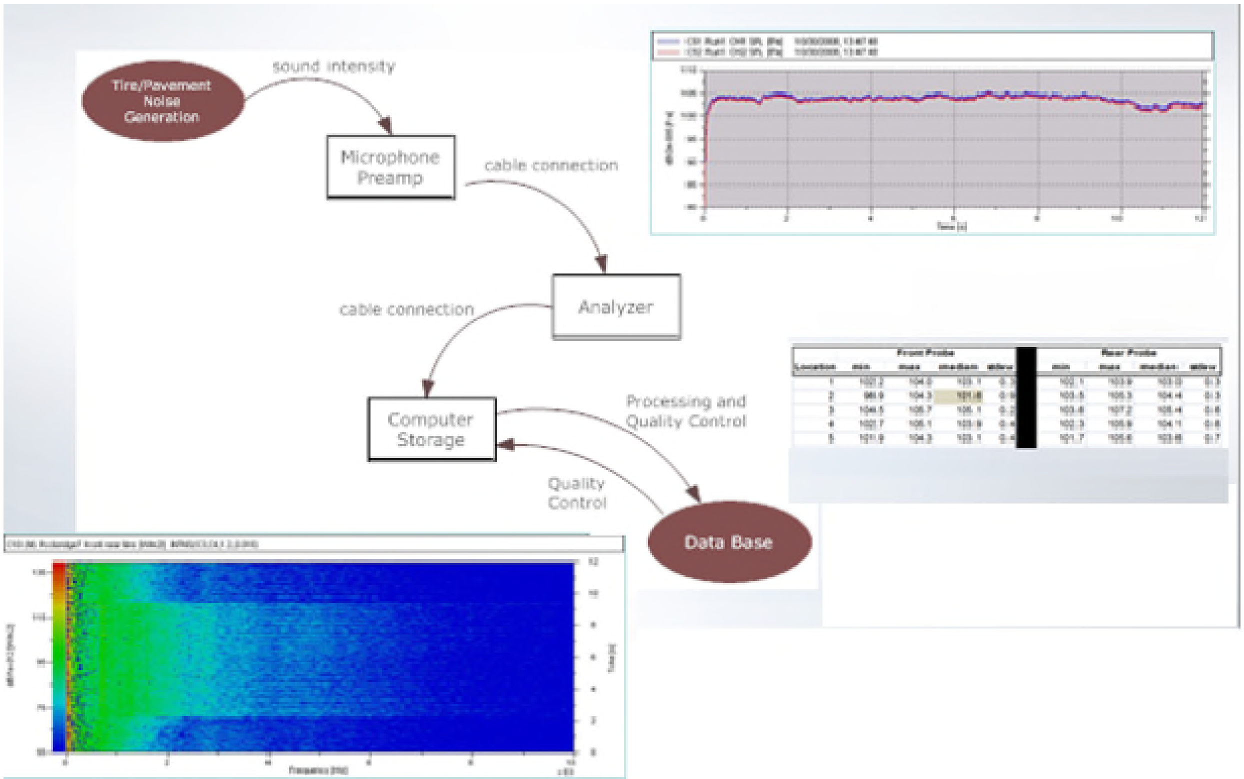


Figure 9. Overall OBSI Process Overview with Example Output at Various Stages Shown

Table 2. Major Test Equipment

EQUIPMENT	DESCRIPTION
Pimento system	sound analyzer
4 preamps	microphone power and amplification
4 microphones	sound measurement (microphones are in matched pairs)
4 windscreens	microphone protection and wind dampening
test rig	precise microphone and preamp mounting

EQUIPMENT	DESCRIPTION
multiple cables	power and electrical data transfer
SPL calibrator	system calibration of correct noise levels
PRI calibrator	sound intensity calibration check
durometer	testing tire hardness
tire gauge	tire pressure
speed measurement	speed to ± 1 mph
laptop computer	system control and data storage
power inverter	12V DC to 120 V AC power
Uniroyal test tire	ASTM P225/60R16 SRTT
Test trailer	FDOT test trailer altered for intensity probe test rig

The test tire was also a very important component. The Uniroyal Standard Reference Test Tire (SRTT) is manufactured to exacting specifications as specified by the American Society for Testing and Materials (ASTM) specifications (ASTM F 2493). The size used in all phases of this work is P225/60R16. The tread pattern, hardness, and size are key components during sound generation and as such must be normalized by use of this standard test tire. Hardness was checked during testing by use of a precision durometer.

The recording system used in both phases of this work is a four channel analog-to-digital (A-D) signal processor from LMS called the Pimento© system. The system records the sound pressure levels versus time for all four microphones at a 50 kilohertz sample rate. Intensity levels and coherence values are derived during post processing from the stored sound pressure level time history for each probe (a probe consists of two microphones). The coherence is a measure of the extent that two signals are linearly related at any given frequency and insures that the sound measured is from the intended direction, the tire/pavement interface. The intensity and coherence functions have been developed by use of special software used with the Pimento© analyzer system. The data storage and control of the system are accomplished using a lap top computer.

The equipment permitted the collected data to be in frequency bands. These bands, 48 Hertz in range, were later converted during post processing to standard octave bands which allow reporting of sound for various, internationally defined frequency ranges. By collecting not only the amplitude (dB) but the frequency ranges, a more rigorous review of pavement differences was possible with the OBSI measurements. The raw data also permitted combination of the sound levels into a single, overall level by summing the energy in each octave band. Octave band reporting as well as overall level are used in this document.

The measurements can also be *weighted* for various reasons. Weighting is done by changing the magnitude of the values, by frequency, to account for various acoustic phenomena. The most commonly used weighting is the A-scale which approximates the way the human ear perceives the sound by drastically reducing the very low frequencies while also reducing to a lesser degree high frequencies in the audible range. Decibels, dB, are referred to as A-weighted dB and shown by the abbreviation of dB(A) or L_A and are used in this reporting.

Since the draft ASSHTO standard was undergoing revisions during Phase 1, it was determined that all testing would be done at a speed as close to 55 miles per hour (mph) (88 kilometers per hour)(kph) as possible, verified by use of a radar gun. This speed was chosen since many of the facilities had this as the speed limit and some with even a lower speed limit. The measurement period chosen was 10 seconds resulting in a test length of approximately 800 feet (244 meters). As the standard neared completion, standard speeds were provided but 55 mph was not among them. The closest speed was 60 mph (97 kph) and this was used for Phase 2 as the standard speed (test sections for a 10 second sample were now 880 feet in length). However, to allow a direct comparison to Phase 1, the test sections were also measured at 55 mph (88 kph).

Of note, and will be discussed later in this report, is that a special test consisting of a 3 mile long test section was also measured. This was done to check the variation over the same pavement with a greater distance.

As always, great care was taken to perform calibrations of each microphone/preamp and each matched pair prior to beginning each test, multiple times during testing, and at the end of the tests. As described in the procedure, in addition to testing for the correct Sound Pressure Level (SPL), the intensity probes were often calibrated using a PRI (Pressure Residual Intensity) which tests for residual intensity as possible mismatch of microphone systems.

OBSI Measurement Procedures

Good practice is a must in any data collection effort. During any measurements, equipment problems have to be quickly recognized and corrected whether this is just a recalibration or replacement of equipment. After data collection, quality control is again of the utmost importance to filter data before it is placed in the final database. Calibrations should be performed before, during, and immediately after data collection. Field notes should be descriptive and understandable during post processing. These concepts have been integrated into the methodology and were followed in both Phase 1 and 2 of the projects.

Individuals performing tests with the equipment should be familiar with the Standard Test Method (TP 76-13). This will help avoid incorrect measurements that are not comparable to other measurement teams. Major considerations are included in this section to assist the understanding of FDOT personnel. Detailed steps are provided in Appendix A.

The first step is to survey the area for a good test location on straight sections of roadway. Extreme pavement changes (e.g., potholes, uneven abrupt changes, loose material) should be avoided as this will affect the test and could cause damage to the equipment. The pavement should be dry not only on the surface, but within the voids of the surface as well. Experience has shown that several hours are needed for complete drying after a rain event. A starting point should be selected that is easily seen at high speeds and multiple tests should begin at this point until data quality requirements are met as described in TP 76-13. In Phase 1 and 2, 10 second durations were used as previously described. The Test Method TP 76-13 only requires 440 ± 10 feet (134 ± 3 m) lengths at 60 mph (96 kph). In our tests the extra time and length was an internal quality control to allow a more defined average to occur.

Care should be taken to set up the trailer and equipment the same way each time for consistency. Setup should be accomplished on a level surface near the test location to avoid unneeded wear and possible damage to the test tire which is mounted after arriving. The installed electric jack makes this a much easier task than in the past. The electronic equipment is then set up but the microphones are left loose until after calibration. The microphones are then installed in the test rig using the measurement equipment to make sure they are at the exacting position (see Figure 8). Appendix A-1 provides a detailed setup guide. One word of caution is needed. The microphones are in matched pairs and should always be used as such.

The initial quality controlled sound data from the OBSI system must be post-processed using the software purchased with the Pimento analyzer. From the data collected, intensity levels were determined for each location by time and then as energy averages of the test. Intensity levels versus time and frequency graphics were generated as a review and another quality control measure. Each of these types of plots was reviewed for the each actual locations looking for any obvious abnormalities. The Phase 1 report shows examples of these plots.

Data Storage

In addition to the Phase 2 locations, there are also 16 Phase 1 locations where the collected data must be stored. Considering test locations, not included in the data analysis locations, there are data sets for over 60 locations, multiple passes of 10 seconds taken at 4 microphones every 10 milliseconds, for each frequency band, and at two speeds for the last 43 locations (55 and 60 mph). Data also includes location data, speed data, pavement characteristics, and calibration data that must be matched in sets. Additionally there are 35 locations where wayside measurements were accomplished for up to 5 measurement positions (microphone locations), every 0.125 seconds for SPL and 1/3 octave bands and the database becomes even larger. Finally, the database also includes field notes, pass-by information, vehicle speeds, vehicle types, and meteorological data at two heights for wind speed and temperature. This has required a carefully defined format with several million rows of data in tables. These data are processed in various ways to provide meaningful comparisons, data for analysis of surface texture effects, and establishment of wayside predictions. Previous quality control measures were discussed and even more implemented on the data base used to establish the analysis.

Because of the magnitude of information, it was not practical to put all into a report. The data has been supplied to the FDOT State Materials Office in electronic form. To assist FDOT in understanding the file formats and files available descriptive tables have been included in Appendix B of the files available. Also, to further assist FDOT, figures have been included in Appendix B to show examples of the file formats.

This data base will be maintained by the authors for possible future analysis and an important backup for FDOT in case problems occur in the transmitted data at a future date.

Summation of OBSI Data Collection

Figure 10 shows an overview of the entire process. Again, important concepts are included directly in the text, overall detailed procedures are included in Appendix A, and file descriptions/formats are included in Appendix B. Multiple training sessions have occurred and FDOT personnel were trained in an extensive field data collection process as well. As a final assurance, the authors offer any help that may be needed in the future.

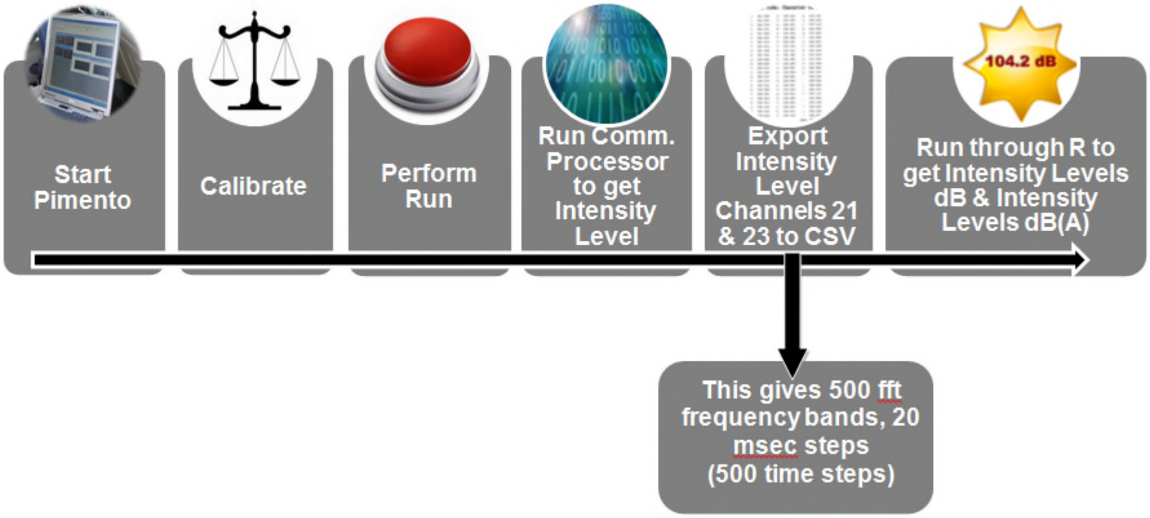


Figure 10. Overview of Measurement Process [CSV refers to comma separated values a common computer term. R is a computer program. The term fft is a mathematical process, fast Fourier transform. The term msec is milliseconds.]

Wayside (Passby) Equipment Description

One of the primary goals of the research was to allow matched pairs of data consisting of OBSI measurements and wayside (passby) measurements. In addition to the OBSI measurements, where practical and possible, wayside measurements were also taken. Wayside measurements consist of measured sound levels along the roadway at some distance to the side of the travel way. The sound data includes amplitude and frequency. Additionally, specific sound levels methods were used included measuring the maximum and equivalent sound levels. All measurements were A-weighted. The equipment for each is described in more detail in the Phase 1 report with important elements and only the major changes in Phase 2 are discussed in this section of the report.

Type 1 sound pressure level analyzers with the capability to measure multiple sound descriptors were used. Of particular importance was the maximum sound pressure level (L_{max}) that occurred during a single vehicle passby because this is directly related to the Reference Energy Mean Emission Level (REMEL) used in traffic noise modeling and the building block used in many traffic noise models. Other descriptors were also measured. One-third octave bands were measured to allow a review of frequency differences at different locations, heights, and also to compare to the OBSI measurements. Fast response was used with one second averaging. The major difference was a different brand of sound level analyzers was used than in Phase 1. However, the sound analyzers still met ANSI Type 1 specifications[7] as before. A picture of the sound level analyzer is shown in Figure 11 during measurements along SR24.

As always, and acoustic calibrator was used to calibrate all sound level analyzers before sampling began, during sampling if any problems were suspected, and after measurements to insure correct operation. Other equipment included tripods, towers (for higher locations), windscreens, and cabling when needed. A radar gun was also used to measure vehicle speeds during the passby data collection.

Precision meteorology data were also collected at two heights. Sonic anemometers were used for wind speed and direction that provide exacting continuous results and make no audible sounds that could interfere with the sound level measurements. Temperature was measured using aspirated thermometers to avoid bias caused from static air when only shields are used. On-site humidity was measured using a sling psychrometer. Barometric pressure was verified by local weather stations. Of course no measurements were made when any precipitation occurred. Data were recorded using a data logger system.

Wayside Measurement Procedures

Wayside measurements were performed near the center of the OBSI test section to avoid any possible end effects of the location. Sound level analyzers were set at varying distances and heights from the roadway to form an array. Figure 12 shows a diagram of the desired test locations that were measured when possible. In some cases local conditions prevented all locations from being measured. However, the location five feet above the pavement surface and 50 feet from the centerline of the test lane was always included when wayside measurements were taken. This location is the standard test position in the U.S. when reference energy mean emission levels (REMELs) are measured.[8] REMELs are used as the building block for transportation noise models.

Figure 11. Sound Analyzer at Near Location Along SR 24

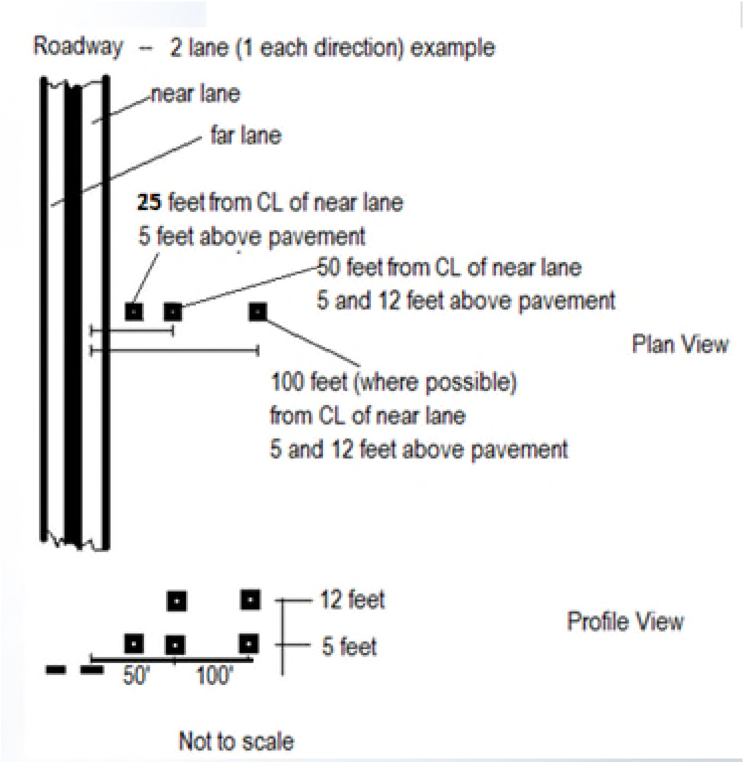


Figure 12. Layout of Desired Sound Level Analyzer Array for Wayside Measurements

During quality control, only “clean passbys” were included in the wayside data base. A clean passby requires vehicle separation from all other vehicles, including both sides of the highway, sufficient for at least a 7 dB(A) difference in SPL from the passby and all other noise sources. This required careful observation of the traffic and when a quality passby was thought to occur, the time, vehicle type, measured speed, and comments were recorded. These passbys were later reviewed using custom software created for this project to determine if the criteria were met to allow inclusion in the final data base. Figure 13 shows graphically how the criteria are applied to vehicle passbys. While 7 dB(A) is acceptable, a goal of 10 dB(A) was also included and information stored based on both criteria. The project concentrated on the vehicle class known as automobiles of the Traffic Noise Model[9] (4 tires and 2 axles) but good passby events of other vehicle types (medium trucks, heavy trucks, motorcycles and buses) were also included in the data base for comparative purposes although not discussed in this report.

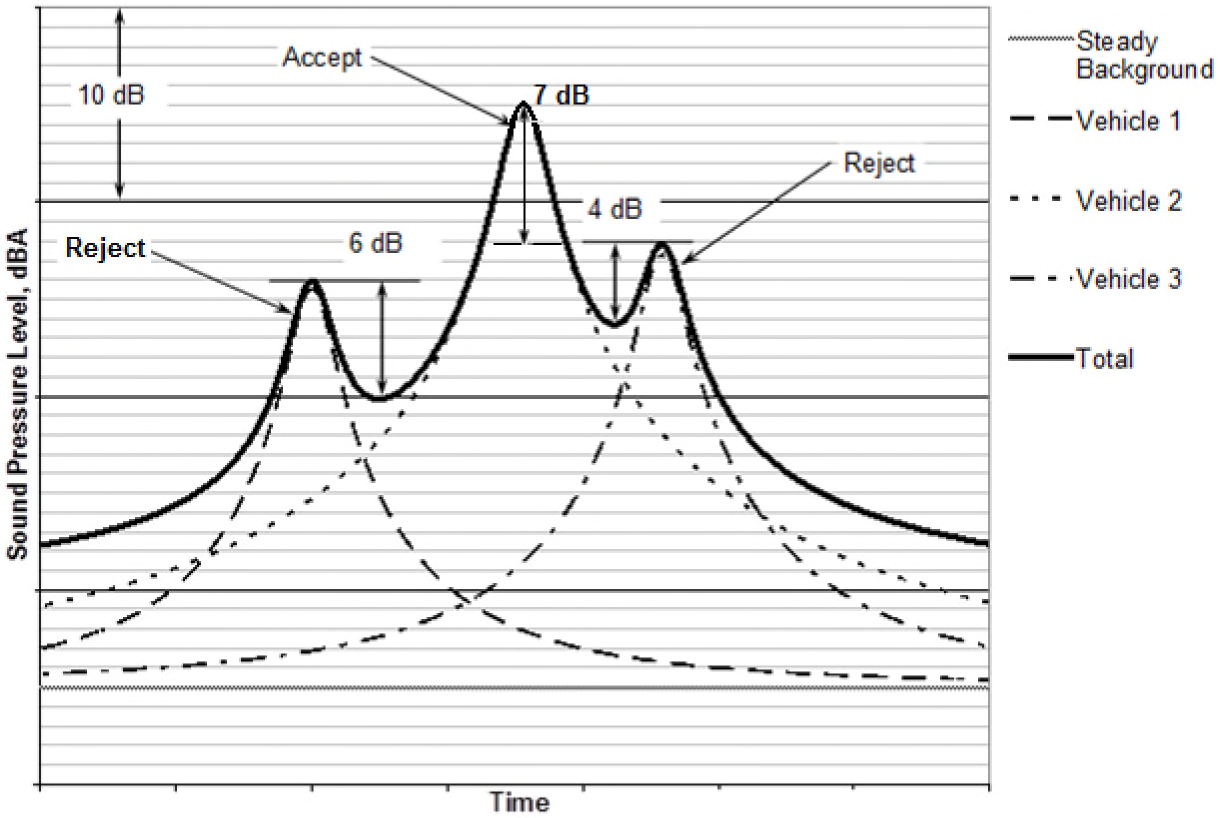


Figure 13. Idealization of Multiple Vehicle Passes and Acceptable Passby
(Note: 10 dB was goal but 7 is acceptable)

The methodology used was similar to the statistical passby method[10] but with certain changes to better reflect U.S. criteria and to better satisfy our purposes. This primarily included changes in microphone placement that was previously shown. A more exacting description is included in the Phase 1 report.

Events of interest were random vehicles typically using the outside (near) lane with sufficient separation to meet the 7 dB(A) criteria. In some cases, where another lane was measured, all distances were changed accordingly. The sound level analyzer positions were time synchronized to a master watch and then put into the record mode for the duration of the test. SPL data were recorded continuously from before the first test trailer passby and stopped after the last measurement of the day for all vehicles. This information was later used in conjunction with the field notes previously discussed to extract data from the sound level analyzers at the wayside positions that would be used in analysis. Of note is that the time and speed of each passby of the OBSI truck/trailer was also recorded during this time to insure the TP 76-13 requirement was met. Also, long horn honks at the beginning and end of sampling allowed a check of the time stamping to make sure no problems occurred with the internal clocks in the sound level analyzers.

Pictures are shown in Figures 14 and 15 of a typical setup on location. Figure 16 shows the meteorology station used when wayside measurements were made. A picture montage of all locations is included as Appendix C to help in understanding of the location local parameters. A picture of each pavement surface along with scenes showing setup and the local area is included.

All equipment, including the meteorology station, was time synchronized at the beginning of measurements to an atomic watch used as a reference for the project. Careful calibration was also performed prior to beginning measurements using an acoustic calibrator and then confirmed at the end of the measurements.

When wayside measurements were possible, detailed meteorological information was also collected at one second sample rates.

Figure 14. Typical Passby Equipment Configuration (sound level analyzers at five and twelve feet above pavement [Nearby meteorological station is not shown.]

Figure 15. Nearby Passby Microphone Location During Tire/Pavement Test

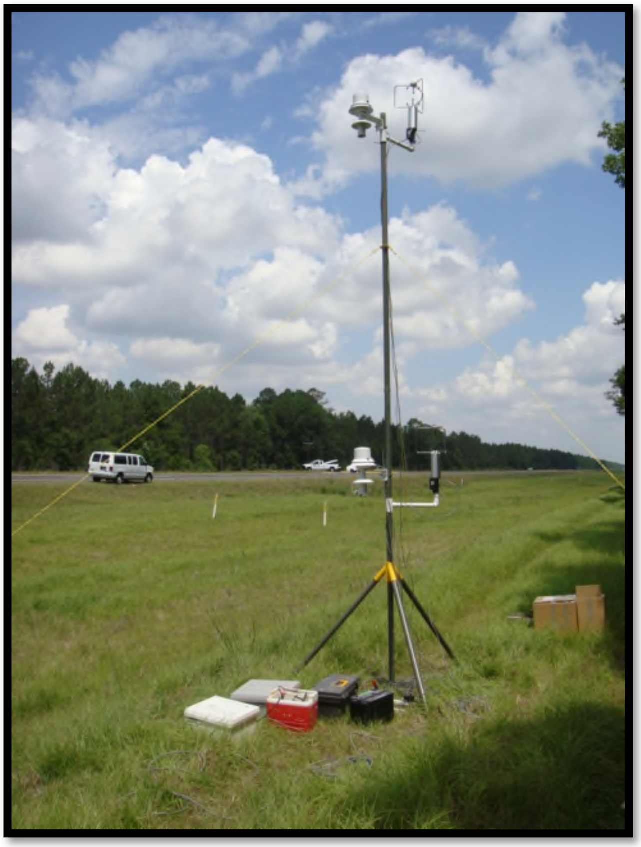


Figure 16. Meteorology Station on Location

CHAPTER 4. MEASUREMENT RESULTS

OBSI measurements were made in Phase 2 included 7 locations from Phase 1 that were measured again and 47 discrete new locations. Where possible due to traffic flow and spatial considerations, wayside measurements were also made. The new data base included data that covered most of Florida to avoid area biases. Figure 17 shows a map indicating the locations and coverage of the State. Table 3 includes general information describing these locations. Of note is that Phase 1 data was also included but the Location ID was changed from that previously shown in the Phase 1 report and Table 1 of this document to eliminate any repetitions of a location. The different Location IDs were used in Phase 1 to show different measurement days but due to the size of the data base, each location now has a unique number. This is important because not only were Phase 1 locations revisited, in Phase 2 many locations were returned to and measured on multiple days. This information is now shown by including those dates in a separate cell of Table 3.

Of note in Table 3 is the color coding to designate the Phase 1 locations (two colors actually used to designate the remeasured locations) and a color for the new Phase 2 locations. The locations that were remeasured allowed a quality control check of newly collected data and a measure of how the aging may have affected the OBSI measurements. Also of note in Table 3 is notation on locations where wayside measurement occurred, mix type and mix design.

OBSI Measured Results

Multiple Runs were made of test locations with the Florida OBSI trailer. After initial quality control, making sure all requirements of TP 76-13 were met, the front, rear, and an average of both probes was included in the data base. Other quality controls were also used for the processed data. For example, the leading and trailing edge intensity probes were compared during quality control since a small difference (less than ~2 dB) is expected but a large difference (greater than ~2 dB) would indicate a problem with one of the intensity probes. All locations included passed this requirement and the average of all locations was 0.4 dB.

Post processing was then applied to the quality controlled raw data. The post processing not only included converting to intensity levels as previously discussed but also correcting these levels for A-weighting and including these values in the final data base. Table 4 includes a summary of these final derived values. Locations 1 and 18, while passing the initial quality controls were measured with an older test tire. This tire

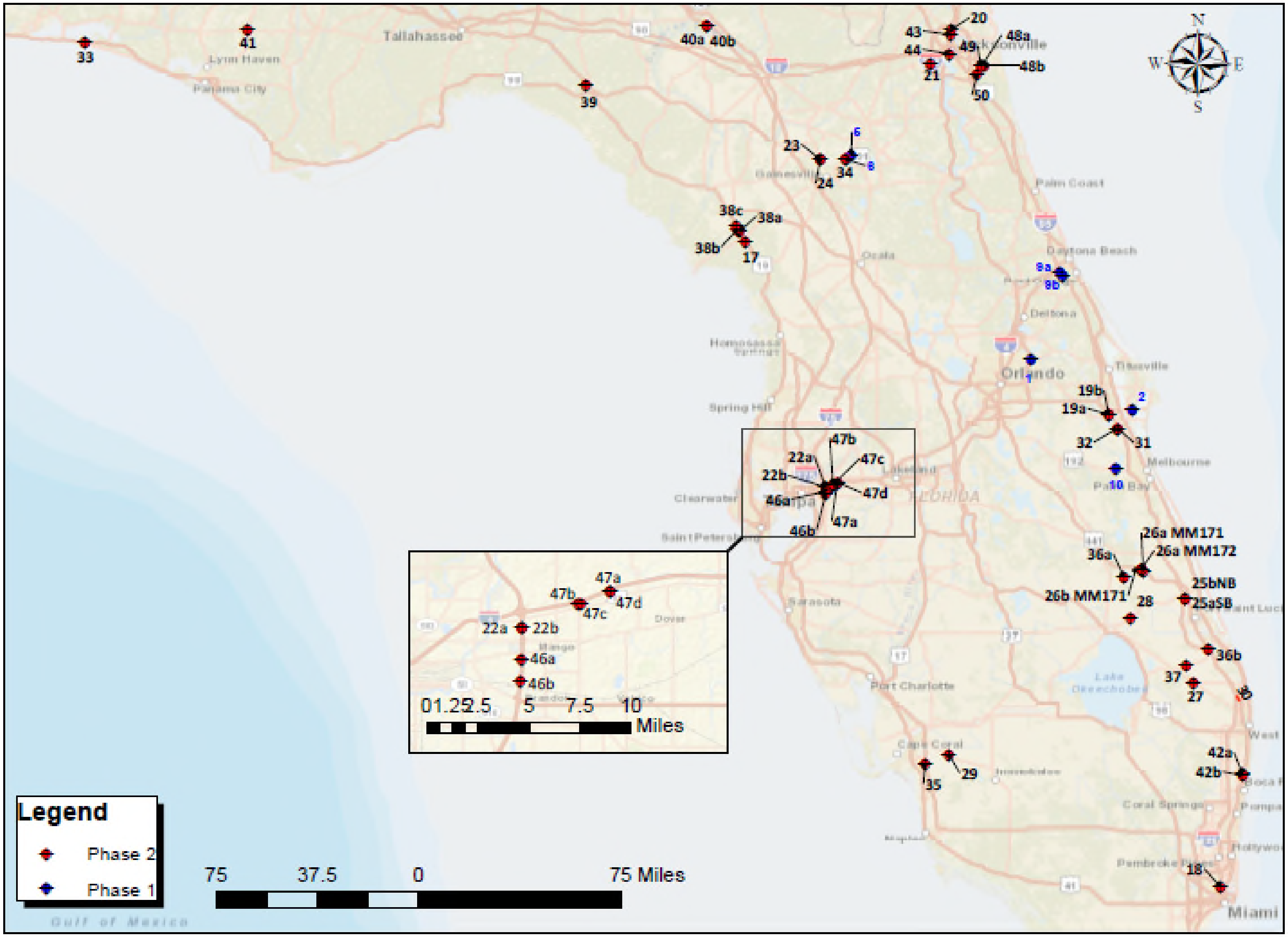


Figure 17. OBSI Measurement Locations

Table 3. Location Description

Location ID	**Date Measured**	**Latitude**	**Longitude**	**Lane Direction**	**Wayside Description**	**Roadway Number**	**District**	**County**	**Mix Type**	**Mix Design**
1	Phase 1 and Remeasured 5Mar12	28.67465	-81.22593	NB	Wayside No 25'	SR-417	5	Seminole	FC125MR	SPM 10-8052B
2	Phase 1 Remeasured 29Oct12	28.405256	-80.681667	WB	No Wayside	SR-528	5	Brevard	FC5	LDWM 09-2597A
3	Phase 1					I-295	2	Duval		
4	Phase 1					I-295	2	Duval		
5	Phase 1 and Remeasured 8Feb12 11Apr12 8Mar12 13Apr 12	29.773986	-82.188871	NB	Full Wayside in Feb	SR-24, Almost to Waldo @ Pwr Sta	2	Alachua	FC5	LD 02-2523A

Location ID	Date Measured	Latitude	Longitude	Lane Direction	Wayside Description	Roadway Number	District	County	Mix Type	Mix Design
6	Phase 1 and Remeasured 11Apr12 13 Apr12	29.752481	-82.218403	NB	No Wayside on remeasure	SR-24, by Austin Cary Memorial	2	Alachua `	FC5	QA 00-9506A
7	Phase 1					SR-600 / US-92, Deland	5	Volusia		
8	Phase 1					SR-600 / US-92, Deland	5	Volusia		
9a	Phase 1 Remeasured 29Oct12	29.146945	-81.070577	NB	No Wayside in Phase 2 position from Phase 1	I-95	5	Volusia	FC5	SP 05-4255B
9b	Phase 1 Remeasured 29Oct12	29.126667	-81.05444	NB	No Wayside in Phase 2 corrected position from Phase 1	I-95	5	Volusia	FC5	SP 05-4255B
10	Phase 1 Remeasured 31Oct12	28.092432	-80.769495	WB	Wayside 5' @ 25, 50 on remeasure	SR-500 (US-192)	5	Brevard	FC5M	
11	Phase 1					I-75	2	Columbia		

Location ID	Date Measured	Latitude	Longitude	Lane Direction	Wayside Description	Roadway Number	District	County	Mix Type	Mix Design
12	Phase 1					SR-40	5	Marion		
13	Phase 1					SR-16	2	Bradford		
14	Phase 1					SR-222, 39th Ave.	2	Alachua		
15	Phase 1					SR-25 by Fletcher's Mill	2	Alachua		
16	Phase 1					US-441 Payne's Prairie	2	Alachua		
17	12-Apr-12	29.310064	-82.75796	SB	Full Wayside on 12Apr2012	US 19 (SR 55) just South of Otter Creek	2	Levy	FC5M	SPM 09-7225A

Location ID	Date Measured	Latitude	Longitude	Lane Direction	Wayside Description	Roadway Number	District	County	Mix Type	Mix Design
18	10-Jul-12	25.85071	-80.20764	NB	No Wayside	I-95	6	Miami-Dade	LGD	No Information
19a	30-Oct-12	28.380706	-80.808691	SB near MM197	No Wayside	I-95	5	Brevard	LGD	LGD 05-1163
19b	30-Oct-12	28.380841	-80.808439	NB	No Wayside	I-95	5	Brevard	LGD	LGD 05-1163
20	27-Feb-13	30.444731	-81.65386	SB	No Wayside	I-95	2	Duval	LGD	No Information
21	11-May-12	30.26067	-81.76367	NB	Wayside all 5' locations; last at 90'	I-295	2	Duval	FC5M	SPM 07-5244A
22a	26-Nov-12	27.992023	-82.326736	SB	No Wayside Near MM 262	I 75 (SR93 A)	7	Hillsborough	LGD	No Information
22b	26-Nov-12	27.991997	-82.326047	NB	No Wayside Near MM 261.5	I 75 (SR93 A)	7	Hillsborough	LGD	No Information
23	9-May-12	29.74837	82.35526	NB	Wayside all 5' locations	SR 121	2	Alachua	FC125	SP 00-0925A
24	9-May-12	29.755567	-82.356662	NB	Wayside all 5' locations	SR 121	2	Alachua	FC125	SP 00-0925B
25a	8-Aug-12	27.392500	-80.397778	SB	No Wayside	I-95	4	St. Lucie	FC5M	SPM 09-7044B

Location ID	Date Measured	Latitude	Longitude	Lane Direction	Wayside Description	Roadway Number	District	County	Mix Type	Mix Design
25b	8-Aug-12	27.392572	-80.398269	NB	No Wayside	I-95	4	St. Lucie	FC5	QA 00-9726B
26a	30-Oct-12	MM171 27.541621 MM172 27.5550648	MM 171 -80.621185 MM 172 -80.634016	EB at MM 171 and 172	No Wayside	Turnpike (SR 91)	4	St. Lucie	FC5M	SPM 08-6360B
26b	30-Oct-12	MM171 27.550603	MM 171 -80.633854	WB at MM171	No Wayside	Turnpike (SR 91)	4	St. Lucie	FC5M	SPM 08-6360B
27	12-Jul-12	26.94475	-80.35422	EB	Wayside no 100' locations	SR710	4	Palm Beach	FC125M	SPM 10-7851A
28	8-Aug-12	27.294532	-80.691335	EB	Full Wayside	SR 70 Rd	1	Okeechobee	FC5	SP 10-8157A

Location ID	Date Measured	Latitude	Longitude	Lane Direction	Wayside Description	Roadway Number	District	County	Mix Type	Mix Design
29	27-Nov-12	26.561564	-31.667465	EB	Full Wayside	SR 82 (Immokalee Rd)	1	Lee	FC125MR	SPM 10-8052B
30	9Aug12	Start 26.874989 End 26.844362	Start - 80.123945 End - 80.105816	SB	No Wayside Special 3 mi test	I95 SB	4	Palm Beach	FC5M	SPM 10-8568B
31	30-Oct-12	28.307566	-80.76049	SB	No Wayside Near MM203.5	I-95	5	Brevard	LGD	No Information
32	30-Oct-12	28.30777	-80.760125	NB	No Wayside Near MM203.5	I-95	5	Brevard	LGD	No Information
33	5-Jun-12	30.37564	-86.29816	EB	Wayside all but 12'@100'	SR 30 (US98)	3	Walton	FC5	QA 03-10857A
34	10-May-12	29.75134	-82.22	NB	Wayside all 5' locations	SR 24	2	Alachua	FC5	QA 00-9506A
35	28-Nov-12	26.511944	-81.794439	NB	No Wayside Near MM129.1	I-75	1	Lee	FC5M	LDWM 09-2597A

Location ID	Date Measured	Latitude	Longitude	Lane Direction	Wayside Description	Roadway Number	District	County	Mix Type	Mix Design
36a	6-Aug-12	27.511665	-80.726668	SB	No Wayside	I-95	4	Martin	FC5M	SPM 08-6360B
36b	6-Aug-12	27.122509	-80.273619	NB	No Wayside	I-95	4	Martin	FC5M	SPM 08-6360B
37	7-Aug-12	27.035422	-80.392793	EB	Full Wayside	SR 76 S Kanner Hwy	4	Martin	FC125	SP 09-6870A
38a	11Apr12 7May12 8May12	29.36313	-82.79015	NB inside	Wayside on 7May all 5' locations	US 19/US 98/SR 55	2	Levy	FC5M	SPM 10-7850A
38b	11Apr12 7May12	29.37692	-82.7986	NB inside	Wayside on 7May all 5' locations	US 19/US 98/SR 55	2	Levy	FCQ	LD 10-2631A
38c	11Apr12 8May12	29.3915	-82.80753	NB inside	Full Wayside on 8May	US 19/US 98/SR 55	2	Levy	FCQ	LD 10-2632A
39	4-Jun-12	30.149909	-83.61448	NB	Full Wayside on 6/4/2012	US 19/US 27/SR 20	2	Taylor	FC5M	SPM 10-7988A
40a	10-Dec-12	30.467768	-82.964465	SB	No Wayside	I-75/SR 93	2	Hamilton	FC5M	SPM 10-8213A
40b	10-Dec-12	30.467733	-82.963928	NB	No Wayside	I-75/SR 93	2	Hamilton	FC5M	SPM 10-8213A
41	7-Jun-12	30.4423	-85.42617	NB	Wayside no 100' locations	US 231/SR 75/Harrison Ave	3	Bay	FC5M	SPM 07-5395A

Location ID	Date Measured	Latitude	Longitude	Lane Direction	Wayside Description	Roadway Number	District	County	Mix Type	Mix Design
42a	11Jul12 12Jul12	26.45711	-80.08988	SB	No Wayside	I-95	4	Palm Beach	FC5M	SPM 11-9138A
42b	11Jul12 12Jul12	26.44708	-80.08971	NB	No Wayside	I-95	4	Palm Beach	FC5M	SPM 11-9138A
43	27-Feb-13	30.418331	-81.65703	SB	No Wayside	I-95	2	Duval	LGD	No Information
44	27-Feb-13	30.314162	-81.66357	NB	No Wayside	I-95	2	Duval	LGD	No Information
46a	28-Nov-12	27.969727	-82.326662	SB	No Wayside Near MM258.5	I-75 (SR93 A)	7	Hillsborough	LGD	No Information
46b	28-Nov-12	27.954732	-82.327264	NB	No Wayside Near MM257.5	I-75 (SR93 A)	7	Hillsborough	LGD	No Information
47a	29-Nov-12	28.017922	-82.264208	WB	No Wayside 2 Pavement Types in Limits, 2 EB and WB Tests	I-4 (SR 400)	7	Hillsborough	FC2	No Information

Location ID	Date Measured	Latitude	Longitude	Lane Direction	Wayside Description	Roadway Number	District	County	Mix Type	Mix Design
47b	29-Nov-12	28.009401	-82.286652	WB	No Wayside 2 Pavement Types in Limits, 2 EB and WB Tests	I-4 (SR 400)	7	Hillsborough	FC5M	SPM 07-5346C
47c	29-Nov-12	28.009413	-82.284711	EB	No Wayside 2 Pavement Types in Limits, 2 EB and WB Tests	I-4 (SR 400)	7	Hillsborough	FC5M	SPM 07-5346C
47d	29-Nov-12	28.017388	-82.263813	EB	No Wayside 2 Pavement Types in Limits, 2 EB and WB Tests	I-4 (SR 400)	7	Hillsborough	FC2	No Information
48a	28-Feb-13	30.251008	-81.487549	EB	No Wayside	SR 202/ J T Butler Blvd.	2	Duval	FC5M	SPM 09-6900A
48b	28-Feb-13	30.25157	-81.476266	WB	No Wayside	SR 202/ J T Butler Blvd.	2	Duval	FC5M	SPM 09-6900A
49	28-Feb-13	30.25211	-81.49538	WB	No Wayside	SR 202 WB Off ramp to Kernan Blvd.	2	Duval	FC5M	SPM 09-6900A
50	28-Feb-13	30.205874	-81.51419	SB	Wayside 25 and 50' for 5' only	I295 S. of Bay Meadows	2	Duval	LGD	No Information

Location ID	Date Measured	Latitude	Longitude	Lane Direction	Wayside Description	Roadway Number	District	County	Mix Type	Mix Design
		Color Code of Cells		Phase 2		🟩				
				Phase 1		⬜				
				Phase 1 and 2		🟫				

Table 4. Final Derived OBSI Intensity Levels (Both Linear and A-weighted)

Final Location No.	Front Probe IL (dB)	Rear Probe IL (dB)	Both Probes (dB)	Front Probe IL (dBA)	Rear Probe IL (dBA)	Both Probes (dBA)
2	105.4	105.1	105.3	104.4	104.4	104.4
5	107.7	106.9	107.3	106.4	106.0	106.2
6	103.1	102.7	102.9	102.0	101.9	102.0
9a	106.9	107.2	107.0	105.9	106.5	106.2
9b	105.8	106.1	106.0	104.5	105.2	104.9
10	104.9	105.0	104.9	103.8	104.3	104.0
17	106.4	106.4	106.4	105.1	105.5	105.3
19a	104.0	104.3	104.2	104.0	104.4	104.2
19b	103.5	104.0	103.8	103.6	104.2	103.9
20	104.7	104.6	104.7	104.6	104.8	104.7
21	104.9	105.1	105.0	103.9	104.5	104.2
22a	104.5	105.8	105.2	104.3	105.7	105.0
22b	103.5	104.8	104.2	103.4	105.0	104.2
23	100.2	101.0	100.6	100.3	101.2	100.8
24	98.6	99.2	98.9	98.6	99.4	99.0
25a	105.4	105.9	105.7	104.4	105.3	104.9
25b	105.3	106.2	105.8	104.2	105.5	104.9
26a	106.7	107.0	106.8	105.8	106.5	106.2
26b	106.6	107.1	106.8	105.6	106.5	106.1
27	100.3	102.4	101.4	100.3	102.3	101.4
28	105.0	105.4	105.2	104.1	104.8	104.4
29	100.8	102.2	101.6	100.8	102.4	101.6
30	104.8	105.5	105.2	103.9	105.0	104.5
31	103.5	104.1	103.8	103.5	104.3	103.9
32	103.4	103.9	103.6	103.4	104.1	103.7
33	104.6	104.6	104.6	103.7	104.0	103.9
34	103.9	104.0	104.0	103.0	103.4	103.2
35	106.5	106.6	106.6	105.4	106.0	105.7
36a	106.0	107.0	106.5	105.1	106.4	105.8
36b	105.6	106.5	106.0	104.6	105.9	105.3
37	100.9	102.8	102.0	101.0	103.0	102.1
38a	103.9	103.7	103.8	103.0	103.1	103.0
38b	101.5	101.7	101.6	100.5	101.1	100.8

Final Location No.	Front Probe IL (dB)	Rear Probe IL (dB)	Both Probes (dB)	Front Probe IL (dBA)	Rear Probe IL (dBA)	Both Probes (dBA)
38c	102.6	102.9	102.8	101.6	102.4	102.0
39	104.7	104.9	104.8	103.7	104.3	104.0
40a	107.1	107.2	107.2	106.0	106.5	106.3
40b	107.0	107.2	107.1	105.9	106.4	106.2
41	103.8	104.2	104.0	102.8	103.5	103.1
42a	104.7	106.3	105.6	103.8	105.7	104.8
42b	103.6	105.2	104.5	102.7	104.7	103.8
43	104.8	104.5	104.7	104.6	104.5	104.6
44	104.3	104.1	104.2	104.2	104.2	104.2
46a	104.9	105.3	105.1	104.8	105.4	105.1
46b	105.2	105.6	105.4	105.1	105.7	105.4
47a	106.9	107.3	107.1	106.0	106.7	106.3
47b	106.6	106.8	106.7	105.6	106.1	105.9
47c	105.8	106.0	105.9	104.8	105.3	105.1
47d	106.0	106.5	106.3	104.9	105.7	105.3
48a	106.4	106.6	106.5	105.5	106.0	105.8
48b	106.5	106.6	106.6	105.5	106.0	105.7
49	103.8	103.6	103.7	102.6	102.7	102.7
50	106.9	106.2	106.6	106.9	106.4	106.7

Phase 2	🟩
Phase 1 and 2	🟫

was later verified to be affecting the levels and as such, this data is not included in Table 4. Additionally, other Phase 1 Locations not measured in Phase 2 are not included in Table 4.

OBSI Analysis

To begin the analysis, a quick comparison of the linear (non-weighted values) to the A-weighted values was accomplished first. It was found that the differences when compared (Linear – A-weighted) only ranged from -0.2 to 1.2 dB with an average difference of 0.5 dB. Because of the very similar values only the A-weighted values for both probes will be discussed in this report. The reader may wish to compare using values from Table 4 for any particular point of interest.

The next step in the analysis was to rank the different pavements. Figure 18 shows the pavements from the lowest measured to the highest by location number. The lowest measured intensity level was 99 dB(A) (an FC125, dense graded) and the greatest was 106.7 dB(A)(an LGD rigid pavement) for a range of 7.7 dB(A). This is a very typical range and very similar to other states such as California.[11] 7.7 dB(A) is a significant difference and represents a change in energy created at the tire/pavement interface by over a factor of six. In other words, the louder pavement emissions contain over 6 times the acoustic energy. Another way to look at this from a more practical standpoint is that if a noise barrier were needed, the height requirement would be drastically reduced by the quieter pavement surface and possible in some cases not to be needed.

The next logical question becomes, why are some of the surface textures quieter than others? Figure 19 shows the overall rankings again, but this time by the Mix Type instead of Location Number. These rankings are very important to categorize which surface textures are quieter. Of note is that Location 49 is not considered in most of the analysis since it was for a ramp and at speed of 45 mph (72 kph) and not directly comparable.

Obvious from the rankings in Figure 19 is that there are groupings of mix types. The loudest pavement is a rigid pavement (LGD mix type). A closer review shows that while all rigid pavements are somewhat scattered in the top three-quarters of the rankings with a range from 103.7 to 106.7 dB(A). On a numerical average of the 51 pavement textures included in the analysis, LGD surfaces ranged from 13 to 51 with an average of 27.1. This would tend to indicate that of the pavement types measured, rigid pavements are often louder than flexible pavements, but this is not always the case as indicated by some lower rankings.

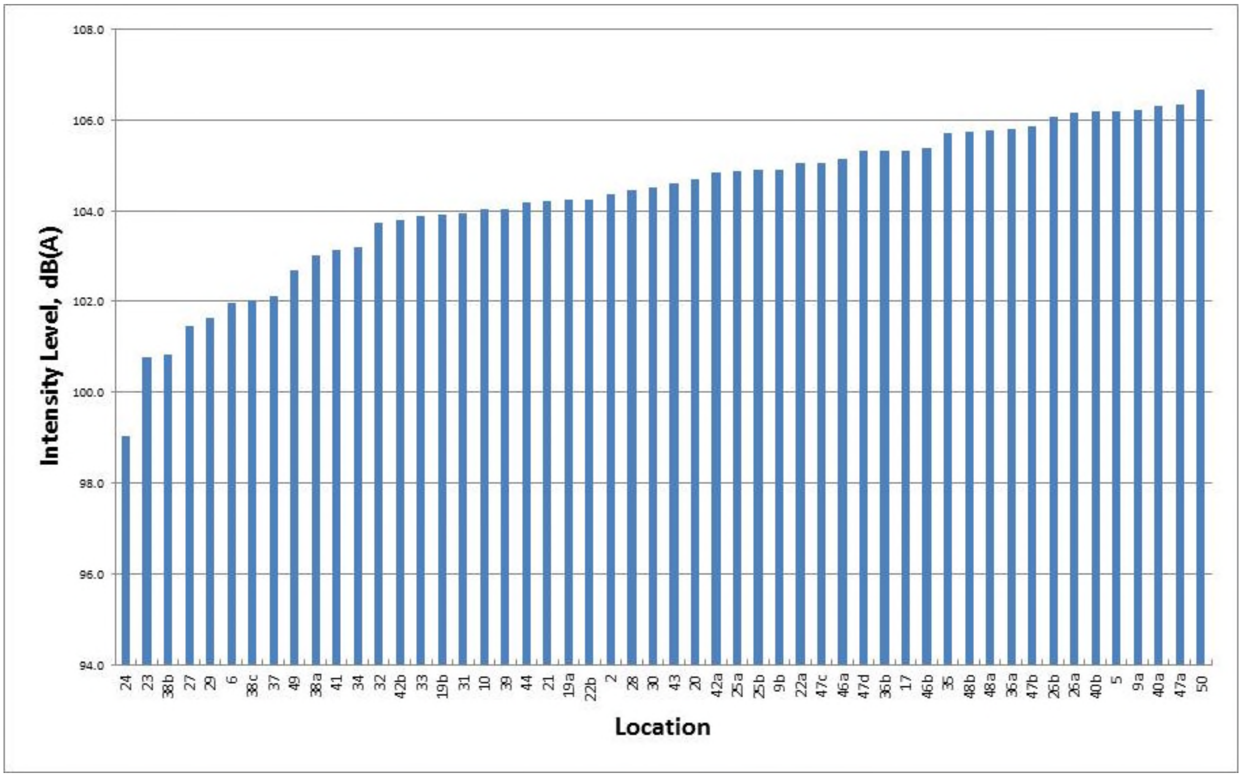


Figure 18. Ranking by Location Number, OBSI Levels

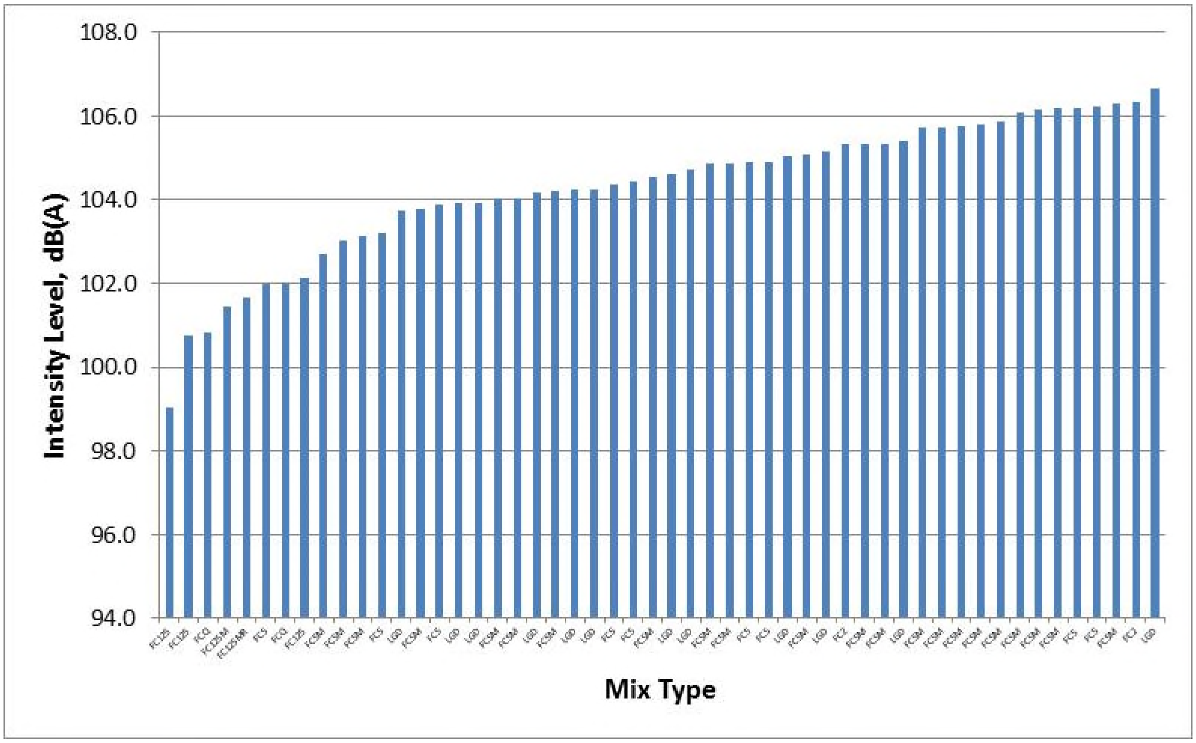


Figure 19. Ranking Shown by Surface Mix Type, OBSI Levels

As shown in Figure 19, the range of flexible pavement surfaces with various mix types ranged from 99 to 106.3 dB(A). Of these the FC2 pavement surfaces are the loudest with an average ranking of 43.5, FC5 surfaces are second with an average ranking of 29.7, FCQ surfaces are next with an average ranking of 4.5 and the quietest surface is FC125 as well as having the lowest average ranking of 4. The FC5 surfaces are open graded while the FC125 surfaces are dense graded. Reasons for these results are explored later in this paper.

If we again look at Figure 19, we see that the twelve quieter pavements are flexible pavement surfaces. This leads to a general finding from this extensive OBSI testing that in Florida, the flexible pavements represent the quieter pavement surfaces at the pavement/tire interface.

This makes these twelve quieter pavement surfaces of particular interest and results are better shown in Figure 20. As can be seen in Figure 20, of these surfaces five are FC125, five are FC5 (actually four because we eliminate Location 49), and two are FCQ (an open graded surface with a different aggregate characteristics). Of note is that some have modified binders designated with an M. As shown in Figure 19, of the quieter pavement surfaces, open graded surfaces (FC5s) tend to be louder while dense graded surfaces (FC125s) tend to be quieter at the tire/pavement interface. Tables 5 and 6 show more detail of the mix for these 12 pavement surfaces.

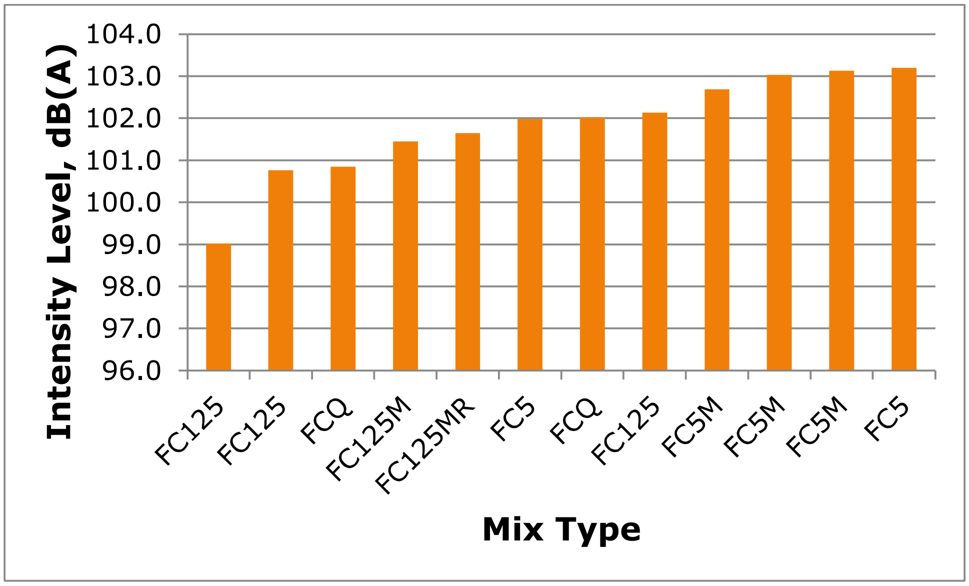
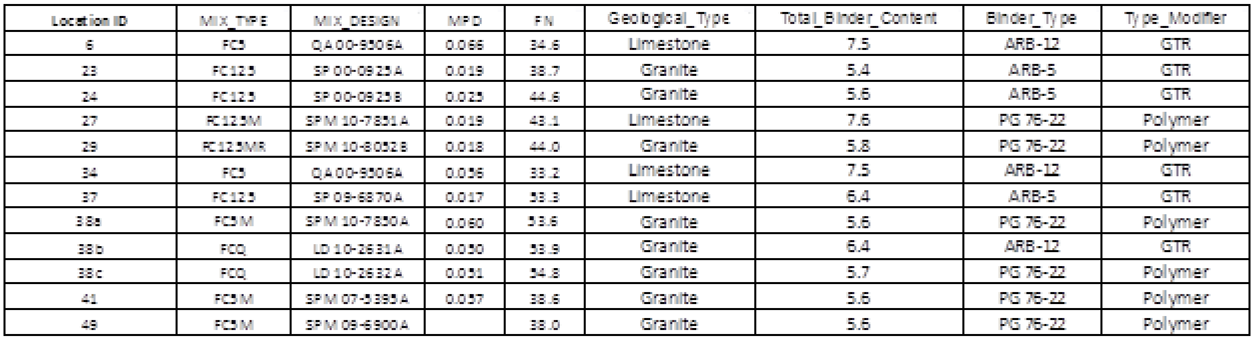


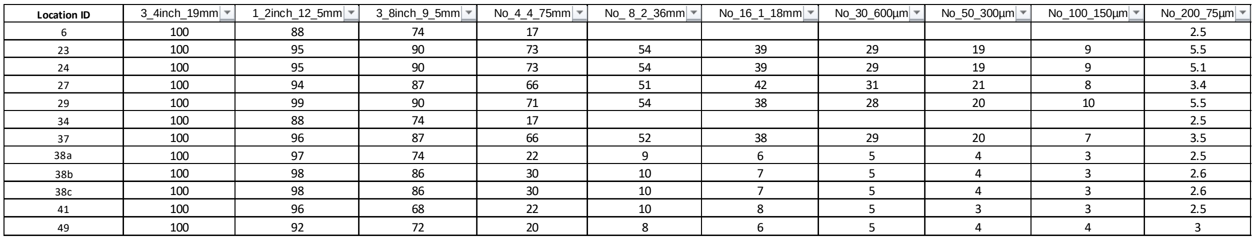
Figure 20. Twelve Quieter Surfaces Selected for Detailed Analysis Based on Initial Results

Table 5. Mix Design, Macrotexture, and Friction Details for Twelve Quieter Surfaces



Location ID	MIX_TYPE	MIX_DESIGN	MPD	FN	Geological_Type	Total_Binder_Content	Binder_Type	Type_Modifier
6	FC5	QA 00-9506A	0.066	34.6	Limestone	7.5	ARB-12	GTR
23	FC12.5	SP 00-0925A	0.019	38.7	Granite	5.4	ARB-5	GTR
24	FC12.5	SP 00-0925B	0.025	44.6	Granite	5.6	ARB-5	GTR
27	FC12.5M	SPM 10-7851A	0.019	43.1	Limestone	7.6	PG 76-22	Polymer
29	FC12.5MR	SPM 10-8052B	0.018	44.0	Granite	5.8	PG 76-22	Polymer
34	FC5	QA 00-9506A	0.056	33.2	Limestone	7.5	ARB-12	GTR
37	FC12.5	SP 09-6870A	0.017	53.3	Limestone	6.4	ARB-5	GTR
38a	FC5M	SPM 10-7850A	0.060	53.6	Granite	5.6	PG 76-22	Polymer
38b	FCQ	LD 10-2631A	0.050	53.9	Granite	6.4	ARB-12	GTR
38c	FCQ	LD 10-2632A	0.051	54.8	Granite	5.7	PG 76-22	Polymer
41	FC5M	SPM 07-5395A	0.057	38.6	Granite	5.6	PG 76-22	Polymer
49	FC5M	SPM 09-6900A		38.0	Granite	5.6	PG 76-22	Polymer

Table 6. Aggregate Gradations for the Twelve Quieter Surfaces



Location ID	3_4inch_19mm	1_2inch_12_5mm	3_8inch_9_5mm	No_4_4_75mm	No_8_2_36mm	No_16_1_18mm	No_30_600μm	No_50_300μm	No_100_150μm	No_200_75μm
6	100	88	74	17						2.5
23	100	95	90	73	54	39	29	19	9	5.5
24	100	95	90	73	54	39	29	19	9	5.1
27	100	94	87	66	51	42	31	21	8	3.4
29	100	99	90	71	54	38	28	20	10	5.5
34	100	88	74	17						2.5
37	100	96	87	66	52	38	29	20	7	3.5
38a	100	97	74	22	9	6	5	4	3	2.5
38b	100	98	86	30	10	7	5	4	3	2.6
38c	100	98	86	30	10	7	5	4	3	2.6
41	100	96	68	22	10	8	5	3	3	2.5
49	100	92	72	20	8	6	5	4	4	3

Mean Profile Depths (MPD), where known, ranged from 0.017 to 0.066. The FC5 surfaces, with one exception, have higher values than FC125 and FCQ. If we compare these MPD values to all surfaces we find the ranges are 0.002 to 0.099 with an average of 0.048. As such, the FC125 surfaces all below the average while the FC5 and FCQ surfaces are above the average. In general it appears that MPD has an effect on the noise generation due to increased macrotexture as has been previously reported by others[1] and discussed in Phase 1.

With one exception, the FC5 surfaces have the lower friction numbers (using the ribbed tire results). Friction numbers range from 25 to 56 with an average of 38. With the one exception, FC5 surfaces were generally at or below this average value while the other surfaces (FC125 and FCQ) were well above. It may be hypothesized that the friction number represents a measure of the microtexture which is important for noise control and affect sounds caused by adhesion as well. Based on this idea, friction number could be an important crossover measure for noise evaluation as well.

The aggregate size seems also to be important as previously reported with the FC125 aggregates being smaller in general than the FC5 and FCQ surfaces. Again, this matches with previous reportings since the macrotexture is affected causing greater tire vibrations. Additionally, while more data are needed to add certainty and verification, it would follow that one reason the FC2 surfaces are among the loudest is due to larger aggregate. Again, more data is needed for final proof, but this does appear to be a logical conclusion. More detail on analyzing the mix variables for flexible surfaces is included later in this report.

Rigid pavements of course are very different. The primary reason in these measurements they are among the loudest is likely due to tining and that several sections were much older showing some cracking. Of particular note is that the loudest surface, Location 50 on Interstate 295, had transverse tining. Increased reflectivity of the sound wave also resulted in high wayside levels as discussed later,

Frequency varies with pavement texture and was also reviewed. This is an important aspect since not only does the overall loudness change with pavement types but so does the frequency spectra. Contributions from all frequencies sum to the overall dB(A) reported level. Table 7 includes the measured values in 1/3 octave bands representing the frequency spectrum from the measurements.

Table 7. Spectrum Data from Probes

Location ID	Visit No.	Speed (mph)	500 Hz	631 Hz	800 Hz	1000 Hz	1260 Hz	1590 Hz	2000 Hz	2500 Hz	3200 Hz	4000 Hz
2	Visit1	55	94.6	98.9	100.2	95.8	92.2	88.2	84.1	80.3	78.1	72.4
2	Visit1	60	95.8	99.3	100.4	96.0	92.8	89.4	85.8	82.4	80.1	74.5
5	Visit1	55	96.5	101.1	102.1	93.8	88.6	85.3	79.7	74.6	72.7	67.2
5	Visit1	60	98.1	102.4	103.3	95.0	89.8	86.4	81.0	76.2	74.5	69.2
6	Visit 1	60	93.7	97.3	98.3	93.4	88.8	86.0	82.7	79.4	77.2	71.9
10	Visit9	55	94.2	99.3	100.1	95.3	90.7	85.6	81.4	78.0	76.1	70.5
10	Visit8	60	94.9	99.3	100.5	96.0	91.5	86.5	82.7	79.7	77.6	72.0
17	Visit1	55	92.1	97.9	100.2	94.8	90.4	86.5	79.8	72.4	70.5	66.1
17	Visit1	60	93.2	98.6	101.2	96.1	91.8	87.7	81.4	74.6	72.7	68.0
18	Visit1	55	85.1	89.8	97.5	97.7	91.5	92.6	90.0	86.6	83.5	78.6
18	Visit1	60	86.7	90.9	97.5	98.6	93.2	92.9	90.9	88.1	84.5	80.5
19a	Visit2	55	86.9	91.5	98.2	98.2	93.7	92.8	89.9	86.7	83.2	77.6
19a	Visit1	60	87.7	91.7	98.0	99.3	95.6	94.0	91.3	88.2	84.4	79.5
19b	Visit1	55	86.2	91.1	98.4	98.5	93.3	93.1	90.2	86.8	83.2	77.6
19b	Visit2	60	86.4	91.0	97.6	99.1	94.7	93.9	91.4	88.5	84.0	79.5
20	Visit1	55	87.9	92.5	98.5	98.5	94.1	93.8	91.2	87.1	84.0	79.4
20	Visit1	60	88.8	93.0	98.8	99.2	96.3	94.5	91.8	88.3	84.7	80.7
21	Visit1	55	93.3	98.3	100.7	95.1	90.9	87.8	83.5	77.6	72.1	64.8

Location ID	Visit No.	Speed (mph)	500 Hz	631 Hz	800 Hz	1000 Hz	1260 Hz	1590 Hz	2000 Hz	2500 Hz	3200 Hz	4000 Hz
21	Visit1	60	93.8	98.7	101.4	95.8	91.8	88.9	84.8	79.3	74.0	67.1
22a	Visit1	55	88.5	94.3	99.7	98.3	93.6	92.9	90.0	86.5	83.3	78.1
22a	Visit1	60	90.1	95.5	100.5	99.0	95.5	93.9	91.2	88.2	84.4	79.9
22b	Visit1	55	87.2	92.4	98.5	98.6	93.7	93.1	90.1	86.8	83.7	78.6
22b	Visit1	60	87.8	92.4	98.4	99.2	95.3	93.6	91.0	88.0	84.6	80.4
23	Visit1	55	80.9	86.5	95.1	96.0	90.0	89.9	86.9	83.7	79.7	73.7
23	Visit1	60	81.9	86.0	94.0	96.3	92.1	90.5	88.1	85.2	81.0	75.5
24	Visit1	55	80.8	86.4	93.9	93.8	89.3	87.0	84.6	81.3	77.5	71.4
24	Visit1	60	81.7	86.0	93.0	94.1	91.1	87.7	85.6	83.2	79.0	73.2
25a	Visit4	55	94.0	98.9	100.8	96.4	91.5	86.3	80.0	74.6	74.7	69.8
25a	Visit4	60	95.1	99.8	101.6	97.2	92.5	87.2	81.3	76.1	76.0	71.1
25a	Visit 1	60	82.0	86.1	94.1	96.7	92.0	90.1	88.4	85.0	83.0	79.2
25b	Visit4	55	94.6	99.4	100.5	96.8	91.2	84.8	78.1	75.5	75.7	69.8
25b	Visit3	60	95.4	100.3	101.4	97.5	92.1	85.3	78.9	76.9	77.1	71.2
26a	Visit5	55	94.5	100.8	101.6	98.1	95.0	90.1	82.7	75.6	76.8	72.3
26a	Visit3	60	95.5	101.4	102.6	99.0	96.2	91.3	84.8	77.5	77.2	72.9
26b	Visit3	55	94.7	101.1	101.4	98.1	94.5	88.9	81.0	76.0	77.0	71.9
26b	Visit3	60	95.5	101.6	102.0	98.9	95.2	89.1	81.4	76.9	77.9	72.9
27	Visit1	55	82.6	87.0	95.1	96.4	90.2	89.7	87.3	83.7	81.8	76.0
27	Visit2	60	85.3	87.3	94.6	97.0	92.6	90.6	88.6	85.4	82.8	78.4
28	Visit6	55	93.0	98.6	100.5	96.3	91.3	85.0	78.2	75.1	74.6	69.1
28	Visit7	60	94.0	99.3	101.2	97.1	92.4	85.7	79.3	76.6	76.2	70.8
29	Visit1	55	83.2	89.2	96.8	96.7	91.1	91.0	87.2	82.7	80.4	74.7
29	Visit1	60	84.3	88.8	95.6	96.8	93.2	91.5	87.9	83.9	81.3	76.5
30	Visit1	55	93.7	98.6	100.8	97.4	94.2	89.5	84.9	80.2	78.4	73.7
31	Visit3	55	85.9	91.1	97.8	97.8	93.4	92.3	89.5	86.5	83.1	77.6
31	Visit1	60	86.8	91.5	97.8	98.9	95.6	93.4	90.8	87.8	84.2	79.4
32	Visit1	55	86.1	91.2	97.7	97.6	93.5	92.1	89.5	86.3	82.7	77.2
32	Visit1	60	86.2	91.3	97.5	98.8	95.7	93.0	90.6	87.7	84.1	79.6
33	Visit1	45	90.5	95.2	98.4	91.9	87.4	84.7	80.5	75.7	71.5	64.9
33	Visit1	55	91.8	96.7	100.4	94.9	90.2	87.3	83.4	79.0	75.2	69.4
33	Visit2	60	92.7	97.6	101.1	95.9	91.7	88.9	85.2	81.0	77.2	71.3
34	Visit1	55	91.7	97.0	99.3	94.6	89.8	86.0	81.7	77.9	75.7	70.4
34	Visit1	60	92.4	97.8	100.1	95.5	91.0	87.2	83.1	79.5	77.3	72.1
35	Visit1	55	94.6	99.8	101.0	96.6	92.9	88.1	82.9	77.0	73.9	68.8
35	Visit1	60	96.3	100.9	102.1	97.7	94.4	89.2	83.8	78.0	75.6	70.9
36a	Visit1	55	93.3	99.2	102.1	97.2	93.4	89.3	83.7	76.1	73.5	69.3
36a	Visit1	60	94.4	100.0	102.8	98.2	94.7	90.1	83.9	76.9	75.8	71.6
36b	Visit1	55	93.8	99.2	101.3	96.9	92.7	88.2	82.8	77.1	74.7	69.6
36b	Visit1	60	94.6	99.7	102.2	97.8	93.8	89.1	83.9	78.3	76.0	70.9

Location ID	Visit No.	Speed (mph)	500 Hz	631 Hz	800 Hz	1000 Hz	1260 Hz	1590 Hz	2000 Hz	2500 Hz	3200 Hz	4000 Hz
37	Visit1	55	81.4	87.5	96.6	97.6	90.8	91.4	88.2	84.5	81.7	75.6
37	Visit1	55	79.9	86.2	96.1	97.6	90.1	90.7	88.2	84.5	82.7	76.6
37	Visit1	60	82.8	87.1	95.3	98.0	92.9	91.9	89.4	86.0	82.7	78.2
37	Visit1	60	81.5	85.7	94.5	97.9	92.4	91.1	89.2	85.8	83.3	79.4
38a	Visit1	55	91.9	97.1	99.0	94.6	90.2	86.0	80.5	72.4	69.3	65.9
38a	Visit1	60	93.2	97.7	99.8	95.4	91.2	86.8	81.6	73.9	71.3	67.5
38a	Visit1	60	93.7	98.2	100.0	95.9	91.6	87.1	81.7	74.0	71.9	68.2
38b	Visit1	55	91.3	94.9	96.3	94.0	87.4	81.9	78.1	75.8	73.7	66.8
38b	Visit1	60	91.7	95.3	97.0	94.4	88.7	83.2	79.1	76.6	74.8	68.5
38b	Visit1	60	92.4	95.9	97.6	94.9	89.5	84.0	79.9	77.0	75.3	69.4
38c	Visit1	55	91.2	96.0	97.6	95.0	89.7	83.7	76.9	73.3	74.1	68.5
38c	Visit1	60	92.1	96.5	98.0	95.8	90.7	84.4	77.9	74.6	75.3	69.9
38c	Visit1	60	91.4	95.9	98.0	95.2	90.8	86.3	80.8	72.8	72.2	68.6
39	Visit1	55	95.5	100.3	101.2	94.8	90.0	86.0	79.8	72.1	70.7	66.0
39	Visit1	60	96.6	101.6	102.0	95.8	91.3	86.9	80.7	73.3	72.4	67.8
40a	Visit1	55	95.8	100.4	101.9	97.0	93.4	89.2	84.7	78.6	75.5	71.0
40a	Visit1	60	97.3	101.5	102.9	97.9	94.4	89.9	85.4	79.6	76.8	72.5
40b	Visit1	55	96.4	100.6	101.6	97.1	93.2	88.4	83.3	77.5	76.4	71.6
40b	Visit1	60	97.5	101.6	102.6	97.9	94.1	88.9	84.0	78.3	77.0	72.2
41	Visit1	55	92.5	97.2	99.2	94.7	89.6	85.3	80.2	75.7	72.8	66.8
41	Visit1	60	93.4	98.0	99.7	95.5	90.5	86.0	81.3	77.0	74.1	68.5
42a	Visit3	55	93.2	99.3	101.0	97.1	93.6	88.2	80.9	75.1	75.6	71.4
42a	Visit2	60	93.8	99.5	101.2	97.8	94.3	87.9	80.6	77.0	77.3	72.8
42b	Visit3	55	90.9	96.8	98.5	96.6	92.5	86.1	78.4	74.9	75.6	70.8
42b	Visit3	60	92.8	97.9	99.5	97.5	94.1	87.8	80.3	75.9	76.5	72.1
43	Visit1	55	88.0	92.9	99.1	98.0	94.0	92.8	89.7	85.4	81.5	76.4
43	Visit1	60	88.8	93.5	99.5	98.9	96.1	93.8	90.8	87.1	83.0	78.2
44	Visit1	55	94.9	98.5	100.2	99.5	99.4	97.8	94.0	90.2	85.9	80.1
44	Visit1	60	94.8	98.8	102.4	100.3	100.7	98.8	95.5	91.3	87.0	81.5
46a	Visit11	60	88.5	93.2	99.4	99.9	96.2	95.2	91.9	88.3	84.9	80.7
46b	Visit1	55	88.7	93.6	99.9	98.5	93.8	93.9	90.2	86.0	82.4	77.5
46b	Visit10	60	89.2	93.8	99.9	100.1	96.4	95.2	91.7	88.3	84.6	80.2
47a	Visit5	55	94.5	100.0	102.2	97.7	93.7	89.0	83.9	78.8	76.4	70.4
47b	Visit2	55	95.5	100.2	101.8	96.9	93.3	88.8	83.7	76.7	71.4	65.5
47b	Visit11	60	96.4	100.6	102.7	97.6	94.0	89.5	84.3	77.6	73.2	67.7
47c	Visit7	55	94.4	99.1	99.9	96.2	91.8	86.0	80.1	75.2	74.9	69.4
47c	Visit12	60	95.9	99.9	101.5	97.5	93.5	88.2	83.2	78.8	77.3	71.6
47d	Visit4	55	96.2	99.8	100.2	95.9	90.5	85.5	82.1	79.4	78.1	72.0
48a	Visit1	55	94.6	100.3	101.1	97.8	94.5	88.9	81.8	75.0	74.9	70.1
48a	Visit1	60	95.6	100.6	102.1	98.5	95.5	89.0	82.2	76.3	76.1	71.3

Location ID	Visit No.	Speed (mph)	500 Hz	631 Hz	800 Hz	1000 Hz	1260 Hz	1590 Hz	2000 Hz	2500 Hz	3200 Hz	4000 Hz
48b	Visit1	55	95.7	100.7	101.1	97.6	93.7	87.4	80.1	74.6	74.9	69.4
48b	Visit1	60	96.4	101.1	101.7	98.3	94.9	88.0	80.7	75.8	76.1	70.7
49	Visit1	45	94.2	98.8	98.9	94.1	90.4	84.5	77.4	71.6	70.6	63.7
50	Visit1	55	90.4	95.3	100.1	99.2	97.3	96.3	93.0	88.6	84.3	78.9
50	Visit1	60	91.1	96.3	101.0	100.0	98.4	97.4	94.2	89.7	85.4	80.4

As can be seen in Figure 21, there would appear to be two distributions when the twelve quieter pavement surfaces are reviewed. To further explore these results, a comparison was made by plotting individual types of FC5, FC125, and FCQ. Figure 22 shows these results.

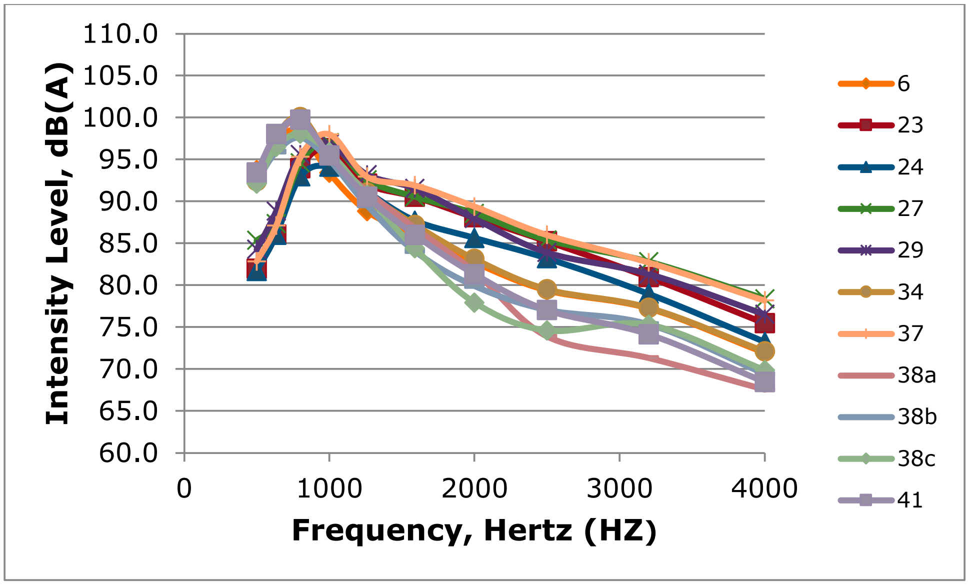


Figure 21. Frequency Comparison of Quieter Pavements

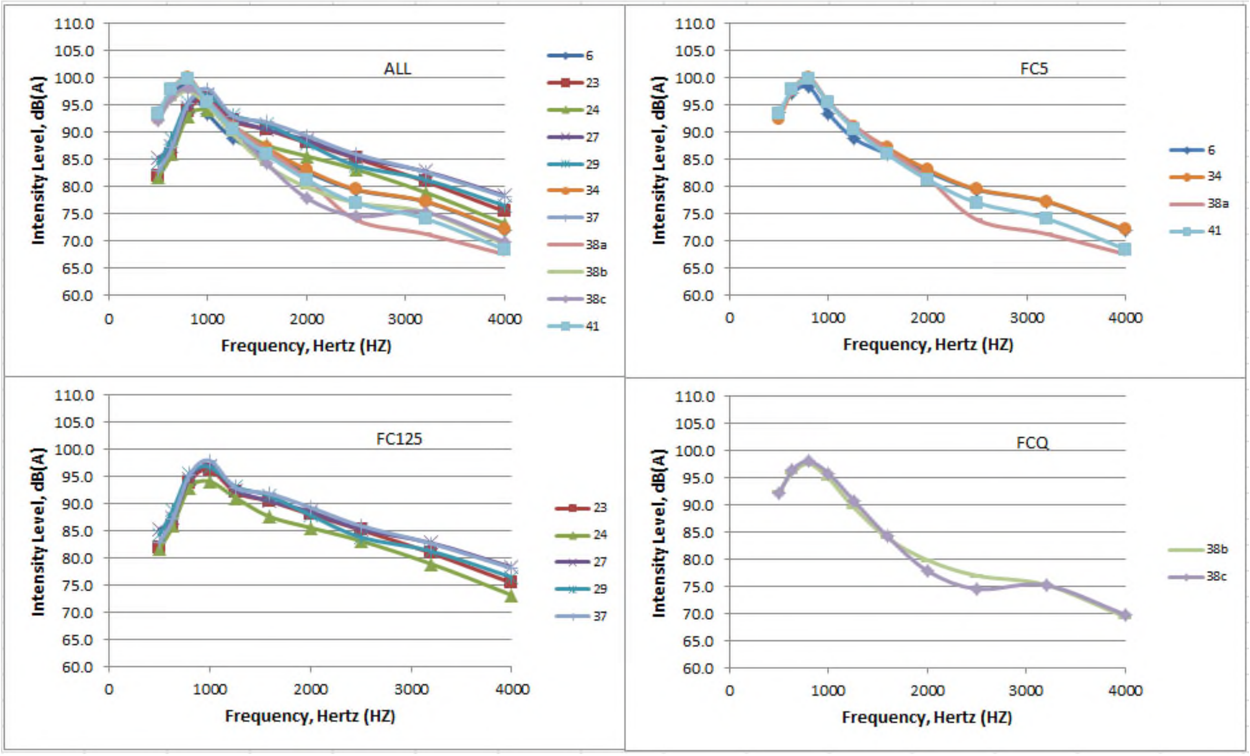


Figure 22. Comparison of Frequency Spectra by Surface Type

It can be seen from this comparison as shown in Figure 22 that the spectra are dependent on surface types tend to fall into various groups. The FC5 surfaces have a maximum (peak) at approximately 800 Hertz while the FC125 peak is about 1000 Hertz. The maximum peak is greater for the FC5, leading to the generally louder pavement. However, while the FC125 tend to have a linear falloff for the higher ranges, the FC5 surface has a noticeable dip over 2000 Hertz. The FCQ, which is essentially a FC5 surface with different aggregate characteristics, follows the trends of the FC5 surface which would be expected.

The results (maximum peak) show why open graded surfaces tend to be louder at the tire/pavement interface and this can be perceived by drivers within the vehicle when the greater tire vibrations are passed to the axle and then the vehicle resulting in greater noise levels within the vehicle. However, we must also review the noise levels at the wayside, which is more important from a public exposure viewpoint. This will be explored when the wayside measurements are discussed.

While all surface spectra were reviewed and show interesting results, to allow readability, typical results are shown in Figure 23. In this figure, graphical data for 2

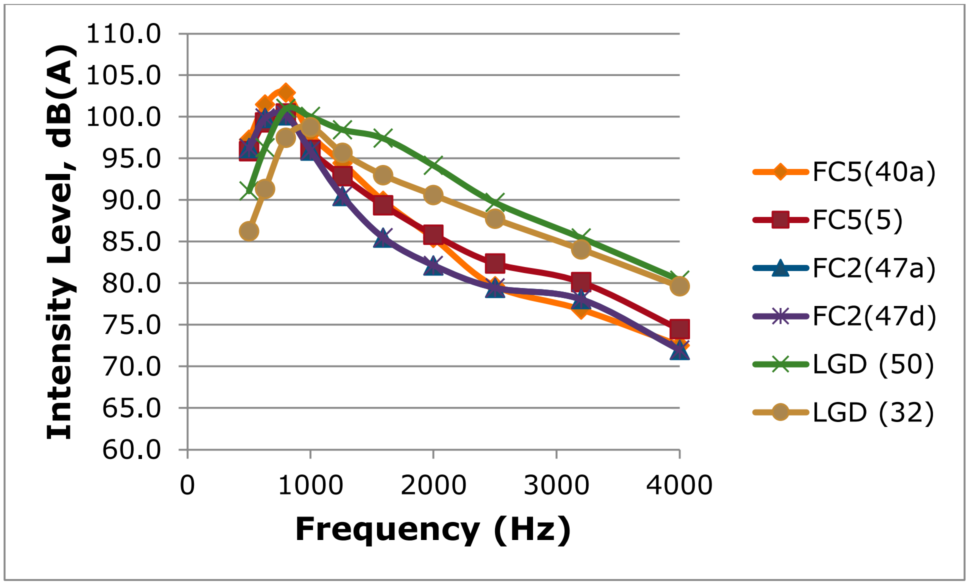


Figure 23. Comparison of Louder FC5 to FC2 and LGD Surfaces

measurements of the FC5, FC2, and LGD surfaces are shown. For this example, the greater amplitude FC5 surfaces were selected to compare to the louder FC2 and LGD surfaces. Of note is that even though the FC5 surface is greater in amplitude, the spectrum shape is still similar to the quieter FC5 surfaces with the peak still about 800 Hertz but this time the dip above 2000 Hertz is not as pronounced, resulting in greater overall sound level and intensity levels. Aggregate size or shape could be the reason in this case but cannot be proven at this time.

FC2 surfaces were similar at the peak to FC5, displayed very similar characteristic across the frequency bank, and tended to fall off faster at higher frequencies than the FC5 surfaces. The LGD surfaces were slightly different in that the peaks were at a higher frequency, and tended not to fall off as fast at the higher frequencies. Many assumptions can be made but in reality this needs to be further explored by the pavement design engineers and acoustic analysts coming together.

The frequency components definitely show differences between surfaces with FC5, FCQ, and FC2 being similar, FC125 very different for the peak and falloff, and LGD surfaces also with a higher frequency peak and greater higher frequency components.

Implications of Aging

While much more is needed, the effects of aging were also evaluated. There were four locations where the same surface was in place. Table 8 shows these results.

Table 8. The Effects from Aging

Location ID	Date Measured Phase 1	Date Measured Phase 2	Elapsed Time	Phase 1 (dB)	Phase 2 (dB)	Change (dB)	Change/Year (dB)
2	29-Sep-07	29-Oct-12	5 yr 1 mo	104.4	105.3	0.9	0.2
5	28-Oct-08	11-Apr-12	3 yr 5 mo	106.4	107.3	0.9	0.3
9	6-Nov-07	29-Oct-12	4 yr 11 mo	105.3	106.5	1.2	0.2
10	9-Nov-07	31-Oct-12	4 yr 11 mo	104	104.9	0.9	0.2

From the measurements it shows that indeed the pavements did get louder as generally expected. However, the values were very small on the order of 0.2 to 0.3 dB per year. Much more data is needed to confirm this, especially since a new test rig and other equipment were put in place.

Wayside Measurement Results

Up to this point in the analysis we have been reviewing the OBSI results. We found the dense graded pavement to be quieter in general and rigid pavement now in service to be louder. This section deals with the wayside measurements.

As with OBSI, extreme quality control was accomplished and previously discussed. This also applied to other data sets for the wayside including weather data and field notes on vehicle passby measurements. Literally thousands of data were taken but only 396 events passed the final quality control. The checking for any occurrences of other background noise that would cause problems in absolute levels was previously discussed. Careful review of calibration data and possible meter drift were checked as well. The data of interest in the wayside data was for individual passbys to allow a comparison to the OBSI measured values and determine the effects on the noise due to propagation across the various pavement surfaces.

The events of interest (single vehicle passbys with low background noise) were identified using a manual process in Phase 1. This process including reviewing each time history plot with the field note times of events to identify possible good passbys was very time consuming. Special software was written for Phase 2 to automate this process. While multiple vehicle types were measured (automobiles, medium trucks, heavy trucks, buses and motorcycles) automobiles were the vehicle type simulated by the test trailer and the vehicle type reviewed in this report.

Figure 24 show the locations measured for wayside sound levels in conjunction with the OBSI measurements. Of note is that these measurements were concurrent so that weather and other conditions were exactly the same. Wayside locations were also previously listed in Table 3 with details on measurement positions that were used.

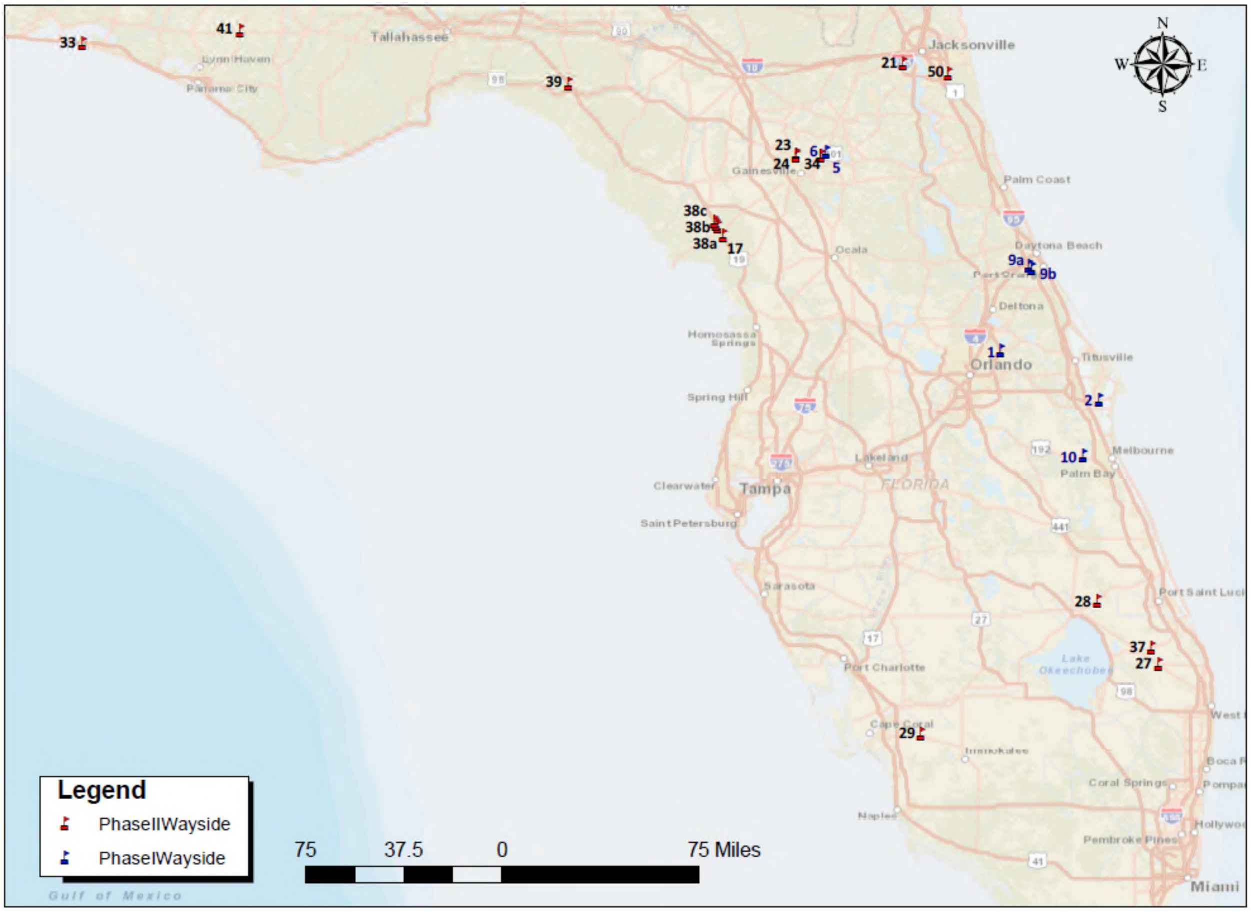


Figure 24. Wayside Measurement Locations

As previously mentioned, five vehicle types were measured at the wayside. The quality controlled raw data base, established after quality control, includes the data for all vehicle types. However, unless otherwise noted, data reported here are only for automobiles. Table 9 shows the final, reduced data base for automobiles along with the average reduced vehicle speed for analysis and the number of good passbys that passed quality control and were included in the data base.

Table 9. Results of All Microphone Positions After Quality Control

Location ID	# of Good Passbys	Distance to CL Near Lane (feet)	Height Above Roadway Surface (feet)	Average Vehicle Speed (MPH)	Sound Level dB(A)
10	2	25	5	61.0	76.4
10	2	50	5	61.0	71.5
10	2	50	12	61.0	73.1
17	7	25	5	60.1	77.2
17	7	50	5	60.1	71.2
17	7	50	12	60.1	73.2
17	7	100	5	60.1	62.6
17	7	100	12	60.1	66.7
23	12	25	5	60.3	75.7
23	12	50	5	60.3	71.0
23	12	100	5	60.3	64.0
24	5	25	5	59.4	71.4
24	5	50	5	59.4	66.5
24	5	100	5	59.4	59.6
27	10	25	5	59.8	75.5
27	10	50	5	59.8	70.1
27	10	50	12	59.8	70.8
28	7	25	5	60.6	76.3
28	7	50	5	60.6	71.7
28	7	50	12	60.6	71.3
28	7	100	5	60.6	64.5
28	7	100	12	60.6	66.4
29	12	25	5	59.8	73.6
29	12	50	5	59.8	68.7
29	12	50	12	59.8	69.0
29	12	100	5	59.8	61.2
29	12	100	12	59.8	63.3
33	4	25	5	59.8	75.8
33	4	50	5	59.8	70.9

Location ID	# of Good Passbys	Distance to CL Near Lane (feet)	Height Above Roadway Surface (feet)	Average Vehicle Speed (MPH)	Sound Level dB(A)
33	4	50	12	59.8	71.4
33	4	100	5	59.8	64.0
34	6	25	5	59.8	75.6
34	6	50	5	59.8	70.6
34	6	100	5	59.8	66.5
37	7	25	5	59.3	74.0
37	7	50	5	59.3	68.5
37	7	50	12	59.3	69.9
37	7	100	5	59.3	61.5
37	7	100	12	59.3	63.8
38a	4	25	5	60.3	74.1
38a	4	50	5	60.3	69.5
38a	4	100	5	60.3	61.7
38b	7	25	5	60.1	72.6
38b	7	50	5	60.1	67.6
38b	7	100	5	60.1	58.8
39	4	25	5	60.5	76.9
39	4	50	5	60.5	72.2
39	4	50	12	60.5	72.1
39	4	100	5	60.5	65.4
39	4	100	12	60.5	67.5
41	11	25	5	60.0	75.5
41	11	50	5	60.0	69.5
41	11	50	12	60.0	70.8
50	12	25	5	59.8	82.6
50	12	50	5	59.8	76.8
Total	**396**				
Average				**60.0**	
Std Dev				**0.45**	

As previously noted, key meteorological data were also collected and included in the overall quality controlled data base. The primary collected data are shown in Table 10.

Table 10. Meteorological Observations

Location ID	Height Above Ground	Average Wind Speed (MPH)	Dominant Wind Direction	Wind Difference by Height
10	6.4	1.9	SE	0.5
10	15.75	2.4	SE	
17	15.75	1.2	SW	-0.1
17	6.4	1.1	SW	
21	15.75	1.0	NE	0.1
21	6.4	1.2	NE	
24	15.75	1.8	SW	0.1
24	6.4	1.9	SW	
27	6.4	1.7	SE	0.4
27	15.75	2.1	SE	
28	6.4	1.7	SW	0.4
28	15.75	2.1	SW	
33	15.75	1.8	SW	0.1
33	6.4	1.9	SW	
34	6.4	2.0	NE	0.3
34	15.75	2.2	NE	
38a	15.75	1.8	S	0.3
38a	6.4	2.1	S	
38c	6.4	1.4	S and W	0.1
38c	15.75	1.5	SW	
39	6.4	1.5	E	0.1
39	15.75	1.6	E	
41	6.4	1.9	NE	0.3
41	15.75	2.2	NE	
50	6.4	1.4	NE	

Additionally it should be noted that the passby data in the final data base did not all occur at 60 MPH (97 kph). To determine the needed values at or near 60 mph as shown in Table 9, a regression analysis was required at each location based on multiple events. Figure 25 has been included to show the real speed variation. All data were statistically analyzed with regression techniques to determine the average 60 mph sound pressure level which is reported and used in this analysis. The two peaks in the results are due to events at the test speed from the test vehicle that was measured to provide a quality control among final data for frequency analysis.

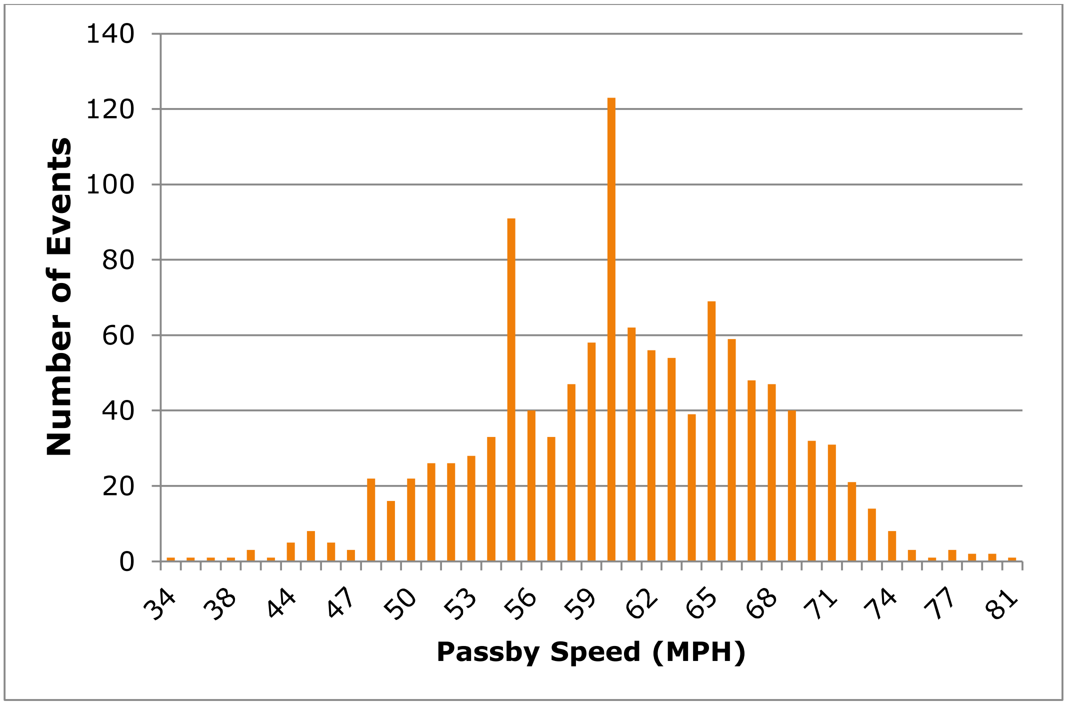


Figure 25. Measured Vehicle Speed Distribution

Wayside Analysis

The first step as with OBSI was to rank the pavement surfaces. To do this, the 50 foot (15 m), 5 feet (1.5 m) above the roadway height was selected. This is because this is the crucial location where the Reference Energy Mean Emission (REMEL) measurements are made and used as the core for model development in the U.S.[8,9] Figure 26 shows the overall ranking by Location.

The first thing that is evident is that the ranking does not follow the same order as the OBSI results. This is shown in Table 11. While relative rankings remain somewhat constant for many of the surfaces, there are some notable changes. The most noticeable are Locations 23 and 27. These FC125 surfaces were among the quieter surfaces at the tire/pavement interface but at the wayside this is no longer true. The greatest possibility is that as reported in the literature, the dense graded surface does not absorb the same energy and results in a greater reflective path contributing to the overall sound level at the side of the roadway resulting in increased sound levels. This phenomenon, but in reverse, seems to be occurring at Locations 10 and 39 which are FC5M surfaces. In these cases, the open graded structure of the surface is absorbing and scattering the reflective wave resulting in a reduced level at the wayside. The same trends were observed in Phase 1.

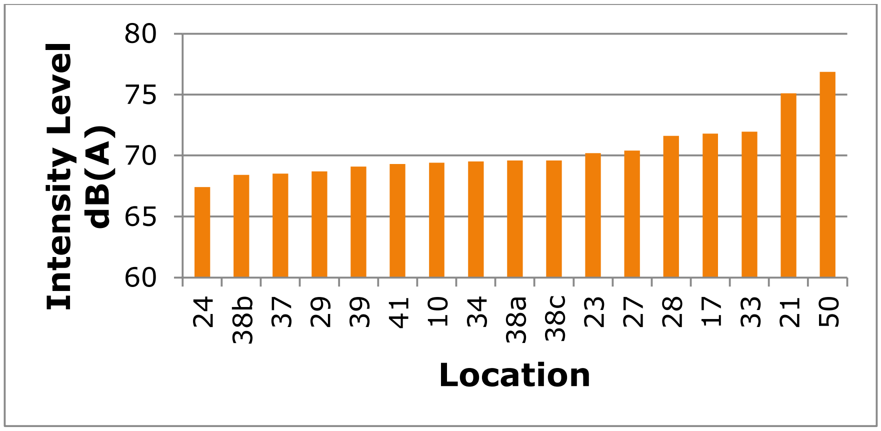


Figure 26. Ranking of Wayside Locations

Table 11. Comparison of Wayside and OBSI Measured Values and Ranking

Location ID	Wayside SPL, dB(A) 60 MPH	OBSI, IL dB(A) 60 MPH	Wayside Ranking*	OBSI Ranking**	Delta (IL-wayside)	Mix Type
24	67.4	99.0	1	1	31.6	FC125
38b	68.4	100.8	2	3	32.4	FCQ
37	68.5	102.1	3	8	33.6	FC125
29	68.7	101.6	4	5	32.9	FC125MR
39	69.1	104.0	5	19	34.9	FC5M
41	69.3	103.1	6	11	33.8	FC5M
10	69.4	104.0	7	18	34.6	FC5M
34	69.5	103.2	8	12	33.7	FC5
38a	69.6	103.0	9	10	33.4	FC5M
38c	69.6	102.0	10	7	32.4	FCQ
23	70.2	100.8	11	2	30.6	FC125
27	70.4	101.4	12	4	31.0	FC125M
28	71.6	104.5	13	25	32.9	FC5
17	71.8	105.3	14	38	33.5	FC5M
33	72.0	104.9	15	15	33.0	FC5
21	75.1	104.2	16	21	29.1	FC5M
50	76.9	106.7	17	51	29.8	LGD
			* out of 17	** out of 51		
		Average			**32.5**	
		Maximum			**34.9**	
		Minimum			**29.1**	
		Std Dev			**1.62**	

To place this in context, consider Figure 27. There is a direct wave path from the tire/pavement interface to the side of the road (not shown), but there is also a reflective wave path. The surface differences affect the reflective wave causing different amount of scattering and absorption to occur. At the side of the road, this results in less energy arriving at a position and reduced sound levels. This is a frequency dependent phenomenon related to the characteristics of the surface.

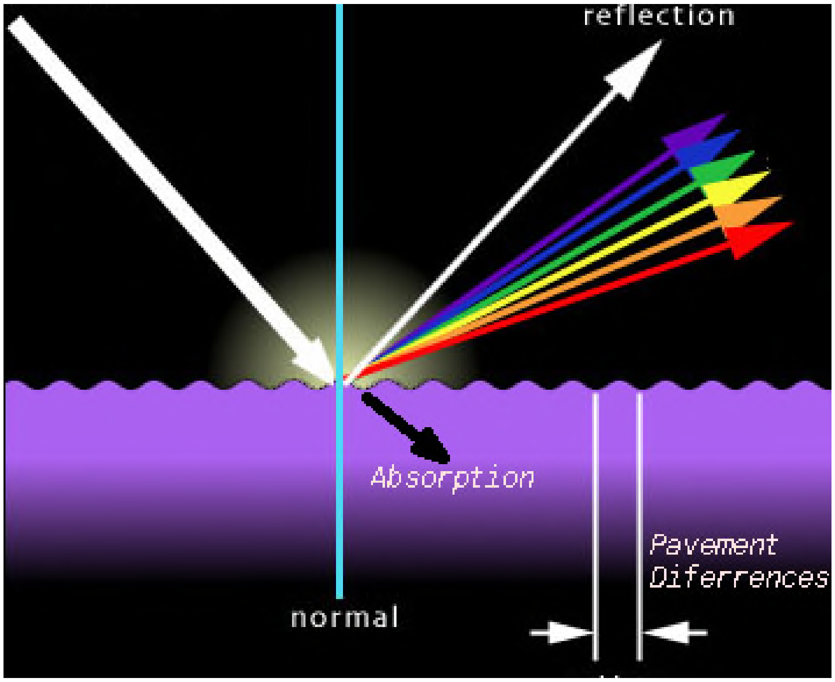


Figure 27. Illustration of Reflective Wave Interaction With Surface

This leads to an analysis of the difference in the levels at the tire/pavement interface and the wayside (OBSI – Wayside). This data is also shown in Table 11. Note that the range of values is 29.1 to 34.9 dB(A) with an average of 32.5. Of note that the difference found in Phase 1 was 32.2 dB(A), showing close agreement to Phase 2 data. The standard deviations were 2.5 and 1.62 in Phases 1 and 2, respectively. As reported in Phase 1, this then leads to a general first order approximate method to be used to determine wayside sound levels if OBSI measurements are made. This general first order approximation is shown by Equation 2.

$$\text{Wayside SPL [dB(A)]} = \text{OBSI Sound Intensity Level} - 32.5 \qquad [2]$$

The uncertainty is ± 3.5 dB(A) based on 2.15 standard deviations.

The FC5 mixes resulted in the greatest decreases at the wayside, being the top three reductions and except for one glaring exception in the top half of rankings based on the noise difference (OBSI – Wayside). The dense graded mix (FC125) was generally in the bottom half of the rankings for the noise reduction during propagation. LGD also showed poor reduction in the propagation path with only one surface have less reduction, a FC5M.

Locations 21 and 39 were reviewed in greater detail because these were FC5 mixes and represented very different results with Location 39 having a 5.8 dB(A) greater reduction in the propagation path than Location 21 and the mix data were available for both. MPDs were approximately the same (0.060 for Location 39 vs. 0.063 for Location 21). Friction numbers were different at 45.6 for Location 39 and 34.5 for Location 21 which would represent a greater microtexture for Location 39. Aggregate sizes were somewhat consistent but Location 21 has slightly more aggregate above ½ inch (12.5 mm) while Location 39 has slightly more aggregate above between ½ (12.5 mm) and 3/8 inch (9.5 mm) which would result in a very slight increase in macrotexture for Location 21. Both were granite with a polymer binding. This would indicate that Location 21 has a slightly coarser gradation and lower microtexture, when compared to Location 39. The difference could be a result of the amount of wear and smoothing of the surface. More wear and smoothing most likely has occurred on Location 21. While both were placed in service in 2010, Location 21 is on heavily traveled Interstate 295 in a large urban area while Location 39 US 19 is on much less travelled roadway in a more rural area. In this case the reflective wave could be much greater resulting in the increased sound level. This is a situation where porosity most likely comes into play but no data are available. More investigation into this type of situation would be needed to make a final determination of the texture properties resulting in the large difference in sound level decrease during propagation.

Other possibilities could be due to local ground effects or a difference in atmospheric refraction on the measurement date. However, during quality control, the falloff rates at all microphone locations were reviewed to determine if any unusual conditions were occurring, particularly ground effects and atmospheric refraction. From the 25 to 50 foot locations, with soft ground cover, a general difference of 4.5 dB(A) would be expected. The locations differences were 4.9 and 4.7 dB(A) for Locations 21 and 39, respectively indicating no unusual ground effect occurrences. Wind speeds were also very similar at both locations on average (1.1 and 1.2 mph) and relatively constant with height indicating that refraction was also not the reason for the very different results.

Locations 23, 27 and 38c were also reviewed in more detail due to the large change in the rankings when the OBSI and Wayside measurements were compared. The two dense graded surfaces (Locations 23 and 27) with the lower microtexture (MPD of 0.019 and friction numbers of 38.7 and 43.1) also indicate a greater reflected wave is occurring causing this change. Location 38c is more difficult because it is an open graded mix with a good MPD (0.051), higher friction numbers (54.9), and similar aggregate sizes to the other FC5 surfaces (see Table 12). Since this is an FCQ surface, it is hypothesized that something in the aggregate change may have caused this large shift in ranking.

Table 12. Aggregate Sizes in Location 23, 27, and 38c.

New_Location_No	MIX_TYPE	3_4inch_19mm	1_2inch_12_5mm	3_8inch_9_5mm	No_4_4_75mm	No_ 8_2_36mm	No_16_1_18mm	No_30_600µm	No_50_300µm	No_100_150µm	No_200_75µm
23	FC125	100	95	90	73	54	39	29	19	9	5.5
27	FC125M	100	94	87	66	51	42	31	21	8	3.4
38c	FCQ	100	98	86	30	10	7	5	4	3	2.6

Frequency was also measured at the wayside microphone positions as well. While an extensive review of this data occurred, only Locations 23, 27, and 39 are discussed in this report due to brevity and these include results of more interest. Further work is still underway on all spectra for both OBSI and Wayside data.

Figure 28 shows a significant difference in the spectra between an open graded surface (FC5) and the dense graded surfaces (FC125). Of note is that the results are all for average spectra of the test vehicle to minimize the differences in the vehicles, all are at 60 mph, and have been adjusted for the same overall level of 70 dB(A). While the peak is slightly greater, the falloff at higher frequencies is much greater for the open graded surface. Again, scattering and absorption are frequency dependent and more pronounced at higher frequencies and this seems to be dramatically shown in Figure 28. The overall result is a greater reduction in sound levels at the side of the road from open graded surfaces even though the rough surface creates more sound energy near 1000 Hertz at the tire/pavement interface.

To further investigate, these three locations were compared to the measured OBSI spectra at the same locations. Results have been plotted in Figures 29, 30, and 31. The effect of the scattering and absorption is readily apparent in these three figures. The open graded mix causes a dip in the higher frequency components while the dense graded mix show a much more linear falloff.

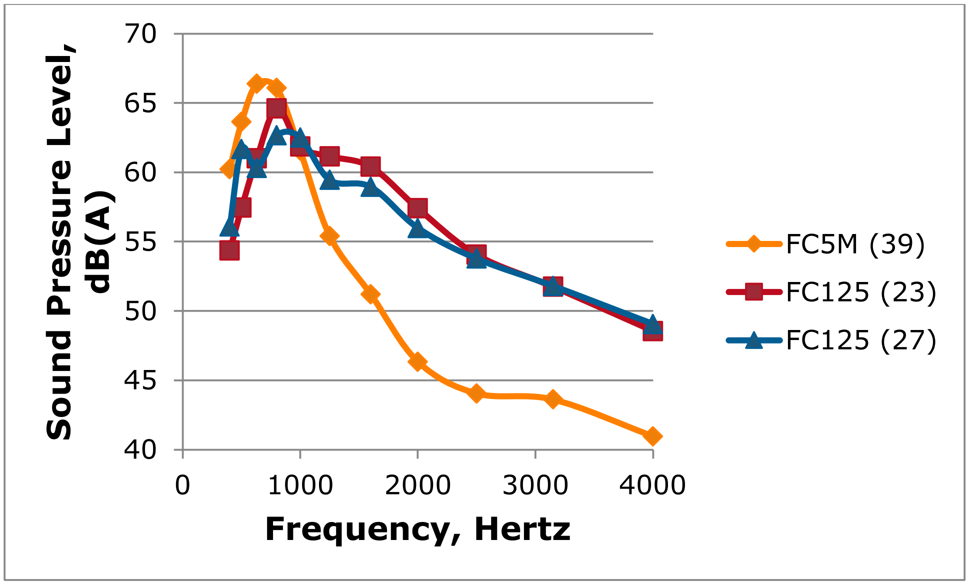


Figure 28. Comparison of Open Graded and Dense Graded Spectra at Wayside

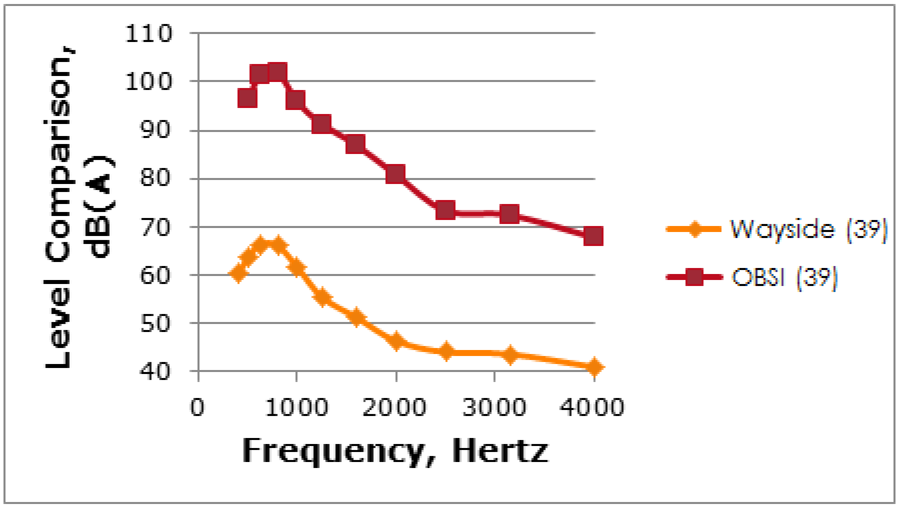


Figure 29. Comparison of Wayside to OBSI at Location 39 (Open Graded)

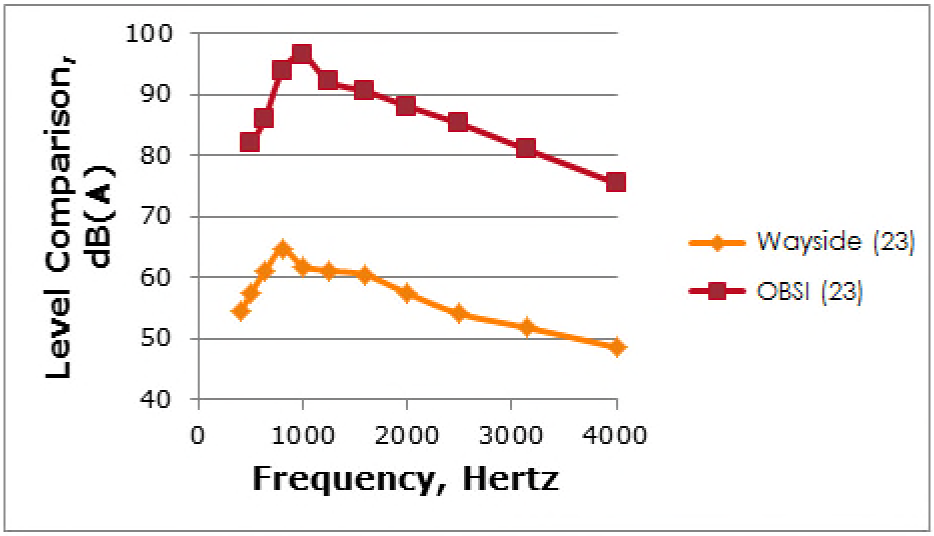


Figure 30. Comparison of Wayside to OBSI at Location 23 (Dense Graded)

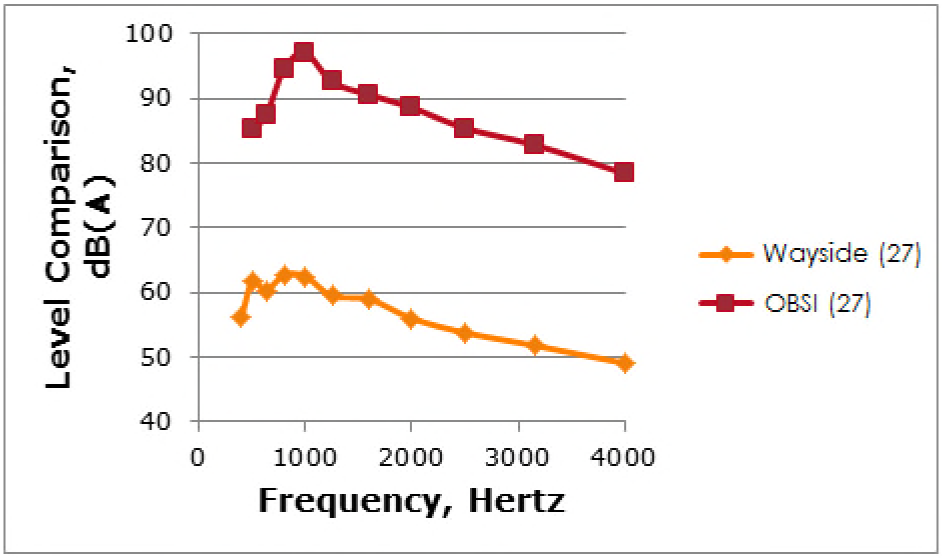


Figure 31. Comparison of Wayside to OBSI at Location 27, Dense Graded

In summary, the propagation path is significantly affected by the pavement surface resulting in a greater reduction along the path by the open graded pavement.

Multi-variant Analysis

Equation 2 provides a first order approximation of a way to predict the wayside sound pressure level at a defined location from the OBSI measured value. Refinement is needed in this however because with a possible error of 3.5 dB(A), hard decisions cannot be made. In Phase 1 it was hypothesized that some of the pavement testing could provide information that could serve as a surrogate for acoustic information to permit a transfer function to be created. Initial testing at that point using the friction number, mean profile depth, aggregate size, and the sand patch test led to some preliminary, but promising results. In Phase 2, the work of defining a methodology to compute why these differences occur and more accurately predict the wayside value was continued. The process is first defined and then the work summarized in this document.

In Figure 27 it was illustrated how a reflective wave interacts with the pavement surface. But we must also consider the direct path as well. Consider the two possible paths from a source (the tire/pavement) traveling to a receiver (wayside) as shown in Figure 32.

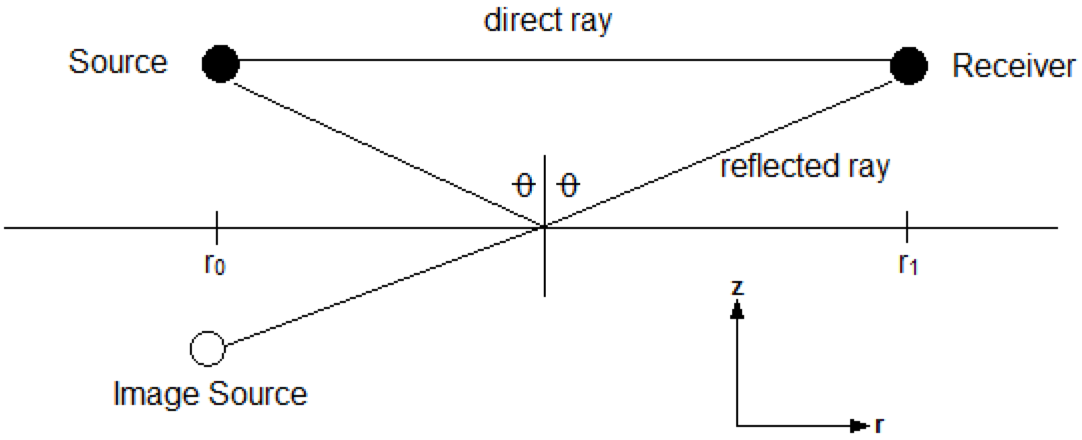


Figure 32. Direct and Reflected Path, Tire to Receiver

There would be a direct path and a reflected path as shown in the figure. Using a common approach, the reflected path can be visualized as a straight line propagation path from the image source to the receiver as shown. We can define the complex pressure amplitude, p_c, at the receiver by:

$$p_c = S\frac{\exp{(ikR_1)}}{R_1} + QS\frac{\exp{(ikR_2)}}{R_2} \qquad [3]$$

Where:

S = a constant for spherical wave turbulent phase fluctuation based on amplitude
k = wave number (the number of waves that exist over a specified distance)
R_1, R_2 = distance source to receiver and image source to receiver, respectively
Q = spherical wave reflection coefficient (relates amplitude of reflective wave)

In the measurements made for this project, the source location was at the center of a lane to a receiver 50 feet to the side and 5 feet above the pavement surface and the distances remain constant. While the wave number is frequency dependent, we will assume in this case we can have a single derived value for an overall A-weighted value. This results in all variables shown in Equation 3 to be constants with the exception of Q, the spherical wave reflection coefficient. This term would be a variable and determined by the pavement surface. Q, a complex number, can be computed from equation 4.

$$Q = 1 - 2\frac{k_1}{Z}\frac{R_2}{\exp{(ik_1R_2)}}\int_0^\infty \exp{(-\frac{qk_1}{Z})}\frac{\exp{(ik_1\sqrt{r^2+(z+z_s+iq)^2})}}{\sqrt{r^2+(z+z_s+iq)^2}}dq \qquad [4]$$

Where:
k_1 = the wave number above the surface
Z = specific acoustic impedance
q = tortuosity of porous media (the wave making many turns entering surface)
r = horizontal distance
z = receiver height
z_r = source height

While Equation 4 appears challenging, in reality once again all variable are constant in our situation with the exceptions of the specific acoustic impedance (Z) and the tortuosity of the pavement surface (q) if we continue to assume the wave number can be kept constant for an overall A-weighted case.

The equations could be solved, and the overall problem, if we had appropriate values for k_1, Z and q. But this comes from detailed acoustic testing and something not readily available. However, we are dealing with a grazing incidence ($\theta \cong \pi/2$). In this case R_2 >> Z + Z_s and taking the limit of $(Z+Z_s)/R_2$ we approach zero which could lead to a simplified solution but would still leave us short of the goal.

The specific acoustic impedance and the tortuosity of the porous media remain as our variables with the very large assumption of the wave number included. The tortuosity and the acoustic impedance are also related with:

$$Z = \sqrt{\frac{q_c}{\Omega}} \qquad [5]$$

Where:
q_c = a defined term where $q \equiv qc$
Ω = porosity of the surface

The tortuosity is also computed by:

$$q_c = \frac{c_s}{\Omega} + i\frac{\sigma}{\rho\omega} \qquad [6]$$

Where:
c_s = structure constant of porous media
σ = effective flow resistivity of surface
ρ = atmospheric acoustic density
ω = angular frequency

During data collection we accounted for the acoustic density and we have already made an assumption about the wave number which we also will assume for the angular frequency. This would imply that the difference in the values when OBSI is compared to wayside would be due to the structure constant (c_s), porosity (Ω), and the flow resistivity (σ) of the porous media (pavement surface). Because these variables are over a limited range in our situation, we can approximate with a constant value, which allows simplifying our analysis to:

$$p_c = C_1 + C_2(f(q)) \qquad [7]$$

Where:
C_1 and C_2 = constants
f(q) = function of tortuosity

The form of Equation 7 results in a regression line with the complex pressure amplitude being the dependent variable and the structure constant, porosity, and the flow resistivity of the porous media (pavement surface) being independent variables.

It is envisioned that these variables can in turn be related back to parameters listed in Table 13 adapted from Ulf Sandberg and Jerzy Ejsmont text[1] where the idea was originally presented in the Phase 1 report.

Working with the tremendous support of the State Materials Office in Gainesville, the authors obtained test data on pavements as previously shown (mix design, mix type, aggregate sizing, MPD, friction number, total binder content, binder type, geological type, and type modifier) were then used in a multi-variant analysis to see if the regression equation for tortuosity could be developed. This equation would provide the necessary transfer function to determine the wayside value to a more exacting prediction that the simple first order approximation based on a simple average difference cannot do.

To begin the process, individual parameters were reviewed using the wayside data. Graphical results are shown for MPD, friction number and aggregate size in Figures 33, 34 and 35. The sand patch tests and/or other void space values were not available and as such were not considered. The binder type and content was attempted to be used for flexibility but did not seem to show any trends. Consistency in the wear course thickness resulted in very similar numbers for all surfaces was not considered.

Table 13. Parameters with a Potential Influence on Tire/Pavement Noise (from the Tyre/Road Noise Reference Book)[1]

Parameter	Degree of Influence	Possible Pavement Testing as Surrogate Parameter*
Macrotexture	Very high	MPD, Aggregate Size
Megatexture	High	NA, As Roads in Good Condition
Microtexture	Low-moderate	Friction Number
Unevenness	Minor	Not Considered
Porosity	Very high	Void Content, Sand Patch Test
Thickness of layer	High, for porous surfaces	Wear Course Thickness
Adhesion (normal)	Low/moderate	Friction Number
Friction (tangent.)	See microtexture	Friction Number
Stiffness	Uncertain, moderate (?)	Binder Type and Content

*added by authors

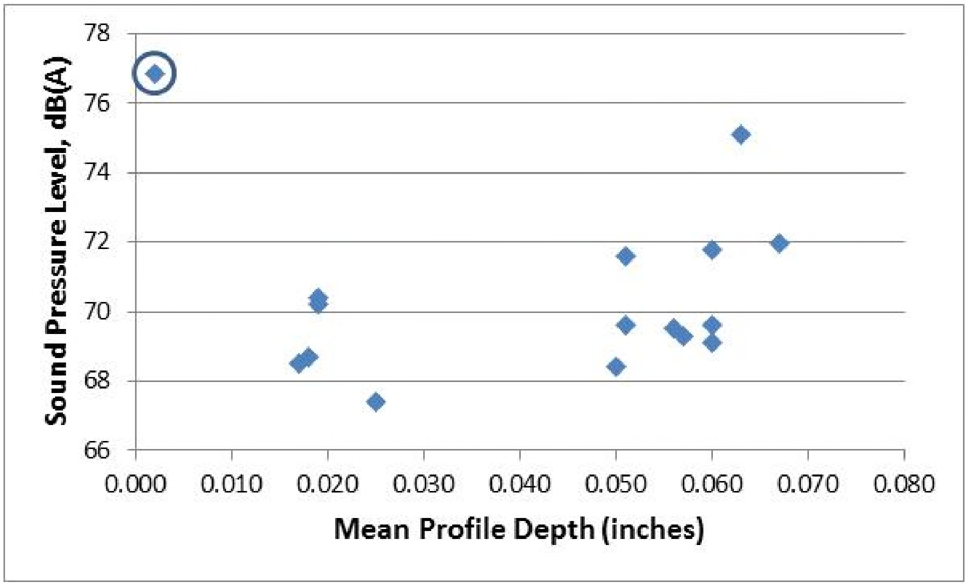


Figure 33. Mean Profile Depth Compared with Wayside Levels

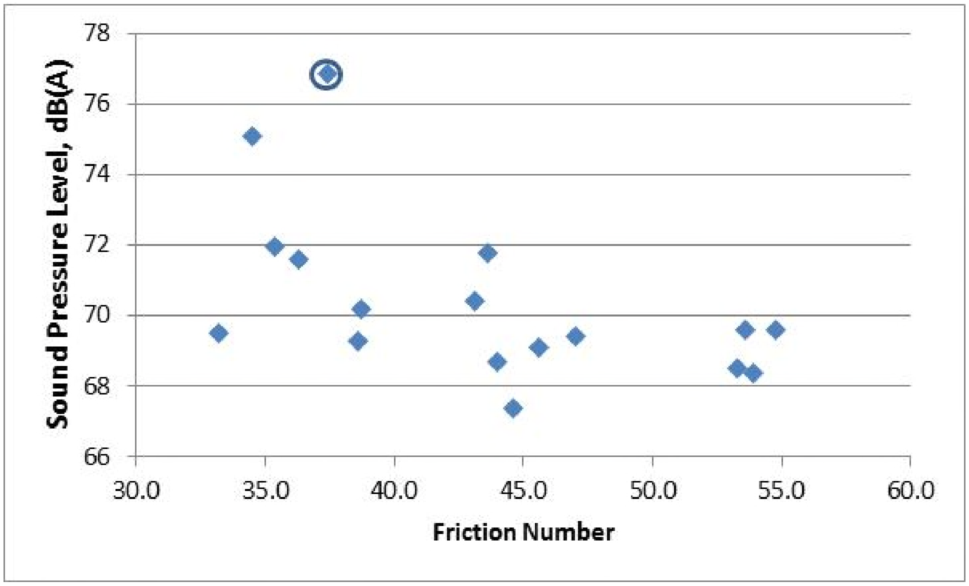


Figure 34. Friction Number Compared with Wayside Levels

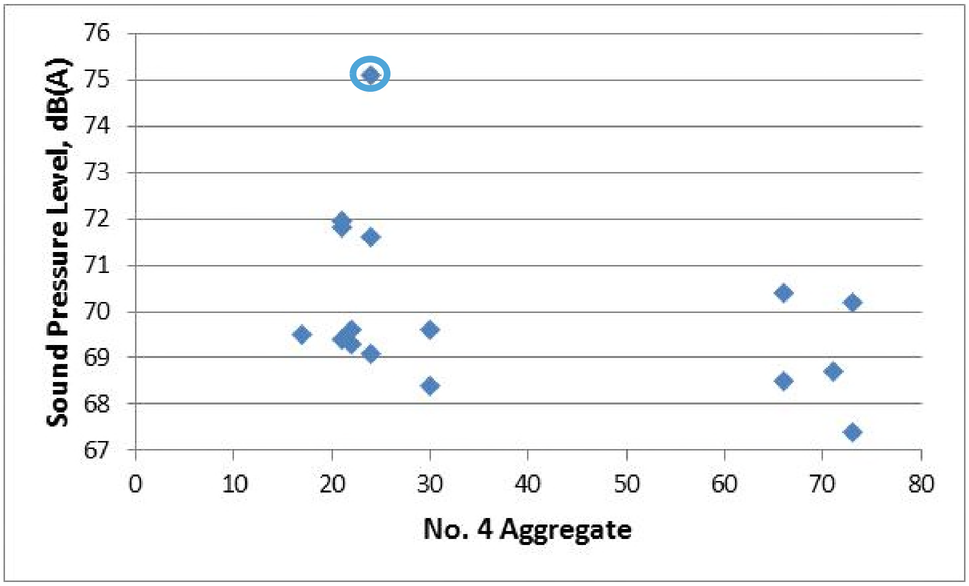


Figure 35. Aggregate Compared to Wayside Levels

In Figure 33 three groupings can be seen as would be expected. The circled value is a rigid pavement. Very low MPD but a high sound pressure level most likely due to the reflective wave. The other data falls into two groupings, dense and open graded pavements with the dense graded surfaces having the lower MPD. In these cases, less noise is generated at the tire/pavement interface as previously shown. The lower MPD results in a smoother macrotexture allowing for a more efficient reflective wave. Based on our ideas of tortuosity, the open graded surface allows more absorption of the reflective wave and with the higher MPD more scattering in the reflective resulting in sound pressure levels being similar at the wayside positions although generally a little higher at the tire/pavement interface as previously shown.

In Figure 34, the friction number is compared to the wayside results. Again, the rigid pavement value has been circled. While there is no trend by mix, it can be seen that there is a general trend for friction number and the sound levels with greater friction numbers resulting in lower sound pressure levels at the wayside. It can be assumed that this accounts for the microtexture parameter.

The results in Figure 35 for aggregate size show two groupings for the dense and open graded pavement as expected. Although many aggregate sizes were reviewed, Number 4 Aggregate was chosen because it appeared to be the most representative of change when reviewing the data. There is a trend for the smaller aggregate size to result in less noise at the wayside, due to less noise created at the tire/pavement interface as previously shown by the OBSI results for dense graded surfaces. This provides another surrogate for macrotexture. It should be noted that the x-axis in Figure 35 is based on the percent of aggregate passing a screen and as such, larger numbers for the No. 4 aggregate represent a greater percentage passing the screen and smaller aggregate. Again, the rigid pavement value has been circled.

Several models were tested for regression analysis relating the difference of Florida OBSI trailer intensity level in dB(A) by front/rear probe and combined to the wayside 50 foot position. The difference between the OBSI and wayside level has been previously shown and in this analysis has been referred to as the ‘delta’ value in this report. The delta value was considered to be the dependent variable while several independent variables were tested for significance as surrogates for the parameters of tortuosity. Table 14 contains the full list of variables assessed via the regression analysis. Of note is that effects of meteorology were taken into account to be sure refraction was not affecting the results. The analysis was conducted for all variables and multiple sub-sets of the variables.

Table 14. Regression Variables

Regression Variable	**Comment**
Friction number (FN)	
Texture (MPD)	
Wind direction	Wind direction, upwind, down, or crosswind
Wind speed 2 meters	Wind speed m/sec
Wind speed 5 meters	Wind speed m/sec
Mean(ribbed tire)	
Mean(smooth tire)	
Aggregate Sieve 10%	Aggregate size (mm)
Aggregate Sieve 50%	Aggregate size (mm)
Aggregate Sieve 90%	Aggregate size (mm)
Mean_rib*mean_smooth	Interaction term
FN*texture	Interaction term

The Statistical program “R” was used to perform the multi-variant regression analysis. R is a widely used statistical and graphical package that provides flexibility by allowing the user to customize analysis by simple programming methods. Tables summarizing the parameter estimate process and t-values/p-values for the datasets are listed in Appendix D. In some cases, a step-wise regression approach was used that started with a minimum model and added significant variables in a step fashion until the full parameter list was used, grossly insignificant variables are dropped in this process.

Key findings include that friction number, MPD, and aggregate size appear to be significant and while prediction error is greater than expected, hold hope. This led to a final model of:

$$\Delta = 32.57 + 0.0349(\mathrm{FN}) + 18.094(\mathrm{MPD}) - 0.0493(\mathrm{AG4}) \quad [8]$$

Where:

Δ = difference between OBSI and Wayside Level at REMEL location
FN = friction number average for ribbed tire
MPD = mean profile depth
AG4 = percent aggregate at No. 4 screen (4.74 mm)

Use of this transfer function results in over 70 percent of the results being explained with an R^2 value of 0.7328 and a residual standard error of 1.0 dB(A). This is a large reduction from the 3.5 dB(A) error from the simple first order approximation. Of note is that the F-statistic was equal to 9.143 on 3 and 10 degrees of freedom and the p-value was equal to 0.003248.

More is needed and some results were surprising. For example use of just the No. 4 aggregate value provides good results with a slightly less R^2 value (0.7086 but better p-value.

Rodeo

In Phase 1, part of the quality control was a single comparison to another researcher's established system. In Phase 2, an OBSI Rodeo was held by the FDOT on December 11, 2013. Teams are not listed here until further confirmation but results are reported in general, and a stand-alone report is reviewed by all. As such, teams will be referred to as A, B, C, and D where A is the Florida OBSI Trailer.

Four test sections were selected and are located on US-19 in Levy County, FL. Table 15 lists the details for the test sections. Each test section was approximately 0.8 mile in effective pavement length, whose start and end limits were clearly marked for the start and end of section, respectively. Wayside measurements were made at 50 feet (15 meters) from centerline of the test lane at 5 feet (1.5 meters) above the roadway surface. A meteorology station was also set up to make sure of the weather conditions at the location. All tests were performed according to TP 76-12 with one exception, a 10 second time duration was used.

Table 15. Test Sections Location (Northbound Passing Lane)

Road Name	Lane	BMP	EMP	Test Speed	Test Section	Section Name	Description
SR-24 (US-19)	R1	22.640	22.810	60 mph	1	FC-5M (PG 76-22) SPM 09-7225A	NB passing lane (R1) Wayside MP 22.725
		26.798	26.968	60 mph	2	FC-5M (PG 76-22) SPM 10-7850A	NB passing lane (R1) Wayside MP 26.883
		27.876	28.046	60 mph	3	FC-Q (ARB-12) LD 10-2631A	NB passing lane (R1) Wayside MP 27.961
		29.006	29.174	60 mph	4	FC-Q (PG 76-22) LD 10-2632A	NB passing lane (R1) Wayside MP 29.102

Figure 36presents the final results from the four test sections. As can be seen, the Florida OBSI test trailer was slightly higher than the other systems. While there is no absolute method to show accuracy of all systems, follow up testing with a newly created OBSI calibrator system showed Test Team B to be best match these results. If this is indeed the case, then the Florida system is approximately 1 dB(A) higher and this is the same amount was shown when the newly created calibration system was applied to the FDOT OBSI Trailer.

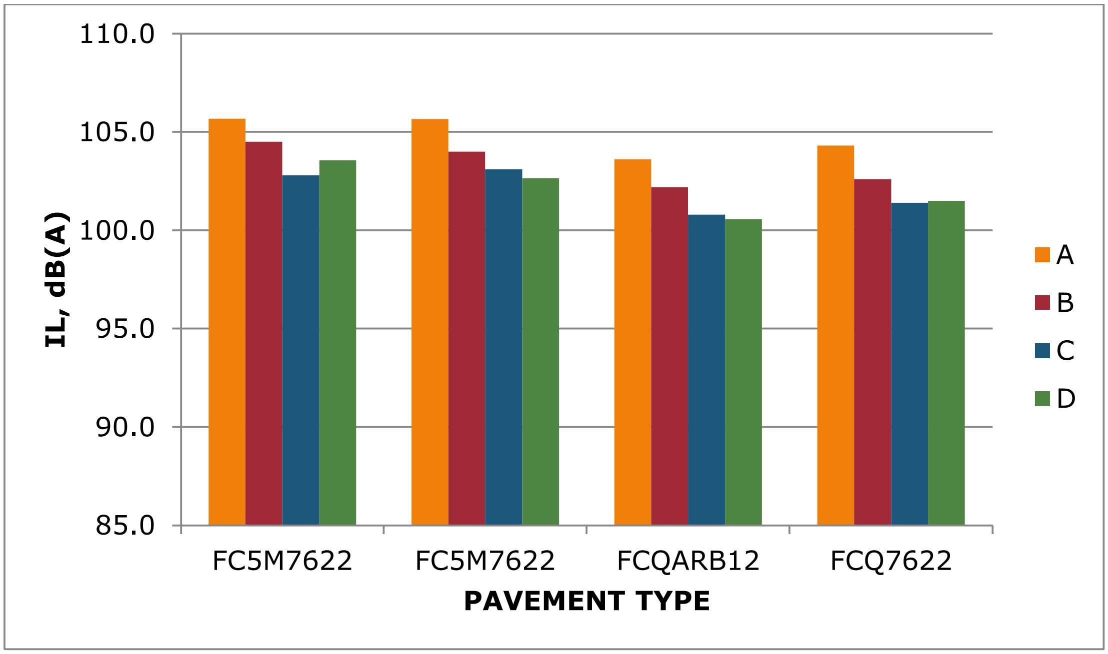


Figure 36. General Results of Rodeo

This analysis was taken further by assuming the surface texture designation FC5M76-22 test section is a reference pavement surface for Florida. Figure 37 shows the results when all are compared to the reference test section. This clearly shows that all systems would have rated the pavement surfaces the same way. It can be concluded that while we strive for absolute accuracy, pavement general ranking appear correct as the different systems respond in a like manner.

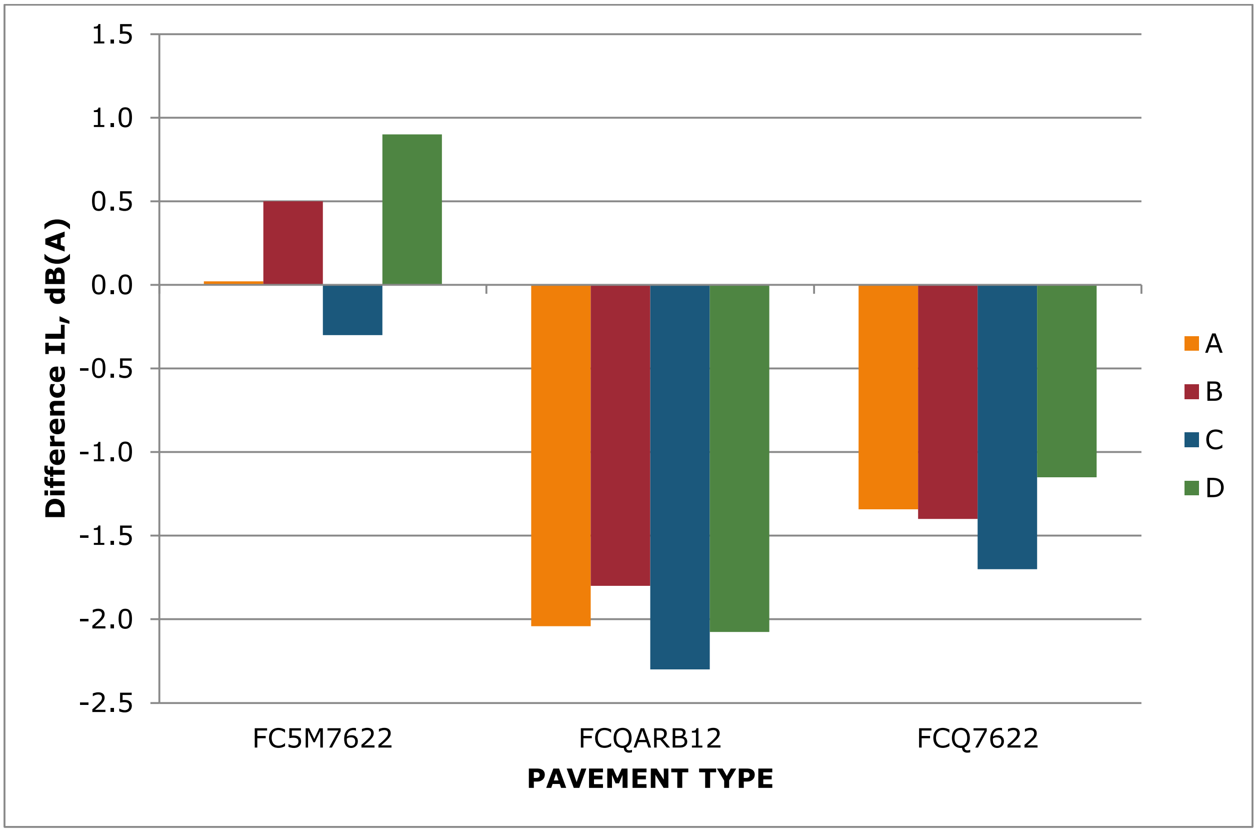


Figure 37. Results of Rodeo Comparing to the FC5M7622 Surface

CHAPTER 5. OBSERVATIONS AND CONCLUSIONS

Extensive testing and analysis has permitted some general conclusions to be drawn from this effort. These include:

- A final test rig design has been developed and thoroughly evaluated. It should provide service to the FDOT for many years.
- The FDOT Test Trailer has been greatly improved with multiple upgrades and again should provide service for many years.
- A solid methodology has been defined for collection and analysis of OBSI data. This has been turned into a guidance document attached to this report as Appendices A.1, A.2, and A.3.
- A tremendous data base of OBSI intensity levels, matched wayside sound pressure levels, meteorological data, and field notes has been established. While considerable analysis has occurred and is included in this report, much more work could be accomplished if resources were available.
- FDOT personnel have been trained on multiple occasions and should be able to collect quality data. However, much more detailed training may be necessary to start to understand the full acoustic concepts associated with this testing.
- A large number of surface textures (wear courses) have now been evaluated and ranked both at the source (tire/pavement interface) and at the wayside of the roadway.
- Flexible pavements appear to represent the quieter pavements in use in Florida.
- Three variables that seem significant in the pavement texture in terms of noise control are mean profile depth, aggregate size, and friction number. These variables were selected for analysis because of the general use in pavement design, availability, and are thought to act for surrogates of the acoustic parameters.
- Both the amplitude and frequency spectra were shown to be different based on the variables above.
- Rigid pavement (LGD), dense graded asphalt (FC125), and open graded asphalt (FC5 and FCQ) display distinctly different patterns in frequency spectra.
- The FC5 surface has a maximum (peak) at approximately 800 Hertz while the FC125 peak is about 1000 Hertz. The maximum peak is greater for the FC5, resulting in greater intensity levels at the tire/pavement interface.
- While the FC125 tend to have a linear falloff for the higher ranges, the FC5 surface has a noticeable dip over 2000 Hertz in the frequency spectra.
- The FCQ, which is essentially a FC5 surface, with different aggregate characteristics, follows the trends of the FC5 surface which would be expected.
- In Phase 1 an average difference of 32.2 dB(A) occurred when matched pairs of OBSI and wayside data were compared. The standard deviation was 2.5. This compares very favorably with results from Phase 2 where an difference of 32.5 dB(A) was measured with a standard deviation of 1.62.

- The difference or delta consistency allows a general first order approximate method to approximate wayside sound levels if OBSI measurements are made. This general first order approximation is:

  Wayside SPL [dB(A)] = OBSI Sound Intensity Level – 32.5

  The uncertainty is ± 3.5 dB(A) based on 2.15 standard deviations.

- The FC5 mixes resulted in the greatest decreases in the propagation path caused by the interaction with the pavement surface (the top three reductions and except for one glaring exception in the top half of rankings based on the noise difference of OBSI – Wayside). Dense graded pavements were not as effective. Rigid pavements were also not as effective.
- Similar sound levels for open and dense graded surfaces occur at the wayside even though greater intensity levels tend to occur at the tire/pavement interface for open graded surfaces. The dense graded mix (FC125) was generally in the bottom half of the rankings. LGD was surprising good and bad, being fourth and 16th out of 17 surfaces analyzed. Future designs may concentrate on the open graded mix due to safety concerns related to greater vehicle control that occurs.
- Measurement of pavement surface textures over a long span allowed the aging reduction of sound qualities to be quantified (~0.2 dB/year). However, values were very small and since the new test rig and test trailer were in use this needs to be further verified.
- A transfer function was derived that should improve the estimation process but more work, especially validation, is still needed to better quantify the propagation path effects from the various pavement surface textures. The final function was:

  $$\Delta = 32.57 + 0.0349(\mathrm{FN}) + 18.094(\mathrm{MPD}) - 0.0493(\mathrm{AG4})$$

  (R^2 = 0.7328) with a residual standard error of 1.0 dB(A)

  As defined within the text, Δ is the difference to be subtracted from the OBSI intensity level, FN is friction number, MPD is mean profile depth, and AG4 is an aggregate designation used in testing.
- The repeatability of the FDOT OBSI system, calculated from differences in multiple runs for the 95% confidence level, is 0.26 dB. Based on comparison to other systems during the FDOT “Rodeo”, an accuracy of approximately 1 dB can be expected.

In summary, this has project has been very successful. Some delays were experience but the authors wish to thank the Florida Material Lab for their support.

CHAPTER 6. RECOMMENDATIONS

This work has continued to advance the field of OBSI measurements and the FDOT OBSI Trailer is among one of the best systems in the county. It has the advantage of allowing repeatable measurements over long periods of time unlike car mounted systems. However the system measurement components are aging and consideration should be given to the two following purchase in order of need:

1. A newly developed OBSI Calibration System is now available. This is an upgrade to the calibrators now being used and purchase should be heavily considered.
2. While the current system is still functioning well, data reduction can be tedious. Consideration of a new analyzer system for a future purchase should be considered. Continued attendance at rodeos is also recommended.

A tremendous data base has been established. More complete analysis is needed. It should be noted that this is not a trivial exercise and will require considerable resources to completely analyze all of the near terabyte of data. Related to this analysis, six key analysis components are needed.

1. Additional surfaces that exist in Florida should be added to the database.
2. An analysis of the OBSI data with more pavement characteristics is needed. Especially lacking is some measure of porosity.
3. More analysis should occur on evaluating frequency spectra changes with changes in mix of the surface texture.
4. Efforts should be made to implement direct model inputs for highway noise analysis using the OBSI intensity levels.
5. The measurement efforts should continue to evaluate defined variables in mix and to provide a determination of the noise reduction that occurs with time.
6. Exact testing for effects on not only the overall sound level but frequency components should continue as started in this research.
7. The derived transfer function should be validated by additional data.

The next logical step is to use the data base and the findings of this report to develop future pavement mixes. These should be used as test sections for evaluation of the sound reduction produced. Maintaining correct aggregate size, use of open graded surfaces to allow high speed safety considerations over dense graded surfaces, and adaptation of binders to permit greater flexibility are ideas that should be taken forward.

The FDOT Materials Test Lab also has the ability for accelerated testing of pavement durability. This could be adapted to acoustic durability which at this time has a shorter time span than service life.

The FHWA Quiet Pavement Pilot Program effort has been started. This should be continued to allow FDOT to take advantage of quieter pavements in environmental documentation. This could lead to reduced abatement required such as shorter noise walls and even omission of noise walls in some cases.

Finally, work should be accomplished to further evaluate the use of common pavement test procedures such as friction testing, MPD, and aggregate sizing to acoustical testing such as effective flow resistivity, and effects as shown in Table 13 of this report.

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9. U.S. Department of Transportation, Traffic Noise Model; FHWA TNM, Version 2.5 Addendum, Federal Highway Administration, April, 2004.

10. International Organization for Standards (ISO), “Acoustics – Measurement of the influence of road surfaces on traffic noise – Part 1: Statistical Pass-By Method,” ISO Standard 11819-1:1997 Geneva, Switzerland, 1997.

11. Donavan, P.R., The Effect of Pavement Type on Low Speed Light Vehicle Noise Emission, SAE Technical Paper Series, SAE Noise and Vibration Conference and Exhibition, 2005.

APPENDIX A

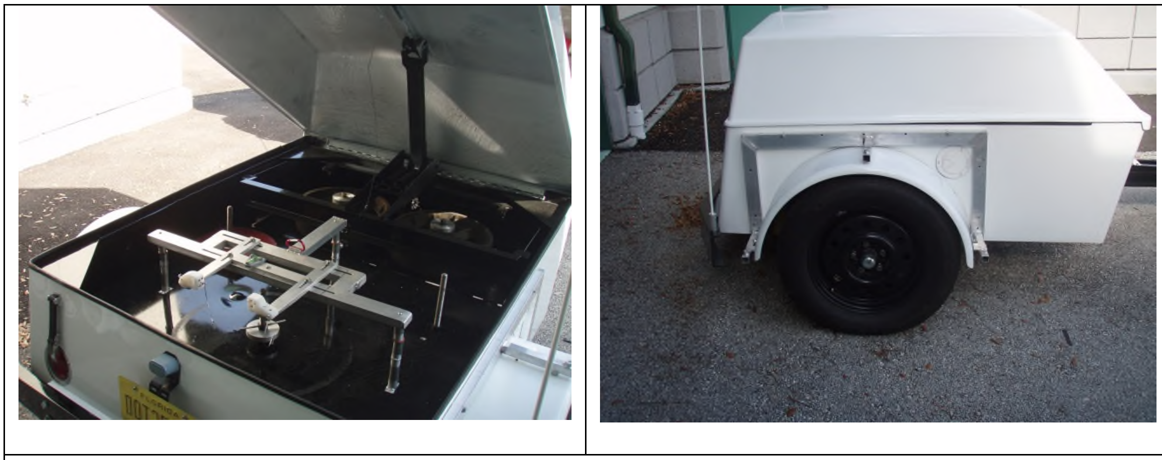
Measurement Procedures

Appendix A-1

OBSI Trailer Setup

Test Procedure (Hardware Installation and Setup)

The following is a detailed guide that has been developed to assist in a consistent measurement setup of the test trailer. Figure A.1.1 shows the test trailer and storage area within the trailer. Normally, the test tire would be also transported in this storage area in the mount provided under the test rig.



Intensity probe rig inside trailer (upper left)

Trailer without rigging (upper right)

Figure A.1.1. Test trailer and trailer storage area

- Remove spare tire from trailer and place inside truck bed.
- To match the weight of a normal passenger car wheel loading, no red weight should be in the trailer on the test tire side but a red weight should be included on the non-test driver side. The heavy steel wheels are in the rig (both sides). Note that the trailer has multiple weight configurations to load the test tire.
- Install the test tire onto the trailer (test tires have the TigerPaw SRTT labeling on them as shown in Figure A.1.2)
- Test tire pressure should be 30 psi when cold.

Figure A.1.2. Identifying test tire

- Install the intensity probe rigging onto trailer using the three leg mounts and secure via wing-nut set bolts (see Figure A.1.3), legs push all the way into the fender mount holders. Once pushed all the way in, the test rig is at the appropriate location that will be needed but will be verified later in the procedure. Note that the test rig is mounted to trailer with nylon washers for vibration control.

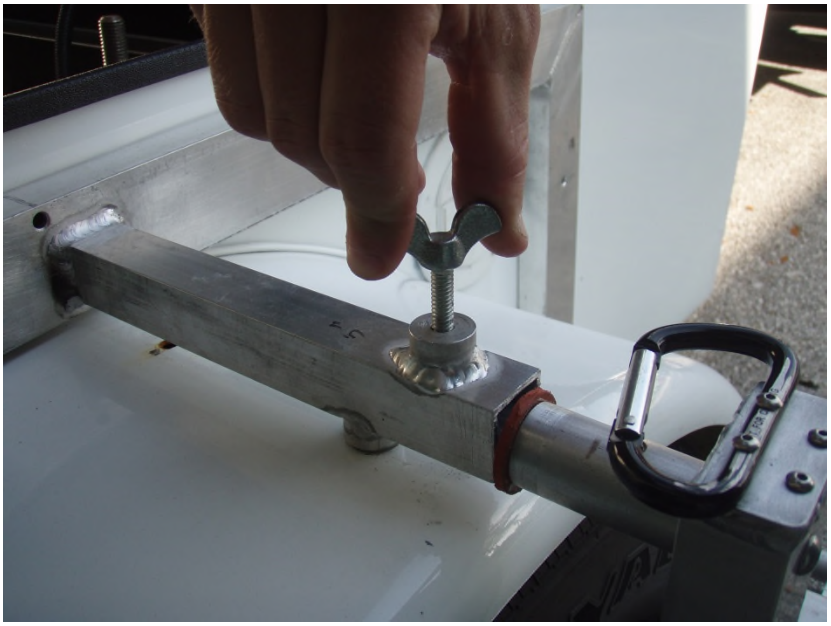


Figure A.1.3. Securing intensity rig to fender mounts with set bolts

Figure A.1.4 shows the test rig mounted.

Figure A.1.4. Test rig mounted to trailer

- Install Pimento analyzer into truck bed mount as shown in Figure A.1.5 in the left figure.

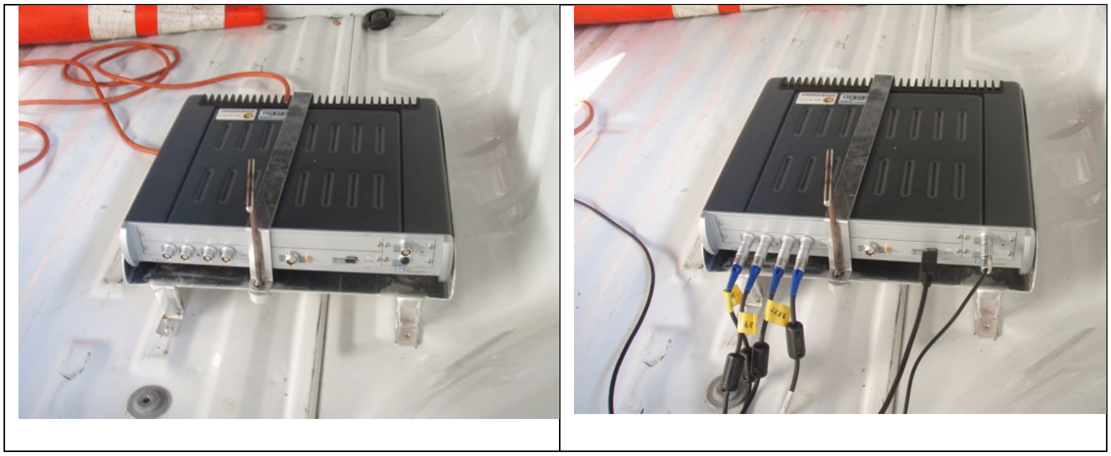


Figure A.1.5. Mounting of Pimento analyzer and cables

- Connect microphone cabling to Pimento (see Figure A.1.6) being careful to note the channel number on the cable ends and matching it to the number indicated on the back of the Pimento at the lemo connection points (be sure to match the red dot on the cable end to the red dot on the Pimento case, this aligns the connector properly and avoids damage)

	
Photo above shows the four channel connections on the back of the Pimento, black channel numbers can be seen printed on the case	Right side of Pimento showing the Firewire connection and power connector

Figure A.1.6. Connectors on the Pimento analyzer

- Route cabling and loom through trailer tongue body using the channel that contains signal light wiring harness (see Figure A.1.7). Continue to route the microphone cabling/loom thru the port on the front of the trailer then inside the trailer and out the port on the passenger side of the trailer.
- Microphone cabling thru carabineers and tied off with twist ties for security on rig to avoid flapping, unwanted noise, and possible damage.

Photos showing tongue with and without microphone cabling in place and routed through tongue channel and trailer port hole

Figure A.1.7. Cable routing on tongue of trailer

- Attach proper preamplifier/microphone combination to the cable ends using the following scheme (match the red dot on the cable end to the red dot on the preamp, this aligns the connector and preamp properly and avoids damage, see Figure A.1.8)

Figure A.1.8. Microphone/preamplifier assembly (left) and proper connection of cable (right)

Be sure the microphone/preamplifier setup is the correct channel. This is made easier by identifying by the serial numbers of the microphones and preamplifiers and relating to the Pimento channel. Table A.1.1 shows an example that was used for part of Phase 2. Note that the numbers will change as equipment is changed.

CH1 , front inside, SN 3828/1445	CH2, front outside, SN 3827/1434
CH4, rear inside, SN 4274/1448	CH3, rear outside, SN 4275/1444

Table A.1.1. Example of bookkeeping for correct cable attachment

- Route the firewire from the Pimento analyzer through truck bed port into cab of truck and connect to laptop. Start the laptop (note that truck must be kept running or power will be lost).
- Plug power cord for Pimento into inverter located in truck bed.
- Figure A.1.9 shows the cable setup for the Pimento.

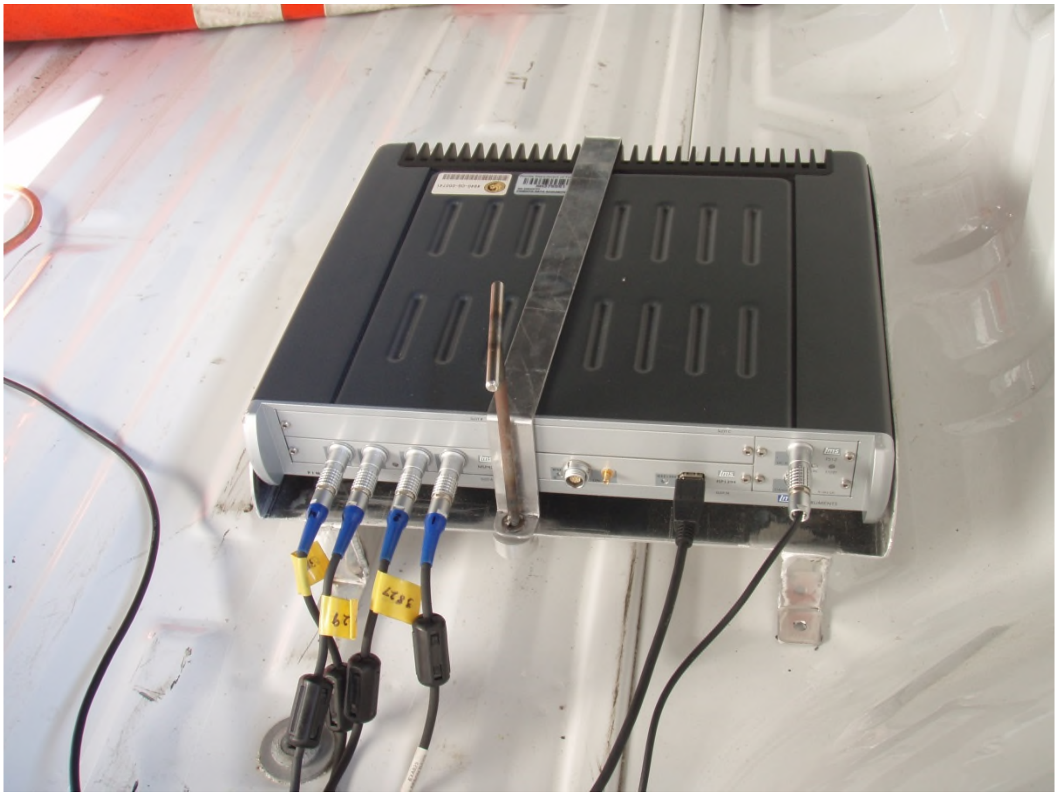
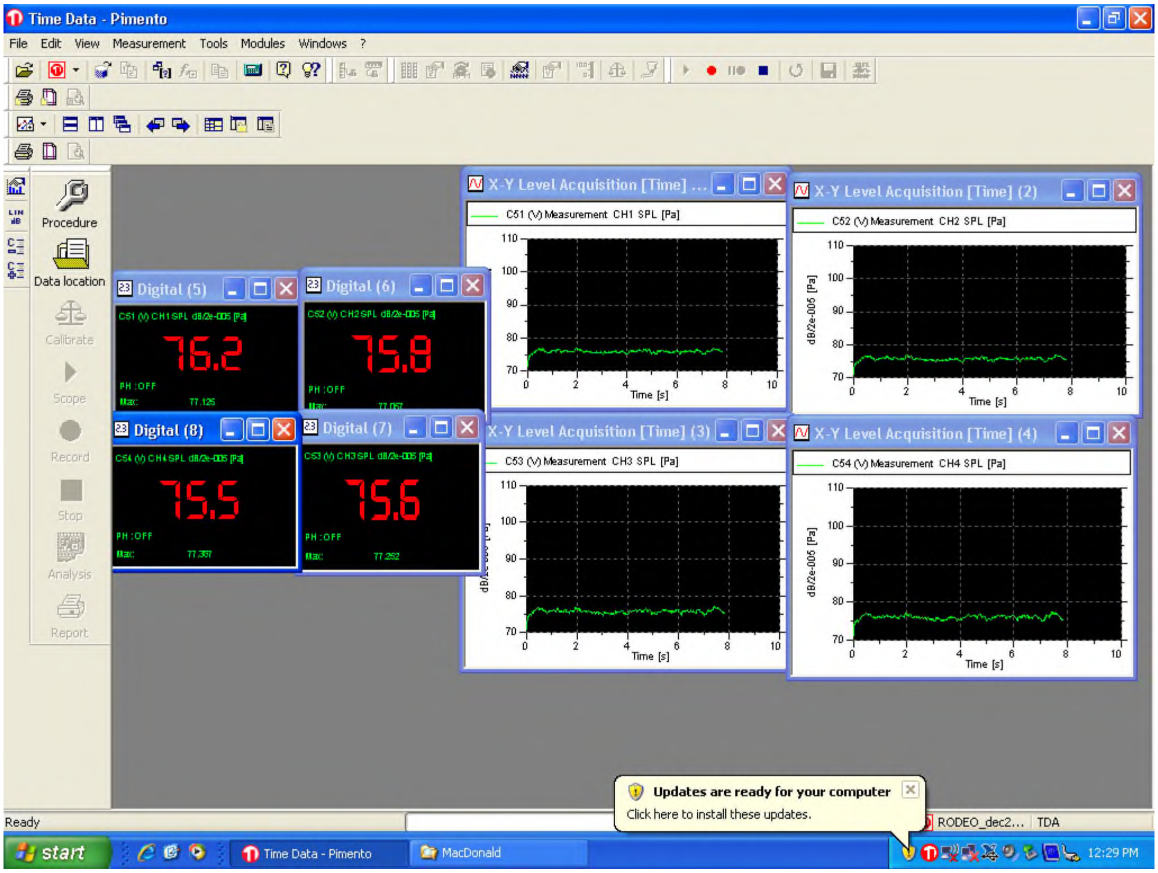


Figure A.1.9. Pimento showing four channel inputs, firewire, and power cable input (left to right)

Figure A.1.10 shows the important components that will be needed for the next steps.

Figure A.1.10. Microphone/preamplifiers (previously attached), neoprene inserts, allen wrench, calibrator, windscreens, windscreens, and probe location tool.

- Run extension cord from inverter into truck cab for laptop
- Start Pimento software using the laptop computer by choosing “Time History” data on initial startup screen
- Load the setup file located in c:\OBSI2, with the file name obsi2_setup.sta, making sure the setup screen appears as shown in Figure A.1.11. A signal is being read from all four channels (in the event that this formatted interface is not present, perform a File/Load Settings command to load the fdotobsi.sta file.

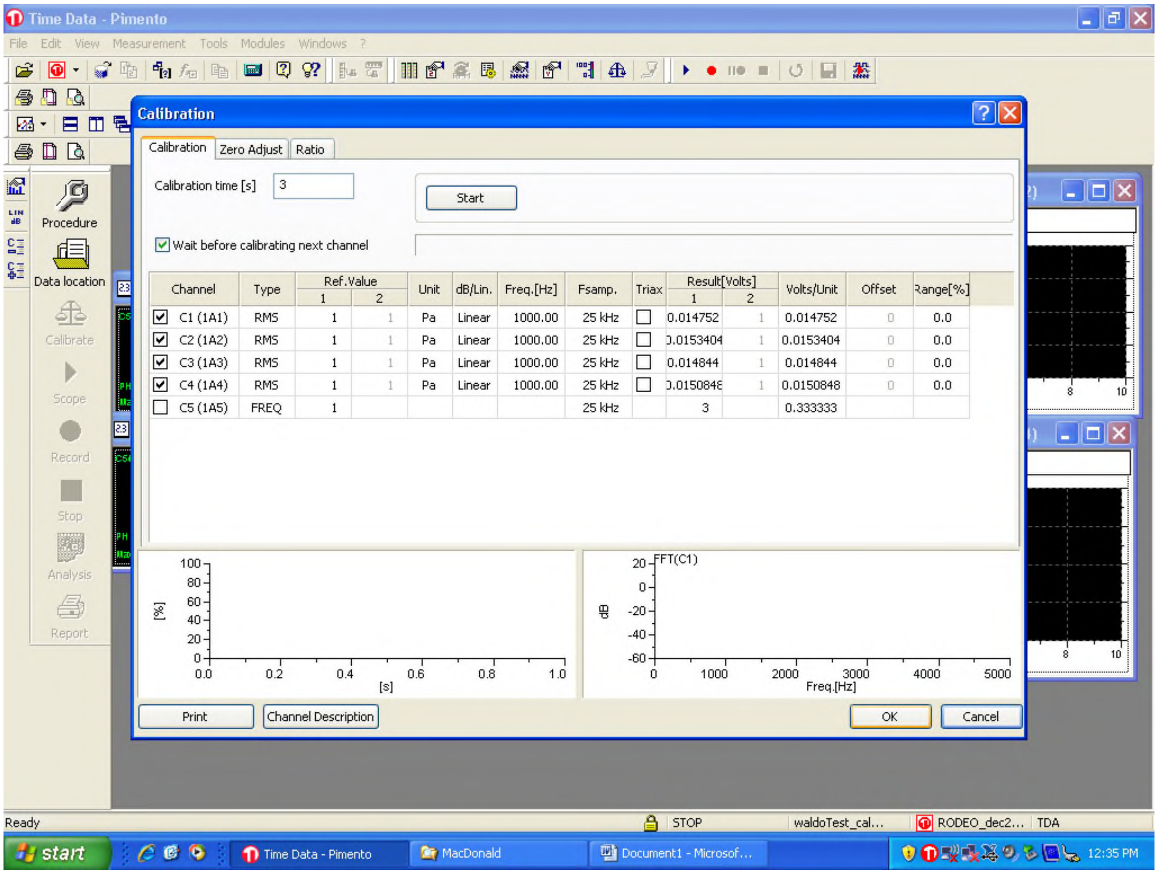


Updates are ready for your computer

Click here to install these updates.

Figure A.1.11. Start of calibration with screen showing all four channels related to each microphone

- Calibration of each channel of the system (microphone/preamplifier sets) must occur upon system start up, before beginning any test, and at the end of testing a pavement section.
- In the event of power loss or if any delay in testing occurs, perform a check of the calibration level of each channel.
- In Tools/Calibrate or using the “scales” button of the graphical interface, select the calibrate feature and the screen as shown in Figure A.1.12 appears.



Calibration time [s] 3

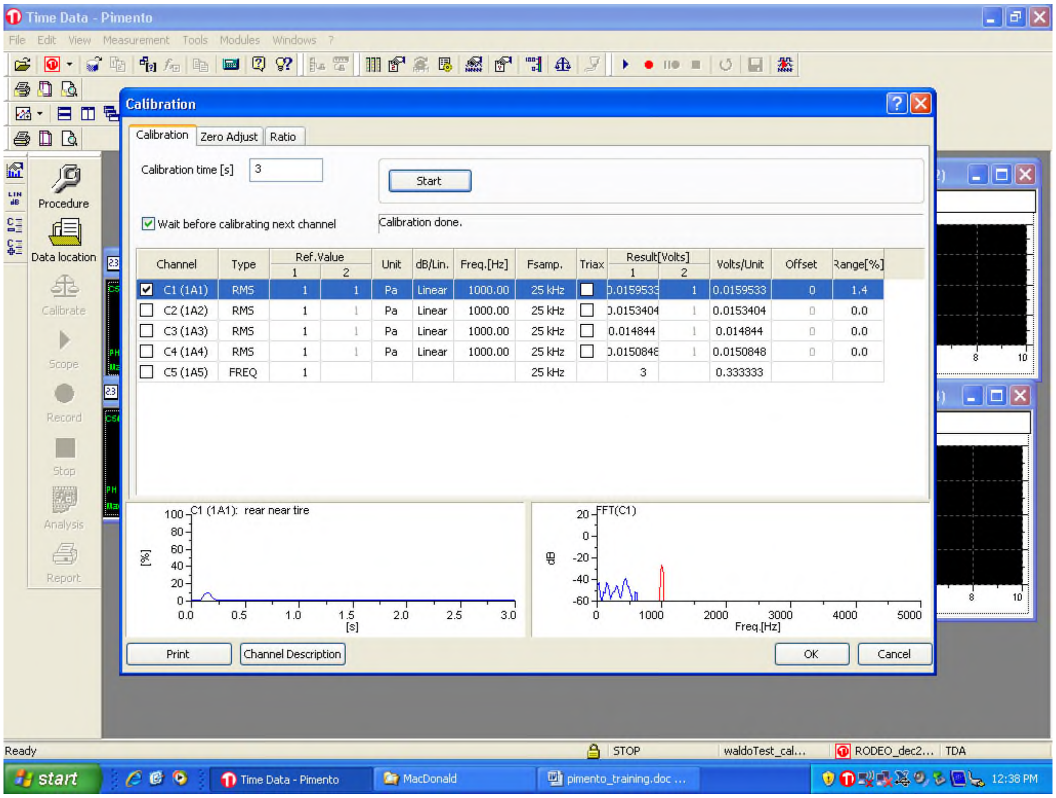
☑ Wait before calibrating next channel

Channel	Type	Ref.Value		Unit	dB/Lin.	Freq.[Hz]	Fsamp.	Triax	Result[Volts]		Volts/Unit	Offset	Range[%]
		1	2						1	2			
☑ C1 (1A1)	RMS	1	1	Pa	Linear	1000.00	25 kHz	☐	0.014752	1	0.014752	0	0.0
☑ C2 (1A2)	RMS	1	1	Pa	Linear	1000.00	25 kHz	☐	0.0153404	1	0.0153404	0	0.0
☑ C3 (1A3)	RMS	1	1	Pa	Linear	1000.00	25 kHz	☐	0.014844	1	0.014844	0	0.0
☑ C4 (1A4)	RMS	1	1	Pa	Linear	1000.00	25 kHz	☐	0.0150848	1	0.0150848	0	0.0
☐ C5 (1A5)	FREQ	1					25 kHz		3		0.333333		

Figure A.1.12. Example of interface screen to begin calibration

- Place the calibrator on the microphone/preamp of the desired channel as shown in Figure A.1.13. Make sure of the calibrator output (94 dB is typical).
- Begin the calibration mode for the four microphone channels by clicking the “scales” button on the toolbar Check the box in the calibrate screen that is next to the channel that you wish to calibrate, then click Start.
- A “spike” should appear on the frequency display chart at the bottom right of the calibration screen, the calibration will last for three seconds (important note: if calibrating alongside a busy roadway it is possible to perform an erroneous calibration if a loud truck or vehicle passes the trailer during the three second calibration).

Figure A.1.13. Sound pressure calibrator applied to end of microphone/preamp combination, a switch is visible that adjusts the calibrator from a 94 dB tone to a 114 dB tone, this is to be set to 94 dB



Calibration time [s] 3

☑ Wait before calibrating next channel

Calibration done.

Channel	Type	Ref.Value 1	Ref.Value 2	Unit	dB/Lin.	Freq.[Hz]	Fsamp.	Triax	Result[Volts] 1	Result[Volts] 2	Volts/Unit	Offset	Range[%]
☑ C1 (1A1)	RMS	1	1	Pa	Linear	1000.00	25 kHz	☐	0.0159533	1	0.0159533	0	1.4
☐ C2 (1A2)	RMS	1	1	Pa	Linear	1000.00	25 kHz	☐	0.0153404	1	0.0153404	0	0.0
☐ C3 (1A3)	RMS	1	1	Pa	Linear	1000.00	25 kHz	☐	0.014844	1	0.014844	0	0.0
☐ C4 (1A4)	RMS	1	1	Pa	Linear	1000.00	25 kHz	☐	0.0150848	1	0.0150848	0	0.0
☐ C5 (1A5)	FREQ	1					25 kHz		3		0.333333		

C1 (1A1): rear near tire

FFT(C1)

Ready | STOP | waldoTest_cal... | RODEO_dec2... | TDA

Figure A.1.14. Example showing “spike” indicating calibration signal in the bottom right graph

- If no spike occurs the calibrator may have shut off, the calibrator may be placed on a different channel, or the cable connections are incorrect.
- At the conclusion of the three second calibration, exit out of the calibration screen and verify the incoming sound pressure level (94 dB), again making sure that the calibrator has not timed out.
- The value should appear as shown in Figure A.1.15 for the selected channel with a value between 93.9 dB and 94.1 dB. If outside this range, go back into the calibration graphical interface and repeat the calibration procedure for the desired channel.

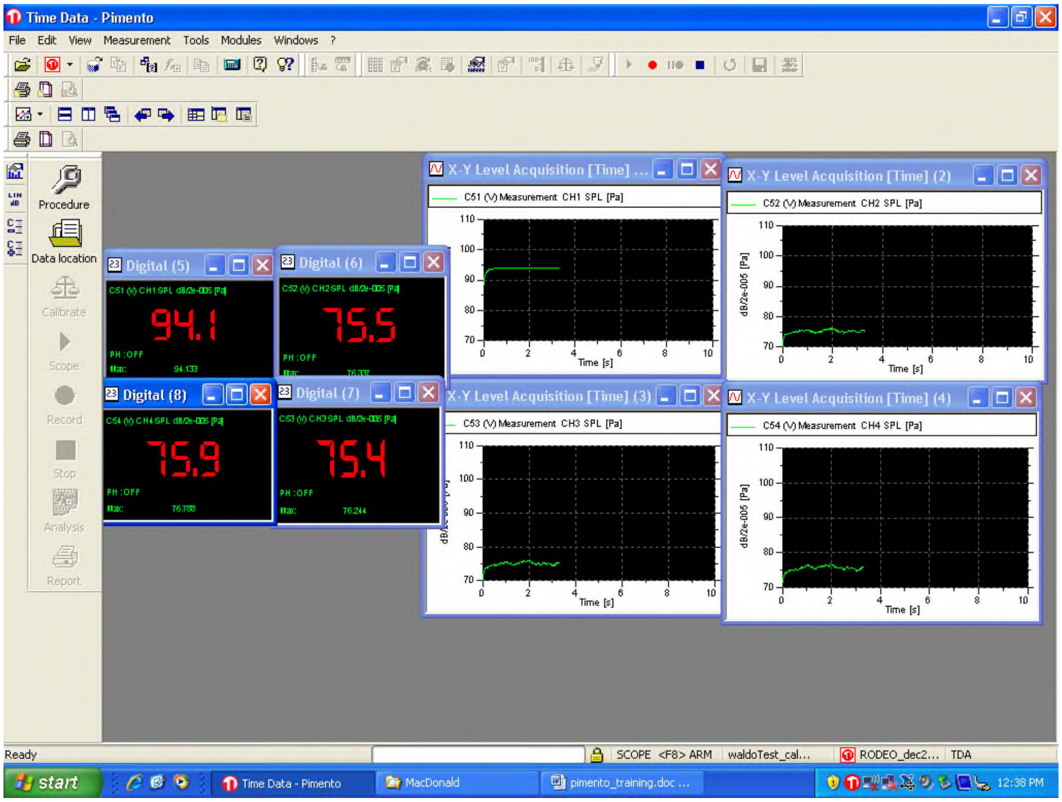


Figure A.1.15. Example of correct reading (94.1 dB) for channel 1

- Record in the field log book the time of calibration and the incoming sound pressure level when the calibrator is applied and the channel number
- Once you are satisfied that the channel is calibrated move the calibrator to the next channel and repeat this process for all channels.
- Record all calibration levels in the field log book along with date, time and test location
- On a regular basis, run the PRI procedure at this time. Refer to the user manual for the detailed instructions.

- Correct microphone positions are as shown below with forward motion of trailer toward top of the page

- ^ CH1 CH2
  |

  | CH4 CH3

- Carefully place the microphone/preamplifiers into the nylon mounting bracket (see Figure A.1.16)

Figure A.1.16. Nylon mounting brackets for the microphone/preamplifier assembly