University of Central Florida

Pavement Noise Research

Modeling of Quieter Pavements in Florida

FDOT Project No. #BD550/RPWO#09

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FINAL REPORT

Roger L. Wayson, Ph.D., P.E.

John M. MacDonald, Ph.D., P.E.

Anjoli Martin, M.S., E.I.T

University of Central Florida

Civil & Environmental Engineering

P.O. Box 162450

Orlando, Florida 32816-2450

Tel: 830 693-0801

Fax: 407 823-3315

Email: wayson@mail.ucf.edu

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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation.

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)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

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)[11]

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

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 of 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 centre 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 of 0.5 m to 50 m, corresponding to wavelengths with one-third-octave bands including the range 0.63 m to 50 m of centre 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

The research on noise created by the tire/pavement interface, while relatively new, has seen considerable interest over the past few years because of the potential benefits and a general desire by the public for quieter highways. The Florida Department of Transportation (FDOT) uses many different pavement mixes based on performance testing. Performance testing for the sound generation from the roadways has been accomplished in the past using wayside measurements. The primary reason for this research was to investigate the sound (noise) generation caused by the tire/pavement interface, how it relates to the wayside noise, the trends related to the various pavement types measured, and explore modeling possibilities. Trends for future modeling were identified and evaluated. This report describes the equipment used, the collection of data, the analysis, and presents conclusions for both the on-board sound intensity (OBSI) method and concurrent wayside sound level measurements for multiple pavement types in Florida. The work was conducted in the State of Florida at 18 different locations with some locations repeated for quality control purposes.

17. Key Word	18. Distribution Statement
On-board sound intensity, OBSI, sound, intensity, wayside, noise, pavement, tire/pavement	No restrictions.

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EXECUTIVE SUMMARY

The research on noise created by the tire/pavement interface, while relatively new, has seen considerable interest over the past few years because of the potential benefits and a general desire by the public for quieter highways. Recent documents have described the sound generation mechanisms and the benefits possible from the design of pavements to reduce the tire/pavement noise including work by the authors of this report. These documents have defined three important components to the highway design process which also relate to the design of quieter pavements. These components are safety, durability, and environmental effects. For safety, the component most relevant to noise generation is the surface friction. Durability can also be thought of as pertaining to both physical and acoustic durability. The environmental effect considered in this document is the highway noise. All three components are considered in this report with the emphasis being placed on the noise created by the tire/pavement interface.

The Florida Department of Transportation (FDOT) uses many different pavement mixes based on performance testing. Areas of testing encompass the three components of highway design with the sound generation having been accomplished in the past using wayside measurements. One new area of testing now being considered, and the primary reason for this research, is the sound (noise) generation caused by the tire/pavement interface and the trends related to the various pavement types measured. Trends could be used during modeling in the future if adequately defined. To this end, the FDOT contracted the University of Central Florida (UCF) to investigate roadways in Florida.

This report describes an investigation of on-board sound intensity (OBSI) and concurrent wayside sound levels generated by the vehicles on the roadway. The work was conducted in the State of Florida at 18 different locations with some locations repeated from February 2008 to June 2009. The objectives of the work were the following:

- to investigate the sound intensity levels generated by different surfaces in Florida
- to rank existing pavement types in Florida and determine if certain pavements are quieter than others
- to investigate and attempt to correlate these intensity levels with vehicle wayside (passby) sound pressure levels

- to evaluate pavement properties in relation to generated sound levels
- to eventually lead to the possibility of pavement type as a mitigation method for Florida working with the Federal Highway Administration (FHWA) in the Quiet Pavement Pilot Program

The objectives of the project have all been met or exceeded except one. The last goal which is “to eventually lead to the possibility of pavement type as a mitigation method working with the Federal Highway Administration (FHWA) in the Quiet Pavement Pilot Program” is as stated an on-going task that will require additional measurements over time. FHWA has not established quiet pavements as a mitigation measure at the current time. Only states with significant data over multiple years are allowed any adjustments during modeling. However, this effort successfully begins the FDOT’s Quiet Pavement Pilot Program a goal of a Florida adjustment allowed based on continued measurements.

Other applicable conclusions from this effort include the following:

- A working trailer based system has been developed for on-board sound intensity (OBSI) measurements in Florida. This system, being trailer based, should provide continuity for continued measurements. It is recommended that the prototype design for the test rig (sound intensity probe mount) be further developed based on the experience now gained.
- A methodology for data collection using the OBSI equipment has been established and can be continued following guidelines for standard testing now in draft form.
- 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 have been formed for Florida highways. This work should continue to further develop this data base. Specific surfaces such as the friction course (FC-5) pavements and the differences in pavement characteristics causing changes in generated sound levels should be reviewed.
- Multiple pavement textures/types used in Florida have been ranked by both the sound generated at the tire/pavement interface using the OBSI method as well as at the wayside.
- For the two Portland Cement Concrete (PCC) pavements measured, 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 for reducing noise in the propagation path (difference between OBSI and wayside levels) but where also 3 of the 4 surfaces with less reductions. Understanding why this occurred is paramount to the overall goals of FDOT.

- 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) has been determined. This difference provides 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 is needed 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) tend 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. But more measurements are needed to better quantify this relationship for the micro and macrotextures the variables represent. The relationship between the textures and these key characteristics should 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 tends to indicate a strong possibility for future modeling of wayside sound levels based on OBSI testing. However, as noted by other researchers, this should not be considered a simple task even though the preliminary results are quite encouraging.
- Frequency differences in the spectra between the OBSI measurements and the wayside measurements should be 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 is needed.
- A comparison of the equipment used for the OBSI to that of Donavan gave very similar results, tending to prove the validity of the data and the system. More comparison to other state equipment is needed to allow a comparison of the Florida data to those states.
- 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.
- All future testing should follow the OBSI standard method now in development.

Possible action items are also included. First, work should occur jointly between the noise analyst and the pavements group to further populate the pavement parameters in the data base allowing additional analysis. Second, participation in testing to compare the Florida test trailer to other state equipment should be done. This will not only validate the data but allow comparison of data collected from state-to-state. Third, measurements should continue with new locations and revisiting some locations for specific parameter characterization to determine how levels change over time as required by the FHWA Quiet Pavement Pilot Program. These measurements should also look at the effects of grinding, overlays, and changes in mix and/or texture by using different measurable pavement parameters for various pavement types used in Florida. Fourth, correspondence with the FHWA should be continued to continue the Quiet Pavement Pilot Program with the goal of modeling adjustments being allowed in the Traffic Noise Model (TNM) required by FHWA.

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CHAPTER 1. INTRODUCTION

The research on noise created by the tire/pavement interface, while relatively new, has seen considerable interest over the past few years because of the potential benefits and a general desire by the public for quieter highways. A description of the sound generation mechanisms from tire/pavement noise are included in a comprehensive document designed especially for highway planners and engineers.[1] That document provides details not included in the present report.

A synthesis[2] produced by the Transportation Research Board (TRB) of the known relative information was published in 1998 which pointed out that there are three important components to the highway design; safety, durability, and environmental effects. For safety, the component most relevant to noise generation is the surface friction. Durability can also be thought of as pertaining to both physical and acoustic durability. The environmental effect considered in this document is the highway noise. All three topics are considered in this report but the emphasis is placed on the noise created by the tire/pavement interface.

The Florida Department of Transportation (FDOT) uses many different pavement mixes based on performance testing. Areas of testing encompass the three components of highway design with the sound generation having been accomplished in the past using wayside measurements. One new area of testing now being considered, and the primary reason for this research, is the sound (noise) generation caused by the tire/pavement interface and the trends related to the various pavement types measured. To this end, the FDOT contracted the University of Central Florida (UCF) to investigate this topic in Florida.

This report describes an investigation of on-board sound intensity (OBSI) and concurrent wayside sound levels generated by the tire/pavement interaction of moving traffic. The work was conducted in the state of Florida at 18 different locations with some repeated for quality control purposes. The objectives of the work were the following:

- to investigate the sound intensity levels generated by different surfaces in Florida
- to rank existing pavement types in Florida and determine if certain pavements are quieter than others
- to investigate and attempt to correlate these intensity levels with vehicle wayside (passby) sound pressure levels
- to evaluate pavement properties in relation to generated sound levels

- to eventually lead to the possibility of pavement type as a mitigation method working with the Federal Highway Administration (FHWA) in the Quiet Pavement Pilot Program

The conventional measurement methodology, which is typically used in Florida, is to measure sound pressure levels along the highway. The wayside measurements are simpler to conduct than on-board intensity measurements but in general are more time consuming and require open space along the roadway. This research will explore if the OBSI technique could be utilized in the future to replace passby measurements by use of modeling techniques.

CHAPTER 2. PREVIOUS RESEARCH EFFORTS

The 1998 TRB synthesis presented a comprehensive review of findings by researchers at that time. These reported findings included the following:

- No significant correlation between wayside measurements and measurements at the tire interface
- The most used methodology at that time for tire/pavement sound measurements was the close proximity method (CPX)[3] which was later updated and reported sound pressure levels[4]
- Many of the measurements, and most in Europe, were done using special trailer designs
- Portland Cement Concrete (PCC) pavements, while having better durability and superior surface friction compared to dense graded asphalt, in general were reported to create more noise along the roadway
- Evenly spaced traverse tining led to the greatest noise impacts with tining spaced over 1 inch (26 mm) creating annoying tones
- Noise reduction for transverse tining included texture depth, tine spacing, construction techniques, surface texturing, and aggregate size
- Longitudinal tining resulted in a smaller noise impact but reduced surface friction as well
- Exposed aggregate PCC was reported to provide “better noise quality characteristics”
- Though problematic in use, porous concrete also offered additional noise abatement
- Dense graded asphalt was generally 2 to 3 dB(A) quieter than PCC with an even greater difference when compared to transversely tined PCC pavements (The term dB(A) is the abbreviation for the units of measure for sound, decibels where the (A) indicates it has been frequency weighted to approximate the way the human ear perceives the sound)
- Open graded asphalt seemed to provide the most noise benefit for wayside noise but the acoustic durability diminished with time with benefits occurring for approximately 5 to 7 years
- Open graded asphalt also had similar problems to porous concrete including plugging and a loss of acoustic benefits
- Stone mastic (asphalt surface with a high percentage of larger exposed aggregate) and rubberized asphalt (more than just the binder) also seemed to provide acoustic benefits

At the time of the synthesis, which remains in effect, the FHWA policy is that a small amount of noise reduction is not worth sacrificing safety or durability. This requires pavement characteristics such as friction number to be important in the overall analysis. Friction number is a measure of the microtexture and should be evaluated during investigations for noise reductions. This is done in this report.

A survey was also sent to states as part of the synthesis work. It was found that most states would consider changing pavement types for noise abatement and the three areas considered most important for noise abatement were surface texture, speed, and tire tread.

Work performed since 1998 has generated additional observations, the more significant of which include the following:

- Some reports indicate a constant offset from the measured tire/pavement sound to the wayside sound[5]
- One of the greatest changes has been a shift from sound pressure to sound intensity measurements. On-board Sound Intensity measurements (OBSI) came out of work beginning at General Motors[6,7] and has continued to be adapted to perform in-situ tire/pavement measurements[8]
- CPX measurements have continued with two of the more significant studies in the U.S. being referenced for the interested reader[9,10]
- Continued characterization of the sound requires more emphasis on pavement texture parameters such as air void space, aggregate size, mean profile depth, the type of surface texturing used, and changes with age[11]

The last bullet above includes measurable parameters of surface features that are important components of the noise generation process. Ulf Sandberg and Jerzy Ejsmont, long time researchers in the area of tire/pavement noise, put together a definitive text on the subject.[11] In this text, the authors also define the key surface features in more general terms than as above. This information is presented in Table 1.

Table 1. Parameters with a Potential Influence on Tire/Pavement Noise (from the Tyre/Road Noise Reference Book)[11]

Parameter	Degree of Influence
Macrotexture	Very high
Megatexture	High
Microtexture	Low-moderate
Unevenness	Minor
Porosity	Very high
Thickness of layer	High, for porous surfaces
Adhesion (normal)	Low/moderate
Friction (tangent.)	See microtexture

Stiffness	Uncertain, moderate (?)

The parameters shown in Table 1 are general features related to the noise generation that may be quantified using available measurement techniques. The last bullet in the preceding discussion listed some of these measurement techniques. Sandberg and Ejsmont are quick to point out in their book[11] that "…there is no simple and general relation between the overall noise level and texture." He continues on to demonstrate this fact with measured values of noise levels compared to the mean profile depth, a measure of macrotexture. Since the macrotexture has a "Very high" listing as far as degree of influence (see Table 1) one would expect a very good correlation between noise generation and mean profile depth. But while there was a general trend shown by Sandberg and Ejsmont, large deviations occurred and there was "…poor correlation between macrotexture (as represented by the Mean Profile Depth)." This indicates that the parameters affecting noise generation may not be fully characterized by a single measurement technique but may require a combination of measurement techniques.

One point alluded to earlier was the relationship between the wayside sound (noise) and noise at the tire interface. This comparison is very important since the noise along the highway is the important location since this is where the public is located. The noise propagation path, from the tire to the side of the road, has a direct effect on the energy finally arriving at the side of the road and observed by highway neighbors. This makes the effects of the pavement on the propagation path an important parameter as well and is related to the characteristics of the surface.

The important characteristics relating to the propagation path are not necessarily the same as those of the tire/pavement parameters. The propagation parameters occur after the initial noise has been created and controls how the sound wave interacts with the pavement. If some of the sound energy can actually enter the surface and turn to heat (absorption) then the sound pressure at the side of the road will be less. As such, characteristics such as porosity and surface texture depth become important propagation factors. If the surface is very smooth, the wave will be more effectively reflected to the side of the highway. This makes surface texture an important characteristic in regards to the noise propagation.

CHAPTER 3. METHODOLOGY

Measurement in close proximity to the tire has been done in many countries and continents. As previously discussed, the first methods and the only accepted standard methodology at the time of the writing of this report, is for Sound Pressure Level (SPL). SPL has been measured using the close proximity method (CPX). 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. Figure 1 illustrates the defined positions of microphones for the CPX method.

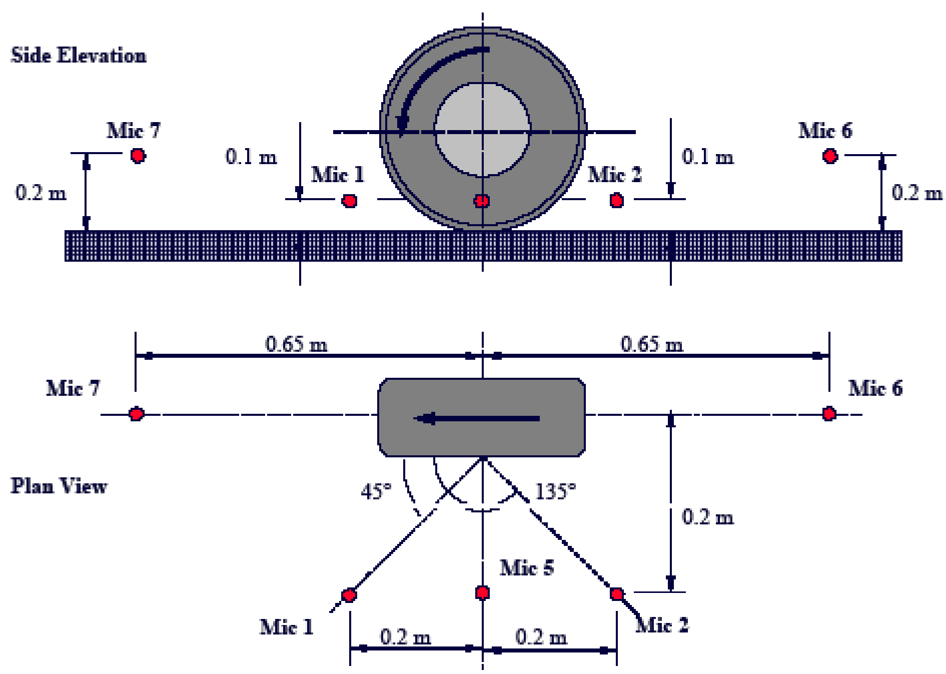


Figure 1. Mandatory and Optional Microphone Locations for the ISO CPX Standard Procedure[4] (note: 1 meter = 3.28 feet)

The problem of nearby sounds, such as traffic, requires SPL measurements to be made without other nearby traffic or in specially designed trailers with acoustic treatment to avoid measurement error. These requirements to avoid errors can be mostly eliminated by the use of sound intensity.

The sound intensity, I, (or acoustic intensity) is defined as the sound power P_{ac} per unit area A. For instantaneous acoustic pressure $p_{\text{inst}}(t)$ and particle velocity $\boldsymbol{v}(t)$ the average acoustic intensity during time T is given by:

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

Of note in this equation is that the intensity, I, is measured at a point and represents the time-averaged rate of energy flow per unit area. As such, sound intensity has a defined direction as indicated by the velocity term.

Because of the directional component, and the fact that sound intensity is a vector quantity and not a scalar as is SPL, two microphones are needed to form a *sound intensity probe* for each measurement position. Measuring the intensity rather than the SPL makes it possible to measure the sound being emitted by the tire/pavement interface and not the sound coming from other directions such as nearby traffic. The directional component, as well as the overall amplitude of the nearby tire/pavement interaction, permits testing to be conducted in normal traffic flow without worrying about nearby sounds.

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 produced their own variations of intensity probes. Figure 2 shows two examples.[8] As will be described later in this section of the report, the UCF team chose to follow the setup in picture (b) of Figure 2 where both the trailing and leading edge of the tire are measured at the same time in a vertical arrangement mounted on a trailer. The primary reason for using a trailer was to allow for continuity over a long time period since it was decided it would be impractical to always use the same vehicle to mount the test probes during measurements. Use of the trailer for the OBSI testing is somewhat unique in the United States.

Octave bands and one-third octave bands allow reporting of sound for various, internationally defined frequency ranges. For purposes related to this study, this permits a review of how the pavement differences change the OBSI measurements with frequency as well as magnitude. All frequencies are also often combined into a single, overall level by summing the energy in each octave or one-third 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, usually by frequency, to account for various acoustic phenomena. The most commonly used weighting is the A-scale. This weighting 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.

After careful consideration, and except where noted, the UCF team decided to measure one-third octave bands, without weighting, for the OBSI measurements. This methodology was chosen since the weighting could always be applied to the raw data in the octave bands if needed to determine weighted sound levels such as A-weighted values. Not weighting the octave bands also permitted a better review of the true low frequency components changes by pavement types that would be masked if A-weighting were used. However, for the wayside measurements, where overall levels were reported, A-weighting was used since this is the common way to present these values.

The OBSI and wayside measurement equipment is discussed in the following sections.

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

Figure 2. Examples of Intensity Probes for Tire/Pavement Sound Measurements[8]

OBSI Equipment Description

A friction test trailer was supplied by the FDOT for use during the measurements. The trailer permitted the tests to be conducted the same way at each measurement location for continuity. A prototype test rig was designed that was capable of holding the two intensity probes at the precise dimensions from the leading and trailing edge of the tire. Figure 3 shows a picture of the test rig installed on the trailer. The method essentially followed the draft standard being prepared for the American Association of State Highway and Transportation Officials (AASHTO). Later changes occurred and the difference with the latest draft standard as summarized later in this document. 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).

The friction trailer is a single axle vehicle and the test tire was located on the *passenger* side of the trailer, 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 trailer was weighed and found to be equivalent to a typical passenger car wheel loading.

Multiple test rigs were evaluated. The final prototype that was used is shown in Figure 3 with two sets of phase-matched microphones in a side by side configuration (intensity probe) at the leading and trailing edges of the tire in a vertical configuration. Of course to measure the sound intensity, one microphone is placed closer to the tire wall than the other in the probe. Figure 4 illustrates the important dimensions of the microphone placement.

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.

It should be noted that at the time the testing began, the OBSI standard method in the U.S. was just beginning development and is still a work in progress. During this development recommended microphone placement dimensions and test procedures have changed from the initial work. The microphone placement differences from this work are now an even 3 inches (76 mm) instead of 2.76 inches (70 mm) used in this study. The new dimensions from the tire face are now 4 inches (102 mm) instead of 3.94 inches (100 mm) from the tire face used in this study. However, the tolerance allowed is 0.25 inches (6.3 mm) so the testing for this study was still within the tolerance ranges. Finally, a separation distance between the microphones is now specified to be 8.23 inches (209 mm) to allow placement in line with the leading and trailing edge of the SRTT. In our study we physically made sure we were in line with the leading and trailing edges of the tire so in theory, with the same standard test tire used (16 inch or

Figure 3. Prototype Test Rig With Intensity Probes

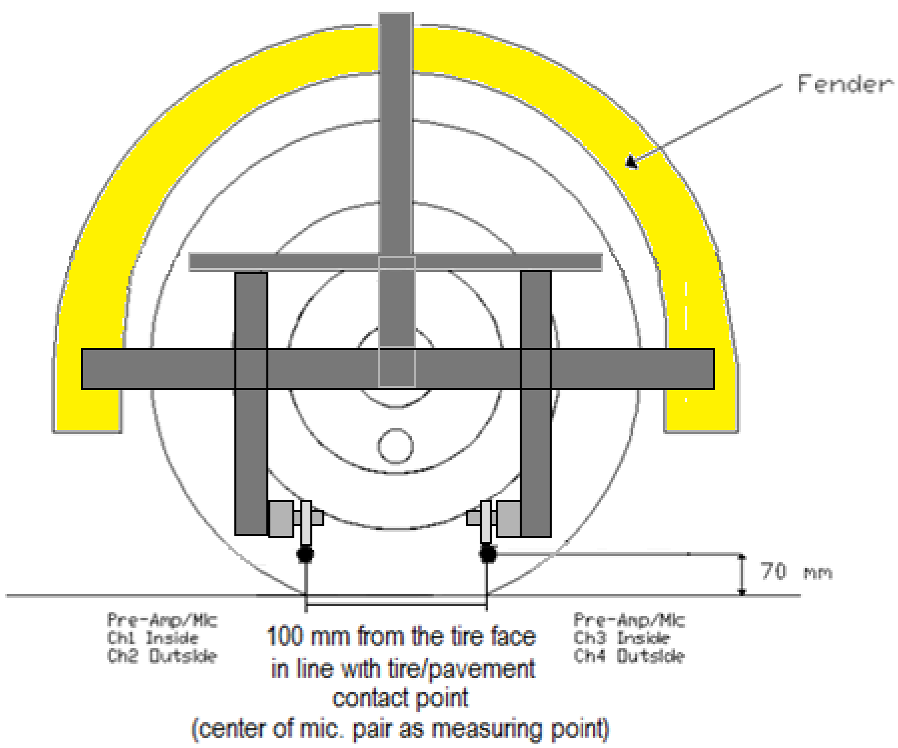


Figure 4. Dimensions Used During OBSI Measurements

Table 2. Major Test Equipment

EQUIPMENT	DESCRIPTION
Pimento system	sound analyzer
4 preamps	microphone power and amplification
4 microphones	sound measurement
4 windscreens	microphone protection and wind dampening
prototype test rig	precise microphone and preamp mounting
multiple cables	power and electrical data transfer
SPL calibrator	system calibration of correct noise levels
PRI calibrator	sound intensity calibration check
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 Friction trailer altered for intensity probe test rig

40.6 cm Standard Reference Test Tire) the UCF procedure was considered to be within tolerance limits.

Because we still met the tolerances of the new dimensions and to help ensure continuity, our setup and procedures were kept static so that all locations and pavements could be directly compared at the end of the testing instead of changing midway through the project. Continuity was important for our testing and was followed even to the extent of using the same truck to tow the trailer during all tests.

The test tire was also a very important component. The Uniroyal Standard Reference Test Tire (SRTT) is manufactured to exacting specifications as specified by American Society for Testing and Materials (ASTM) specifications (ASTM F 2493). The size now used as well as in this study 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.

The recording system consisted of a four channel analog-to-digital (A-D) signal processor from LMS called the Pimento© system. The system recorded the sound pressure levels versus time at a 50 kilohertz sample rate and the intensity and coherence values were post processed from the stored sound pressure level time history for each probe. (Coherence is a measure of the extent that two signals are linearly related at any given frequency.) The intensity and coherence functions are pre-programmed into the Pimento© analyzer software. The data and controls were done by a lap top computer. Figure 5 provides an overview of the entire system

Figure 5. Overview of Entire System

For future reference of others, the detailed test procedure for the OBSI testing has been delineated here. After selection of suitable pavement test locations, away from curves and pavement surface distortions such as potholes, the process included:

1. Install test tire on trailer and drive at least 5 miles (8 kilometers) to warm tire.

2. Install detachable prototype test rig onto trailer.

3. Setup Pimento/laptop and cabling

    a. plug inverter to the vehicle
    b. plug Pimento USB key into laptop
    c. connect Fire wire cable from Pimento to laptop
    d. connect Power supply to Pimento
    e. connect Power supply to laptop

f. Attach rubber-band-retention-device to fire wire cable and laptop

4. Place matched pair microphones on appropriate preamps.

5. Connect cabling to preamps and Pimento.

6. Power on entire system and laptop, checking on correct operation of each. Note that use of inverter may require engine start on tow vehicle.

7. Load and run Pimento software.

8. Verify channel number and correct microphone location by placing the calibrator on one microphone at a time and observing the Pimento display.

9. Perform and record SPL calibration on CH1-CH4 (Pimento-Measurements-Calibration)

10. Perform and record PRI calibration on CH1-CH2 then CH3-CH4

    a. Use the Cal291 and a signal out of the Pimento as input to the Cal 291; turn on Function Generator in Pimento (settings are Random, Pink, Wideband, RMS, 1 Volt signal) and, place microphone pair into Cal 291 and record 10 seconds of data;
    b. Repeat for other microphone pair.

11. Install preamps onto rig according to diagram and required spacing. Be sure preamp insulation material is installed properly.

12. Route cabling along trailer and vehicle and lightly secure with zip ties.

13. Set the test (recording) time in the Measurement/Parameters menu item. This test length is usually determined in seconds according to appropriate guidance material based on facility type and speed.

14. Make sure wayside instruments are ready and all personnel in place.

15. Approach the test area at a constant speed and start the analyzer when entering the section.

16. Proceed at a constant speed until the data have been recorded.

17. End recording and make sure data are saved.

18. Perform quality control in the field on each run by checking SPL results.

19. After four runs, or if any problems experienced redo calibration by repeating steps 9 – 12 as needed.

20. Continue sampling beginning with step 13.

21. Upon return to the lab process data for quality control and analysis using Pimento software, spreadsheets, and other programs as needed.

Since the draft ASSHTO standard was undergoing revisions at the time, we 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. At each location, a minimum of six runs at 55 mph ±1 (88 kph ±1.6) through the test section were conducted. Of note is that the pavement length tested over at least a 10 second time period resulting in a test length of approximately 800 feet (244 meters).

Great care was also taken for calibrations for each microphone/preamp and each matched pair. As described in the procedure, in addition to testing for the correct Sound Pressure Level (SPL), the intensity probes were calibrated using a PRI (Pressure Residual Intensity) test and a residual intensity calibration device prior to beginning each test, multiple times during testing, and at the end of the tests.

Concurrently, to produce matched data sets, wayside measurements were performed at the center of the test section.

Wayside (Passby) Equipment Description

Wayside (passby) sound pressure level data was collected during the OBSI measurements. The emphasis was on individual passby events and the location was in the center of the test section used for the OBSI testing. In the early sampling a controlled passby test, using the truck and OBSI trailer passby for consistency at each location, was considered and attempted. This quickly changed as it became evident that traffic volumes would not permit *clean* passbys of the OBSI truck/trailer. A clean passby would require 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 traffic sources. The interference of other vehicles by the OBSI truck/trailer was unavoidable at the wayside positions. This was due to the traffic tending to bottleneck near the truck/OBSI trailer making it infeasible to rely on the truck/OBSI trailer passby data. Data from the first wayside location measurement did not pass quality control. Nighttime sampling was considered but not used because of safety concerns.

This led to a method similar to the statistical passby method[12] but with certain changes to better reflect U.S. criteria and to better satisfy our purposes. This primarily included changes in microphone placement. Events of interest were random vehicles using the outside (near) lane with sufficient separation to meet the 7 dB(A) criteria. 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 by the test trailer. Meanwhile, personnel were positioned on the road edge with a radar gun and clipboard to identify and the appropriate single passby events of vehicles with the exact time and speed. This information was later used to extract data from the sound level analyzers at the wayside positions and used in later analysis. Of note is that the time and speed of each passby of the OBSI truck/trailer was also recorded during this time.

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. One-third octave bands were also 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 at the U.S. reference distance of 50 feet (15 meters) and 5 feet (1.5 meters) above pavement. Where possible, measurements were also made at 100 feet (30 meters) from the centerline of the near lane and 5 feet (1.5 meters) as well as 12 feet (3.7 meters) above pavement height. The 100 foot position varied at times due to location restrictions and in these cases was measured at the greatest distance possible that allowed at least a 120 degree, unobstructed view of the roadway. Figure 6 shows a graphic of these distances while Figures 7 and 8 show typical locations. All equipment 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.

To help determine the clean passbys based on the imposed requirement of a 7 dB(A) difference in the measured passby and the background noise, personnel at the side of the road observed vehicle separation and other nearby noises noting which vehicles seemed to meet this criteria. This information was included in careful notes and used during data reduction to find the appropriate events. A desired sample size of 100 automobiles was the goal to be used to develop sound pressure level versus vehicle speed curves for each location. Unfortunately, due to vehicle spacing, later quality control, and time restrictions this was not always possible. Good passby events of other vehicle types such as medium trucks, heavy trucks, motorcycles and buses were also included in the data base for comparative purposes.

Detailed meteorological information was also collected including wind speed/direction (using a very accurate sonic anemometer), relative humidity, temperature and atmospheric pressure at one second sample rates.

Table 3 provides a summary of the test locations while Table 4 supplies the number of good passby events recorded based on the background criteria and a summary of the measured meteorology. Aerial maps and a definitive picture of the surface texture are included in Appendix A for each location.

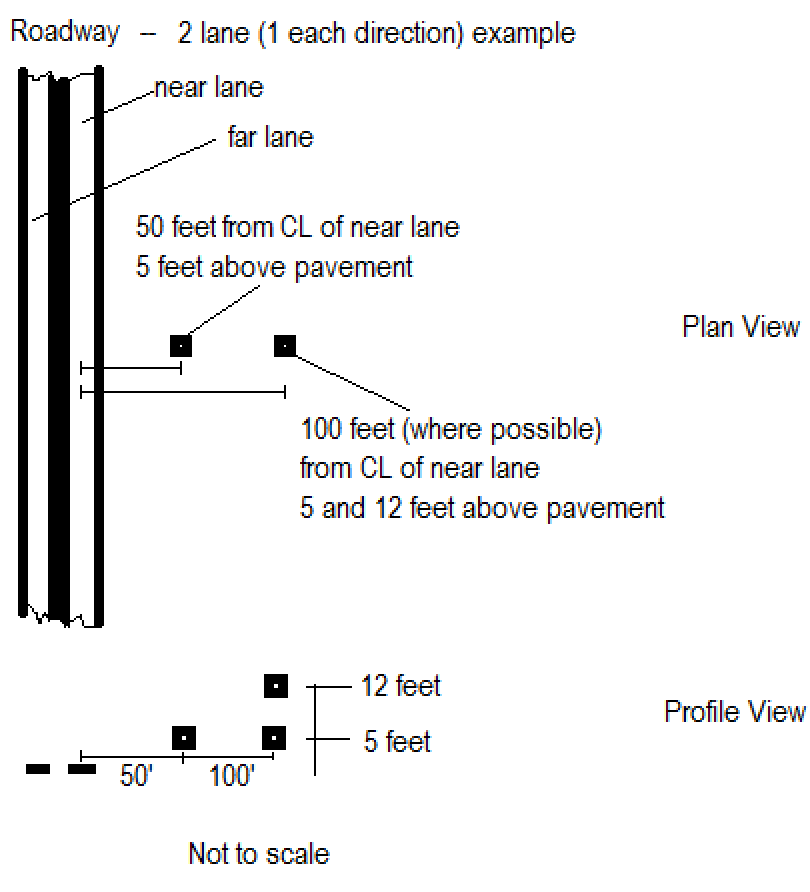


Figure 6. Typical Dimensions of Passby Testing

Figure 7. Typical Passby Equipment Configuration (sound level analyzers at five and twelve feet above pavement and a meteorological station)

Figure 8. Passby Microphones Locations During Tire/Pavement Test

Table 3. General Location Details

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 Volusa
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

Table 3 Continued Next Page

Location No.	Date Measured	Location Description	Lane Tested	Test Limits MP/ Co.
Table 3 Continued				
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
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

Table 4. Overall Summary of Locations and Measurements

Location Description/Date of Test	Location Number	Good passby events	Avg Temp./RH (deg/%)	Wind Speed (m/s)	Wind Direction
SR 417 Winter Springs 9/14/07	1	NA	98/38%	1.1	crosswind
SR528 Beeline 9/29/07	2	22	90/59%	3.5	crosswind
I95 Volusia County 11/8/07	3	42	70/60%	4	crosswind
192 Melbourne 11/9/07	4	70	70/50%	4.5	upwind
SR 417 Winter Springs 2/14/08	5	107	55/50%	2	crosswind
SR 417 Winter Springs 7/9/08	6	54	87/65%	2	upwind
I75 Lake City 7/11/08	7	40	87/90%	3	upwind
I295 Jax, Duval 7/13/08	8	71	89/60%	4	downwind
I295 Jax, Lem Turner 7/13/08	9	39	89/60%	4	downwind
SR40 Ocala 10/27/08	10	58	78/47%	1	crosswind
SR40 Ocala Natl Forest 10/27/08	11	51	78/47%	1	crosswind
SR24 Waldo 10/28/08	12	93	60/30%	2	downwind
SR24 Austin Cary near Waldo 10/28/08	13	64	60/30%	2	downwind
SR16 Starke 10/29/08	14	78	67/25%	1	upwind
SR 417 Winter Springs 10/30/08	15	64	80/40%	3.5	crosswind
SR528 Beeline 11/4/08	16	33	70/80%	4.5	upwind
SR 92, Deland 11/25/08	17	111	74/53%	3	upwind
SR 92, Deland 11/25/08	18	63	74/53%	3	upwind
SR 222, Gainesville 2/16/09	19	57	65/30%	2.	crosswind
SR26, Gainesville 2/17/09	20	8	66/32%	1	crosswind
Paynes Prairie, Gainesville 4/28/09	21	87	82/40%	2.2	downwind
Waldo Rd. SR24, Gainesville 4/29/09	22	69	82/42%	1.1	crosswind

CHAPTER 4. DATA PREPARATION

OBSI

The first, last, and multiple steps during analysis were extensive quality control measures. During measurements, equipment problems had occurred resulting in replacing some equipment so quality control was of the utmost importance. The multiple calibrations taken during the measurements were reviewed and field notes were carefully reviewed as initial steps with particular attention to Location 2 where calibrations problems occurred. Additional quality control occurred during post processing and analysis as values were derived from the raw data.

The initial quality controlled sound data from the OBSI system was 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 an energy average of the test. Intensity levels versus time and frequency graphics were generated as a review and another quality control measure. Figure 9 is an example of the Campbell time history plot produced of the concurrent intensity levels and frequency. Time is shown on the right vertical axis (ordinate) and frequency is along the abscissa. The intensity is shown by color and the legend is along the left ordinate. This example figure, taken during one of the trailer evaluation runs, shows the influence of pavement type on sound intensity as the trailer was driven from an asphalt surface (0-2 seconds into test) onto a PCC paved bridge (2.5 to 9.5 seconds) and then back onto the asphalt highway (9.5 to 12.0 seconds). The plot shows that sound intensity levels increase dramatically in the 1 kHz to 6 kHz spectra region when the OBSI measurements occur on the bridge with PCC pavement versus the asphalt highway. Each of these types of plots was reviewed for the each actual locations looking for any obvious abnormalities.

Figure 10 is another comparison that was used to look at the data in a time history format to determine if problem may have occurred during the test run or if a problem existed with one of the probes. Shown in Figure 10 is an example of the time history of SPL for both microphones in an intensity probe. The variation due to pavement texture is obvious from a review of the figure. The variability is from road imperfections and undulations that occur as the OBSI truck and trailer pass through the test area. During reporting, the values, omitting measurement startup and ending error, are acoustically averaged and processed to calculate a single intensity level but the reader should be aware of the variance. Appendix B contains the intensity time history for all OBSI locations.

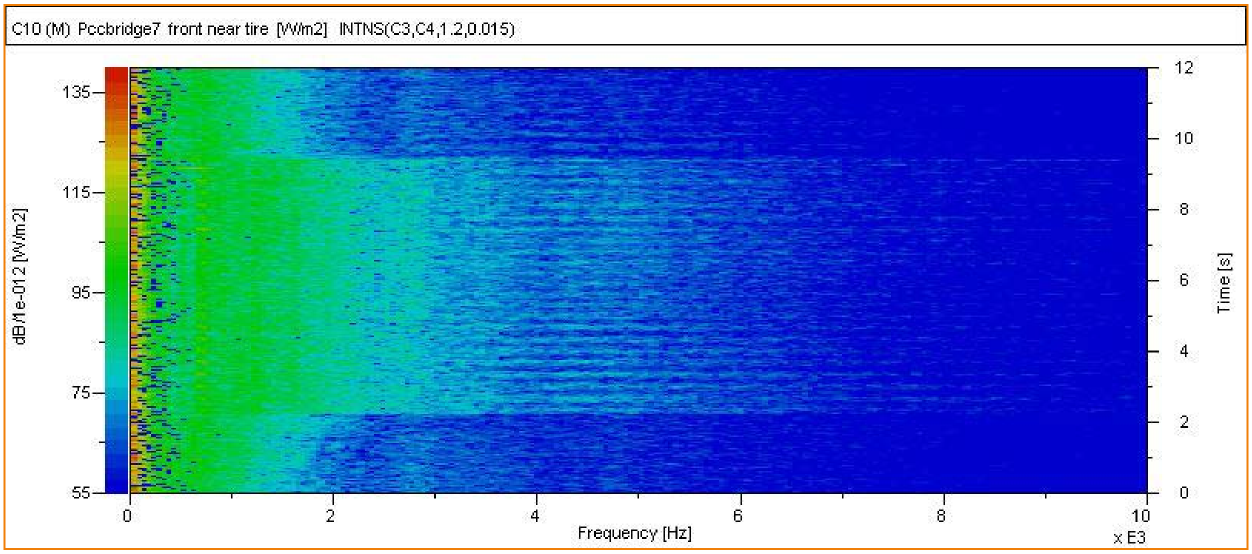


Figure 9. Example of a Campbell Intensity Plot Generated by the Pimento© System [This test shows the OBSI trailer transitioning from an asphalt highway to a cement bridge (time = 2 to 9.5 seconds) and back onto the asphalt surface again]

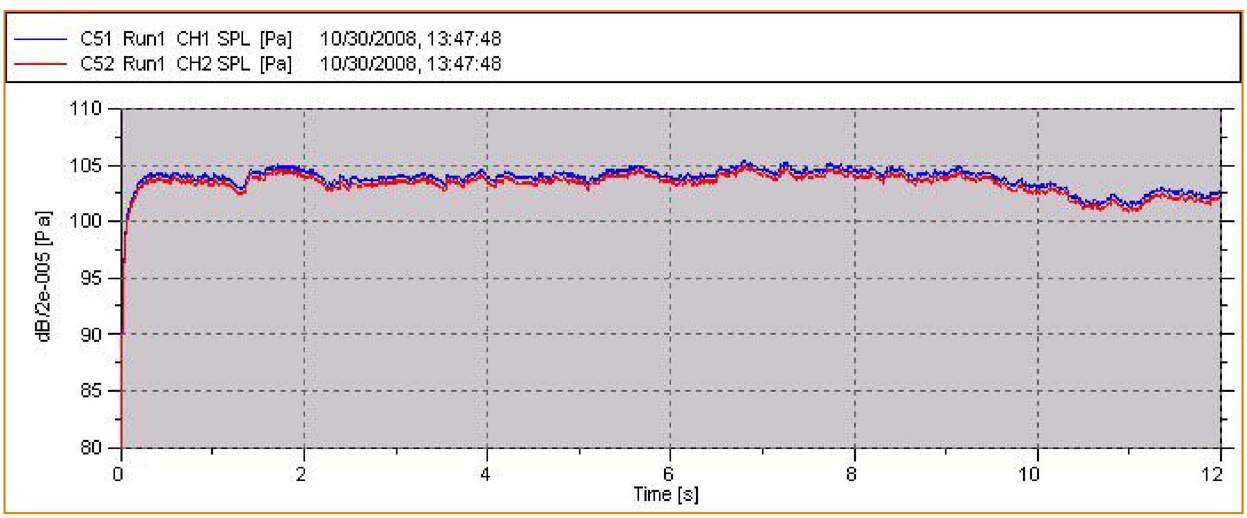


Figure 10. Example of Both Microphones in an Intensity Probes Showing Measured SPL [SPL from both microphones are later used to calculate values of sound intensity]

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. Figures 11 and 12 show these comparisons. In Figure 11, one outlier point is circled on the graph. This is the comparison from Location 2, SR 528. It can be seen that a large error exists. As such, and because of the close proximity to SR 417 to the University, the SR 417 location was visited multiple times as a quality control check of the equipment (Locations 1, 5, 6, and 15). From this extensive testing of the location, the data from the front intensity probe at Location 2 was not considered useable and was not included in final conclusions. Location 2 also had a larger than expected variation. As such, Location 2 was revisited after we were sure of proper equipment operation and is listed as Location 16.

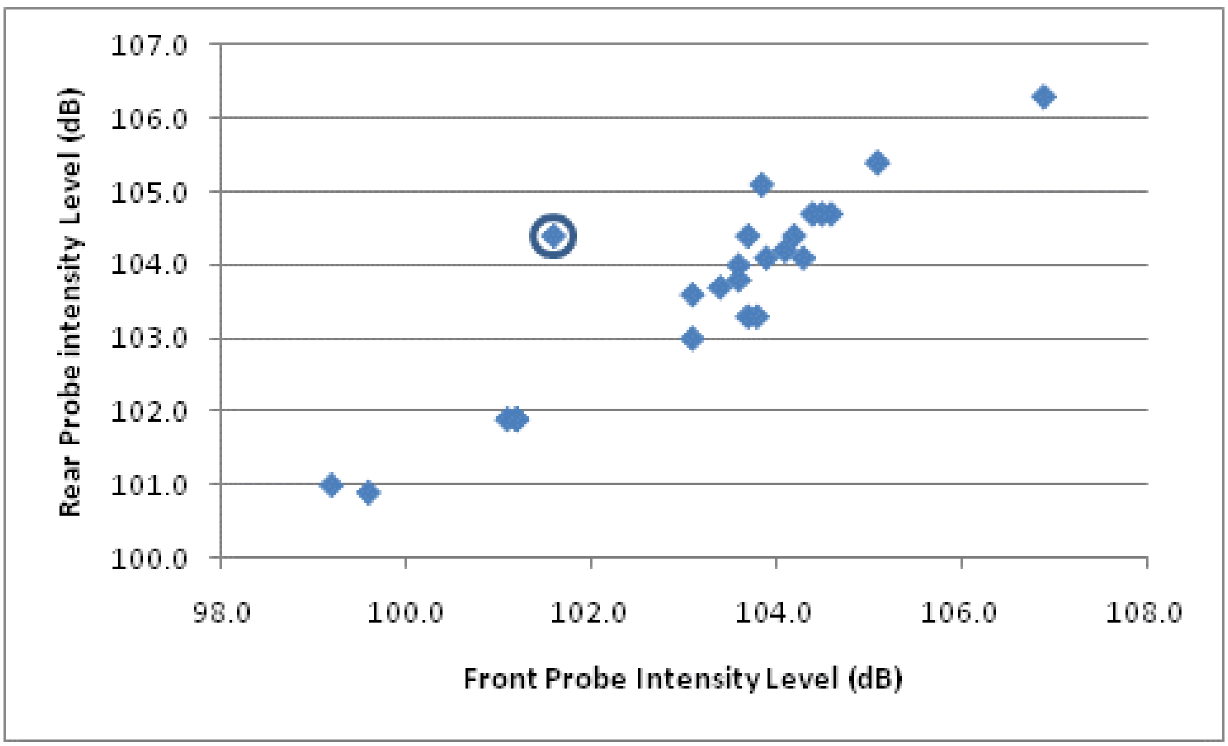


Figure11. Matched Pair Comparison on Front and Rear Intensity Probes

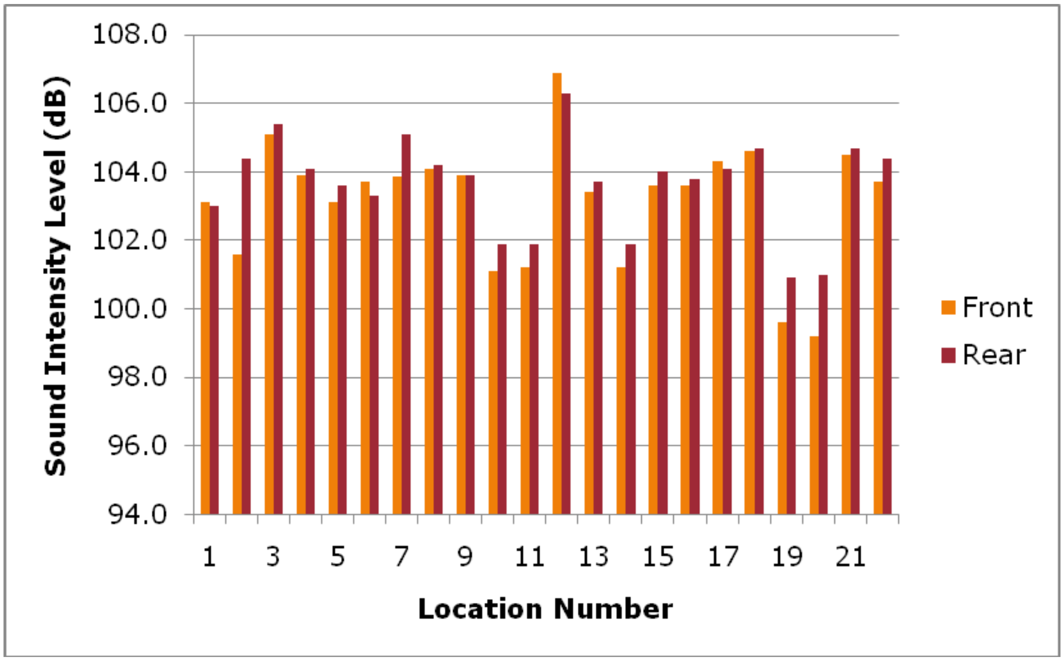


Figure 12. Direct Comparison of Front and Rear Intensity Probes by Location

Figure 12 allowed additional insight by using a different format. It can be seen from this figure that at two additional locations there may have been some unknown problem, although each location had no problems in calibration. As such, Locations 19 and 20 were also flagged and the data from the front probes considered closely in final conclusions.

Frequency varies with pavement texture and was also reviewed. Figure 13 shows an example spectrum from the test. The figure shows results from multiple measurements using the OBSI method and from the wayside (statistical passby method). Of note is that due to considerations such as wind noise, the OBSI spectra is not valid for the lower frequencies and not shown for the expanded spectrum as is the wayside measurement. Fortunately, the human ear does not respond well to these low frequencies making them less of a concern. The wayside spectra will be discussed in the next section.

Table 5 shows the final quality controlled intensity levels with the three data points that are not used in the final analysis shaded. The minimum, maximum, median, and standard deviations are all shown by location.

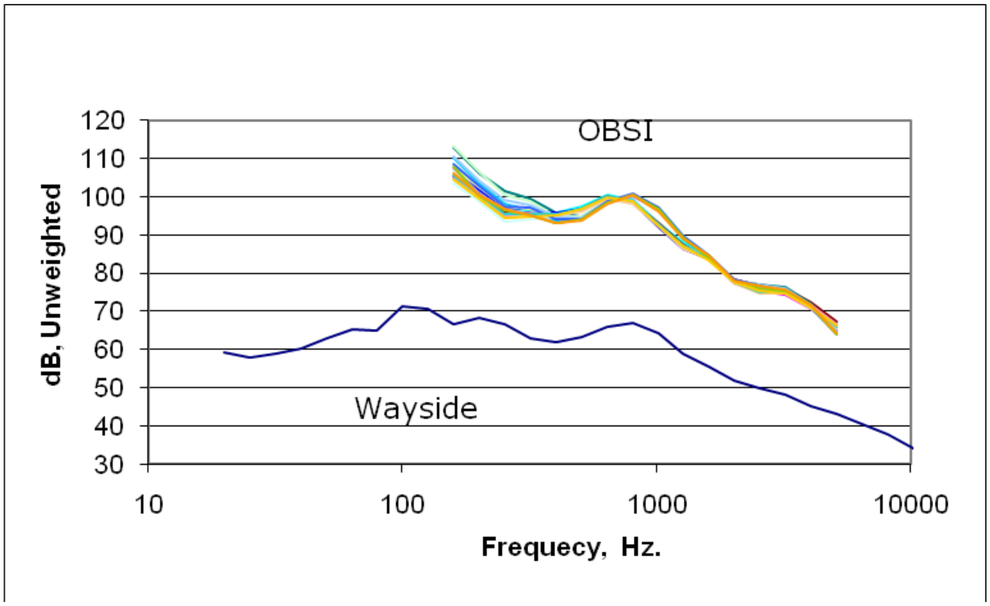


Figure 13. Example of OBSI and Wayside Spectra [unweighted]

Table 5. Summary of Time Acoustically Averaged Intensity Levels (dB)

	Front Probe				Rear Probe			
Location	**min**	**max**	**median**	**stdev**	**min**	**max**	**median**	**stdev**
1	102.2	104.0	103.1	0.3	102.1	103.9	103.0	0.3
2	98.9	104.3	101.6	0.9	103.5	105.3	104.4	0.3
3	104.5	105.7	105.1	0.2	103.6	107.2	105.4	0.6
4	102.7	105.1	103.9	0.4	102.3	105.9	104.1	0.6
5	101.9	104.3	103.1	0.4	101.7	105.6	103.6	0.7
6	102.7	104.7	103.7	0.3	102.1	104.5	103.3	0.4
7	103.1	104.6	103.9	0.2	104.1	106.1	105.1	0.3
8	103.0	105.2	104.1	0.4	103.2	105.2	104.2	0.3
9	103.2	104.6	103.9	0.2	103.1	104.7	103.9	0.3
10	100.4	101.8	101.1	0.2	101.1	102.7	101.9	0.3
11	100.7	101.7	101.2	0.2	101.2	102.6	101.9	0.2
12	106.1	107.7	106.9	0.3	105.6	107.0	106.3	0.2
13	102.9	103.9	103.4	0.2	102.9	104.5	103.7	0.3
14	100.4	102.0	101.2	0.3	101.5	102.3	101.9	0.1
15	102.5	104.7	103.6	0.4	102.9	105.1	104.0	0.4
16	103.0	104.2	103.6	0.2	102.9	104.7	103.8	0.3
17	101.9	106.7	104.3	0.8	101.7	106.5	104.1	0.8
18	103.8	105.4	104.6	0.3	104.0	105.5	104.7	0.3
19	98.7	100.5	99.6	0.3	100.2	101.7	100.9	0.3
20	98.7	99.7	99.2	0.2	100.6	101.4	101.0	0.1
21	103.7	105.3	104.5	0.3	104.1	105.3	104.7	0.2
22	103.7	103.7	103.7		104.4	104.4	104.4	

Wayside

Quality control was also of extreme importance for the wayside measurements. Quality control began as with OBSI by reviewing all calibrations and field notes. A check for any occurrences of other background noise that would cause problems was also determined by a review of the field notes. The events of interest (single vehicle passbys with low background noise) were identified using a manual process. This process including reviewing each time history plot with the field note times of events to identify possible good passbys. These events were further reviewed on the time history plot to make sure the 7 dB(A) criteria was met. The events determined to pass the criteria test were then extracted and used to form a data base. The number of good events for each location after quality control was previously listed in Table 4.

All wayside data spectra were also reviewed for any abnormalities and to allow comparison to the OBSI measurements during analysis. Figure 13, previously shown, is a typical wayside spectra and a comparison to the OBSI data from the same location.

Once the wayside data were quality controlled, each location was plotted by speed and maximum SPL to review the data. Appendix C contains these plots. From each plot, the statistical value that would have occurred at 55 mph (88kph) was determined. The derived values for the 50 foot position ranged from 65 to 76 dB for the wayside noise. Values are shown for each location and the numeric difference between the OBSI levels are shown in Table 6. Of note is the average level and relatively small standard deviation. This allows a general first order approximate method to be used to determine wayside sound levels if OBSI measurements are made. This general method is:

Wayside SPL [dB(A)] = OBSI Sound Intensity Level – 32.2 [dB]

The uncertainty is ± 5.4 dB(A) based on 2.15 standard deviations.

Additional Testing

The last sample period of the measurements (April 29, 2009) provided a unique opportunity made possible by continued FDOT participation and sponsorship. Dr. Paul Donavan, an early and continued developer of the OBSI methodology, was sponsored to come to Florida for the day of testing. Dr. Donavan brought his test equipment to allow comparison to the FDOT noise trailer. This permitted three locations to be compared by the two test systems. Dr. Donavan’s test rig also measurement leading and trailing edge sound from the tire/pavement interface by similar probe placement as used in the FDOT work.

Table 6. Wayside Measurement Values [dB(A)] with Difference to OBSI [dB]

Location	Wayside	Diff to OBSI
1	NA	NA
2	67	37.4
3	73	32.4
4	74	30.1
5	70	33.6
6	75	28.3
7	73	32.1
8	73	31.2
9	67	36.9
10	70	31.9
11	71	30.9
12	73	33.3
13	71	32.7
14	70	31.9
15	70	34
16	76	27.8
17	74	30.1
18	73	31.7
19	68	32.9
20	65	36
21	75	29.7
22	73	31.4

Average	32.2
Std Dev	2.5

Microphone placement in relation to the tire and pavement were slightly different as Dr. Donavan's test rig dimensions were based on the AASHTO draft standard as previously discussed. The reader is reminded UCF began the work before this standard was developed and stayed with the same dimensions to allow direct comparison of all measured data during the research. The differences as previously described are the following:

- UCF microphones were 2.76 inches (70 mm) above the pavement surface while Donavan's were 3 inches (76 mm).
- The distance from the tire/pavement interface for UCF was 3.94 inches (100 mm) from the tire face in line with the tire/pavement contact point whereas Donavan used 4 inches (102 mm) from the sidewall, centered on the tire, and with a separation distance of 8.23 inches (209 mm).
- However, as previously described, the draft standard does state all tolerances to 0.25 inches (6 mm) so the UCF test rig was still technically within the acceptable range and with the same tire designated (16 inch SRTT) UCF should also be within tolerances for this parameter in the standard. But for completeness, these differences are noted.

Equipment differences in the test rig design, equipment manufacturer of processing equipment, and wind screens also occurred. Dr. Donavan's system is described in Reference 8. The primary difference in the equipment is the test rigs used. Donavan uses the tire/fender mounted approach in testing as shown in Figure 14. The reader is reminded that for continuity, the Florida approach utilized a trailer weighted to the same loading as a typical passenger car and was shown in Figure 3.

The data show that the UCF test trailer and Donavan's wheel based test rig both measured somewhat similar results. Figure 15 shows a plot of the spectrums comparing 3 runs for each system at Location 22. D1, D2, and D3 are runs from Donovan while UCF1, UCF2, and UCF3 are those conducted by UCF.

It should be noted that in these tests results were A-weighted by UCF to allow a direct comparison to the values reported by Dr. Donavan.

Similar testing was done for two other locations with similar results farther down the road on SR24. It can be seen that the measurement results were similar and comparable. However, in the lower frequencies UCF system was up to 3 dB(A) higher in some one-third octave bands and in the frequencies around 3000 to 4000 Hertz were about 3 dB(A) lower. As far as the overall A-weighted value, Donavan's average result was 101.4 dB(A) while the UCF average overall A-weighted values was 102.9 dB(A) for a difference of 1.5 dB(A) at Location 22.

Although this agreement was thought to be good, some additional work was conducted in an attempt to find out why these differences occurred, primarily at the lower frequencies. Additional testing was done with larger wind screens, similar to that used by Donavan. The results are shown in Figure 16. While a small difference did occur at the lower frequencies (note scale on Figure 16) results are not commonly reported for frequencies below 500 Hz due to wind induced noise problems. As such, the overall results that would be reported only showed a 0.2 dB difference when compared.

Figure 14. Donavan's Tire/Fender Mounted Test Rig

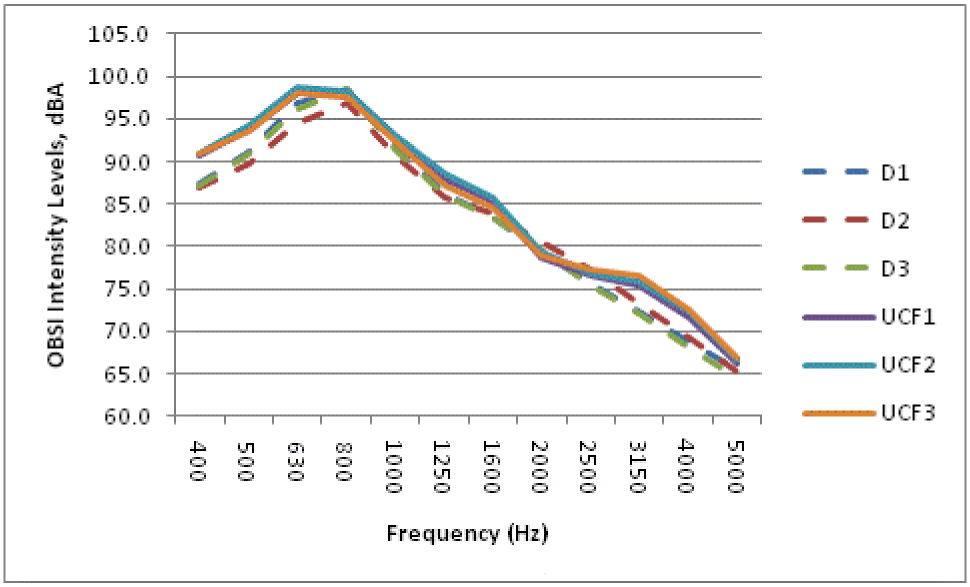


Figure 15. Comparison of Test Trailers

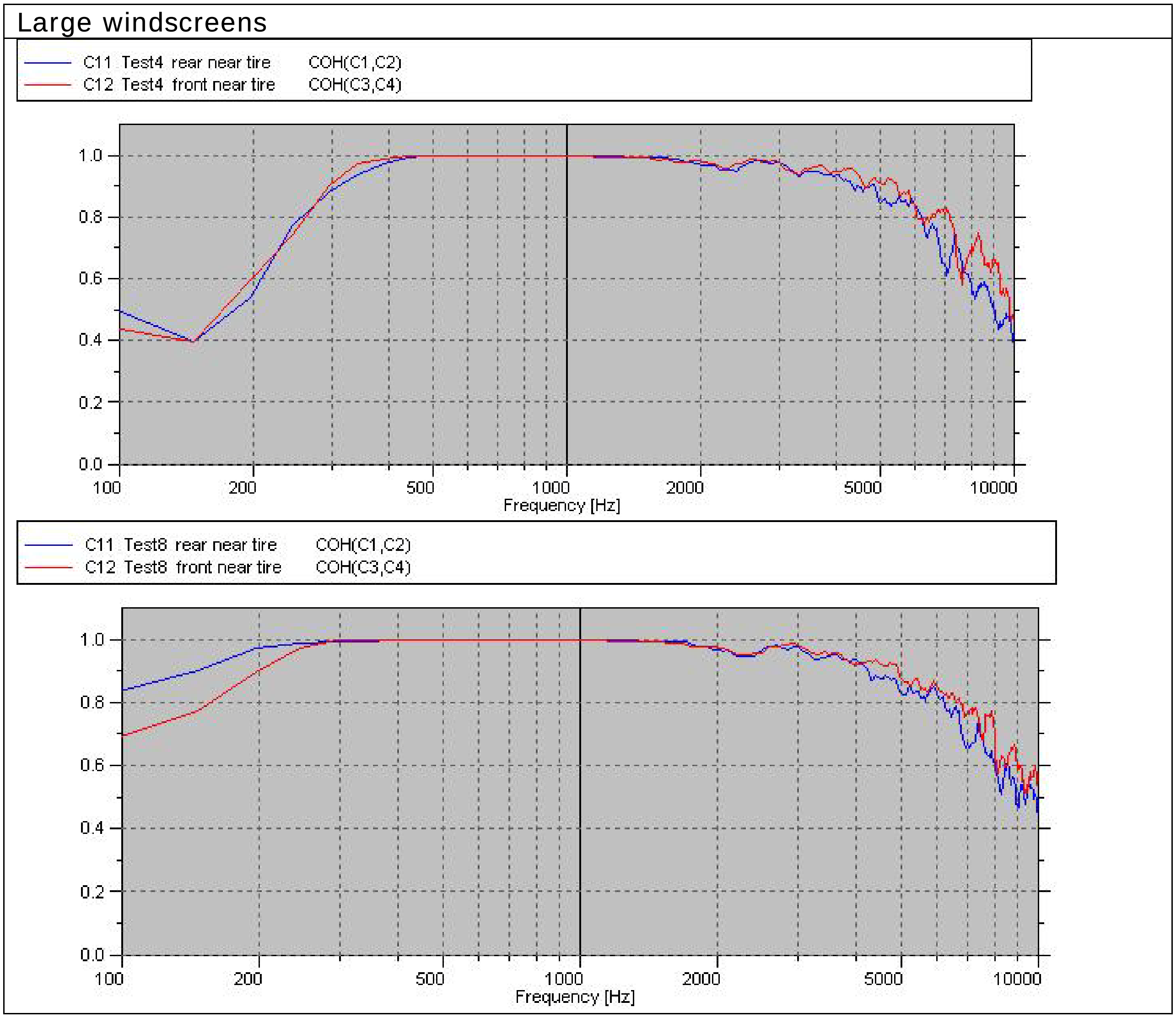


Figure 16. Comparison of Large and Small Windscreens

Measurements were also made changing the microphone dimensions in relation to the tire to those used by Donavan and in the latest draft standard. A result of approximately a 1 dB difference was found. This would further reduce the difference between UCF and Donavan. As such the combination of the two differences (wind screens and microphone placement) would seem to indicate that the systems compared extremely well and if future tests are conducted using the new draft standard dimensions extremely good results would be expected.

CHAPTER 5. OBSERVATIONS AND FINDINGS

The successful development and use of the trailer mounted OBSI equipment has allowed development of an initial data base to investigate the sound intensity levels generated by different pavements and texture surfaces in Florida. The continuity of the measurements can be preserved by use of this same trailer and equipment although a new test rig to replace the prototype would be beneficial. This would also allow moving microphones and probe more easily. Future work should use the exact microphone positions listed in the draft AASHTO standard now under development.[13]

This data base allowed a comparison of 18 different locations in Florida with multiple measurements at two of these locations. Additionally, direct comparison of the FDOT system to be that of Dr. Paul Donavan resulted in very good results, further verifying the overall results. The locations measured included multiple pavements and surface textures used by the FDOT and provided a good representation of Florida pavements. Figures 17 and 18 illustrate the measurement range and variability by location for the front and rear intensity probes, respectively.

The data permitted a ranking of those pavement types/textures measured. Table 7 presents the details on these different pavements. Of note is the column labeled Chart Legend. This is the shortened description used to describe the pavements in subsequent figures. Figure 19 shows the measured values once again but this time with the pavement texture/type included and reordered from lowest to greatest sound level produced at the tire/pavement interface. Of interest from the OBSI measurements near the tire/pavement interface is the following observations:

- the PCC pavements which were older, did not have the greatest sound intensity levels as might be expected
- the dense asphalt was among the lowest intensity levels
- the thick porous asphalt was among the greatest intensity levels
- grinding of the surface resulted in greater sound generation at the tire/pavement interface
- the surface with the greatest sound level was the was the LD 2-2523A surface which is a permeable open graded friction course with ground tire rubber
- the surface with the lowest sound level was the SP 04-3068A surface Dense graded friction course with ground tire rubber most likely due to a very smooth surface and small amounts of tire vibration

But the reader is reminded the results of Figure 19 are at the tire/pavement interface. A further review was conducted for the wayside noise. Figure 20 shows these results in the same order as Figure 19 but with much different results. Figure 21 shows that the same ranking does not apply along the side of the roadway as at the tire/pavement interface.

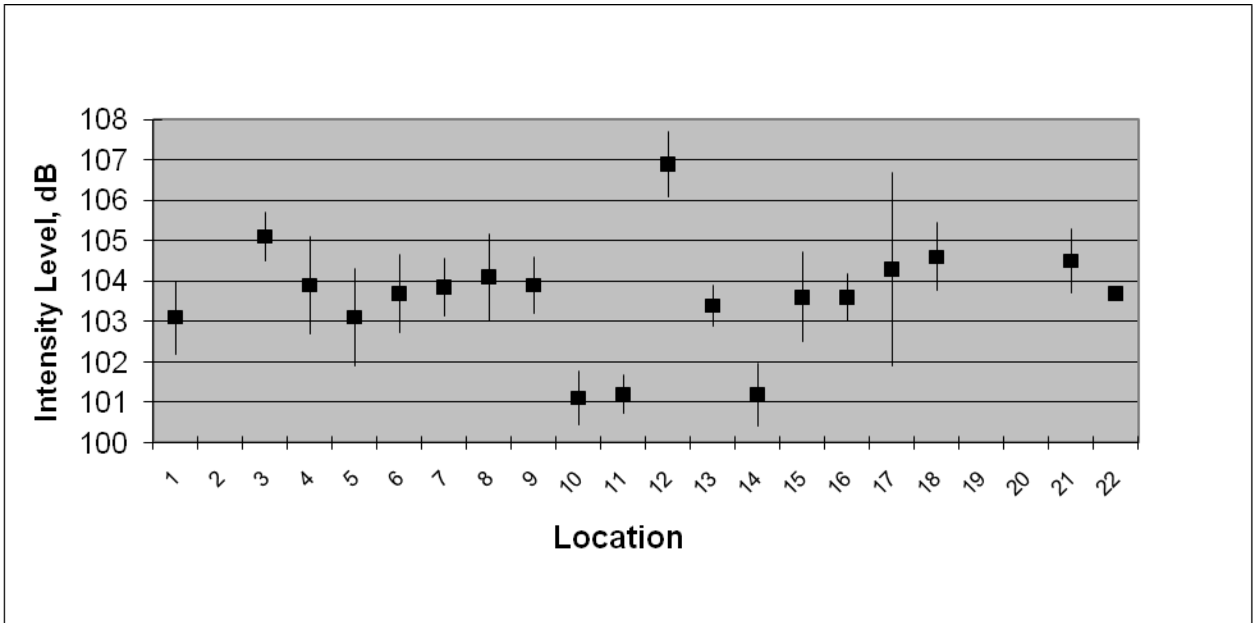


Figure 17. Range of Time Averaged Intensity levels at the Front OBSI Probe

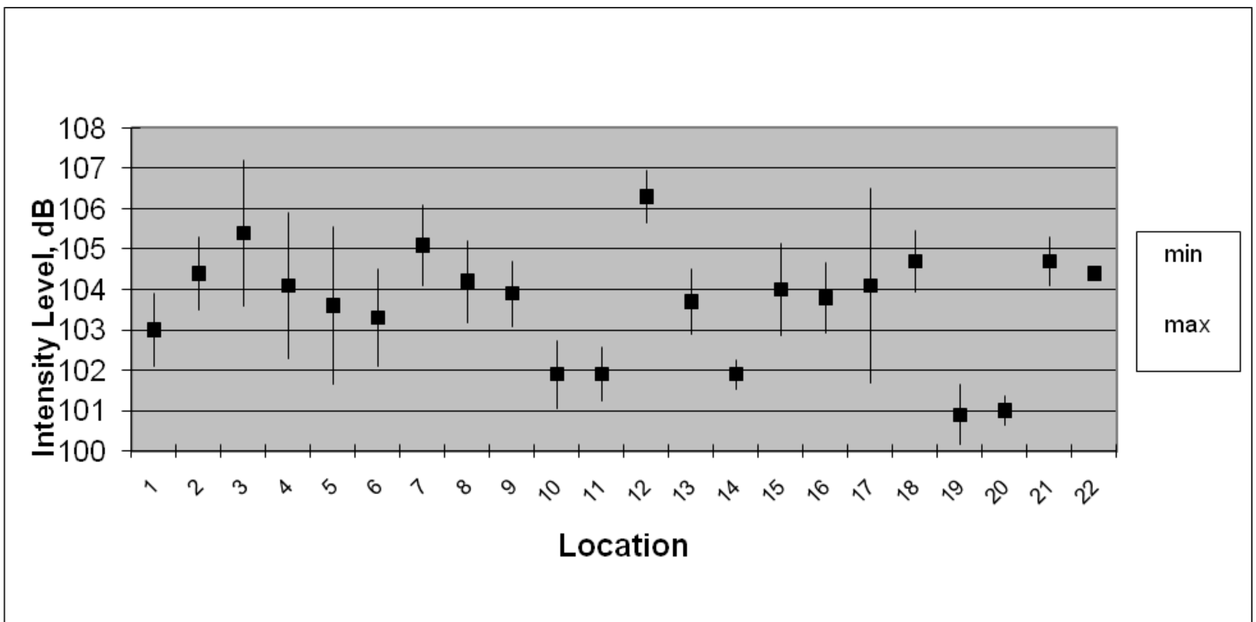


Figure 18. Range of Time Averaged Intensity levels at the Rear OBSI Probe

Table 7. Pavement Type Descriptions

Location	Lane Tested	Test Limits Mi. Post/ County	Material	Mix Design	Chart Legend	Details on Mix and Texturing
1	NBTL	4.000 to 5.000 Seminole	Granite	FC-5	FC5 Poly Mod Bind	Permeable Open graded friction course with polymer modified binder
2	WBTL	Brevard	Limestone	FC-5	FC5 Asp-Rub..	Permeable Open graded friction course with ground tire rubber
3	NBTL	6.881 to 27.147 Volusa	Limestone	FC-5	FC5 Asp-Rub..	Permeable Open graded friction course with ground tire rubber
4	NBTL	0.000 to 9.687 Brevard	Limestone	FC-5	FC5 Asp-Rub..	Permeable Open graded friction course with ground tire rubber
5	NBTL	4.000 to 5.000 Seminole	Granite	FC-5	FC5 Poly Mod Bind	Permeable Open graded friction course with polymer modified binder
6	NBTL	4.000 to 5.000 Seminole	Granite	FC-5	FC5 Poly Mod Bind	Permeable Open graded friction course with polymer modified binder
7	SBTL	33.965 to 34.562 Duval	Granite	Thicker FC-5	Thick Porous Fric..	Permeable Open graded friction course with polymer modified binder
8	SBTL	19.000 to 27.380 Columbia	Granite	FC-5	FC5 Poly Mod Bind	Permeable Open graded friction course with polymer modified binder

Table 7 Continued Next Page

Location	Lane Tested	Test Limits Mi. Post/ County	Material	Mix Design	Chart Legend	Details on Mix and Texturing
Table 7 Continued						
9	SBTL	31.910 to 32.839 Duval	Granite	FC-5	FC5 Asp-Rub..	Permeable Open graded friction course with ground tire rubber
10	EBTL	10.157 to 32.206 Marion	Granite	FC 12.5	FC 12.5 Dense..	Dense graded friction course with ground tire rubber
11	EBTL	10.157 to 32.206 Marion	Granite	FC 12.5	FC 12.5 Dense..	Dense graded friction course with ground tire rubber
12	NBTL	14.380 to 15.285 Alachua	Granite	LD 02-2523A	LD 02-2523A	Permeable Open graded friction course with ground tire rubber
13	NBTL	12.145 to 12.540 Alachua	Limestone	QA 00-9506A	Before Grinding	Permeable Open graded friction course with ground tire rubber
14	EBTL	6.943 to 7.469 Bradford	Limestone	SP 02-1920A	SP 02-1920A	Dense graded friction course with ground tire rubber
15	NBTL	4.000 to 5.000 Seminole	Granite	FC-5	FC5 Poly Mod Bind	Permeable Open graded friction course with polymer modified binder
16	WBTL	Brevard	Limestone	FC-5	FC5 Asp-Rub..	Permeable Open graded friction course with ground tire rubber
17	WBTL	2.452 to 1.930 Volusia	Concrete	1930's	PCC Long..	Longitudinal Grind PCC
18	WBTL	4.807 to 4.460 Volusia	Concrete	1930's	PCC Burlap..	Burlap Drag PCC
Table 7 Continued Next Page						

Location	Lane Tested	Test Limits Mi. Post/ County	Material	Mix Design	Chart Legend	Details on Mix and Texturing
Table 7 Continued						
19	EBTL	12.375 to 12.790 Alachua	Granite	SP 04-3068A	SP 04-3068A	Dense graded friction course with ground tire rubber
20	EBTL	12.220 to 12.520 Alachua	Granite	SPM 05-4408A	SPM 05-4408A	Dense graded friction course with polymer modified binder
21	SBTL	8.150 to 8.840 Alachua	Granite	SPM 07-5509A	SPM 07-5509A	Permeable Open graded friction course with polymer modified binder
22	NBTL	12.145 to 12.540 Alachua	Limestone	QA 00-9506A	After Grinding	Permeable Open graded friction course with ground tire rubber

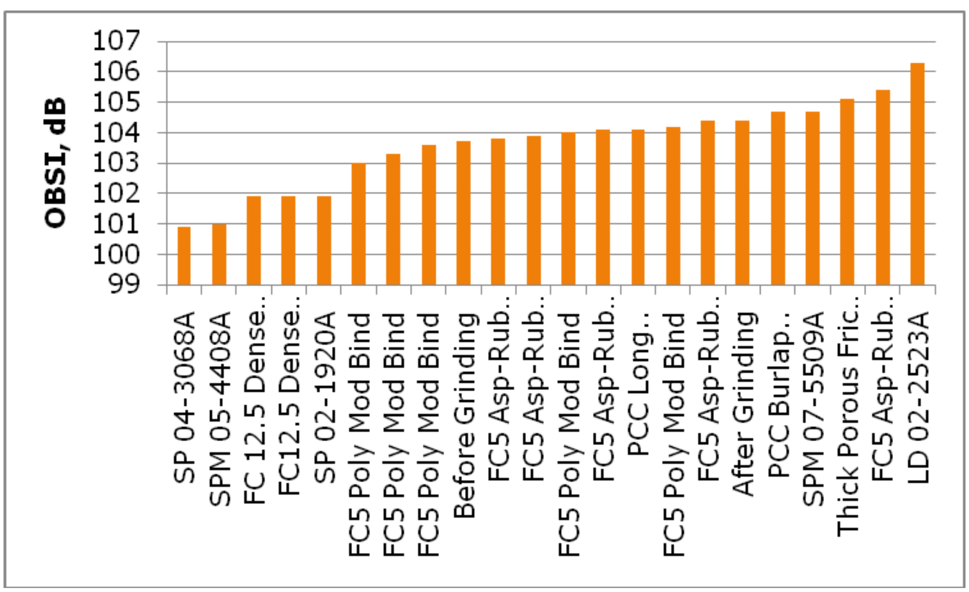


Figure 19. Ranking of OBSI By Pavement Type/Texture

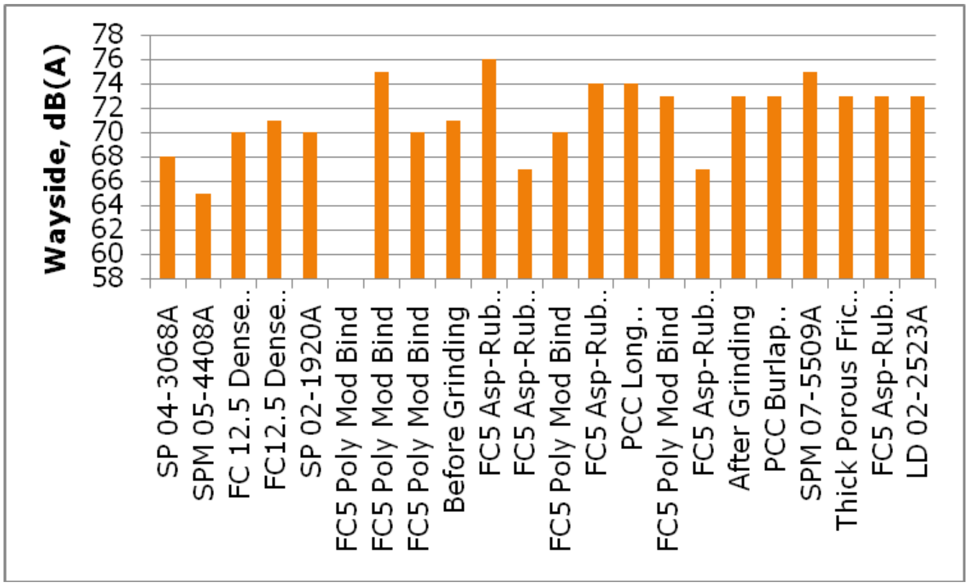


Figure 20. Wayside Sound Pressure Levels [Shown in Same Order as OBSI Ranking]

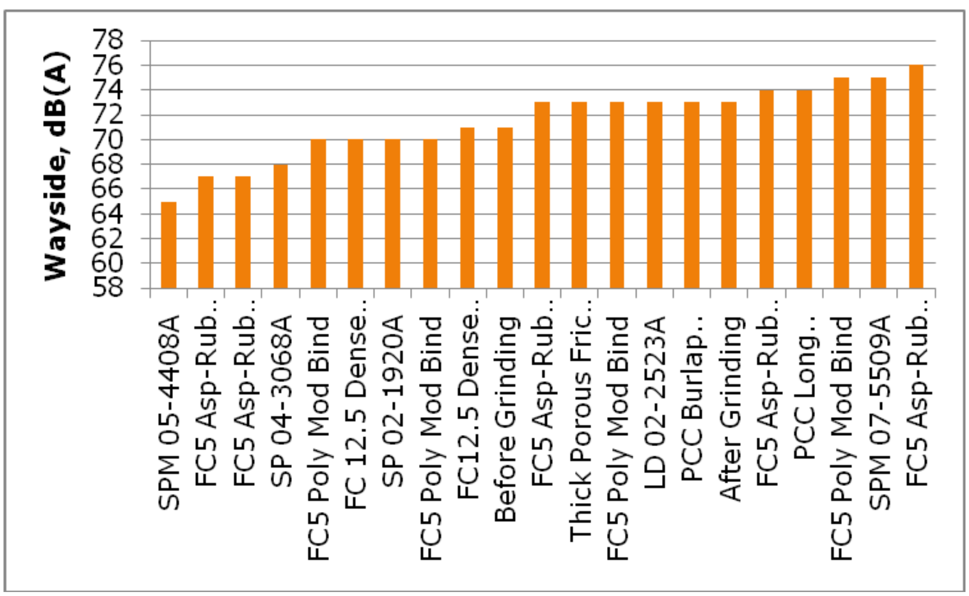


Figure 21. Ranking of Pavement Texture/Types By Wayside Noise Levels

The measurements at the wayside show the following trends:

- PCC pavements became higher in the ranking and were 2.2 dB(A) greater on average that the asphalt pavement average at the wayside (see Figure 20) [only two PCC pavements measured]
- PCC with a burlap bag texture had a higher level at both the tire/pavement interface and the wayside than did the longitudinally tined PCC
- the thick porous friction coat moved down in the rankings from the 3rd greatest OBSI value to the 10th greatest wayside value which indicates significant reduction in the propagation path thought to be primarily due to the pavement surface
- dense graded moved higher in the rankings showing less of a reduction in propagation effects
- the greatest sound levels for the rankings changed from a LD 02-2523A surface from the OBSI measurements to a FC5 permeable open graded friction course with ground tire rubber for the wayside measurements
- The SPM 05-4408A mix (dense graded friction course with polymer modified binder) was the quietest pavement at the wayside primarily due to a very low value at the tire/pavement interface

Again, more detail is needed to make absolute statements and to understand why these trends occurred.

A previous observation was that the numeric difference from the OBSI Intensity Level and the wayside level was on average 32.2 dB less with a standard deviation of 2.5 dB. This difference was between the OBSI and the wayside reference site of 50 feet (15 meters) from the near traffic lane. It was noted the important to note the offset and low standard deviation of the results which allows an approximation using an offset value from the OBSI measurement to determine the wayside SPL. There is an uncertainty of about ±5.4 dB (2.15 standard deviations or ~90 % of the deviation). This 5.4 dB is most likely related to the way the sound propagates to the wayside location and is a large potential error. As previously mentioned, a large part of this propagation effect is related to the pavement surface texture. Figure 22 shows the pavement textures/types ranked by the difference in the OBSI and wayside measurements. As the difference increases, attenuation of the sound from the tire/pavement interface to the wayside increases since distances are the same. A range of approximately 9 dB difference in attenuation occurred for the various pavements. Some of this difference is due to the intervening ground but since these locations are relatively close to the pavement the pavement role is important as well.

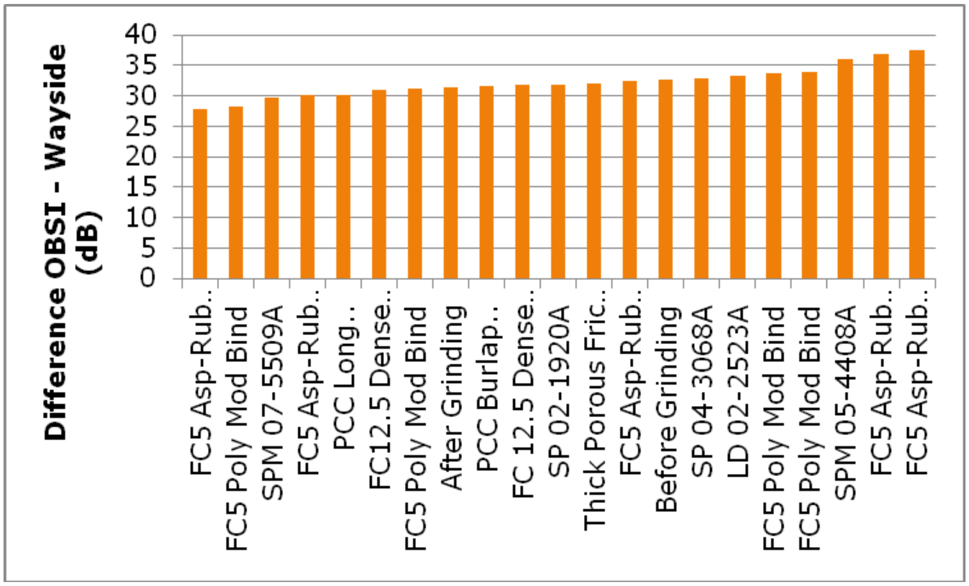
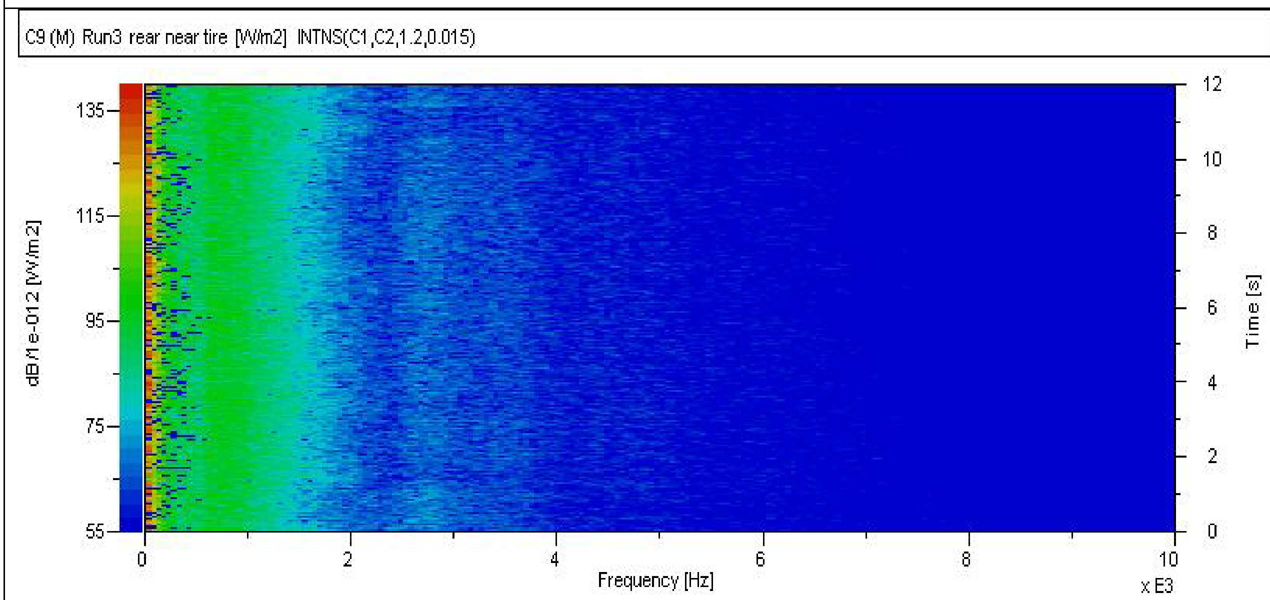


Figure 22. Pavement Texture/Types Ranked by Difference Between OBSI and Wayside Measurements (OBSI – Wayside), dB

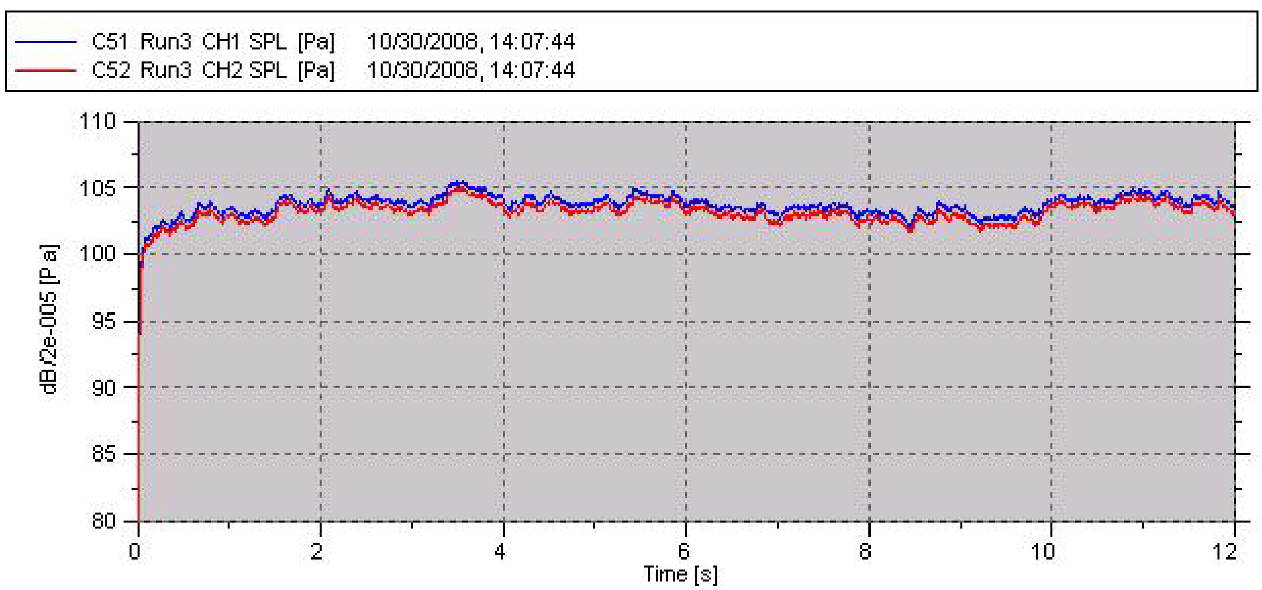
Of interest is that the FC-5 mix with asphalt rubber binder had the two greatest differences between the OBSI measurements and the wayside noise, indicating the greatest reduction of the sound level in the path. FC5 mixes were also 4 out of the top 5 pavements for this reduction. However, FC-5 mixes also demonstrated the lowest two lowest reductions and 3 of the 4 least amount of reduction. The differences in these pavements should be explored in much greater depth to understand why this occurred. Also of note is that the thick porous friction coat was in the mid range.

Frequency dependence on texture/type was also reviewed. Figures 23 and 24 present an example of an asphaltic surface and a jointed PCC surface for contrast. As can be seen, the PCC has a much greater frequency component in the higher frequency bands than does the asphalt example. This is caused by the large macrotexture changes (bordering on megatexture) in the pavements caused by the joints. Very prominent is the joint impacts on the tire in the PCC time history. The joints (macro- to megatexture characteristic) as well surface variations result in a greater variation in the OBSI recorded levels. As such, the asphalt being a smoother surface resulted in less noise at the tire interfaces with the pavement. Two things are worth noting. First, this example is just to show the sensitivity of the OBSI testing to surface changes and a jointed PCC surface was selected for this reason. Second, this is just an example and is not meant to imply PCC surfaces always create greater sound levels at the tire/pavement interface or imply any findings on propagation effects across the pavement surface. This is evident from the measurements where the two PCC surfaces were in the bottom half of

Asphalt Example Results



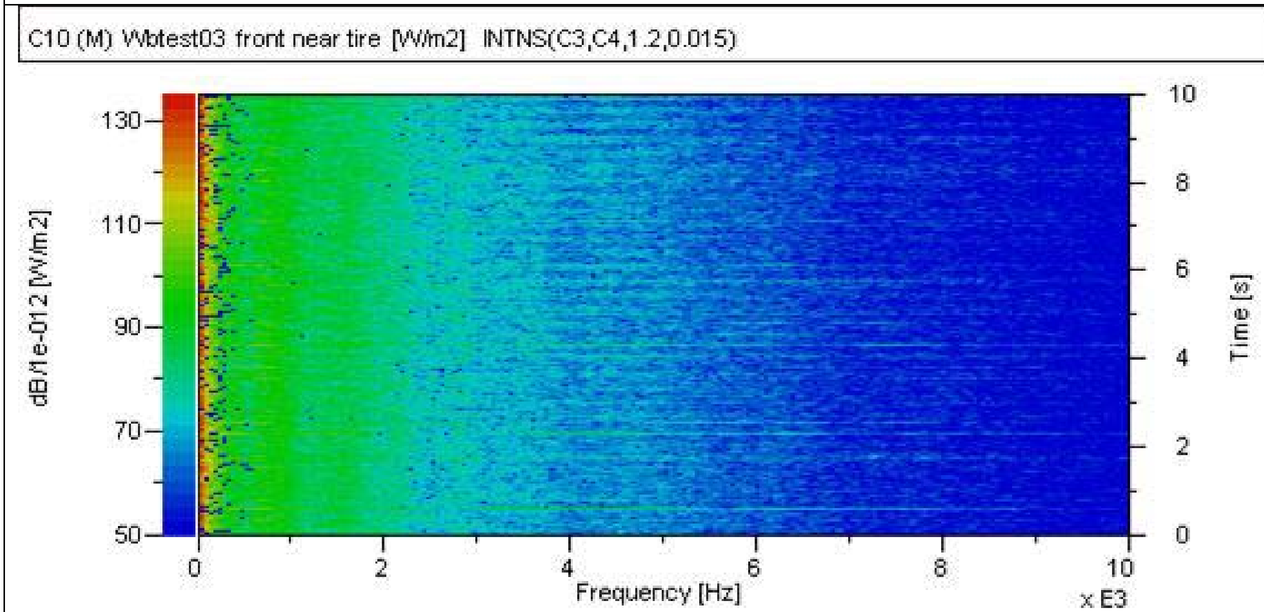
a) Intensity Spectra



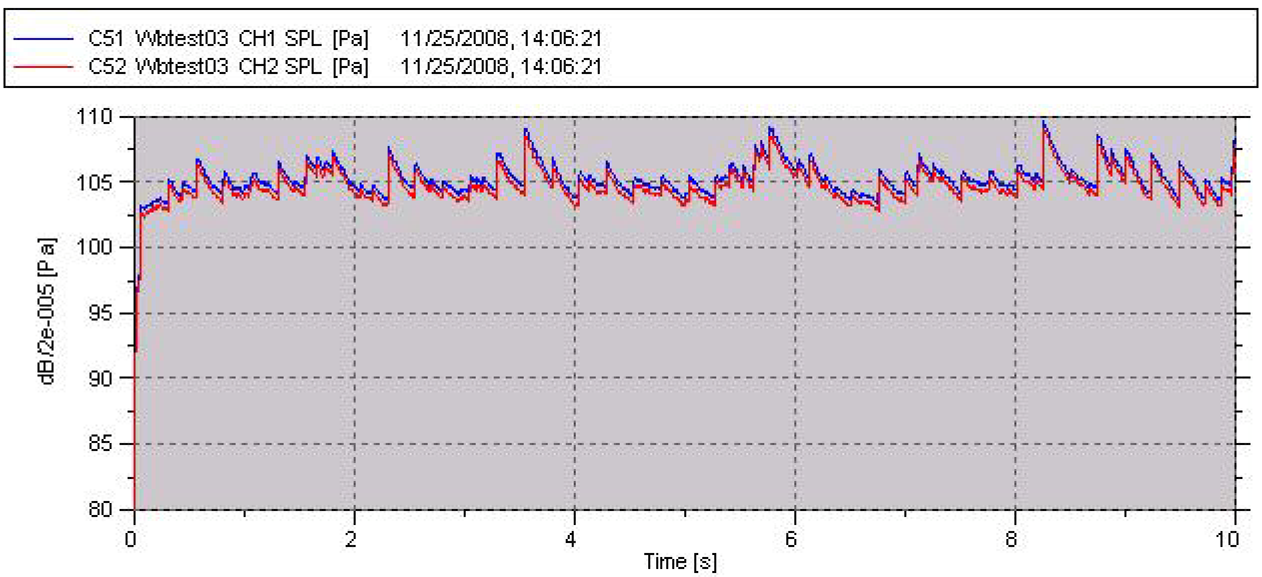
b) Time History

Figure 23. Example of an Asphalt Pavement Results

Example of Jointed PCC Results



a) Intensity Spectra



b) Time History

Figure 24. Example of Jointed PCC Pavement Results

samples of sound at the source (OBSI measurement) but were in the top half of sound at the wayside. This indicates that the PCC surfaces measured created less sound at the tire/pavement interface on average but the reduction attenuation due to the surface was less on average than for the asphalt pavements. Additionally, it should also be noted that these comparisons were for only two PCC surfaces.

This example of the measurement sensitivity does illustrate that changes in the surface texture could be used to control the sound created at the tire/pavement interface and can be measured with the OBSI method and FDOT equipment. More information and work is needed to determine the exact parameter changes to reduce the generated sound and how this affects the propagation of the sound across the surface.

Data were supplied by FDOT on the pavement characteristics. One such parameter was the friction number for both smooth and ribbed tires and was available for 8 of the locations at 50 mph (80kph). Other speeds were also supplied, but 50 mph (80 kph) values were used to be closer to the speed where OBSI measurements were made. While friction is more a function of the microtexture which does not have a great effect on the sound generation, it could be related to other parameters that do have an effect on the noise generated at the tire. These 8 locations were reviewed and Figure 25 shows the overall results when the friction number measured at 50 mph (80 kph) for the smooth tire and is compared to the OBSI intensity levels measured at 55 mph (88 kph). Here, and for all subsequent figures, the best fit regression analysis line is shown. It can be seen that a somewhat strong correlation exists between the OBSI measured levels and the friction number. The correlation for the ribbed tire was less and not shown here. The small sample size does not permit absolute findings to be made but does indicate that more work in this area may result in a way to substantiate how the microtexture and macrotexture are related and how changes might be implemented for noise control. Also of note is that the correlation for the wayside sound levels and friction numbers were poor, indicating that propagation effects need to be considered.

The same type of analysis was conducted for the mean profile depth (MPD) with data available at 10 locations. Figure 26 shows that again a somewhat good correlation occurs for the MPD, which represents a measure of the macrotexture as compared to the measured sound levels at the tire/pavement interface. The correlation, while good, was expected to be stronger since macrotexture is a significant parameter for noise generation. The results somewhat mirror the conclusions of Sandberg and Ejsmont discussed in the Chapter on Previous Research Efforts that multiple parameters may need to be considered in the final modeling process. Again, the sample was small and more work is needed to make absolute conclusions.

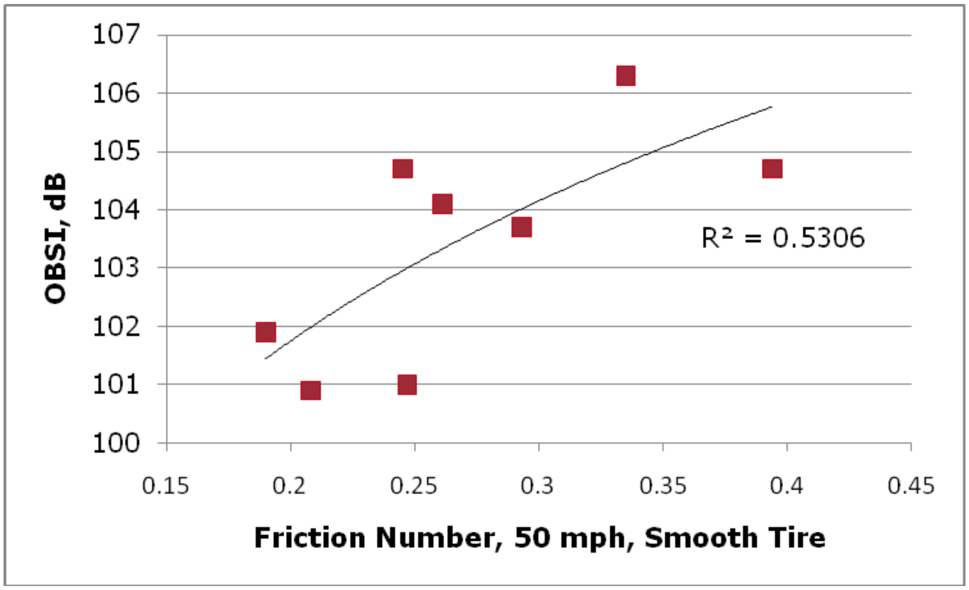


Figure 25. Comparison of OBSI Intensity Levels and Friction Number Measured at 50 mph (80 kph) with a Smooth Tire

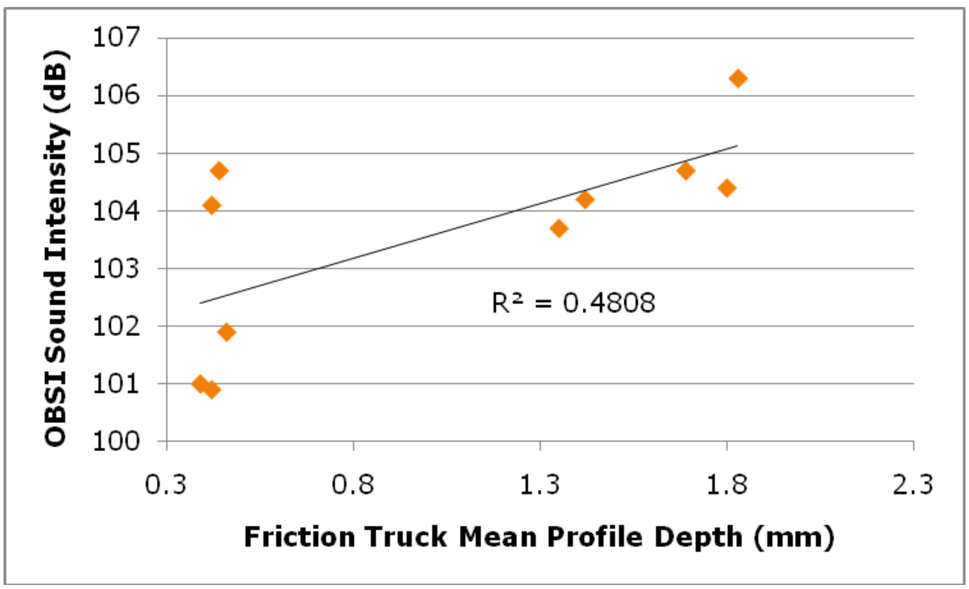


Figure 26. Comparison of OBSI Intensity Levels and Mean Profile Depth in mm (1 mm = 0.039 inches)

Another parameter, directly related to the macrotexture, is the aggregate size used in the mix. Data for 14 locations was compared to the OBSI and wayside measurements. Figure 27 shows the results for the comparison of the nominal maximum aggregate size to the OBSI measurements. Here the correlation was good for the small sample size indicating an area that could be explored in greater detail leading to better modeling and possible noise reductions. Comparisons were also done for wayside and level differences with much less correlation shown indicating that propagation parameters need to be considered.

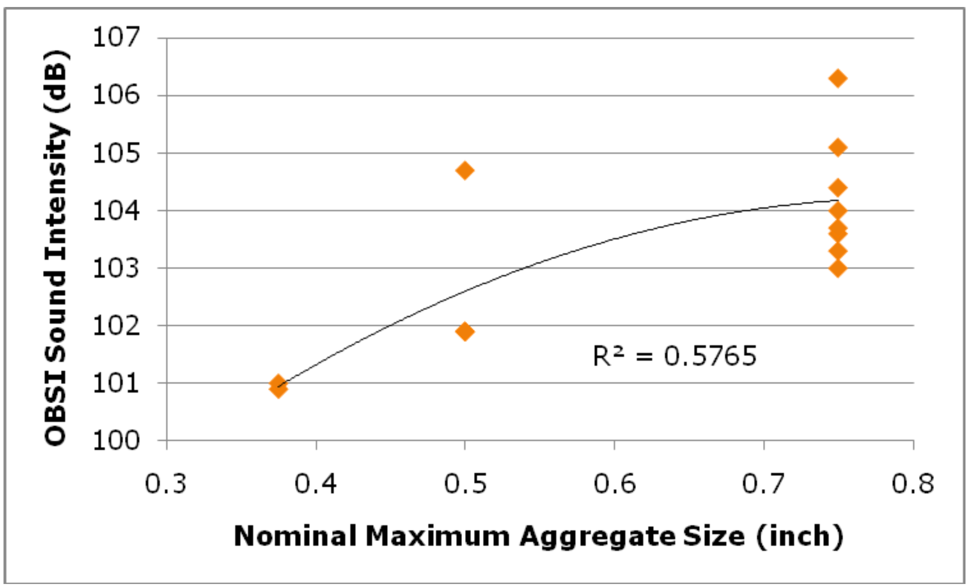


Figure 27. Comparison of OBSI Intensity Levels and Nominal Maximum Aggregate Size in Inches (1 inch = 2.54 cm)

Porosity is usually considered an important parameter for the wayside noise since it is considered to have a significant effect on the propagation of sound across the pavement surface. Figure 28 shows the results from the sand patch comparison, a measure of the porosity as compared to the OBSI measured levels. Data were available for eight of the locations. As shown, the results were not very good although correlation is shown. But as previously indicated, the sample size is very small.

Since the porosity is considered an important parameter for propagation effects, a better correlation was expected when compared to the measured wayside levels and the level

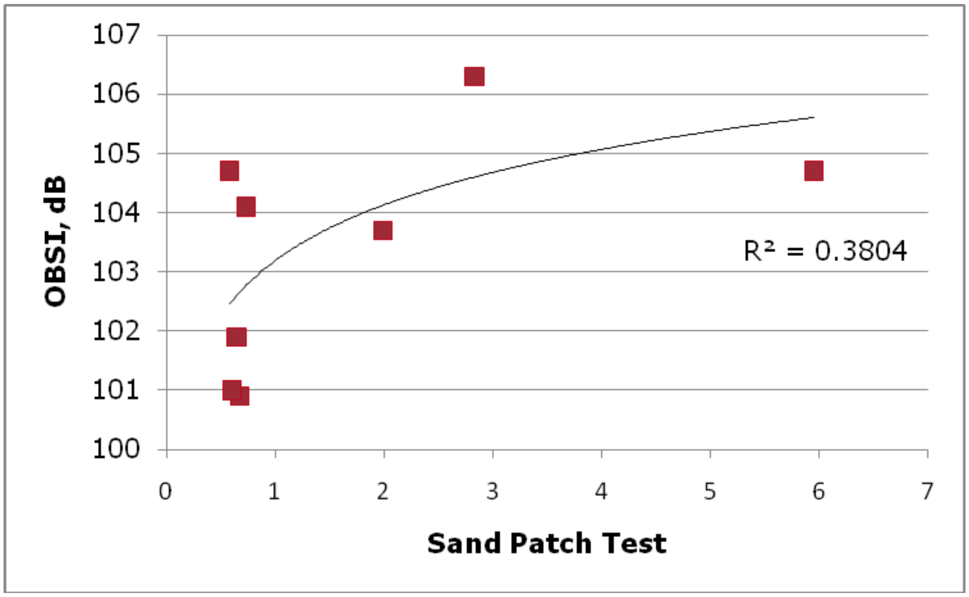


Figure 28. Comparison of OBSI Intensity Levels and Values for Sand Patch Test

differences (OBSI – wayside). The comparison to the wayside levels is shown in Figure 29. Only a small improvement in the correlation coefficient occurred. Correlation when comparing the sand patch test results to the difference between the OBSI and wayside levels resulted in an even lower correlation coefficient. Although again there is a small sample size, this tends to indicate that either other parameters are coming into play or that the sand patch test does not adequately describe the porosity as needed for modeling of the propagation effects for noise modeling.

Finally, the percent of rubber binder content was correlated to the measured levels. The percent of rubber ranged from 0 to 12. No correlations were significant when the rubber binder content was compared to the sound levels of the OBSI, wayside, or differences between the OBSI and wayside levels.

A review by location is shown in Table 8 of the 8 locations where the pavement data were known for most characteristics. Aggregate size was only known for six of the locations as shown. All are listed by location from the lowest to the highest values occurring. For example, OBSI measurements are ranked by the location number from the lowest to the highest sound intensity levels measured. The other columns follow the same pattern, being ranked by location number according to the values for each listed characteristic measure. The columns were grouped by parameters representing the various pavement characteristics representing microtexture, macrotexture, and porosity as shown in the table.

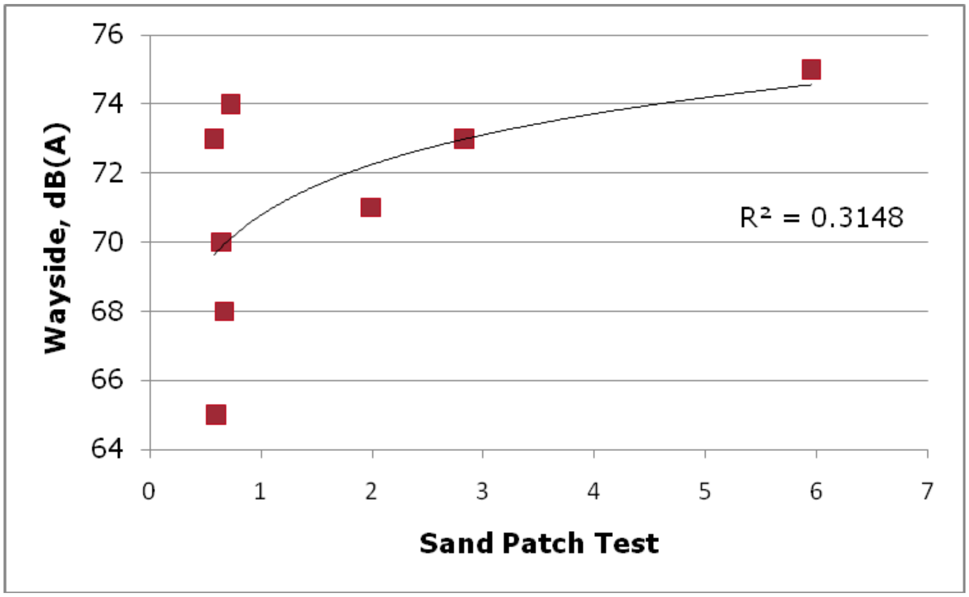


Figure 29. Comparison of Wayside Sound Levels and Values for Sand Patch Test

Table 8. Listing by Location of OBSI and Wayside Sound Levels (dB) and Pavement Characteristic Measures (Friction Number, MPD, Aggregate Size, Sand Patch) in Ascending Order (lowest to highest values)

OBSI	Wayside	Friction Number	MPD	Aggregate Size	Sand Patch
19	20	14	20		18
20	19	19	17	20	20
14	14	18	19	19	14
13	13	20	18	14	19
17	12	17	14	21	17
18	18	13	13	13	13
21	17	12	21	12	12
12	21	21	12		21
Sound Levels		**Microtexture**	**Mactotexture**		**Porosity**

While not in exactly the same order, the four quietest pavements were the same for OBSI and wayside (top four in list) and the pavements with the greatest levels were the same (bottom four in list). Of interest is the grouping of the pavement characteristic measures. The locations of the aggregate size lower three values and upper three values followed the same trend as the measured sound levels. For the friction number, the location of the lowest four values and highest four values, with one exception, was the same as the pavements. This was also true of the sand patch test. The mean profile depth had a mix in that two of the lowest values at locations were the same as the measured noise levels and of course the same trend occurred for the higher values. Again, this is a small sample size but it is encouraging that these values may be used to develop a model to estimate the effects of pavement characteristics on the generated sound and the sound at the side of the roadway.

The characteristics need to be explored further and much more in depth at some locations. For example, Location 18 is among the four locations with the greatest sound levels but has a lower friction number, midlevel mean profile depth, and the lowest sand patch value. This again indicates that a complete sound generation and sound propagation model must be a combination of the microtexture characteristic (friction number in this case), the macrotexture (mean profile depth, aggregate size) and the porosity (sand patch test). This ranking also points out the importance of aggregate size which was in agreement with sound level rankings and had the highest correlation value.

Other observations indicate that modeling may be possible with more data. Location 21, the second greatest value for OBSI and greatest value of the wayside sound levels is also the greatest value for surface friction, the second greatest value for mean profile depth, in the top half for aggregate size, and is the greatest value for porosity. Location 19, the lowest value for OBSI and second lowest value for wayside is in the lower half values for all pavement characteristics. The same occurs for Location 20 although the ranking is switched for OBSI and wayside. This indicates as expected that the greater values of microtexture (surface friction) and macrotexture (mean profile depth and aggregate size) result in greater noise levels.

The sand patch test rankings were unexpected. The results did not show trends in reduction from the propagation path with Location 21 having the least difference in levels (OBSI to wayside) of the eight locations but in this ranking the highest porosity value. This is counter-intuitive and indicates that the sand patch test may be providing a better measure of surface roughness (macrotexture) than porosity. This conclusion is further reinforced by the correlation of sand patch and the difference in levels (OBSI – wayside) resulting in an extremely poor correlation coefficient ($R^2 = 0.1186$). Again, this points to having more information of the pavement textures/types for the locations to expand the evaluation.

Multivariate analysis of similar variables was also reviewed and should be continued. However, with only six complete data points multivariant sampling results would be questionable. As such, and as a first look, the product of the pavement characteristics were reviewed as compared to the measured sound levels. Figure 30 shows that in this very simple first approach, the results were quite good compared to the measured OBSI sound intensity levels. This is quite encouraging that modeling may be quite possible with more data.

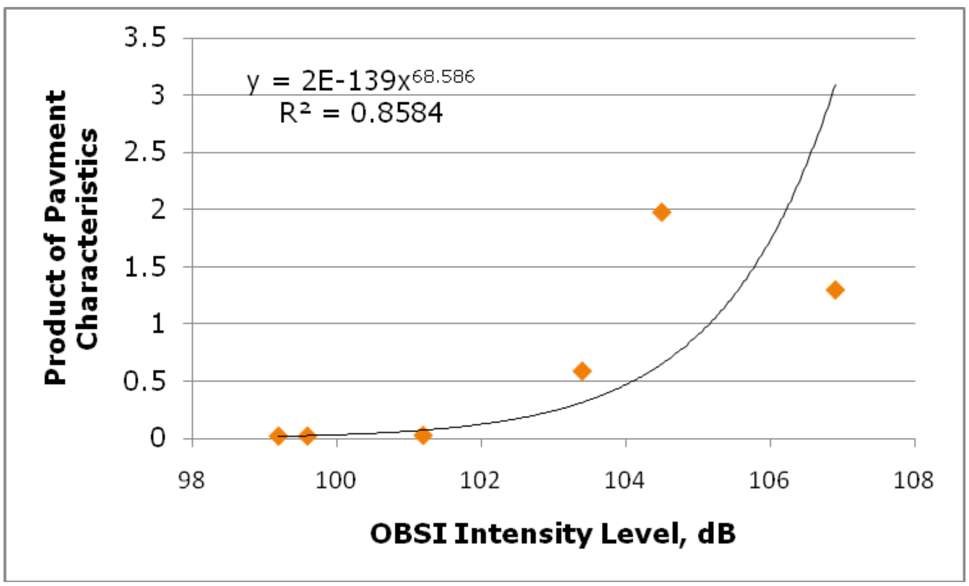


Figure 30. Comparison of the Product of Pavement Characteristics to OBSI Intensity Levels

Continuing the analysis Figure 31 shows the results when compared to wayside levels and again the results were amazing good. Again showing modeling may be quite possible for this complex phenomenon.

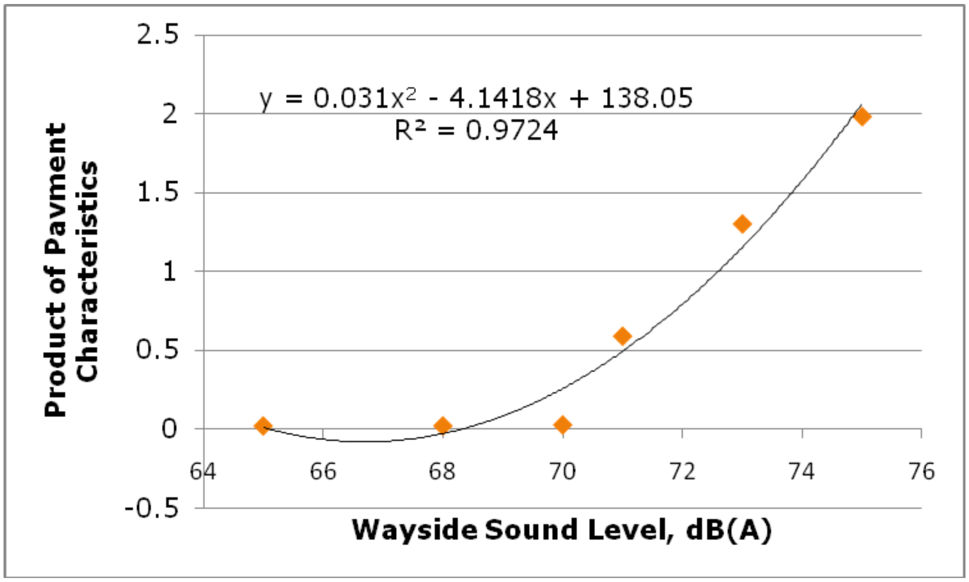


Figure 31. Comparison of the Product of Pavement Characteristics to Wayside Sound Pressure Levels

Another propagation parameter was also reviewed; the spectra of OBSI as compared to the wayside level (see Figure 13 as an example). The spectra exhibited similar shapes with the biggest difference being in the range of 500 to 1000 Hertz. This is most likely due to the ground attenuation of these middle frequencies at the wayside location. This assumption is strengthened when the locations further from the highway and at greater elevations above the ground were reviewed. As such, changes in frequency content from the tire/pavement interface to the wayside need to further investigated.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

The objectives of the project as described in the introduction have all been met or exceeded. The last goal, "to eventually lead to the possibility of pavement type as a mitigation method working with the Federal Highway Administration (FHWA) in the Quiet Pavement Pilot Program" is as stated an on-going task that will require additional measurements over time. FHWA has not established quiet pavements as a mitigation measure at the current time. Only states with significant data over multiple years are allowed any adjustments during modeling. However, this effort successfully begins the FDOT's Quiet Pavement Pilot Program a goal of a Florida adjustment allowed based on continued measurements.

Other applicable conclusions from this effort include the following:

- A working trailer based system has been developed for OBSI measurements in Florida. This system, being trailer based, should provide continuity for continued measurements. It is recommended that the prototype design for the test rig (sound intensity probe mount) be further developed based on the experience now gained.
- A methodology for data collection using the OBSI equipment has been established and can be continued following guidelines for standard testing now in draft form.
- 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 have been formed for Florida highways. This work should continue to further develop this data base. Specific surfaces such as the FC-5 pavements and the differences in pavement characteristics causing changes in generated sound levels should be reviewed.
- Multiple pavement textures/types used in Florida have been ranked by both the sound generated at the tire/pavement interface using the OBSI method as well as at the wayside (Figures 18 and 19).
- For the two PCC pavements measured, 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 for reducing noise in the propagation path (difference between OBSI and wayside levels) but where also 3 of the 4 surfaces with less reductions. Understanding why this occurred is paramount to the overall goals of FDOT.

- 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) has been determined. This difference provides 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

  It must be noted that this first approximation method has a possible error of ±5.4 dB(A). Further work is needed 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) tend 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. But more measurements are needed to better quantify this relationship for the micro and macrotextures the variables represent. The relationship between the textures and these key characteristics should 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 tends to indicate a strong possibility for future modeling of wayside sound levels based on OBSI testing. However, as noted by Sandberg and Ejsmont, this should not be considered a simple task even though the preliminary results are quite encouraging.
- Frequency differences in the spectra between the OBSI measurements and the wayside measurements should be 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 is needed.
- A comparison of the equipment used for the OBSI to that of Donavan gave very similar results, tending to prove the validity of the data and the system. More comparison to other state equipment is needed to allow a comparison of the Florida data to those states.
- 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.
- All future testing should follow the OBSI standard method now in development.[13]

These findings lead to four immediate possible action items. First, work should occur jointly between the noise analyst and the pavements group to further populate the pavement parameters in the data base allowing additional analysis. Second, participation in testing to compare the Florida test trailer to other state equipment should be done. This will not only validate the data but allow comparison of data collected from state-to-state. Third, measurements should continue with new locations and revisiting some locations for specific parameter characterization to determine how levels change over time as required by the FHWA Quiet Pavement Pilot Program. These measurements should also look at the effects of grinding, overlays, and changes in mix and/or texture by using different measurable pavement parameters for various pavement types used in Florida. Fourth, correspondence with the FHWA should be continued to continue the Quiet Pavement Pilot Program with the goal of modeling adjustments being allowed in the Traffic Noise Model required by FHWA.

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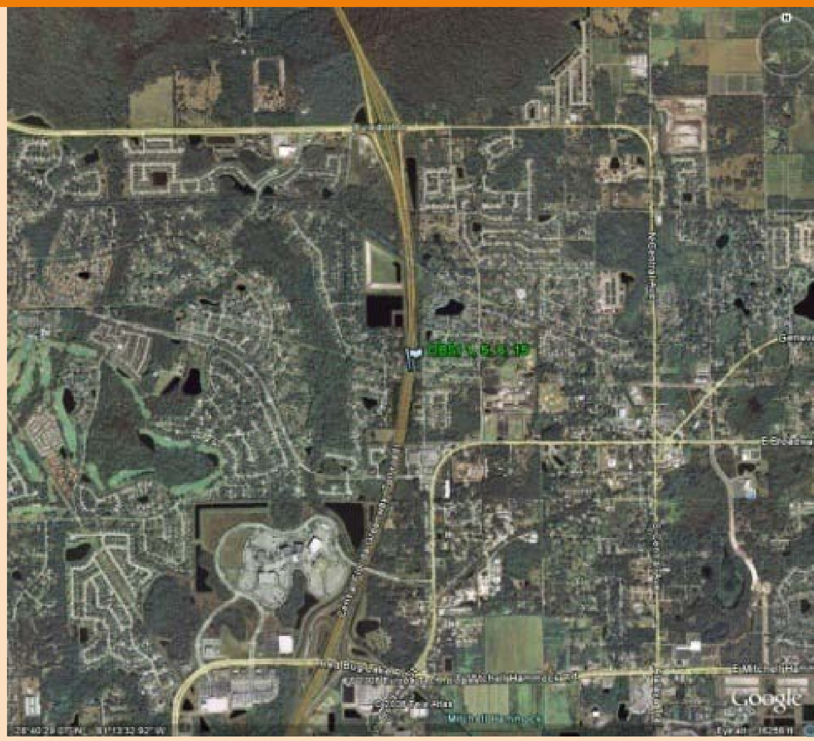
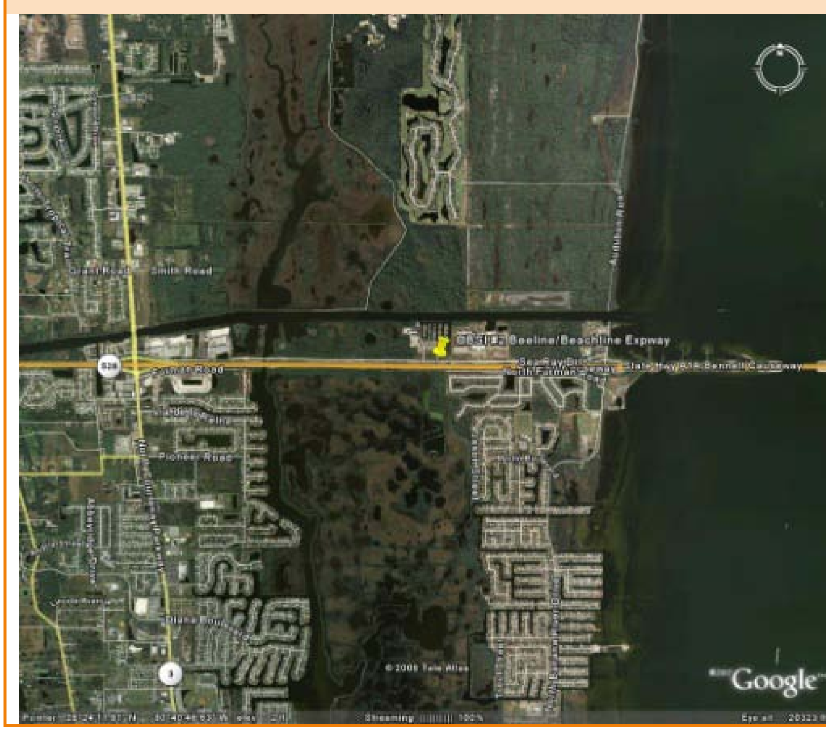
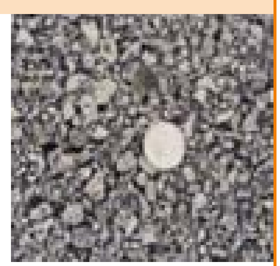
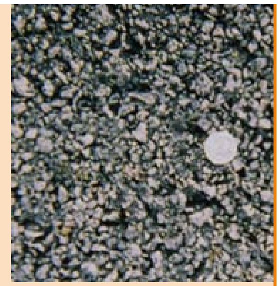
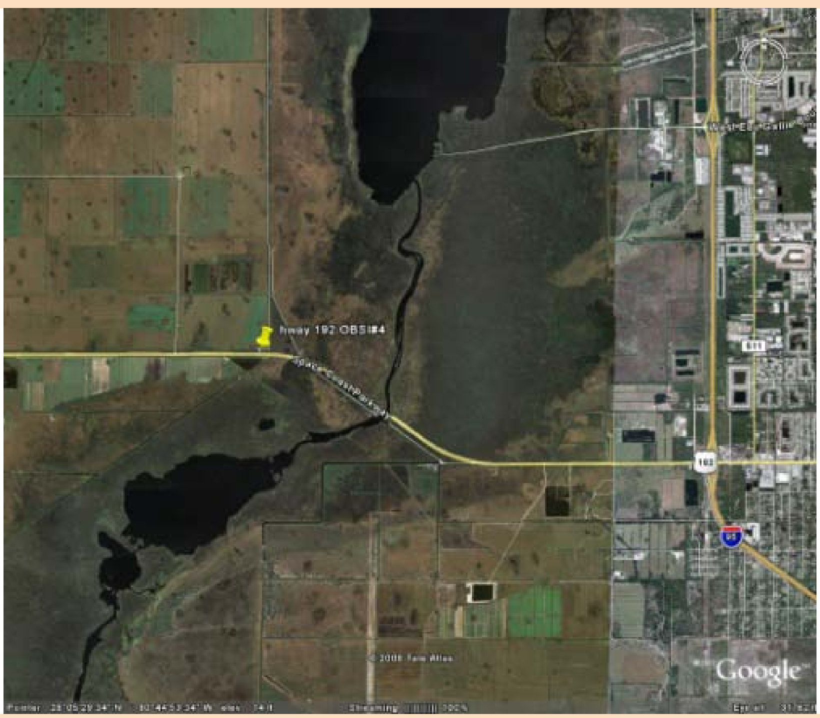
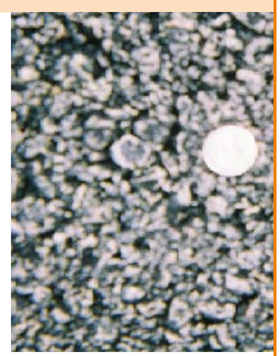
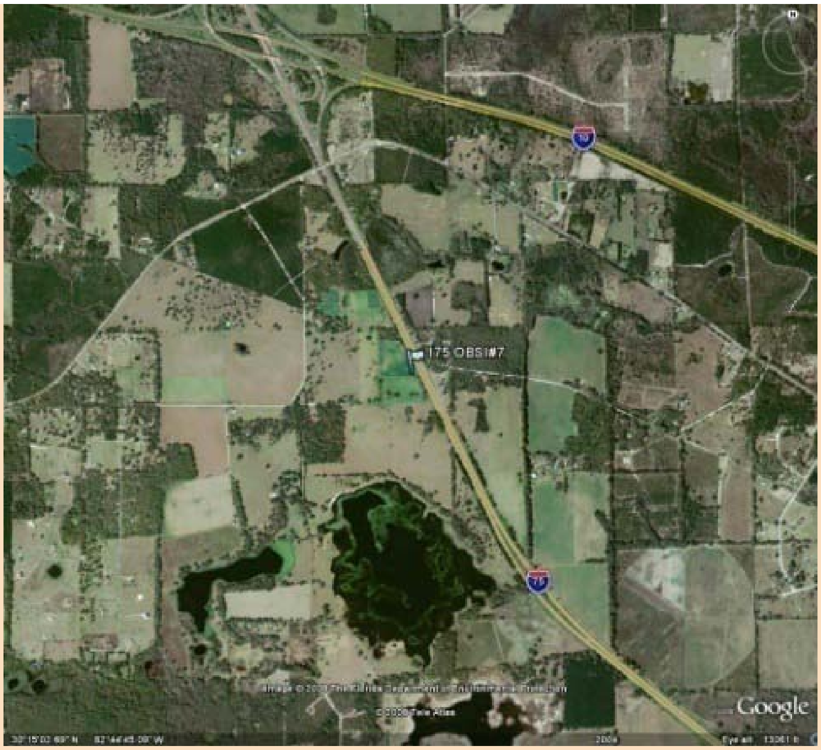
APPENDIX A

Location Aerial Maps And Pavement Texture Pictures

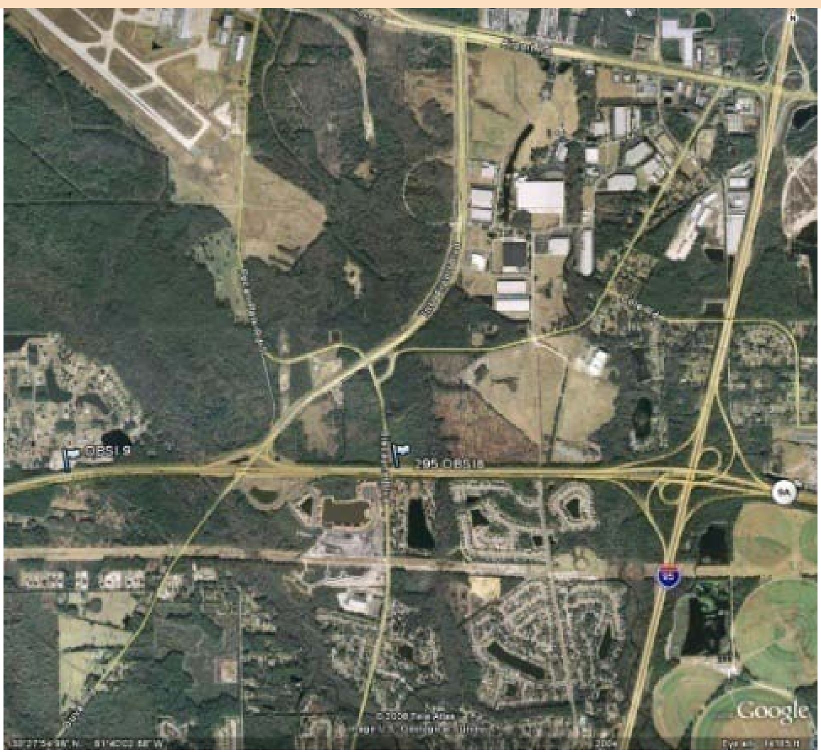
Site	Location Map	Pavement
Location 1 SR 417 Winter Springs		
Location 2 SR528 Beeline		

Location 3 I95 Volusia County	 
Location 4 US192 Melbourne	 
Location 5 SR 417 Winter Springs	Same as Location 1
Location 6 SR 417 Winter Springs	Same as Location 1

Location 7
I75 Lake
City



Location 8
I295 Jax,
Duval



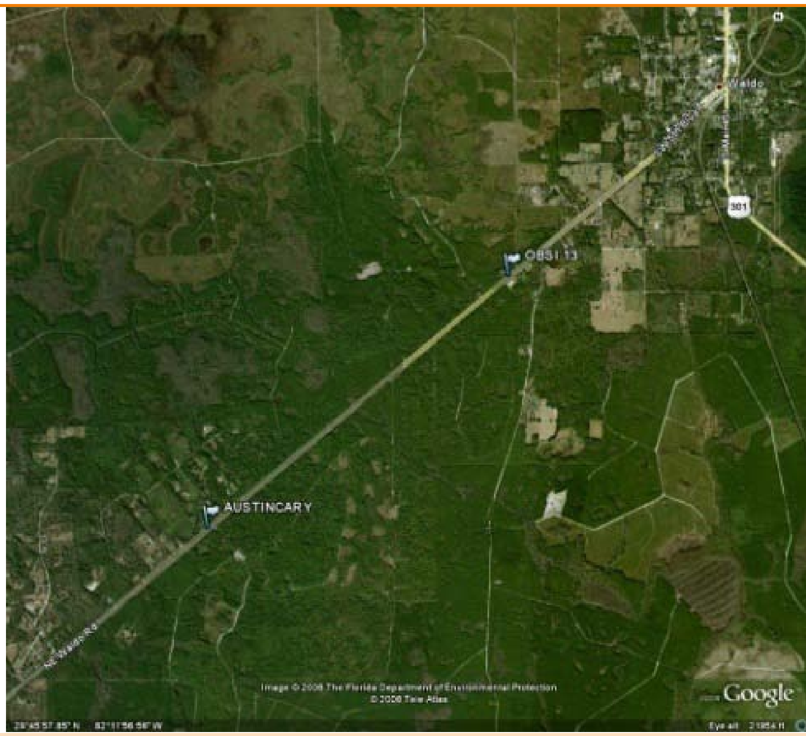
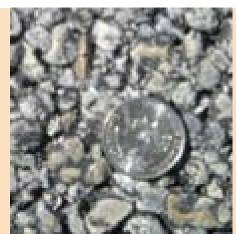
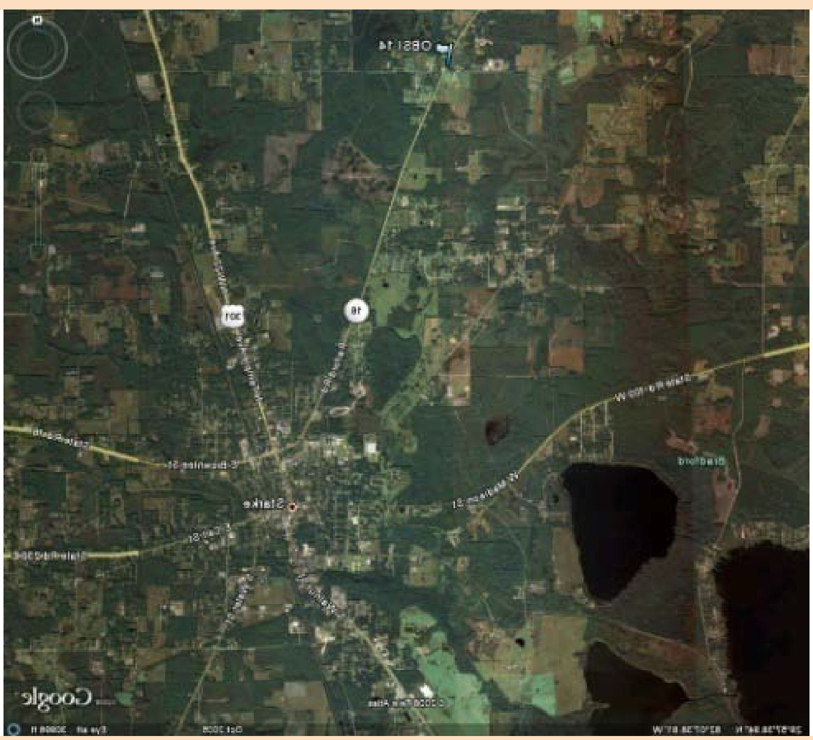
Location 9
I295 Jax,
Lem Turner

See aerial map Location 8

Location 10
SR40
Ocala

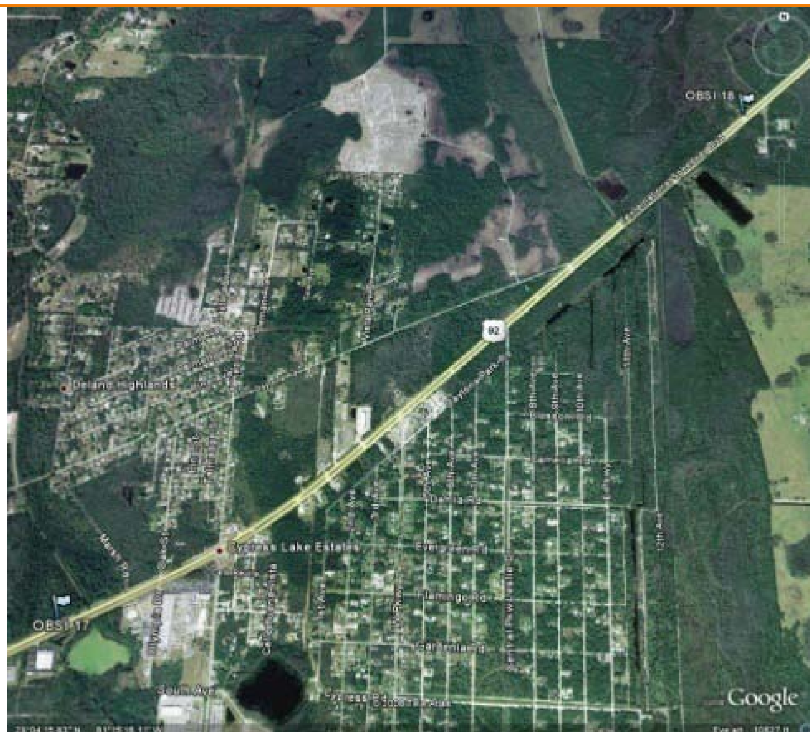
Location 11
SR40
Ocala Natl
Forest

See aerial map Location 10

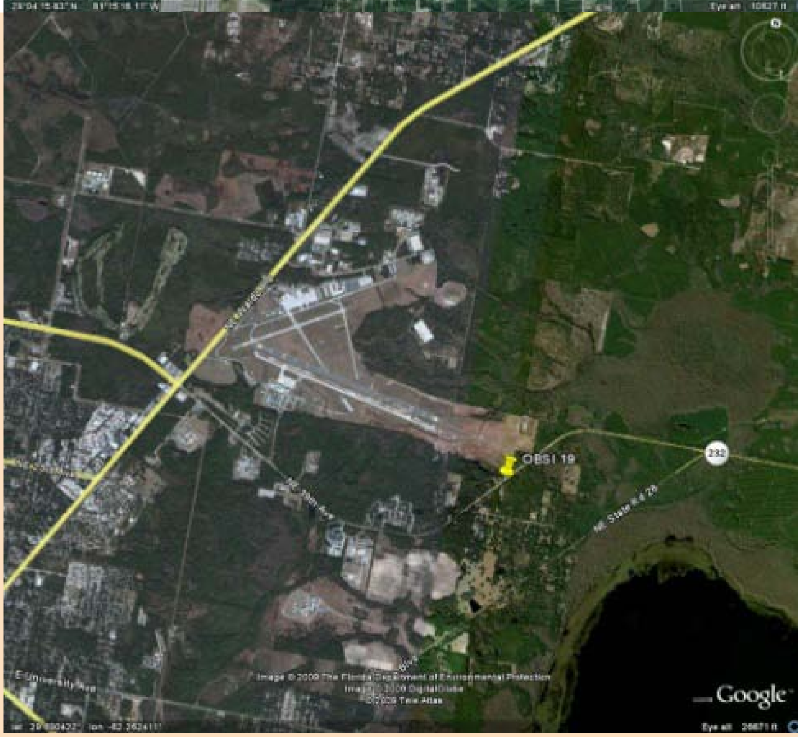
Location 12 SR24 Waldo		
Location 13 SR24 Austin Cary near Waldo	See aerial map Location 12	
Location 14 SR16 Starke		

Location 15 SR 417 Winter Springs	Same as Location 1
Location 16 SR528 Beeline	Same as Location 2
Location 17 US 92, Deland	 

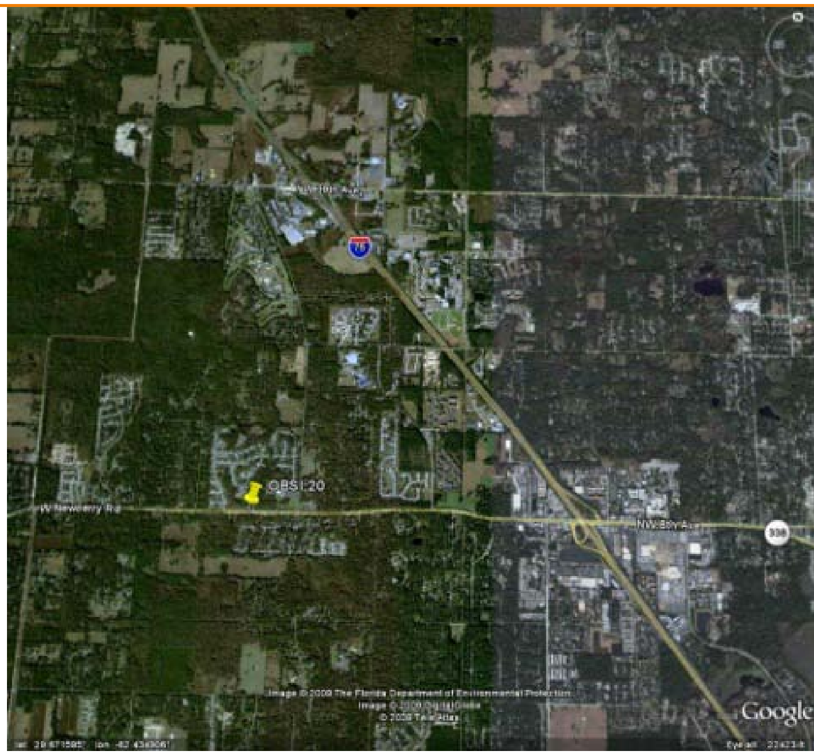
Location 18
US 92,
Deland



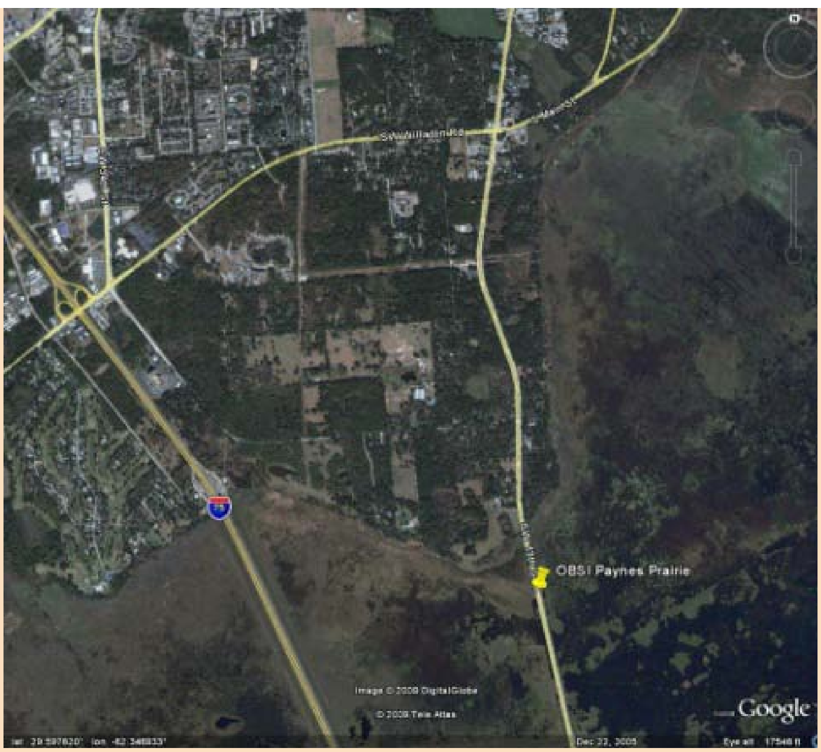
Location 19
SR 222
Gainesville



Location 20
SR26,
Gainesville



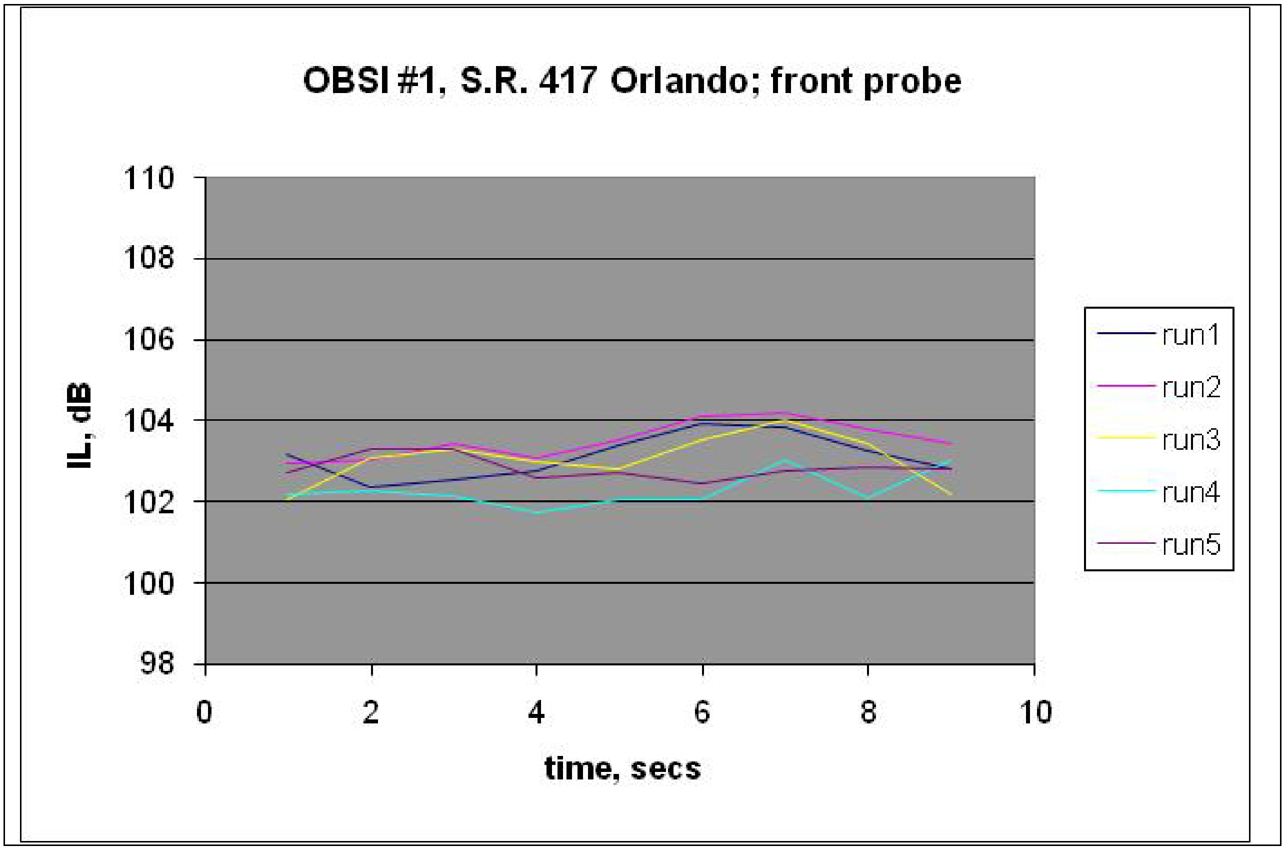
Location 21
Payne's
Prairie,
Gainesville

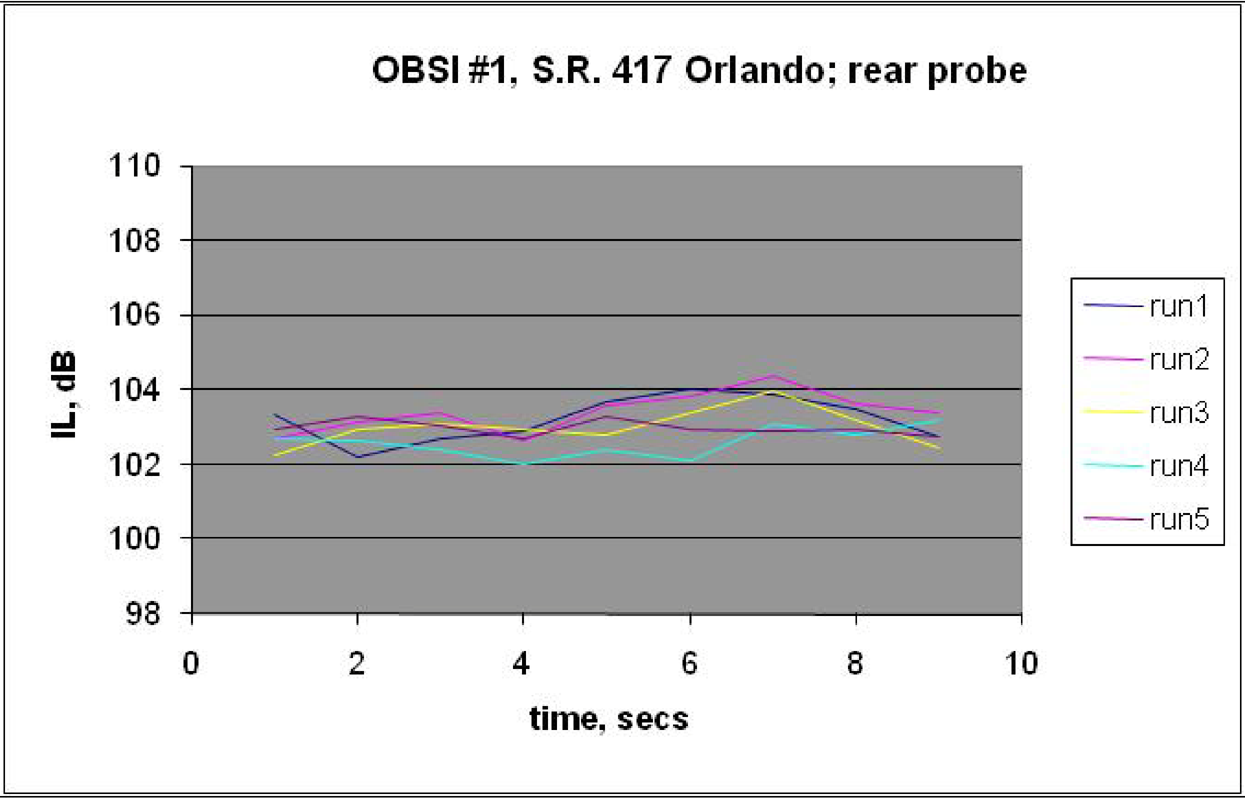


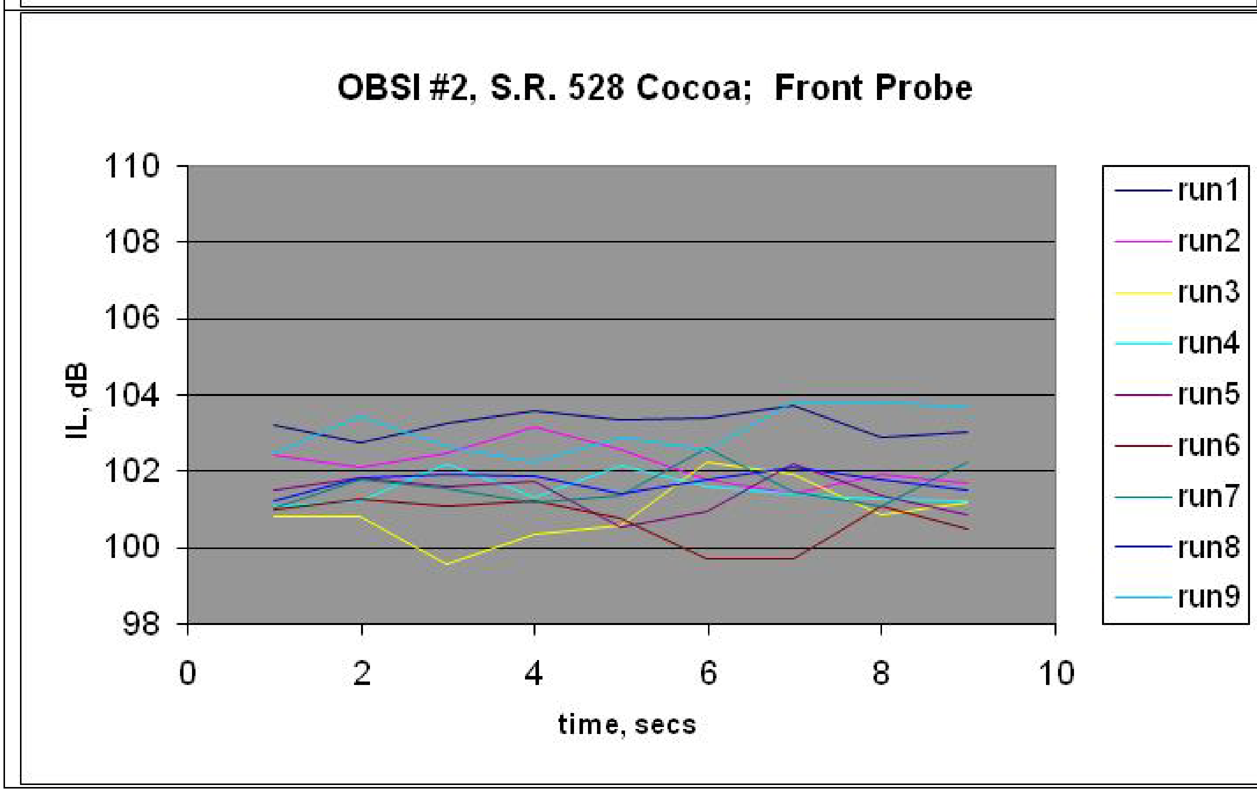
Location 22
Waldo Rd.
SR24,
Gainesville

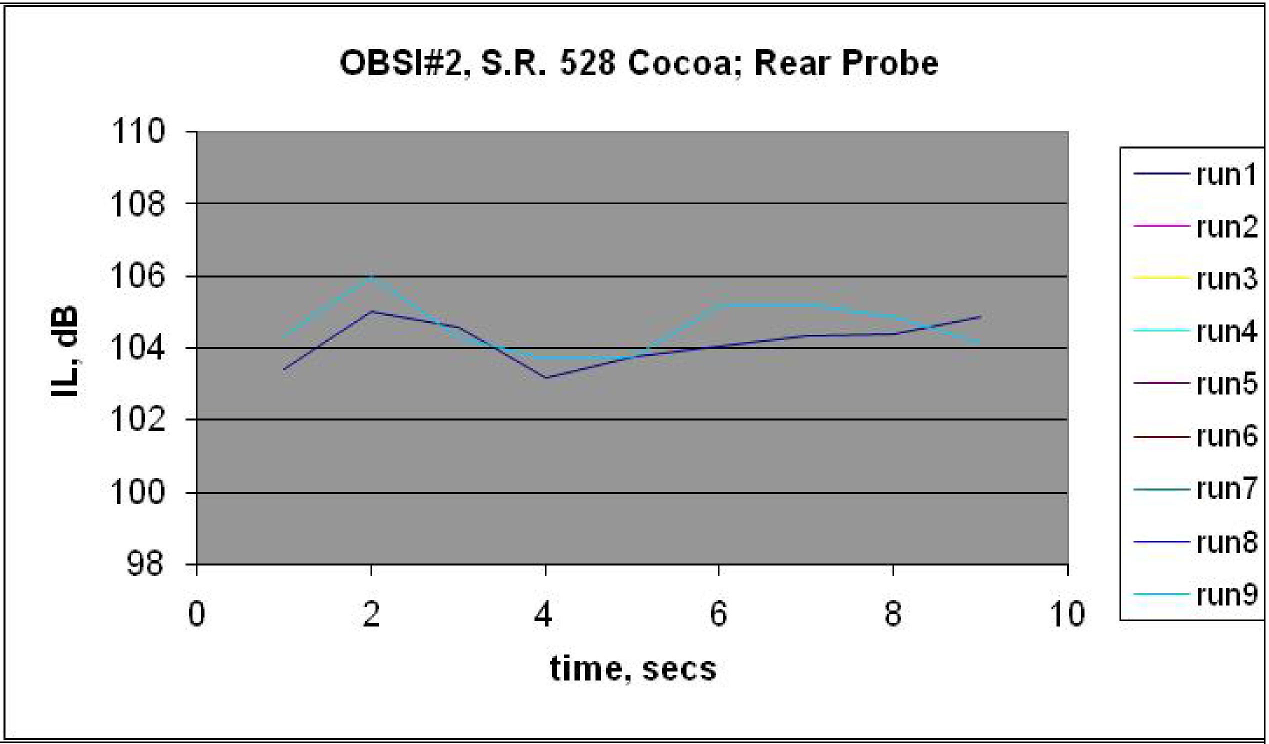
APPENDIX B

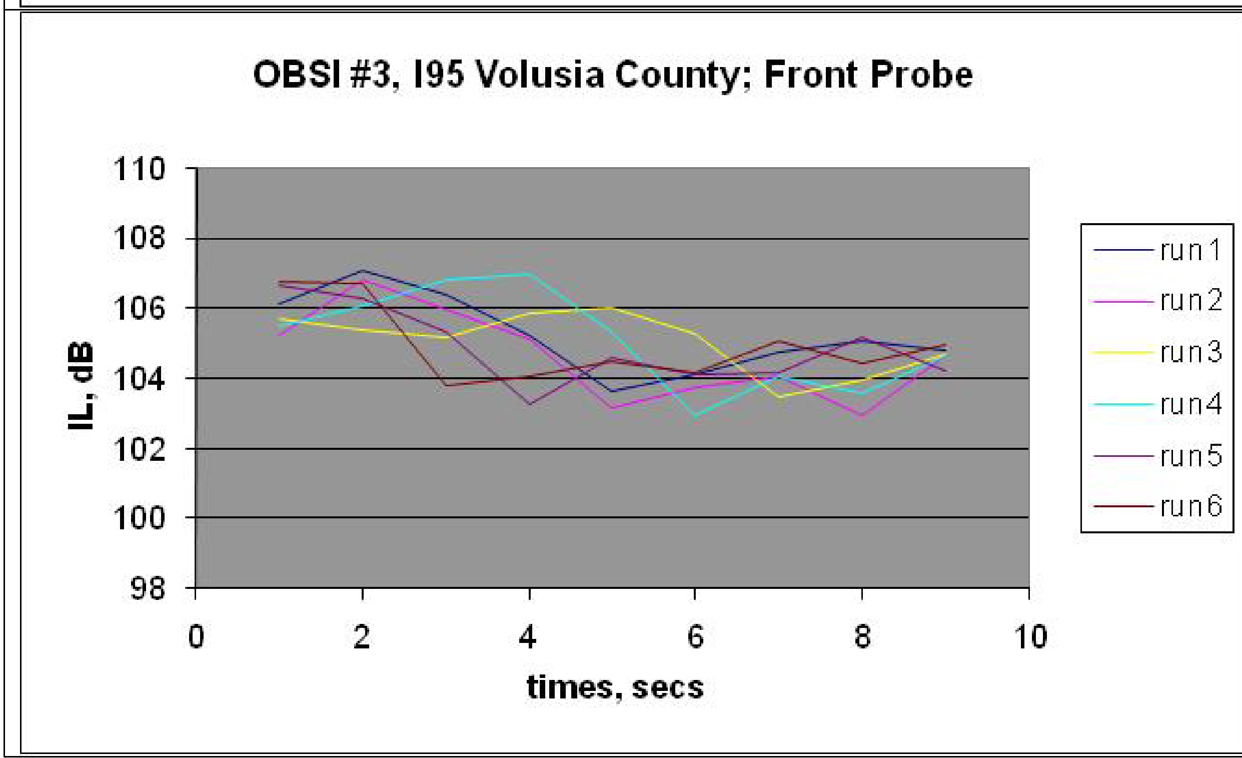
Intensity Levels versus Time at Each OBSI Location

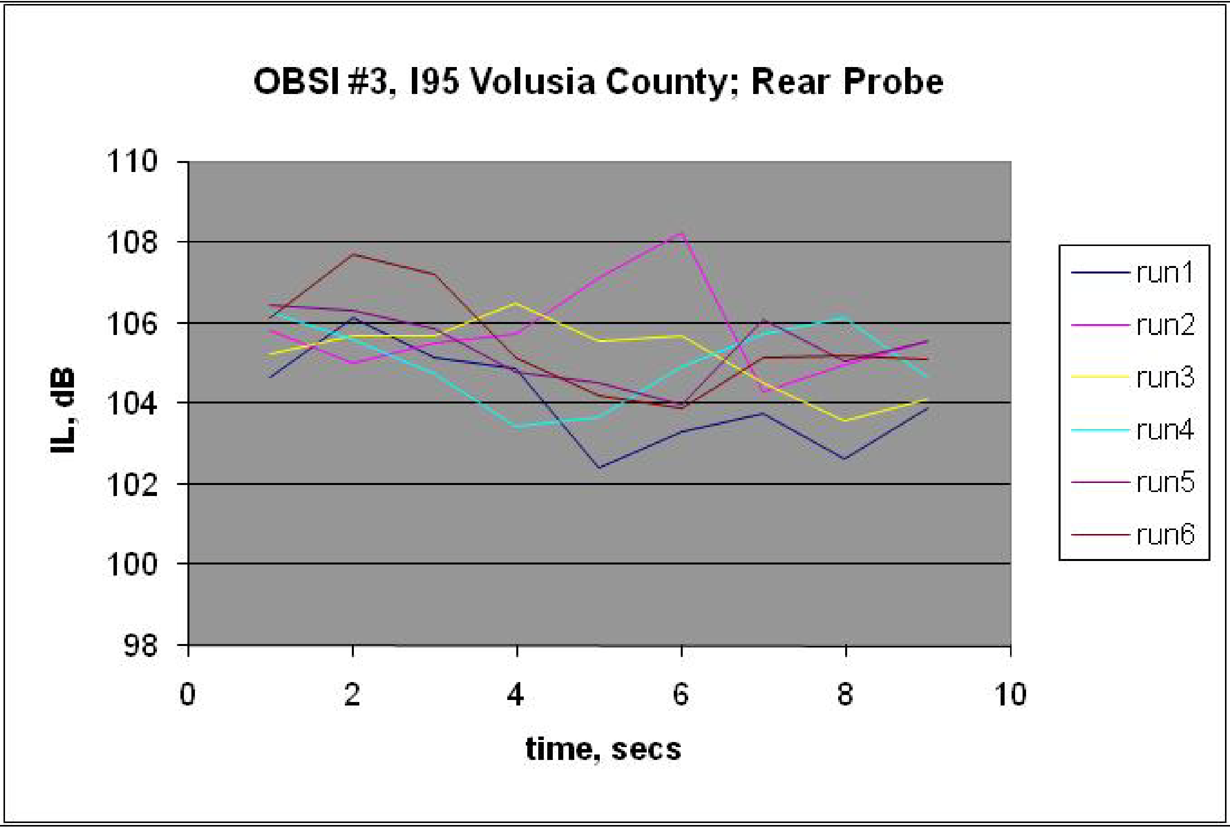

OBSI #1, S.R. 417 Orlando; front probe
110
108
106
104
102
100
98
0
2
4
6
8
10
IL, dB
time, secs
run1
run2
run3
run4
run5

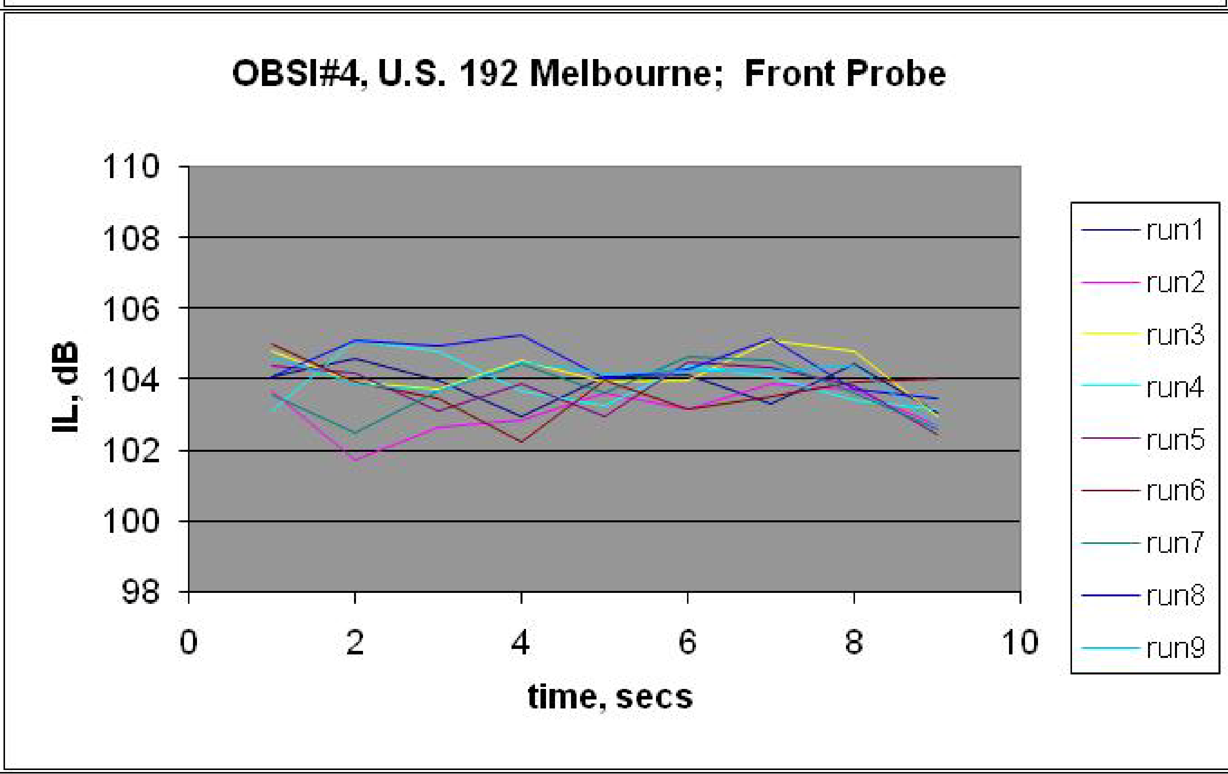

OBSI #1, S.R. 417 Orlando; rear probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time, secs
run1
run2
run3
run4
run5

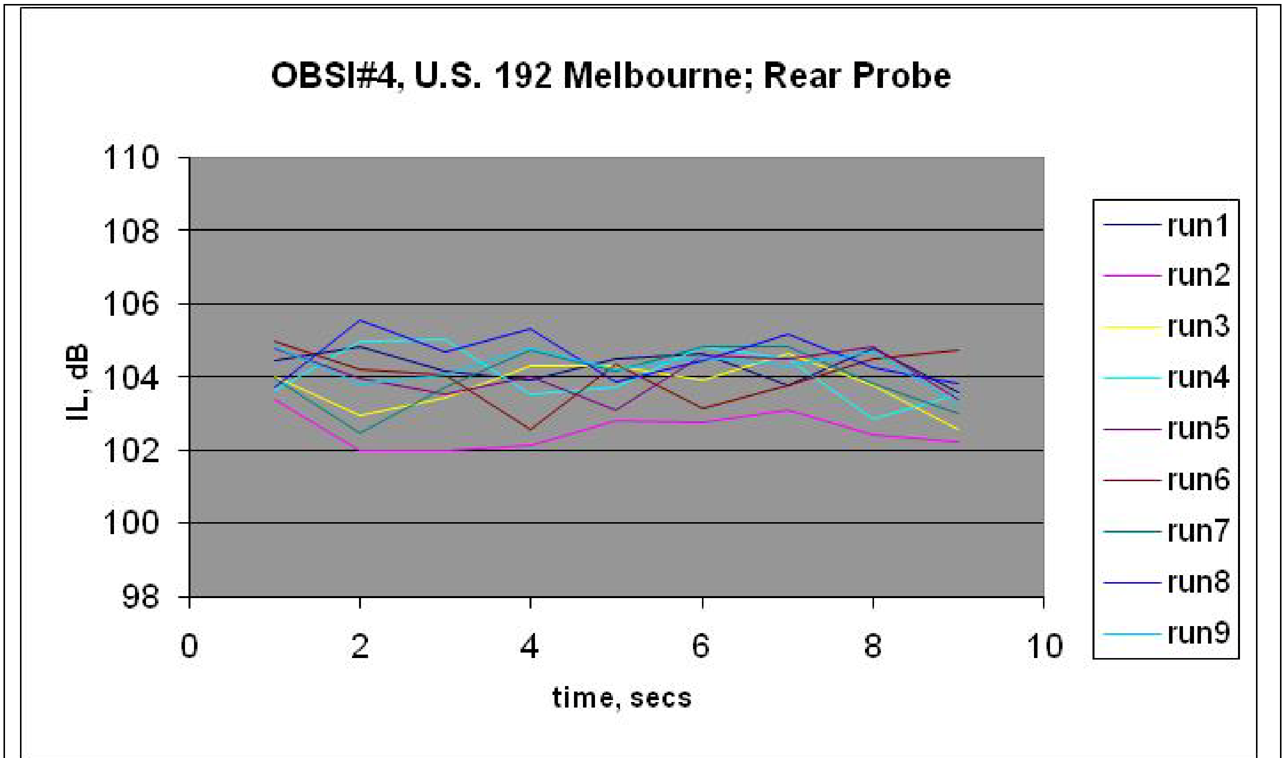

OBSI #2, S.R. 528 Cocoa; Front Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time, secs
run1
run2
run3
run4
run5
run6
run7
run8
run9


OBSI#2, S.R. 528 Cocoa; Rear Probe
IL, dB
110
108
106
104
102
100
98
0
2
4
6
8
10
time, secs
run1
run2
run3
run4
run5
run6
run7
run8
run9

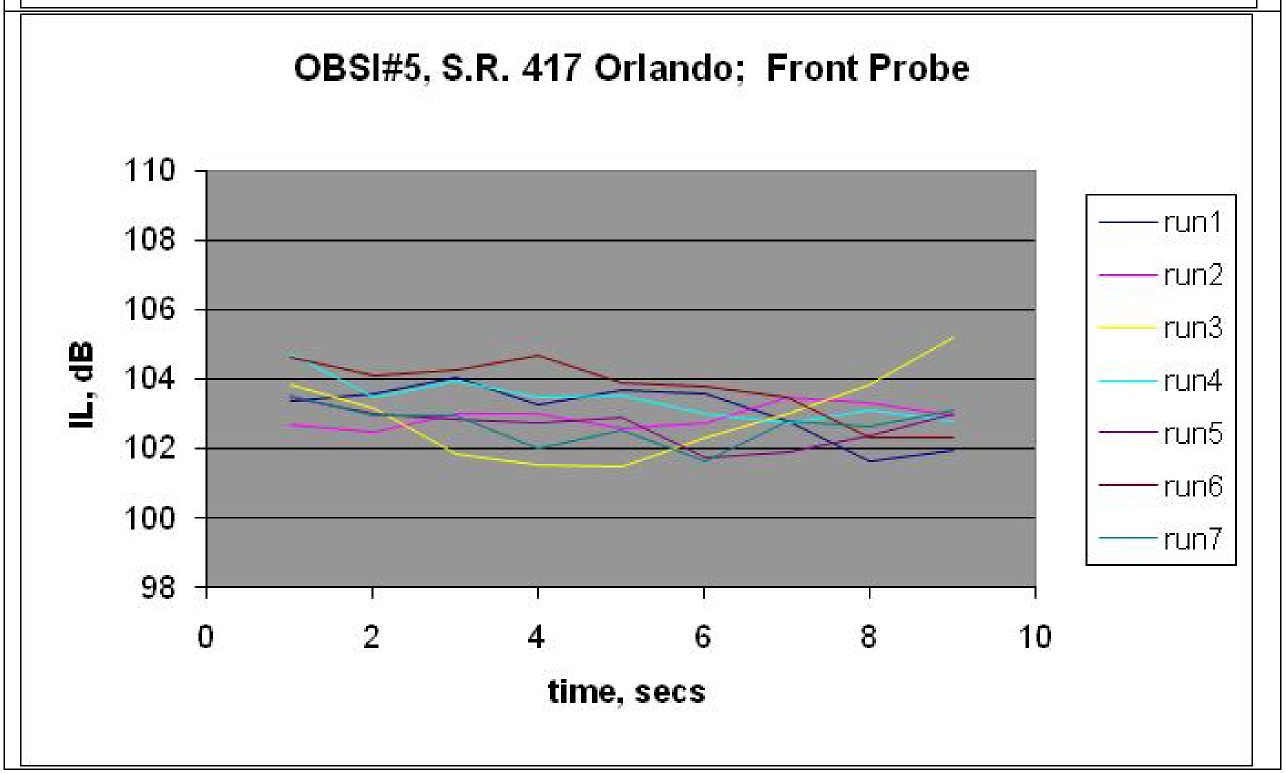

OBSI #3, I95 Volusia County; Front Probe
IL, dB
110
108
106
104
102
100
98
0
2
4
6
8
10
times, secs
run1
run2
run3
run4
run5
run6


OBSI #3, I95 Volusia County; Rear Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time, secs
run1
run2
run3
run4
run5
run6

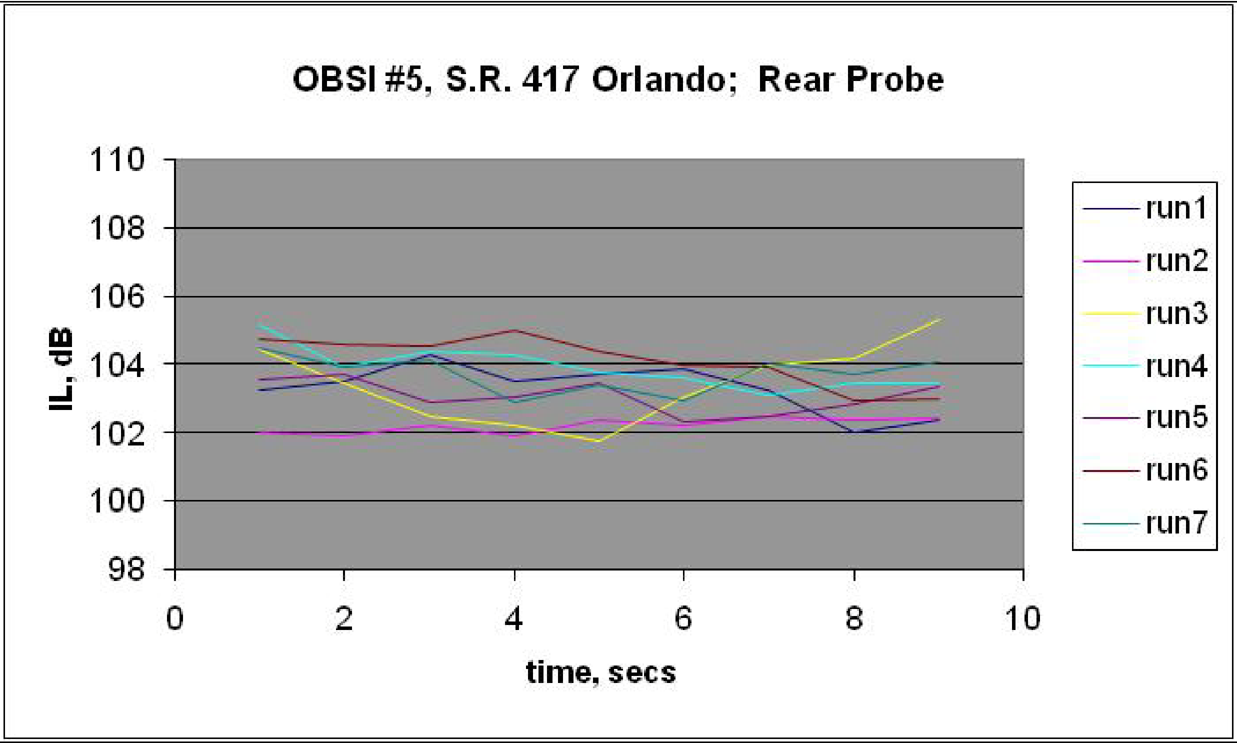

OBSI#4, U.S. 192 Melbourne; Front Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time, secs
run1
run2
run3
run4
run5
run6
run7
run8
run9

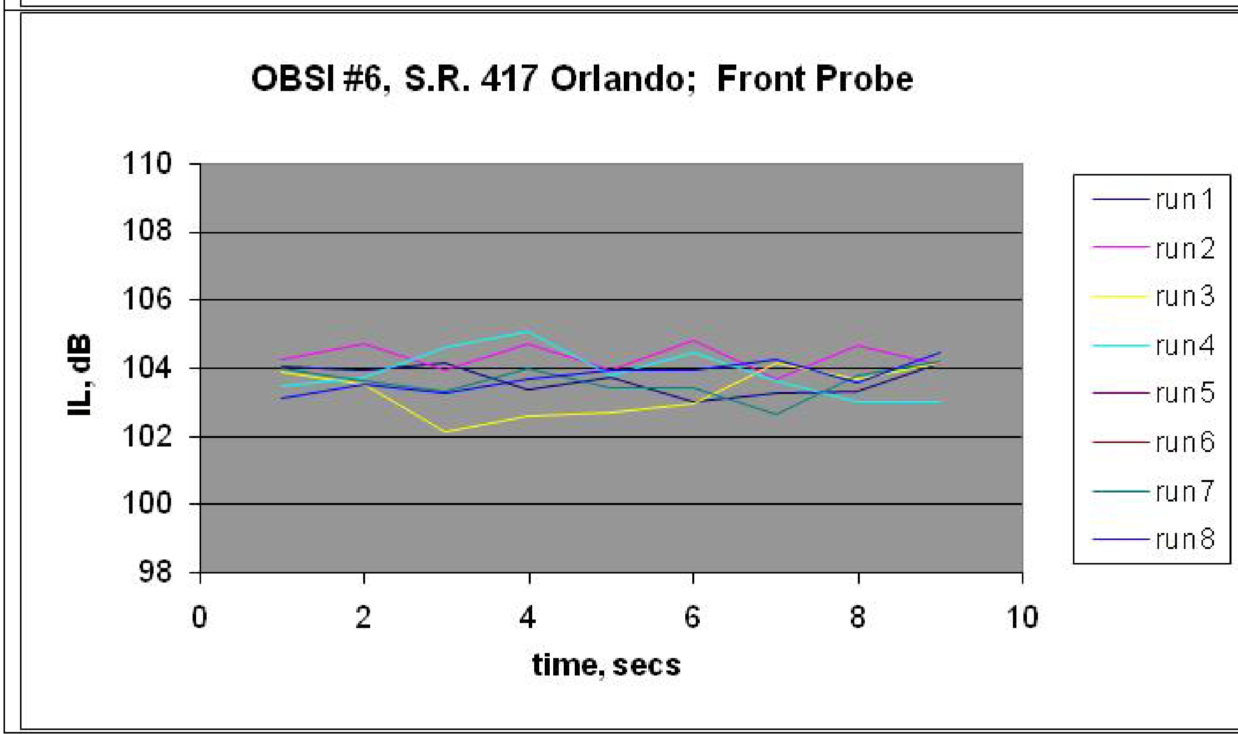


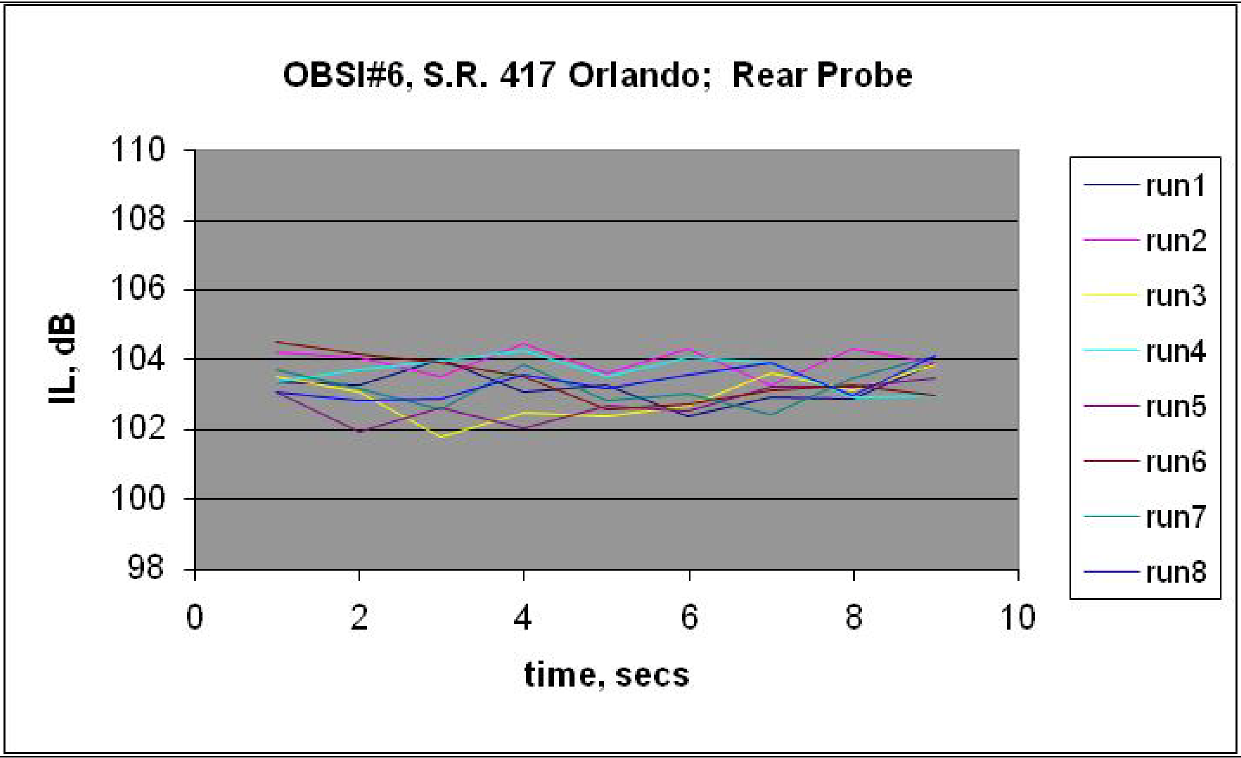
OBSI#4, U.S. 192 Melbourne; Rear Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time, secs
run1
run2
run3
run4
run5
run6
run7
run8
run9

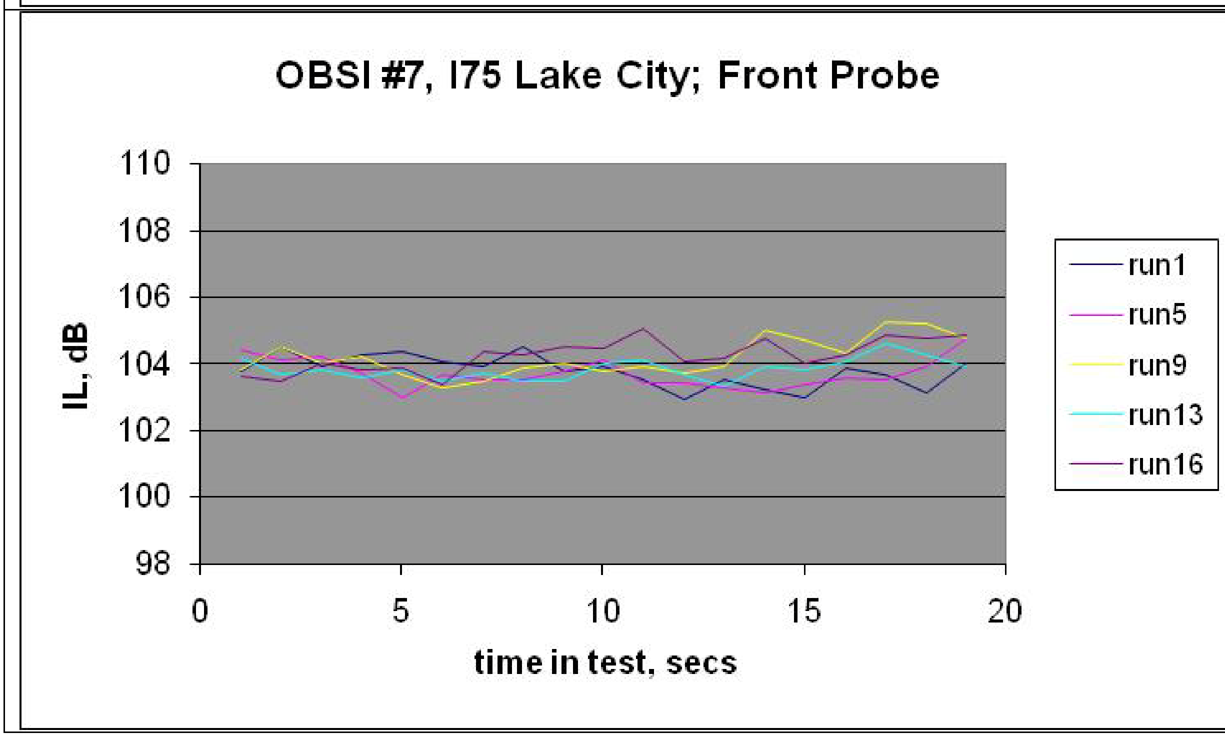


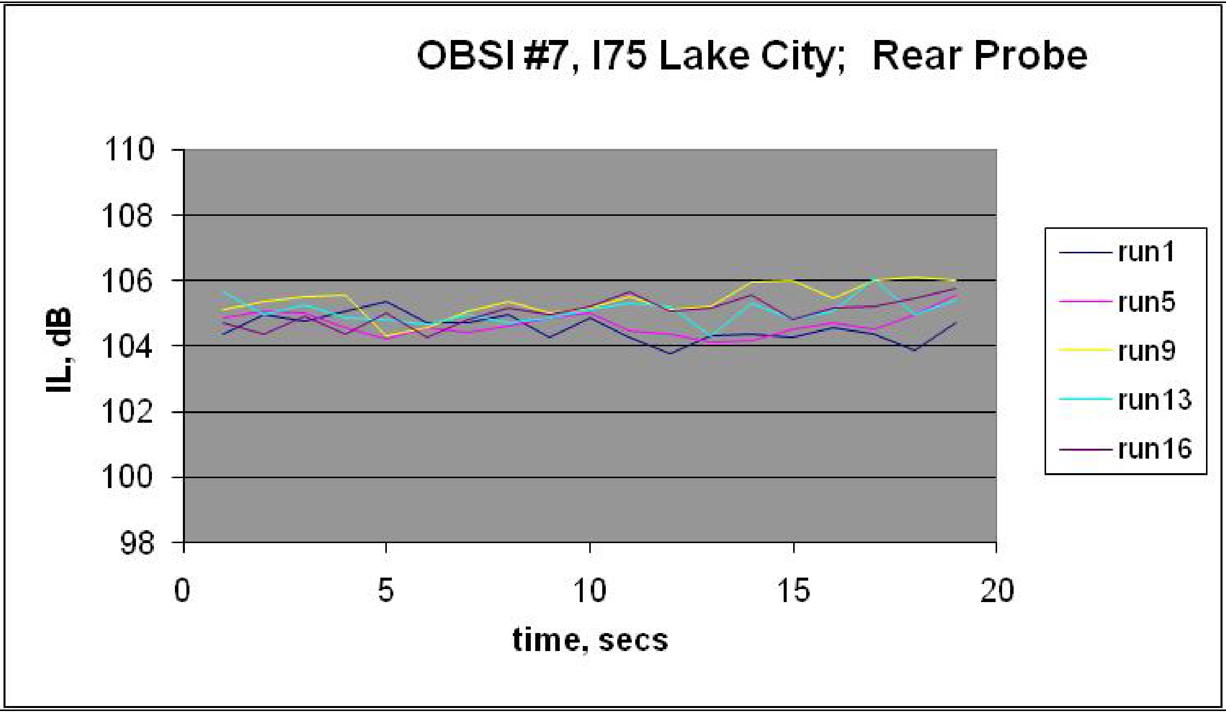
OBSI#5, S.R. 417 Orlando; Front Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time, secs
run1
run2
run3
run4
run5
run6
run7

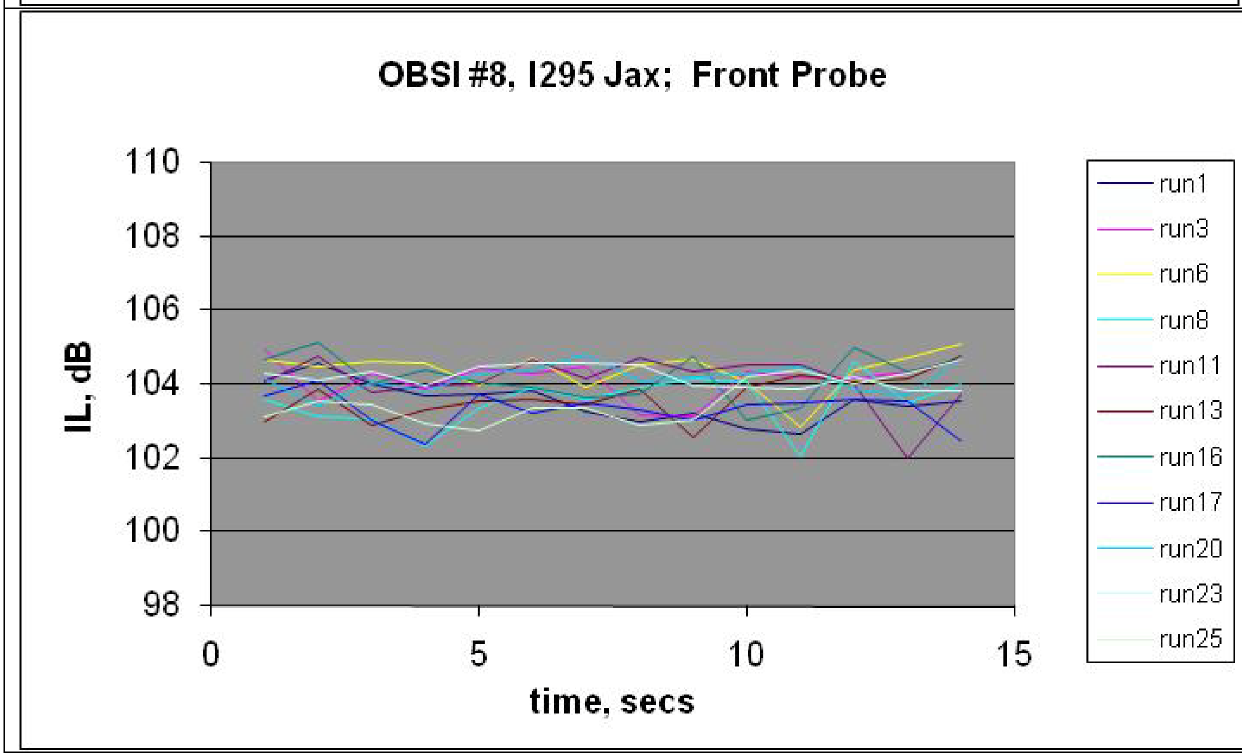

OBSI #5, S.R. 417 Orlando; Rear Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time, secs
run1
run2
run3
run4
run5
run6
run7

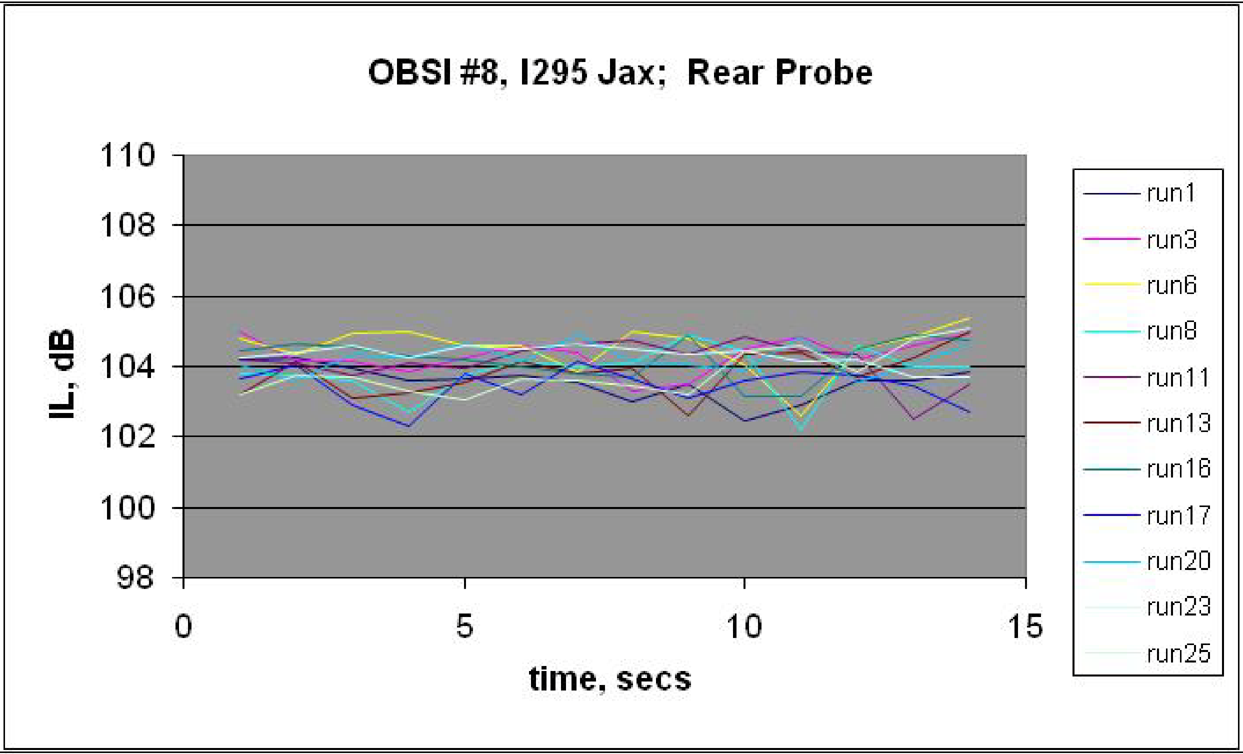

OBSI #6, S.R. 417 Orlando; Front Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time, secs
run1
run2
run3
run4
run5
run6
run7
run8


OBSI#6, S.R. 417 Orlando; Rear Probe
IL, dB
110
108
106
104
102
100
98
0
2
4
6
8
10
time, secs
run1
run2
run3
run4
run5
run6
run7
run8

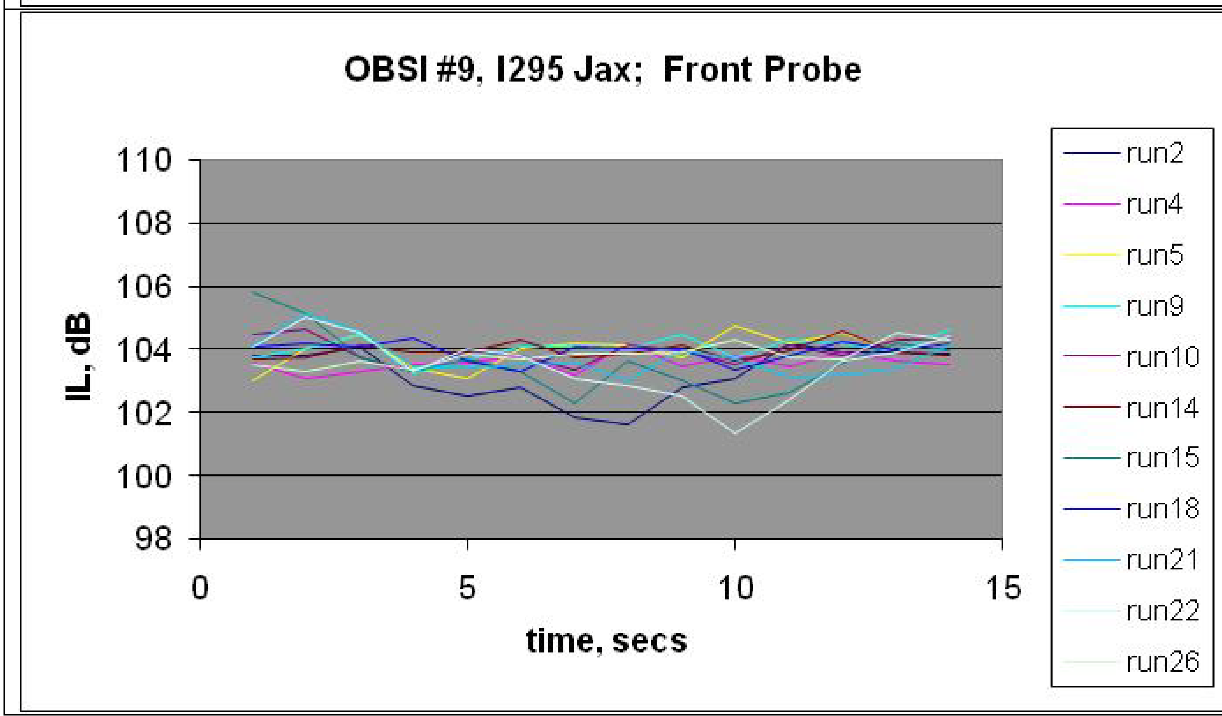

OBSI #7, I75 Lake City; Front Probe
IL, dB
110
108
106
104
102
100
98
0
5
10
15
20
time in test, secs
run1
run5
run9
run13
run16


OBSI #7, I75 Lake City;   Rear Probe
110
108
106
104
102
100
98
IL, dB
0
5
10
15
20
time, secs
run1
run5
run9
run13
run16

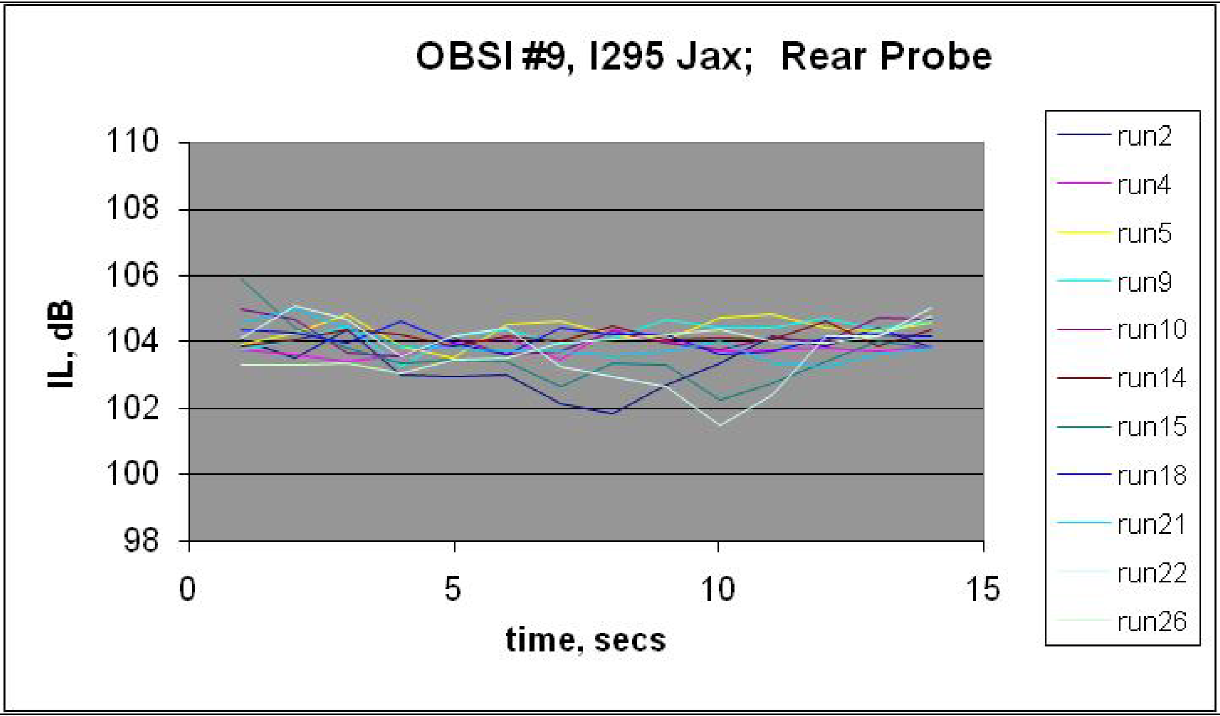

OBSI #8, I295 Jax; Front Probe
110
108
106
104
102
100
98
IL, dB
0
5
10
15
time, secs
run1
run3
run6
run8
run11
run13
run16
run17
run20
run23
run25

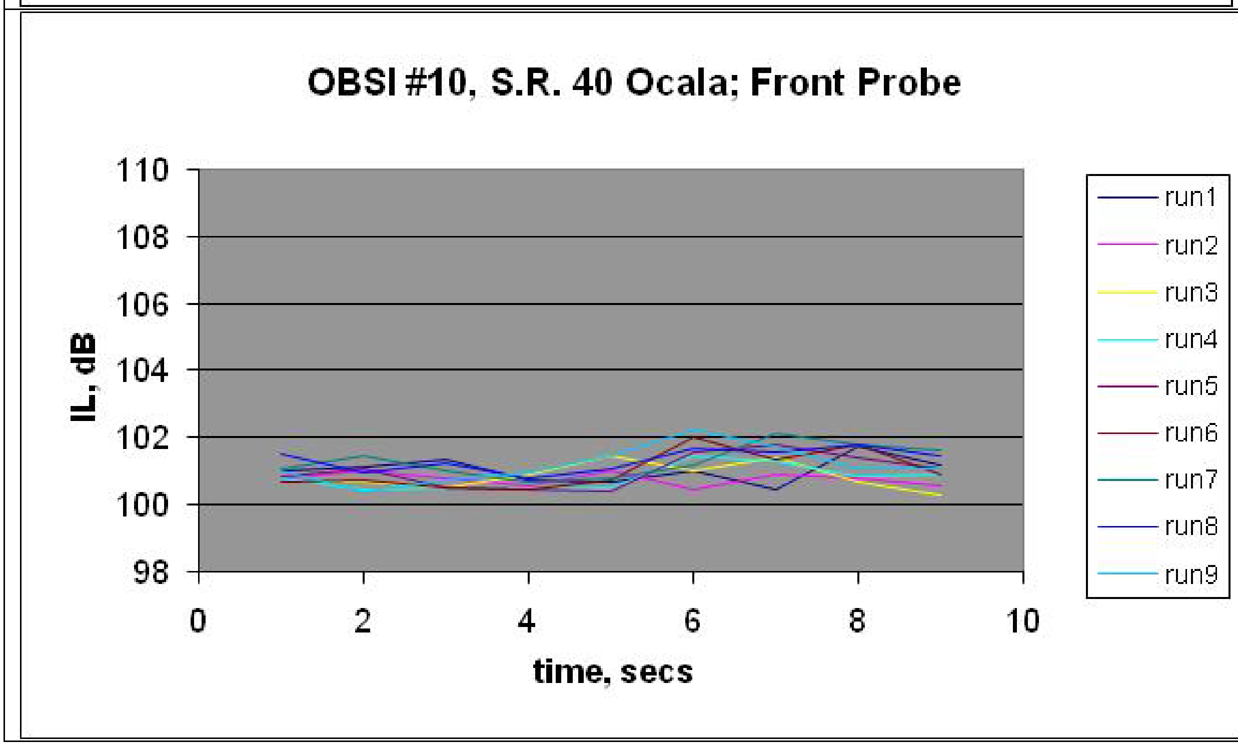


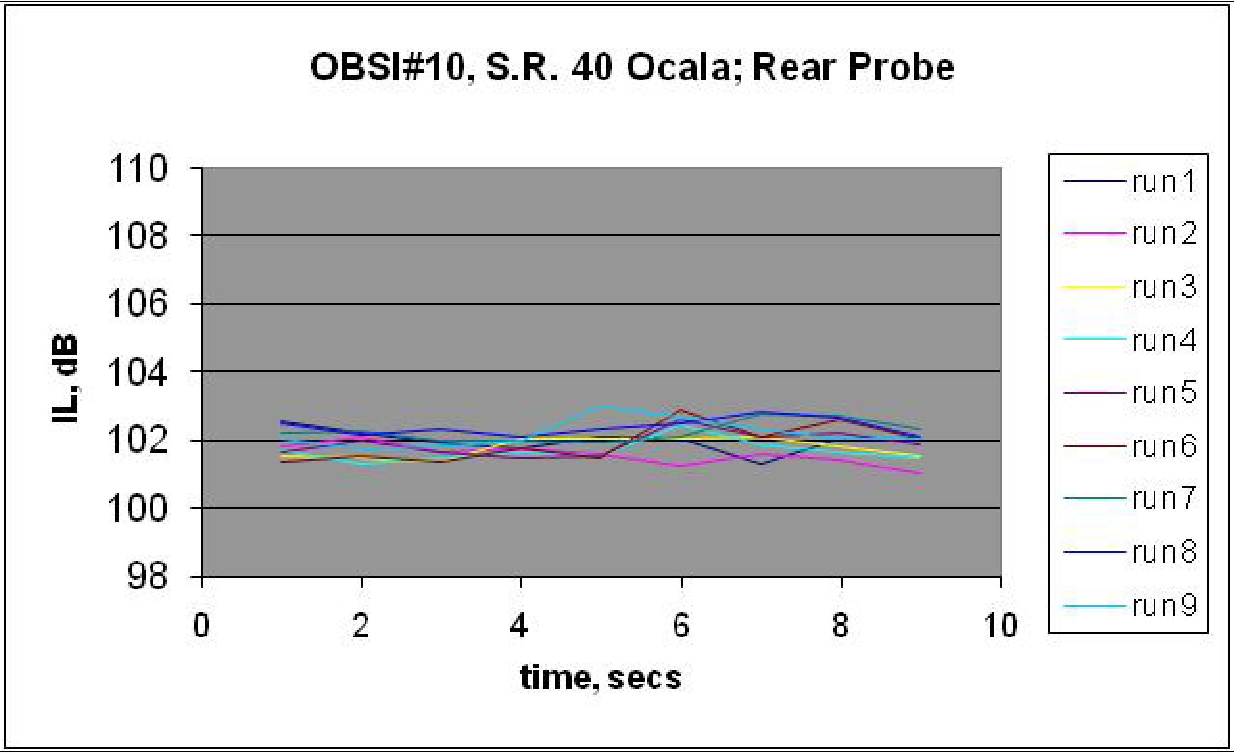
OBSI #8, I295 Jax; Rear Probe
110
108
106
104
102
100
98
IL, dB
0
5
10
15
time, secs
run1
run3
run6
run8
run11
run13
run16
run17
run20
run23
run25

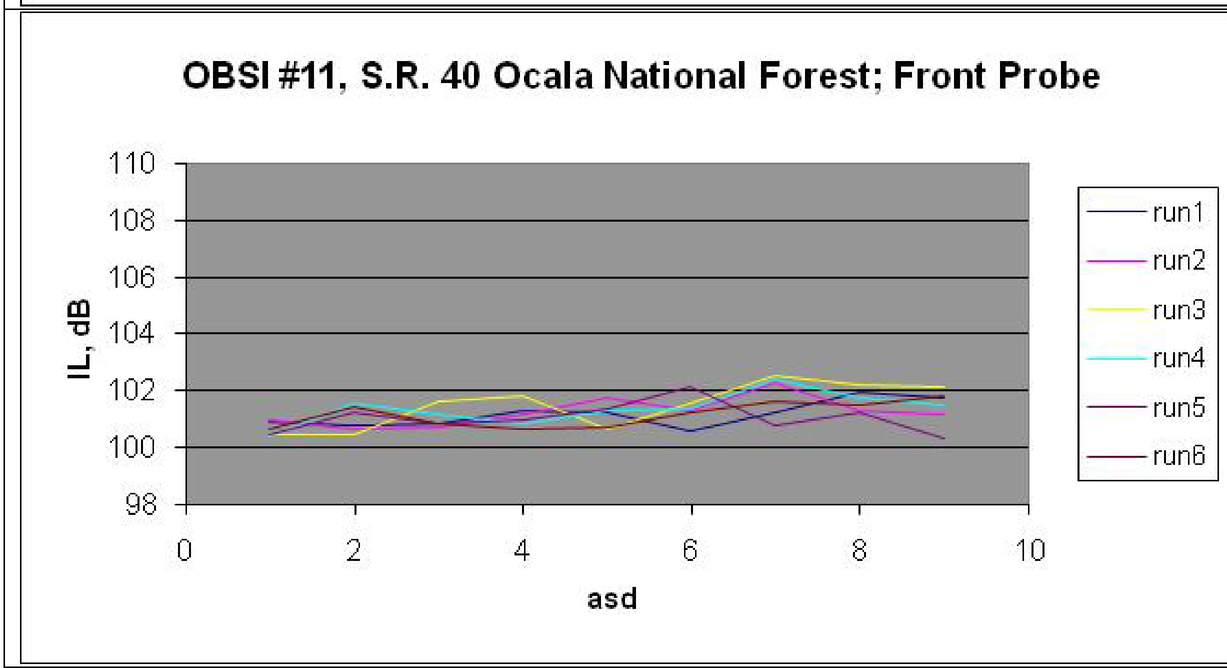


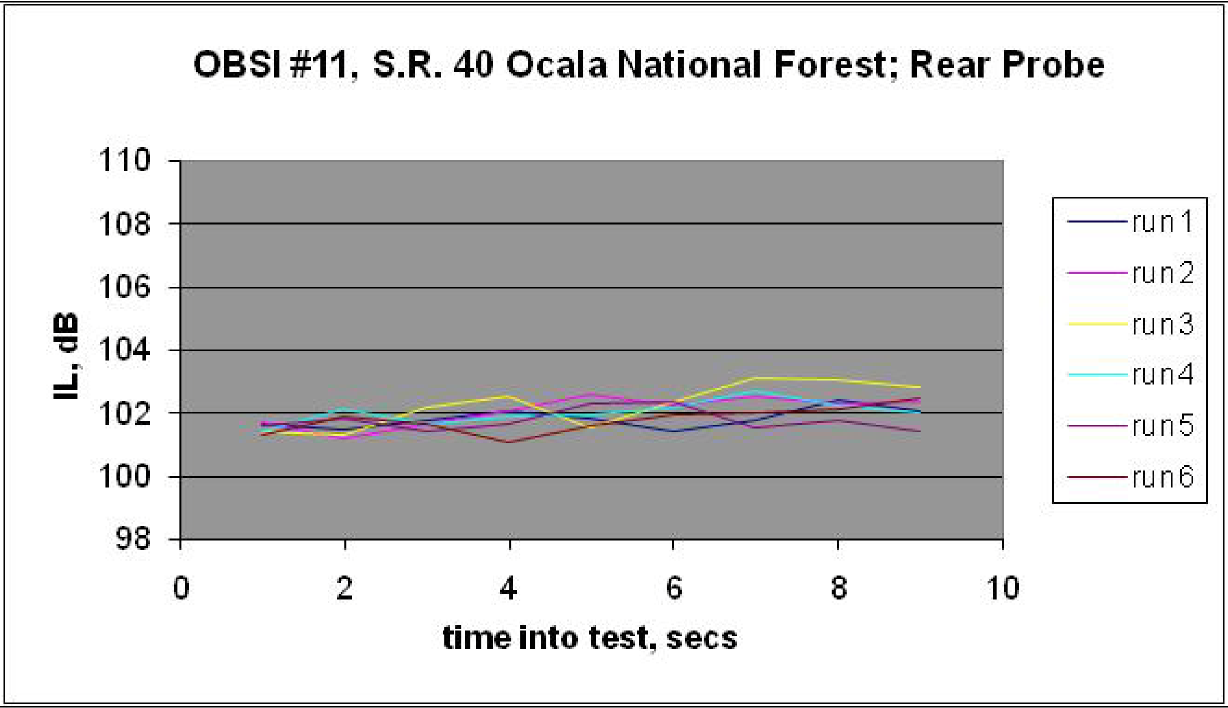
OBSI #9, I295 Jax; Front Probe
110
108
106
104
102
100
98
IL, dB
0
5
10
15
time, secs
run2
run4
run5
run9
run10
run14
run15
run18
run21
run22
run26

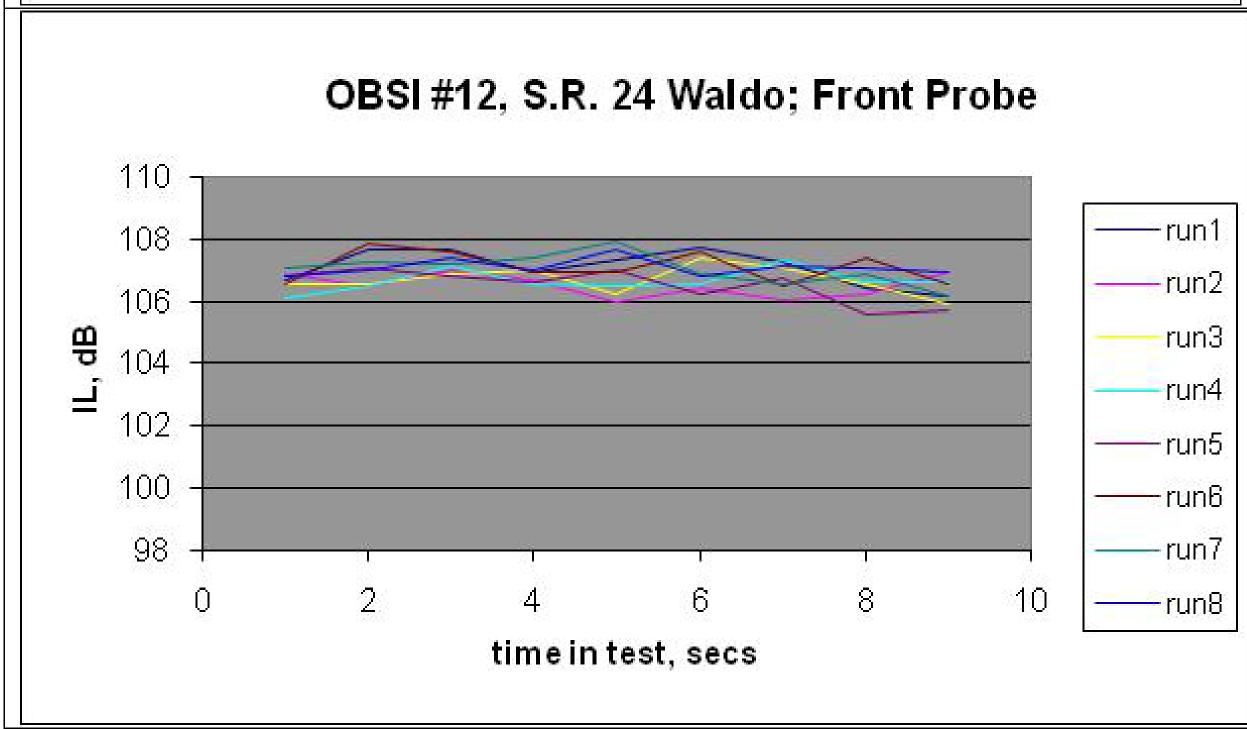

OBSI #9, I295 Jax; Rear Probe
110
108
106
104
102
100
98
IL, dB
0
5
10
15
time, secs
run2
run4
run5
run9
run10
run14
run15
run18
run21
run22
run26

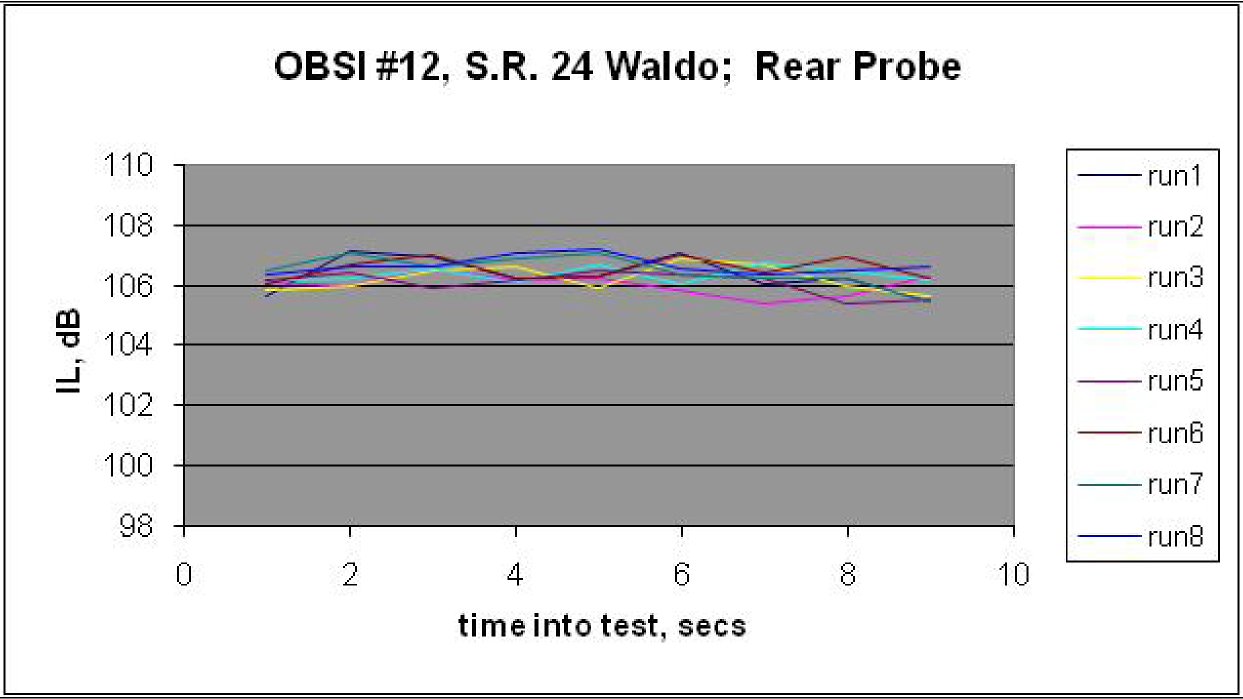

OBSI #10, S.R. 40 Ocala; Front Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time, secs
run1
run2
run3
run4
run5
run6
run7
run8
run9


OBSI#10, S.R. 40 Ocala; Rear Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time, secs
run1
run2
run3
run4
run5
run6
run7
run8
run9

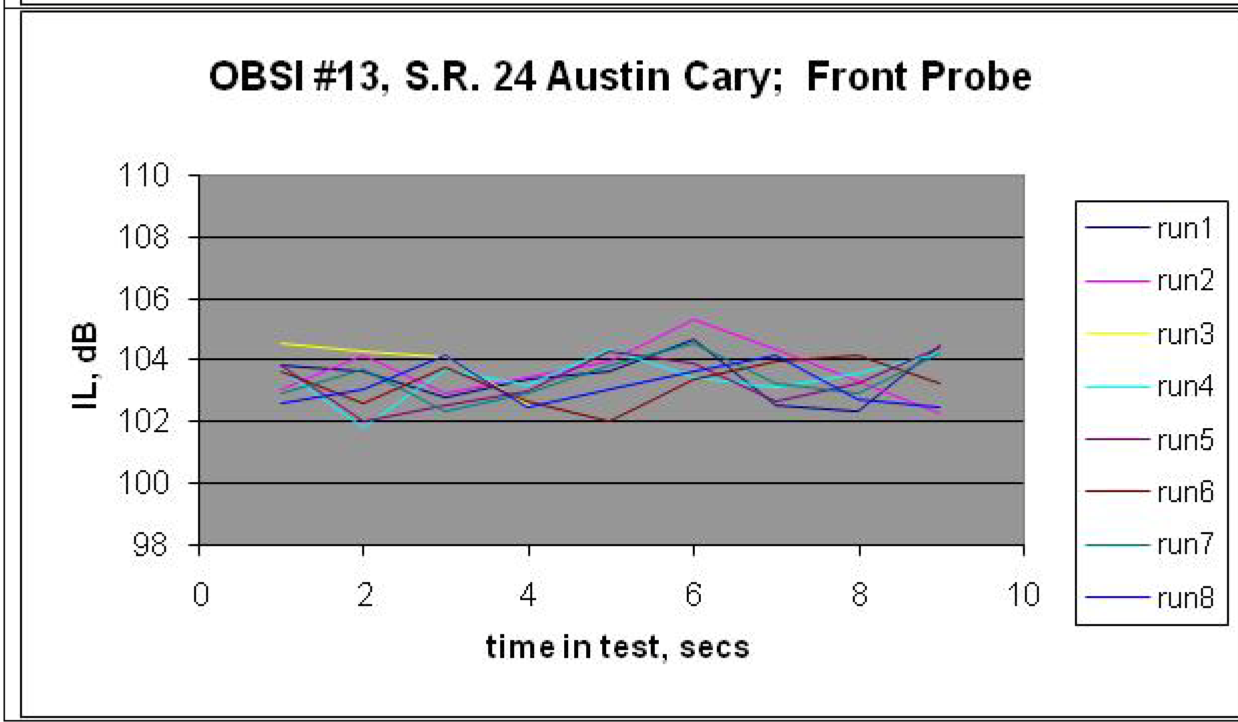

OBSI #11, S.R. 40 Ocala National Forest; Front Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
asd
run1
run2
run3
run4
run5
run6


OBSI #11, S.R. 40 Ocala National Forest; Rear Probe
IL, dB
110
108
106
104
102
100
98
0
2
4
6
8
10
time into test, secs
run1
run2
run3
run4
run5
run6

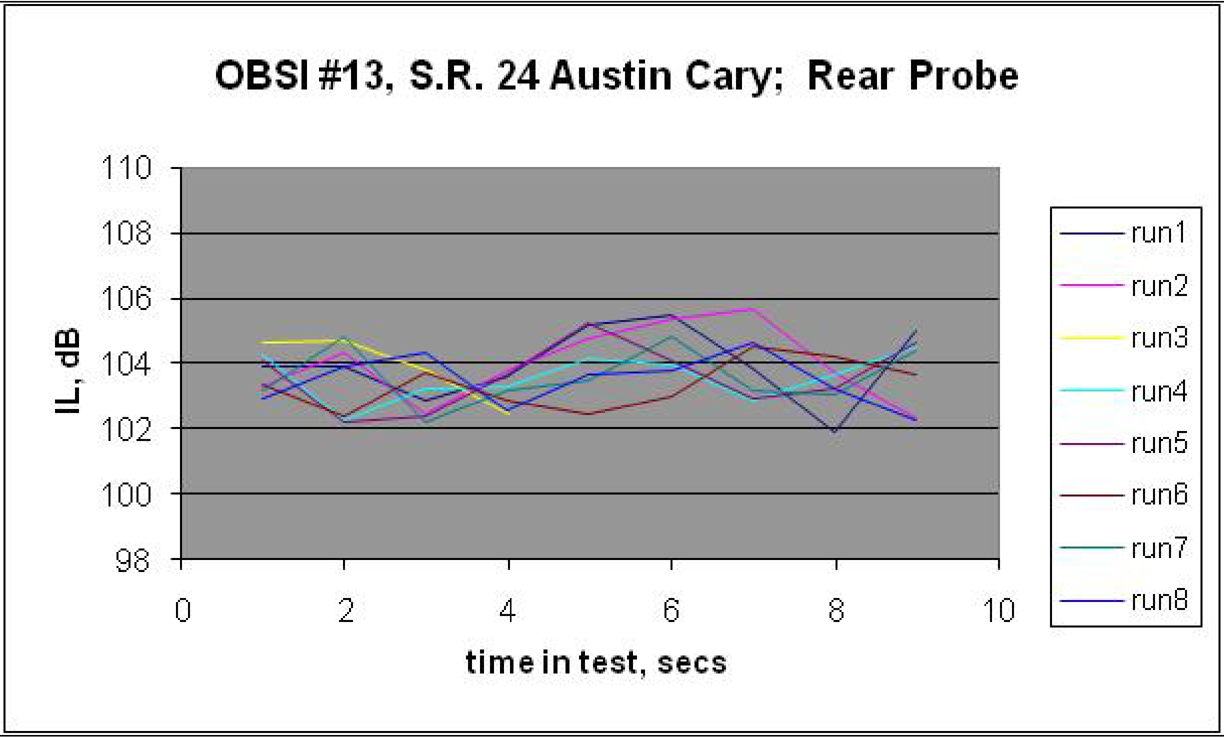

OBSI #12, S.R. 24 Waldo; Front Probe
IL, dB
110
108
106
104
102
100
98
0
2
4
6
8
10
time in test, secs
run1
run2
run3
run4
run5
run6
run7
run8

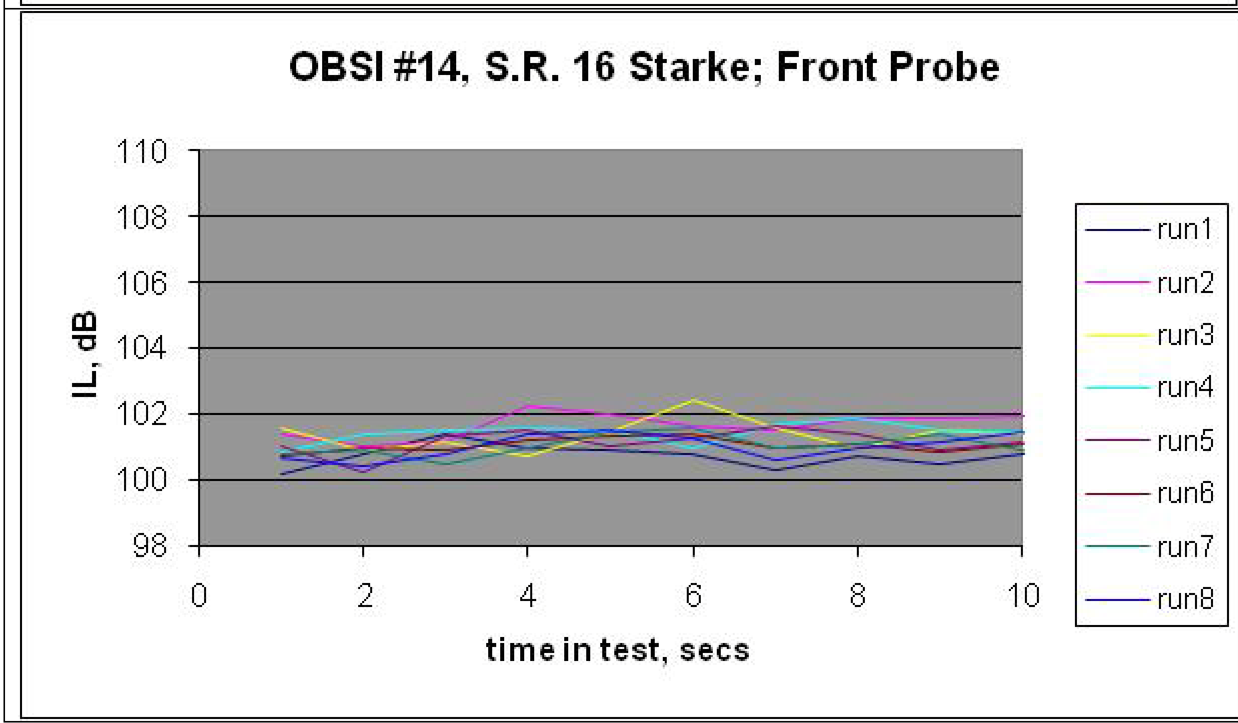


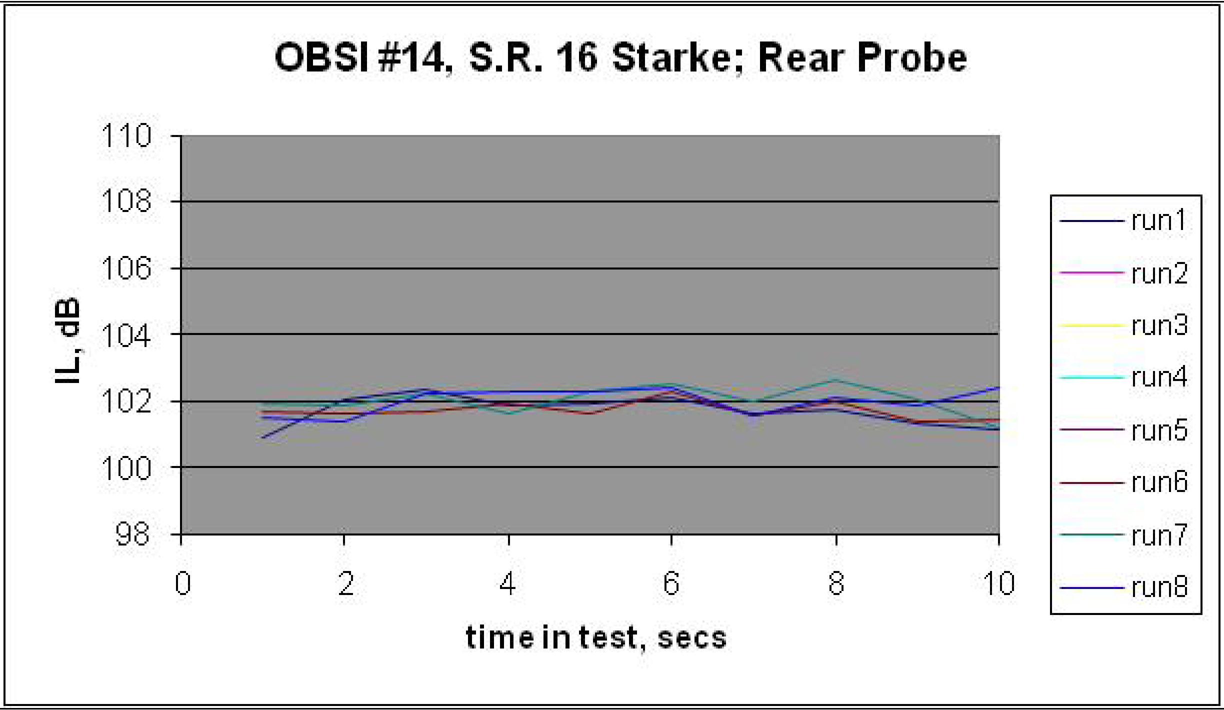
OBSI #12, S.R. 24 Waldo; Rear Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time into test, secs
run1
run2
run3
run4
run5
run6
run7
run8



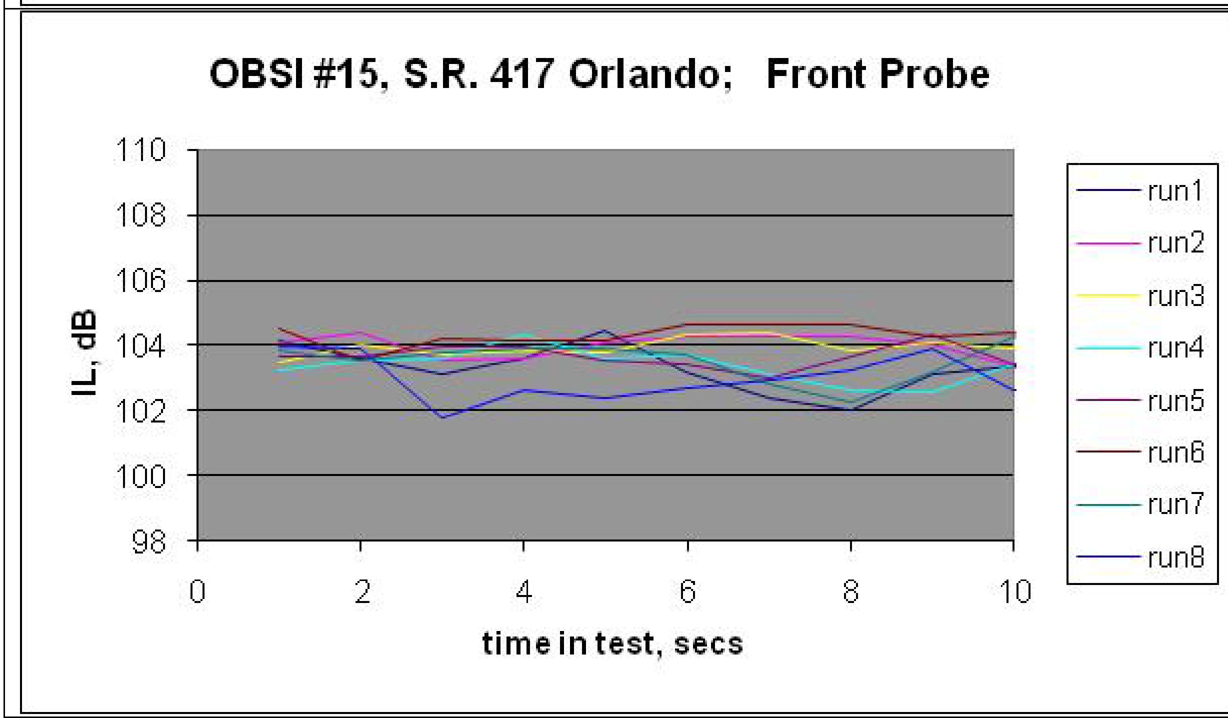
OBSI #13, S.R. 24 Austin Cary; Front Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time in test, secs
run1
run2
run3
run4
run5
run6
run7
run8


OBSI #13, S.R. 24 Austin Cary; Rear Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time in test, secs
run1
run2
run3
run4
run5
run6
run7
run8

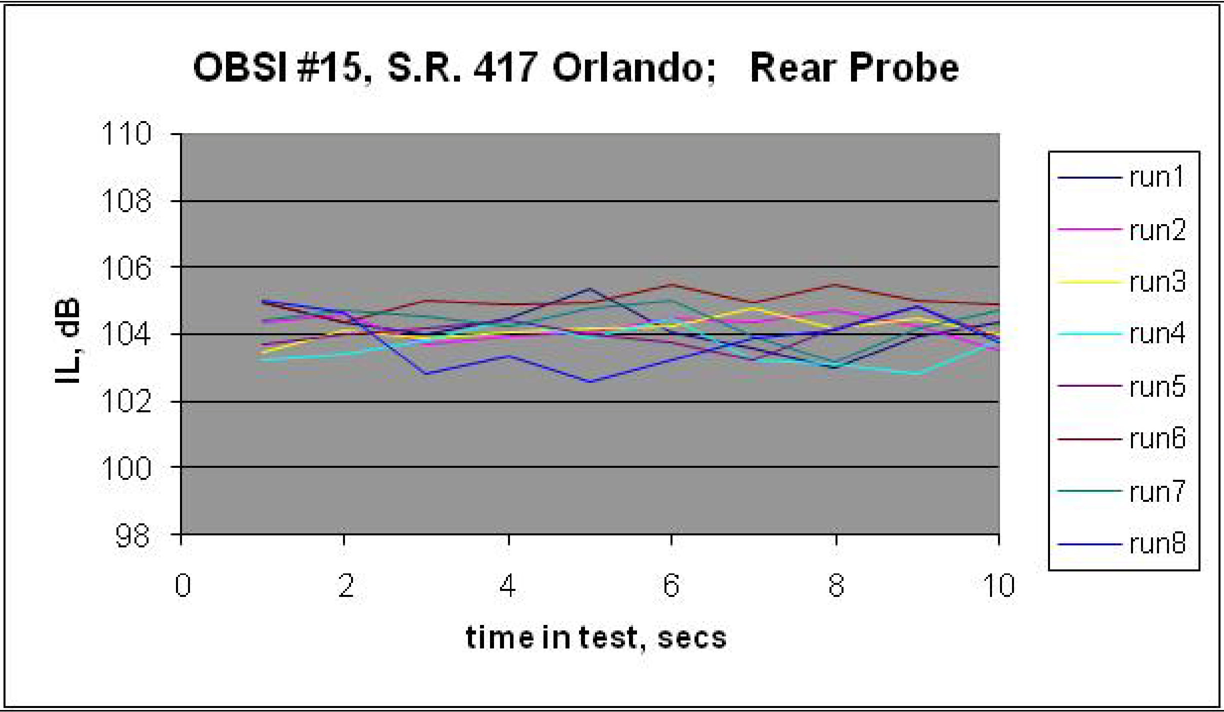

OBSI #14, S.R. 16 Starke; Front Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time in test, secs
run1
run2
run3
run4
run5
run6
run7
run8



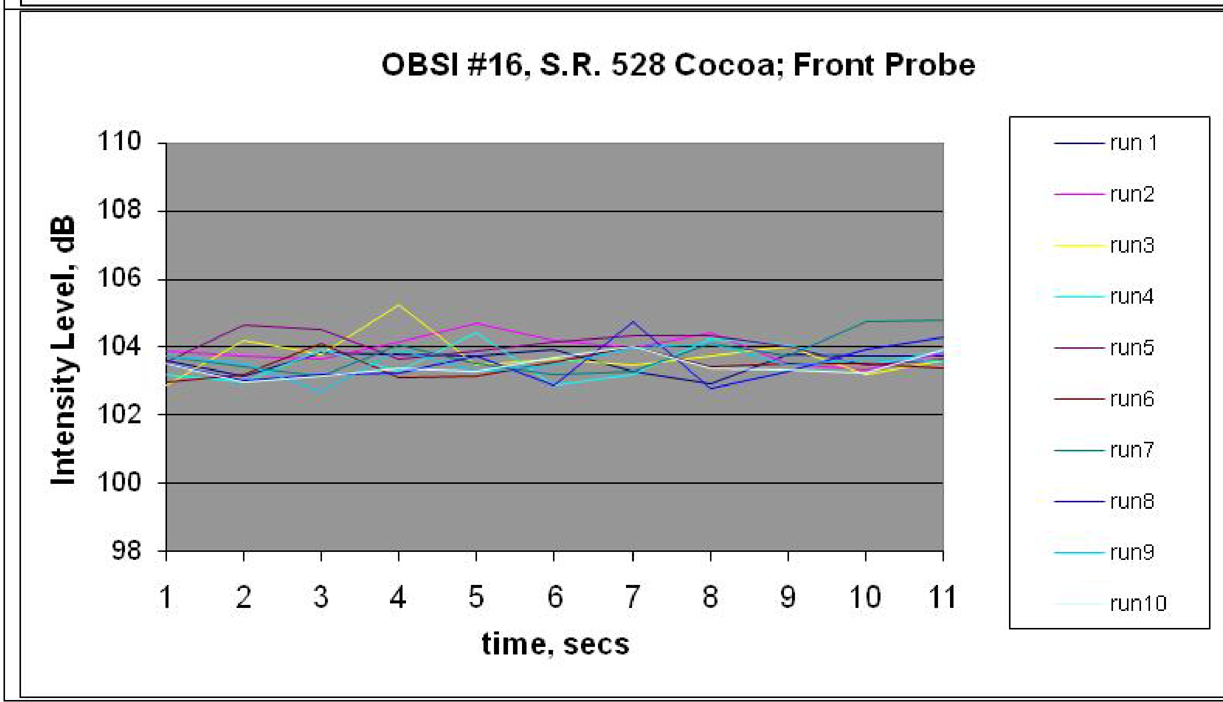
OBSI #14, S.R. 16 Starke; Rear Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time in test, secs
run1
run2
run3
run4
run5
run6
run7
run8



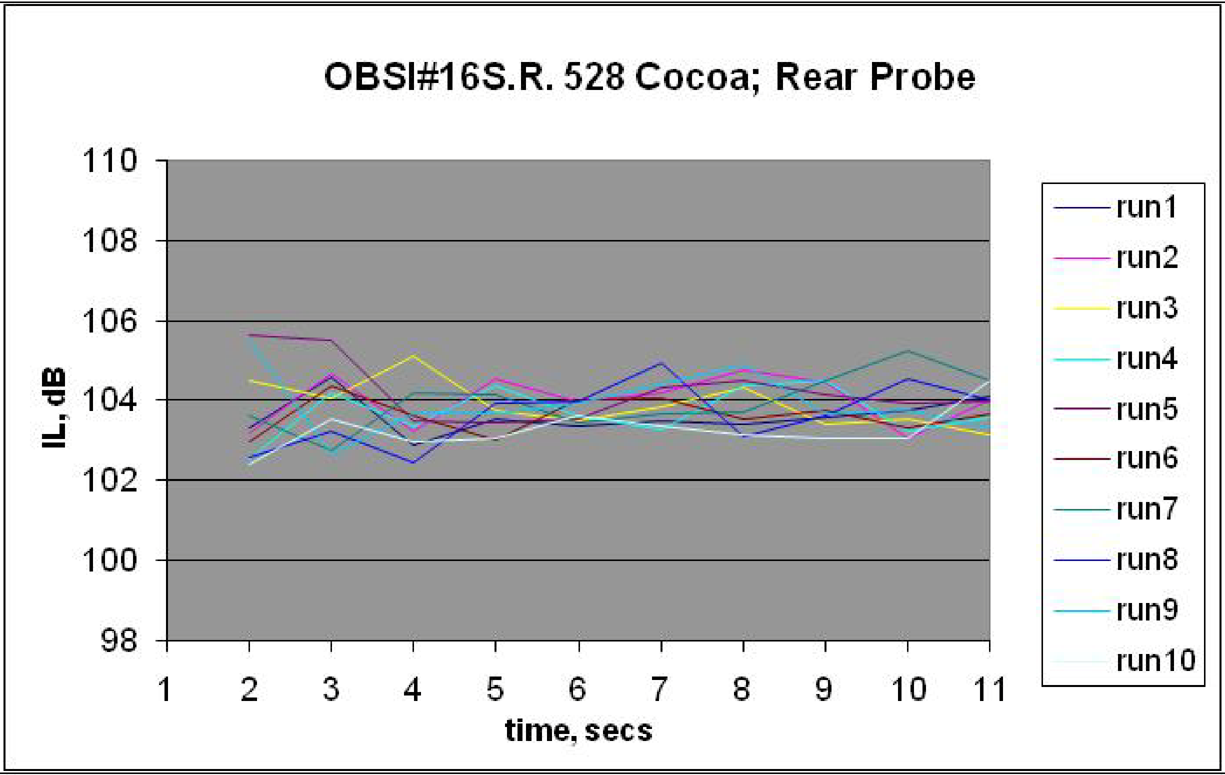
OBSI #15, S.R. 417 Orlando; Front Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time in test, secs
run1
run2
run3
run4
run5
run6
run7
run8

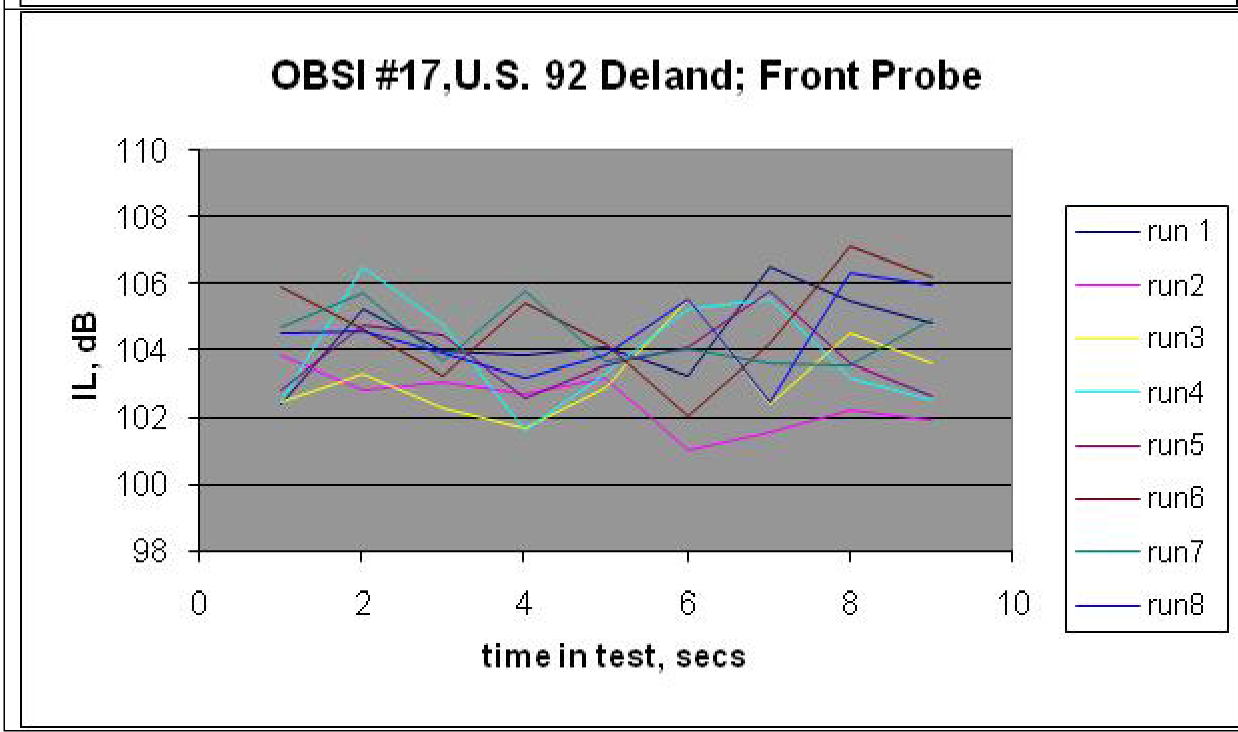


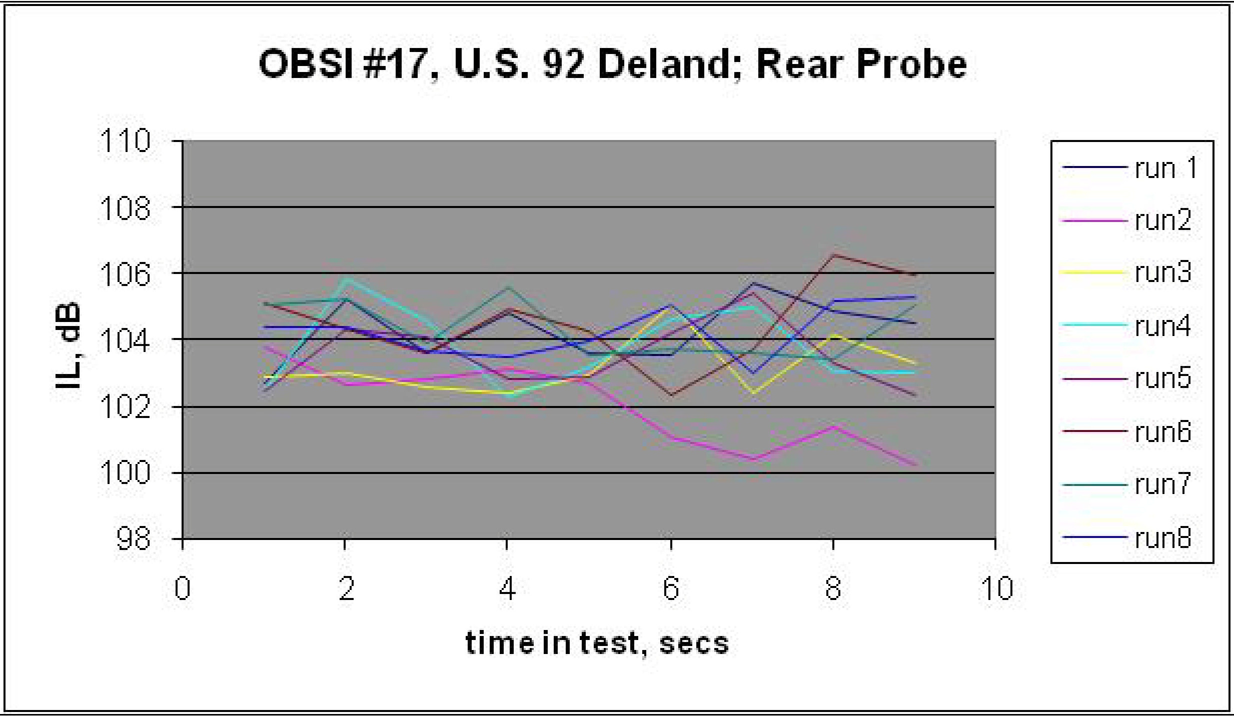
OBSI #15, S.R. 417 Orlando; Rear Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time in test, secs
run1
run2
run3
run4
run5
run6
run7
run8

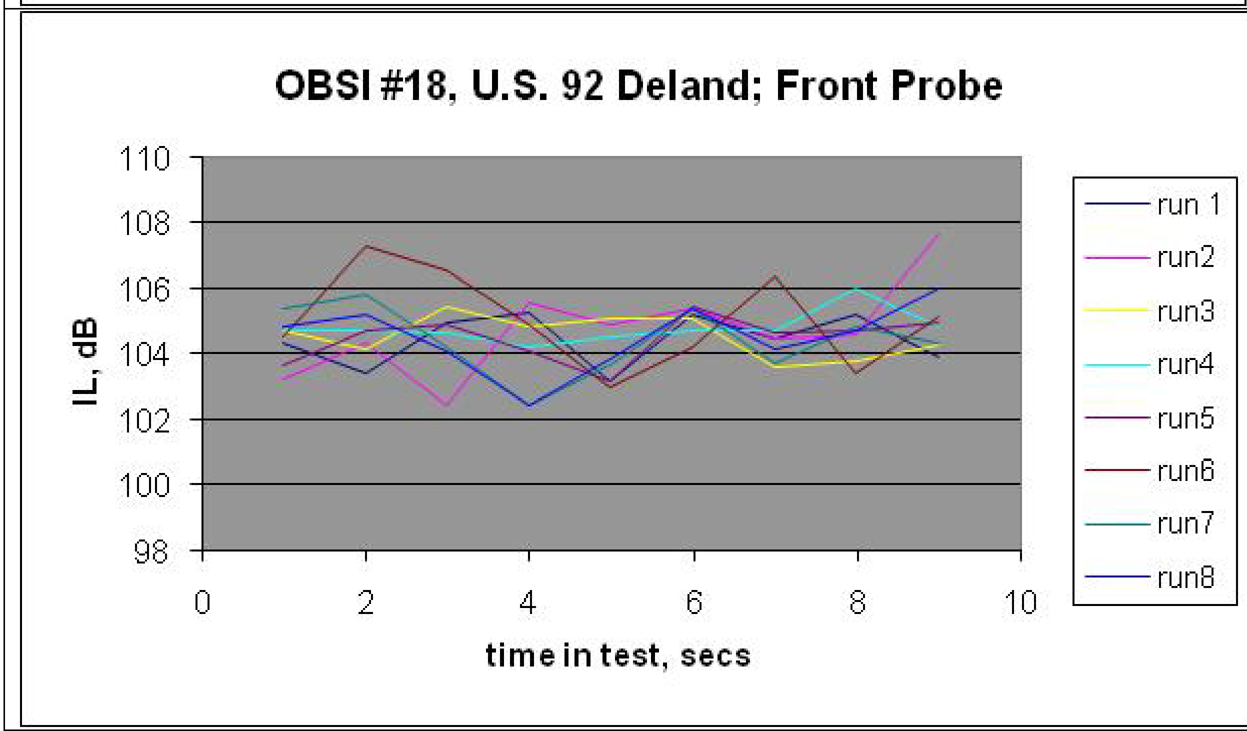


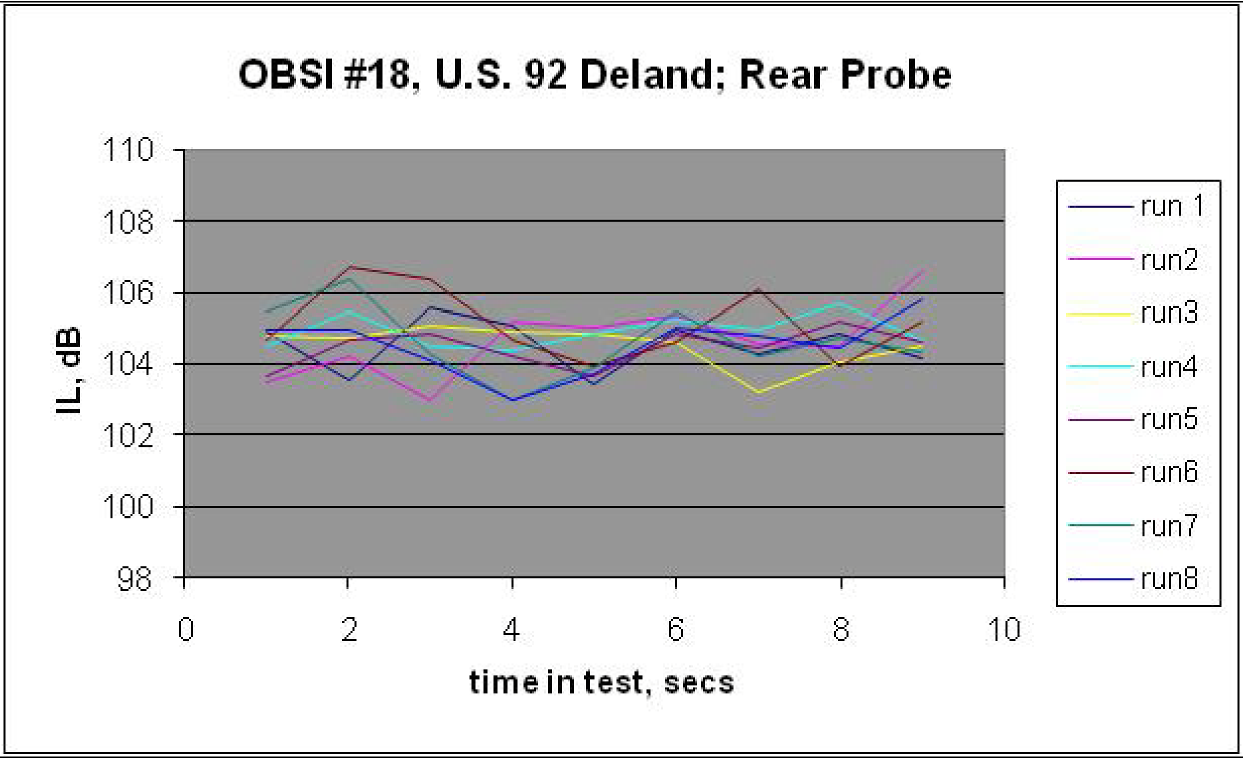
OBSI #16, S.R. 528 Cocoa; Front Probe
110
108
106
104
102
100
98
Intensity Level, dB
1
2
3
4
5
6
7
8
9
10
11
time, secs
run 1
run2
run3
run4
run5
run6
run7
run8
run9
run10


OBSI#16S.R. 528 Cocoa; Rear Probe
110
108
106
104
102
100
98
IL, dB
1 2 3 4 5 6 7 8 9 10 11
time, secs
run1
run2
run3
run4
run5
run6
run7
run8
run9
run10

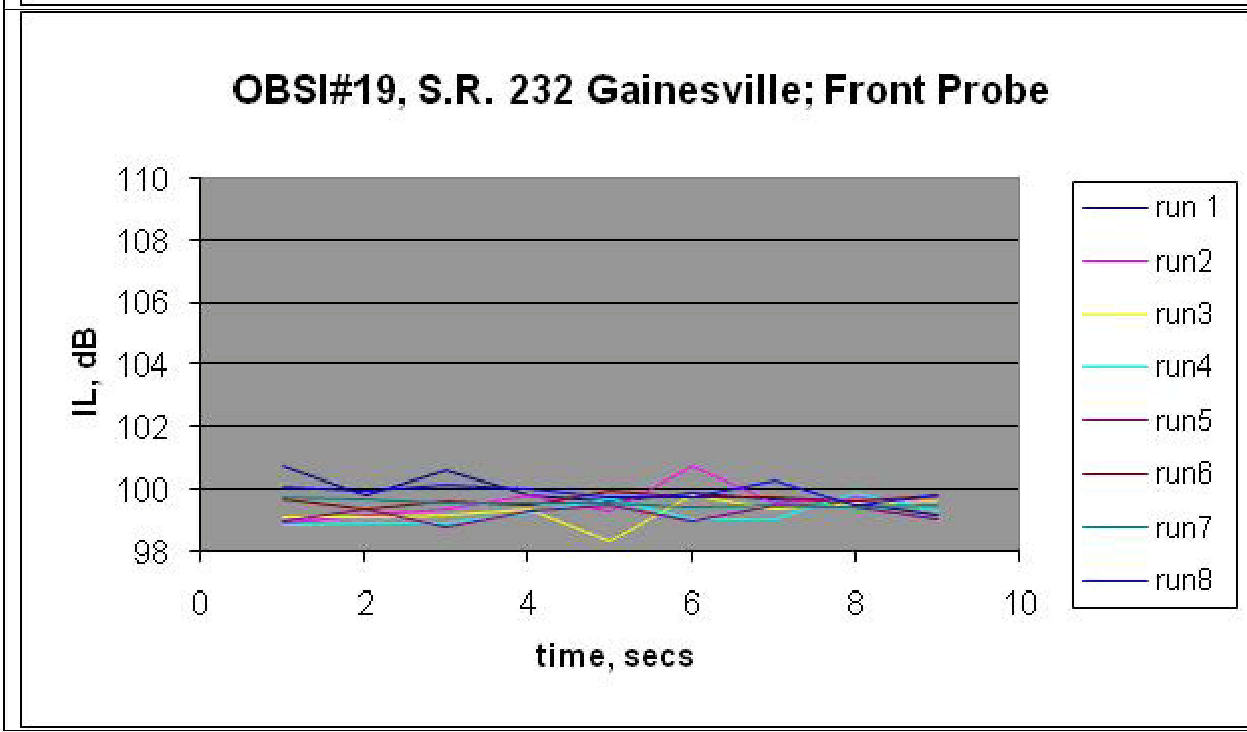

OBSI #17,U.S. 92 Deland; Front Probe
110
108
106
104
102
100
98
IL, dB
0 2 4 6 8 10
time in test, secs
run 1
run2
run3
run4
run5
run6
run7
run8


OBSI #17, U.S. 92 Deland; Rear Probe
IL, dB
110
108
106
104
102
100
98
0
2
4
6
8
10
time in test, secs
run 1
run2
run3
run4
run5
run6
run7
run8

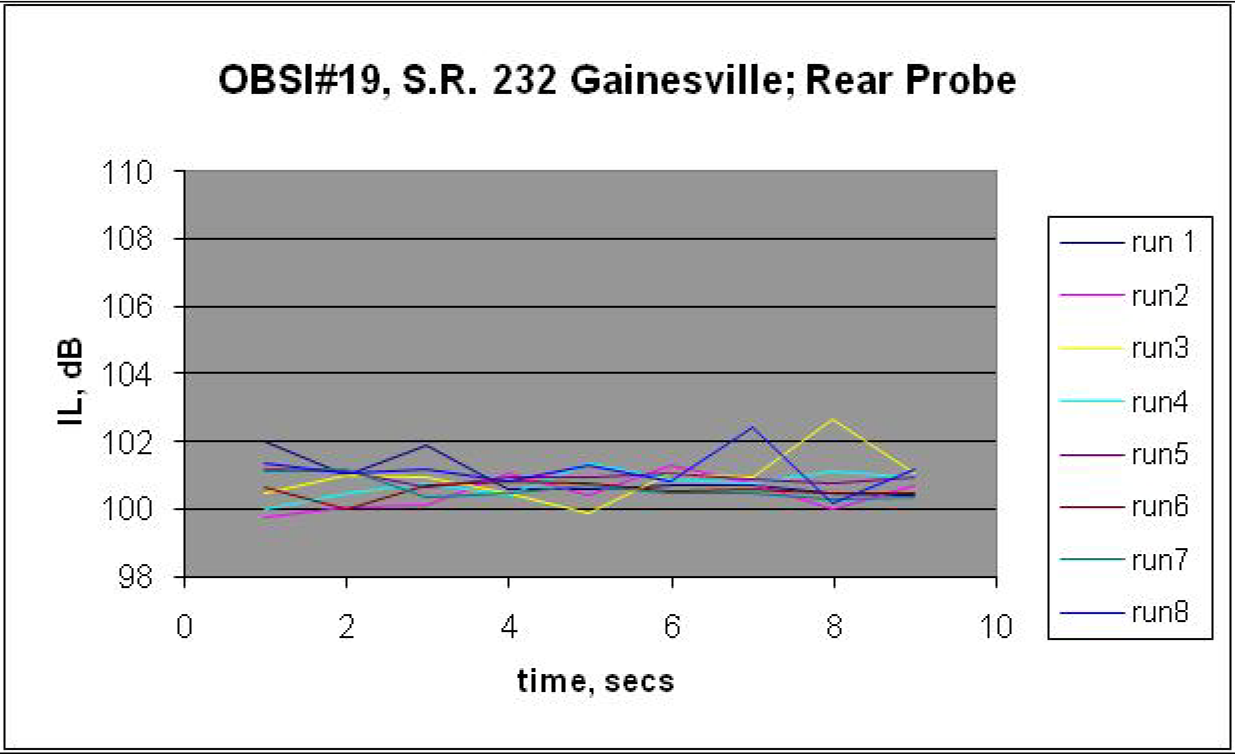

OBSI #18, U.S. 92 Deland; Front Probe
IL, dB
110
108
106
104
102
100
98
0
2
4
6
8
10
time in test, secs
run 1
run2
run3
run4
run5
run6
run7
run8

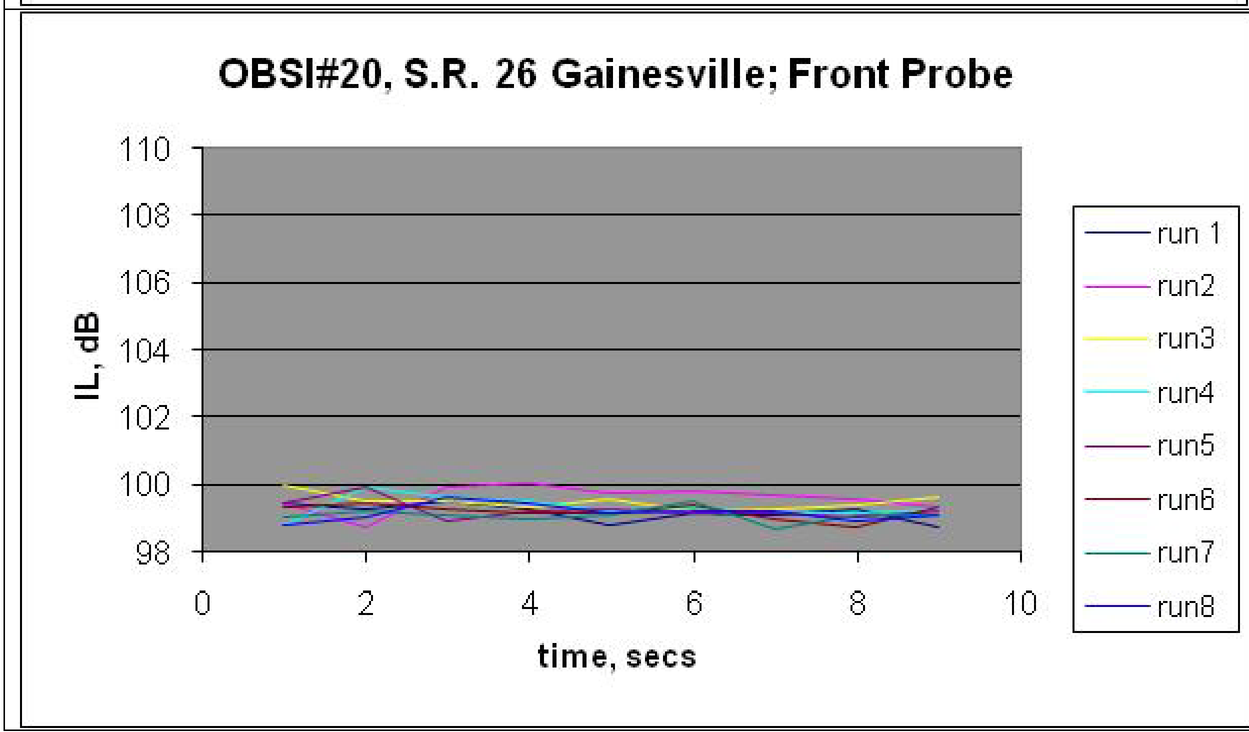


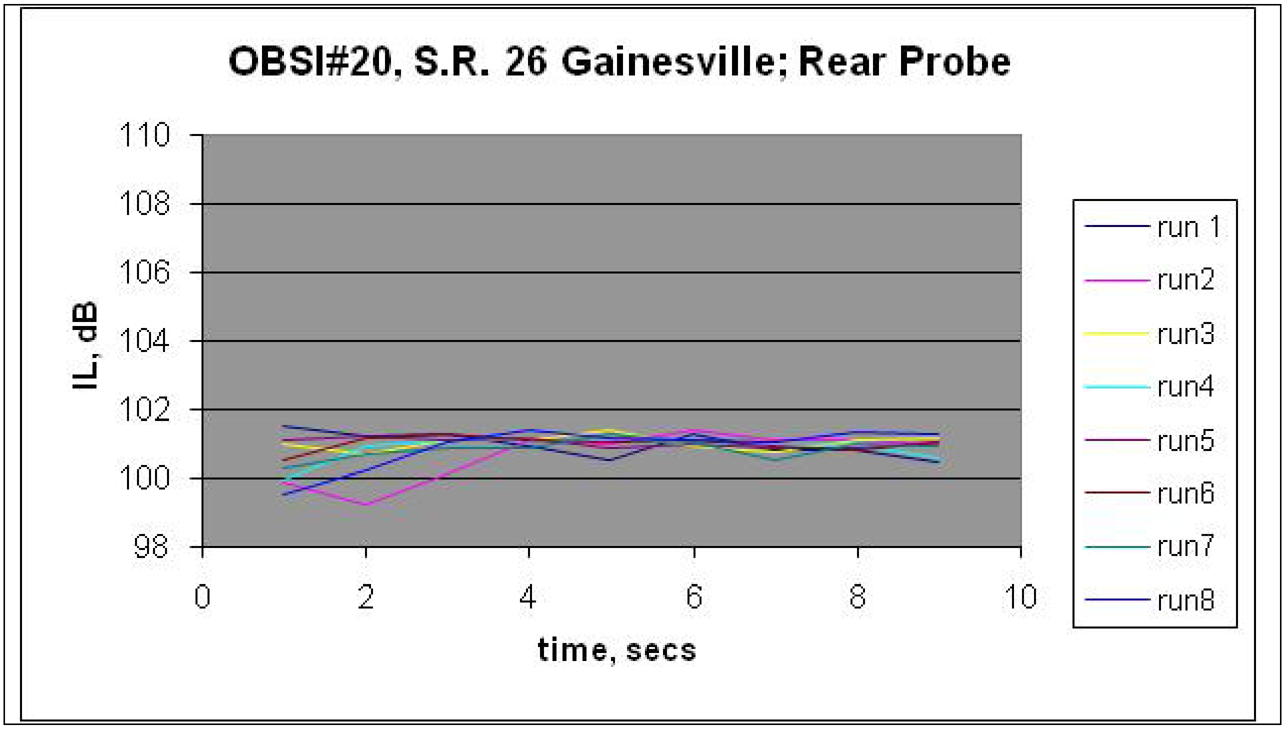
OBSI #18, U.S. 92 Deland; Rear Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time in test, secs
run 1
run2
run3
run4
run5
run6
run7
run8

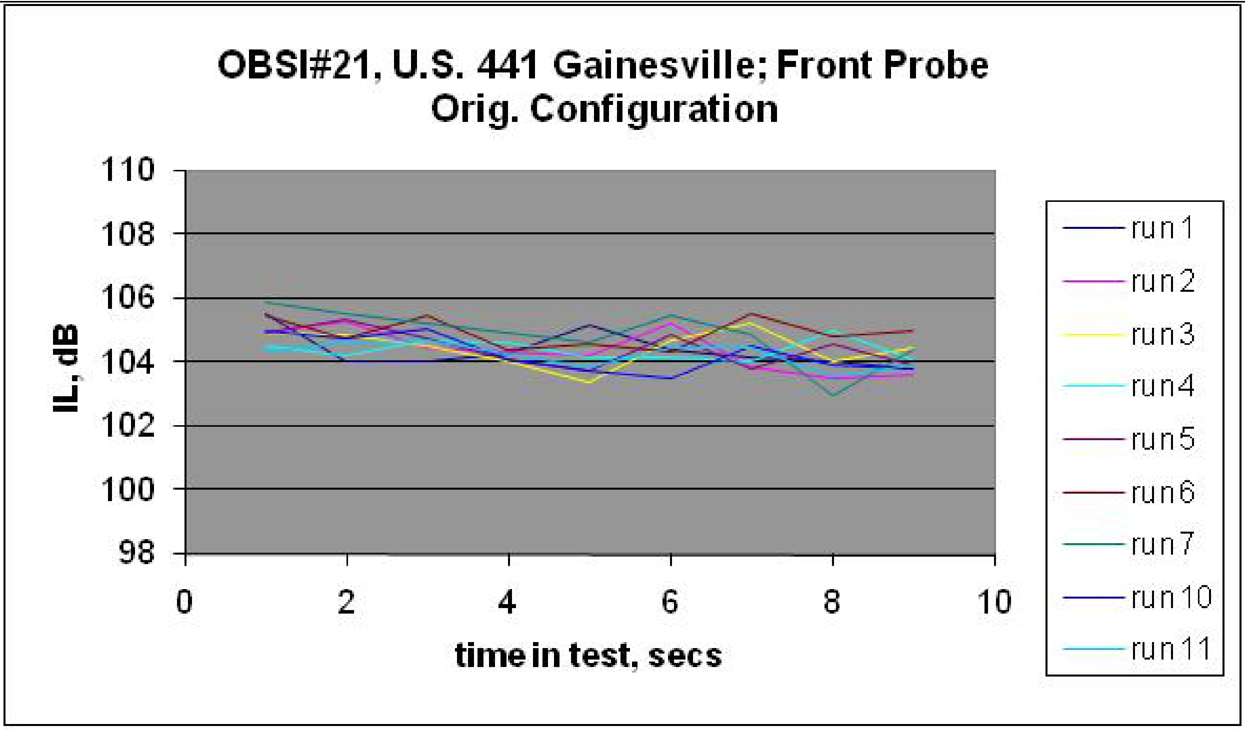


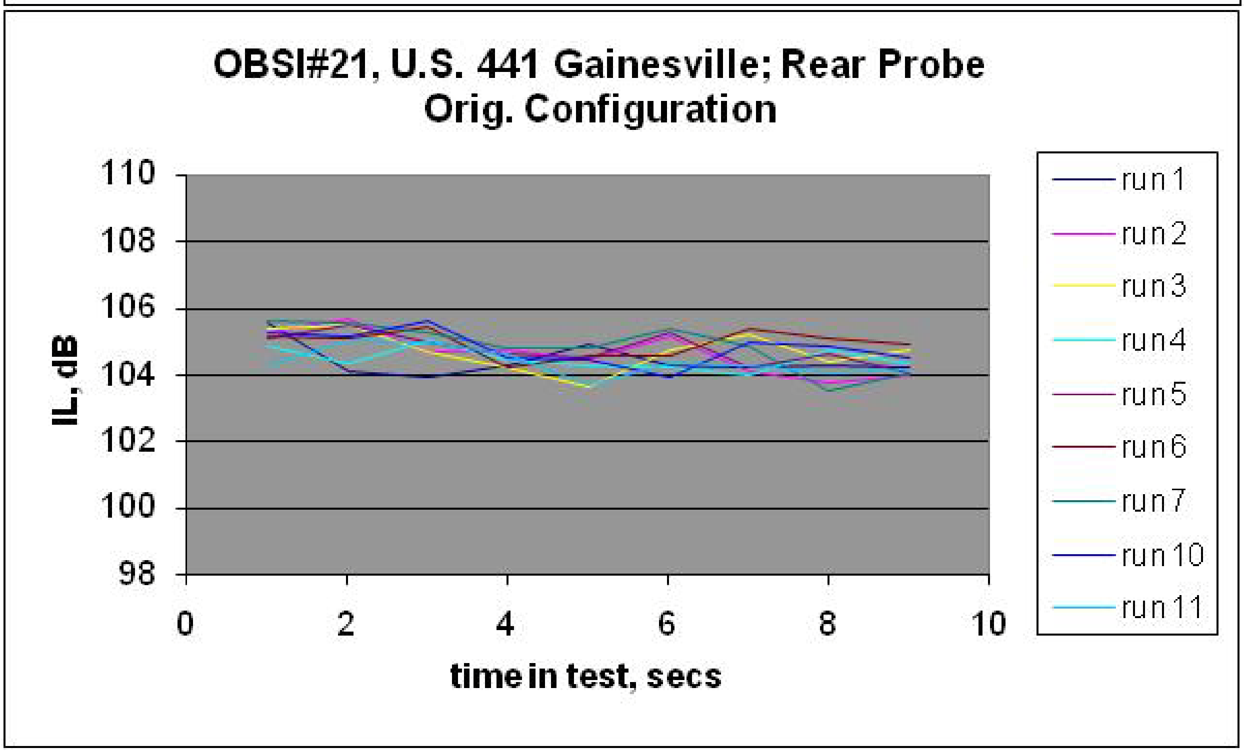
OBSI#19, S.R. 232 Gainesville; Front Probe
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time, secs
run 1
run2
run3
run4
run5
run6
run7
run8

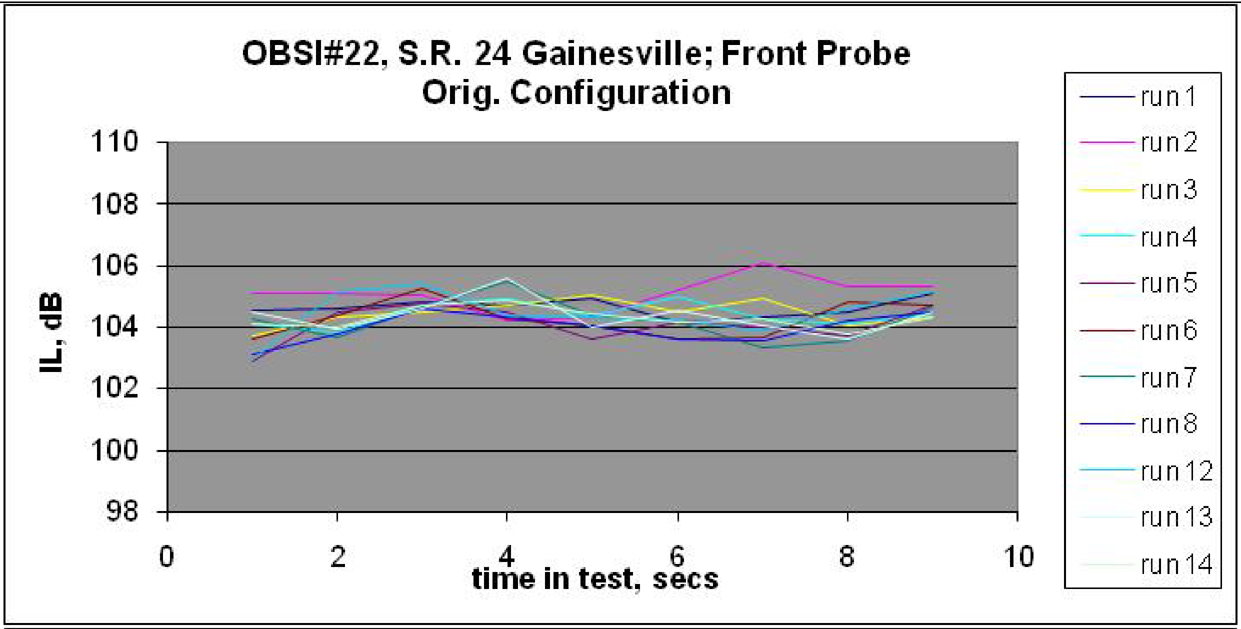

OBSI#19, S.R. 232 Gainesville; Rear Probe
IL, dB
110
108
106
104
102
100
98
0
2
4
6
8
10
time, secs
run 1
run2
run3
run4
run5
run6
run7
run8


OBSI#20, S.R. 26 Gainesville; Front Probe
IL, dB
110
108
106
104
102
100
98
0
2
4
6
8
10
time, secs
run 1
run2
run3
run4
run5
run6
run7
run8

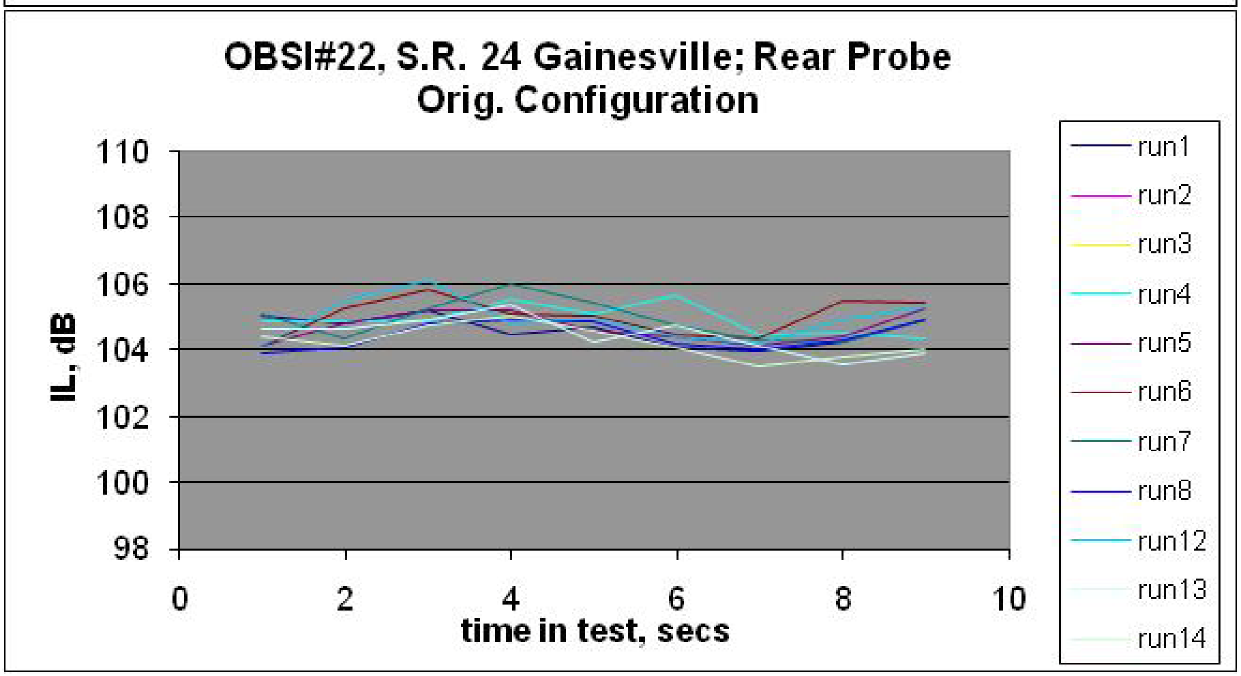

OBSI#20, S.R. 26 Gainesville; Rear Probe
IL, dB
110
108
106
104
102
100
98
0
2
4
6
8
10
time, secs
run 1
run2
run3
run4
run5
run6
run7
run8


OBSI#21, U.S. 441 Gainesville; Front Probe
Orig. Configuration
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time in test, secs
run 1
run 2
run 3
run 4
run 5
run 6
run 7
run 10
run 11


OBSI#21, U.S. 441 Gainesville; Rear Probe
Orig. Configuration
110
108
106
104
102
100
98
IL, dB
0
2
4
6
8
10
time in test, secs
run 1
run 2
run 3
run 4
run 5
run 6
run 7
run 10
run 11



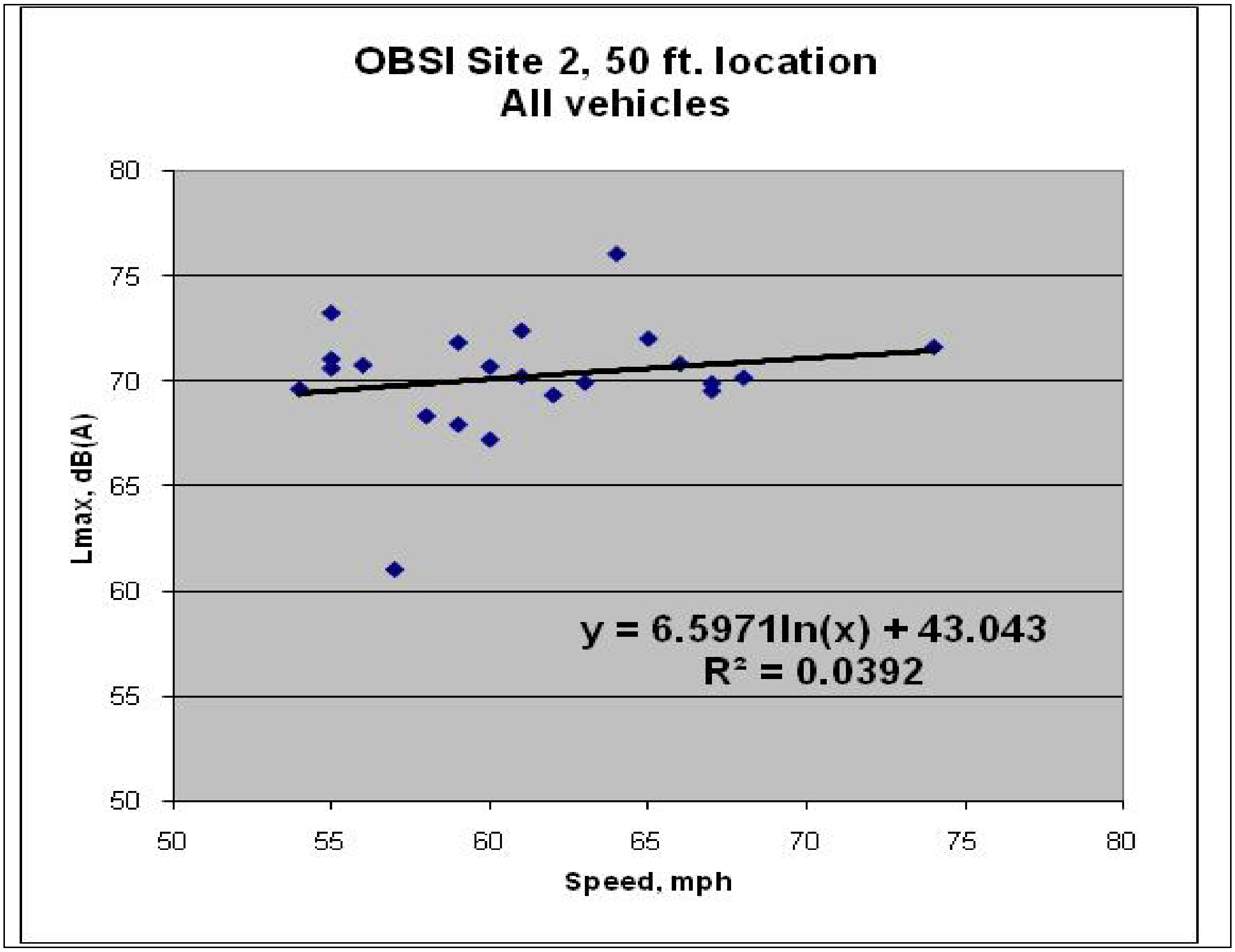
OBSI#22, S.R. 24 Gainesville; Front Probe
Orig. Configuration
IL, dB
110
108
106
104
102
100
98
0
2
4
6
8
10
time in test, secs
run1
run2
run3
run4
run5
run6
run7
run8
run12
run13
run14



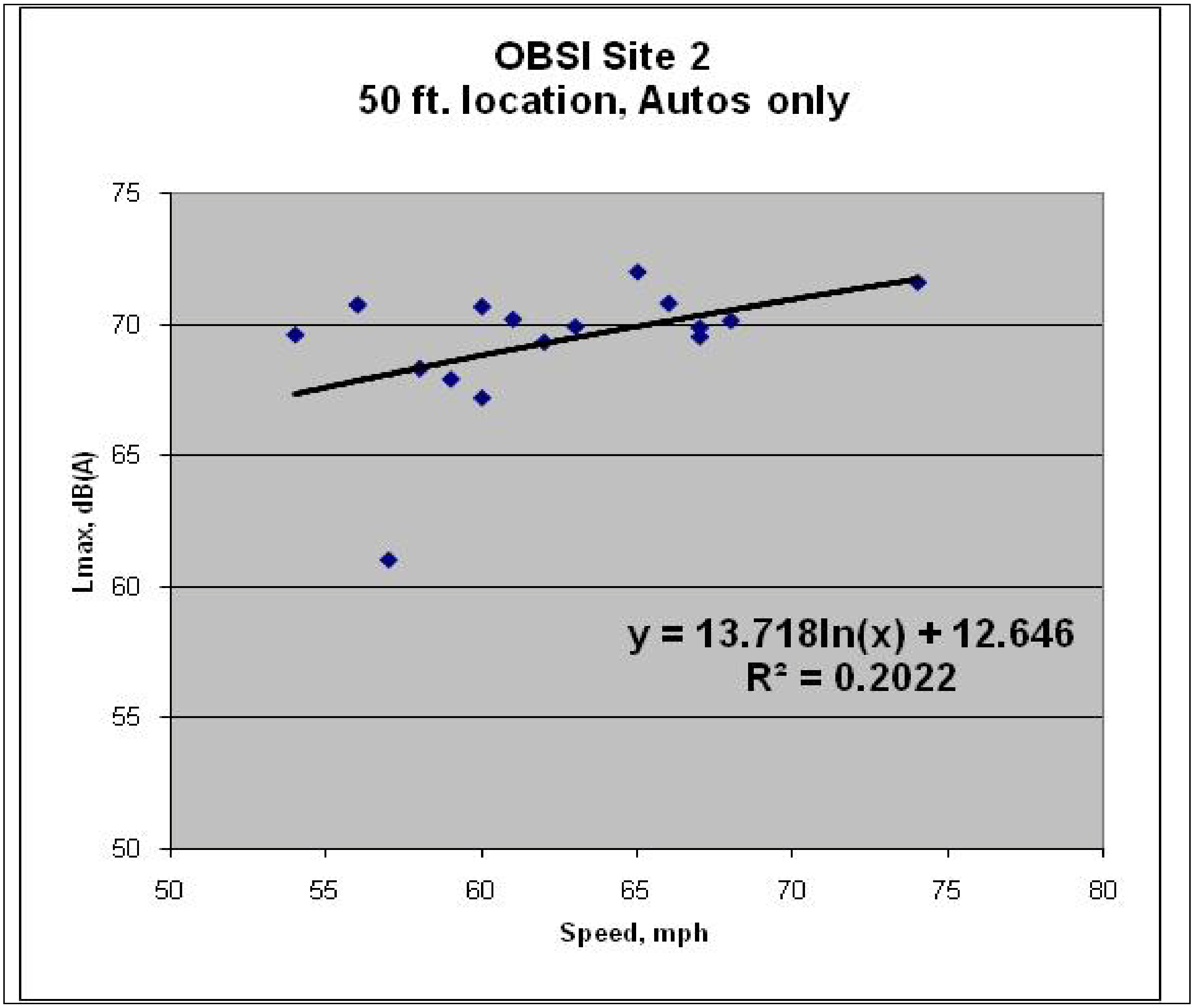
OBSI#22, S.R. 24 Gainesville; Rear Probe
Orig. Configuration
IL, dB
110
108
106
104
102
100
98
0
2
4
6
8
10
time in test, secs
run1
run2
run3
run4
run5
run6
run7
run8
run12
run13
run14

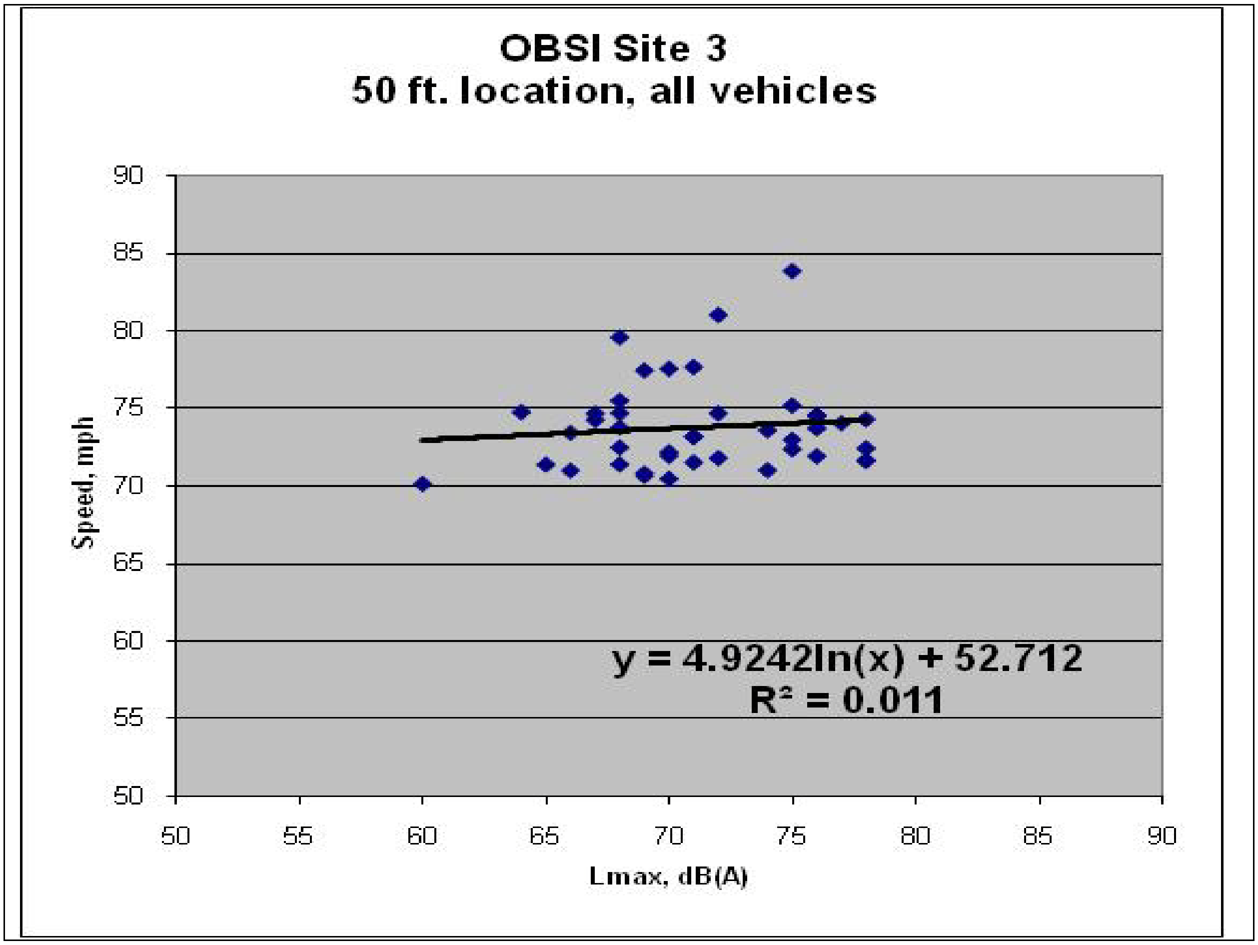
APPENDIX C

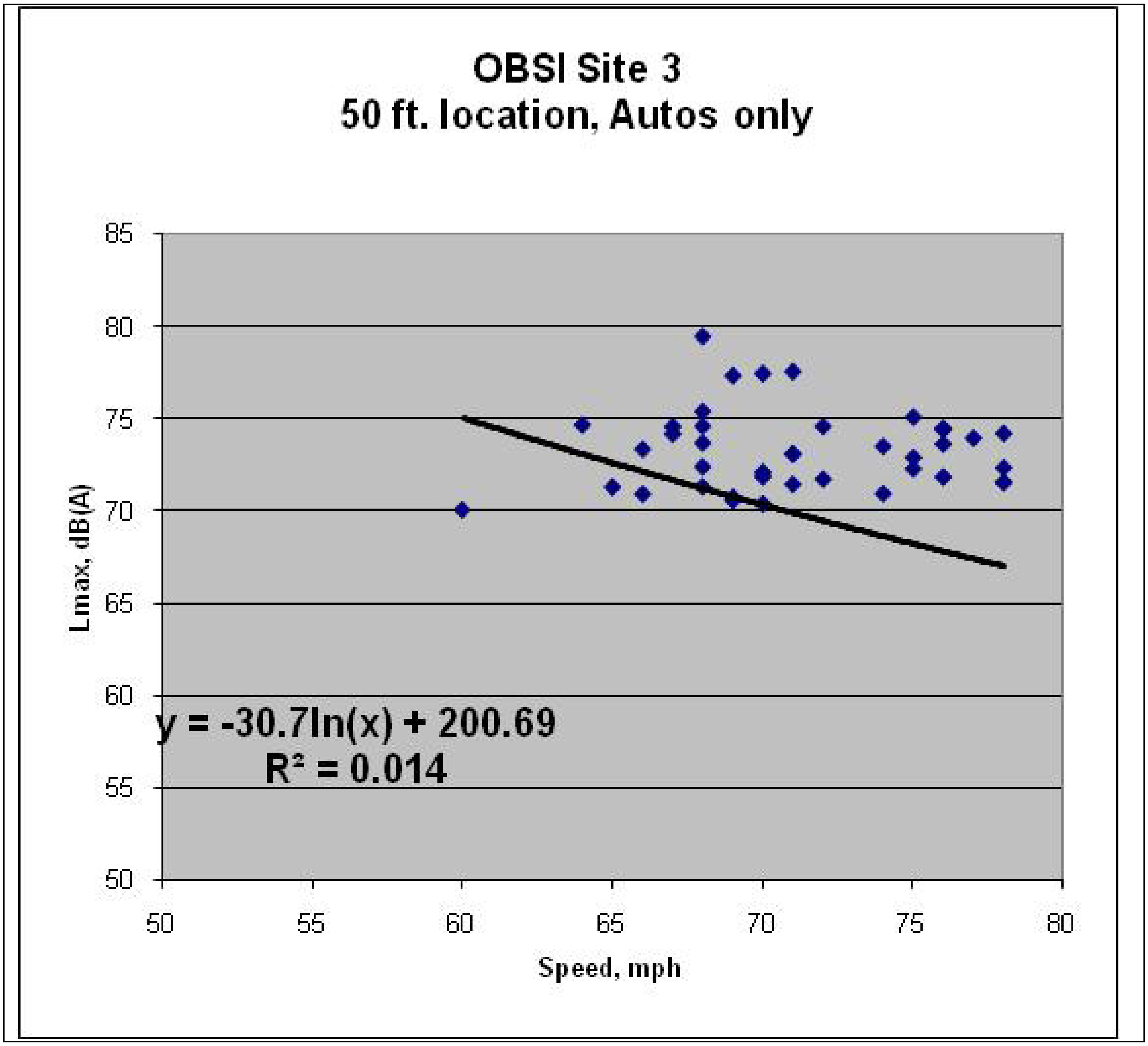
Wayside Lmax Versus Speed Results



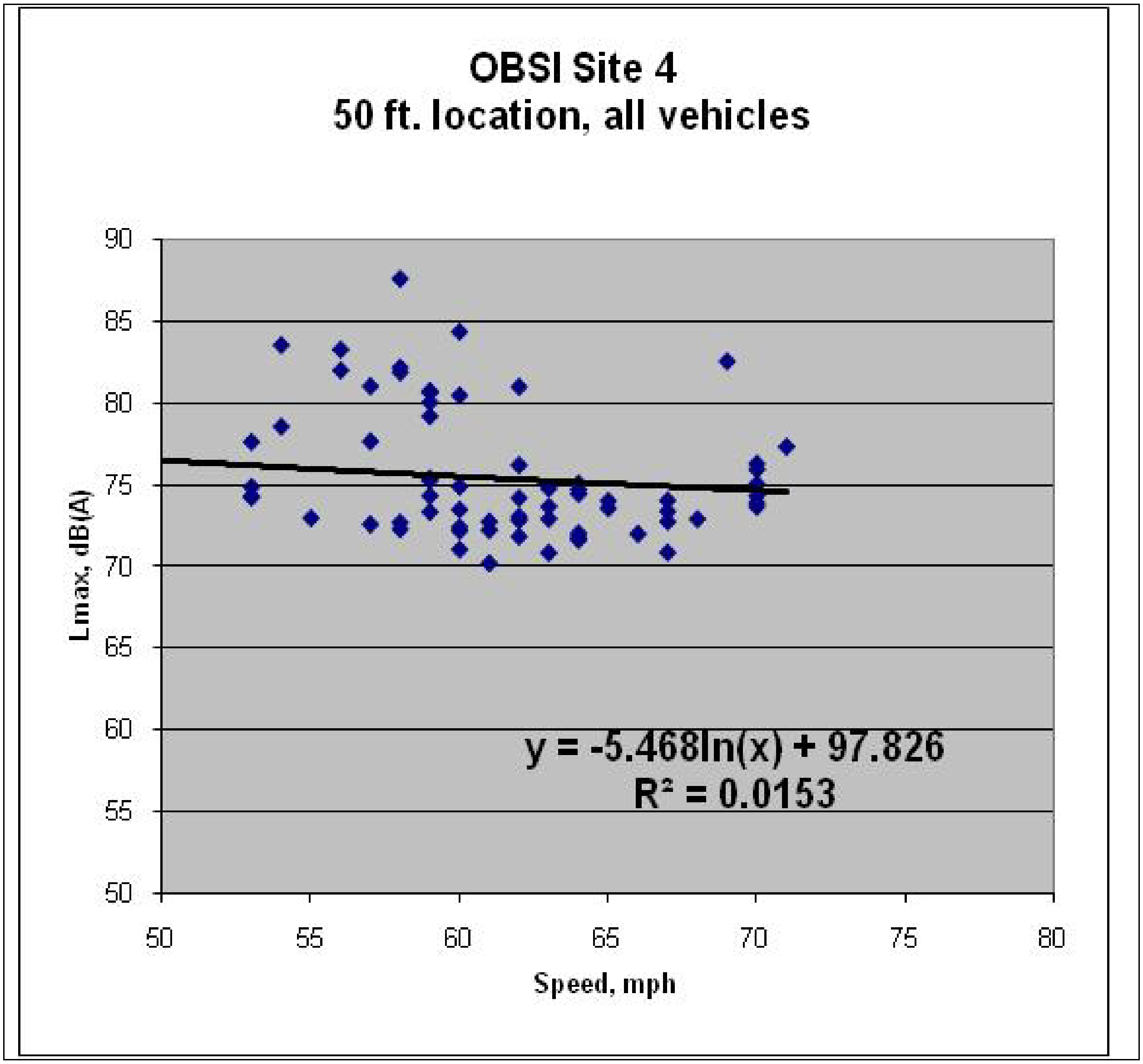
OBSI Site 2, 50 ft. location
All vehicles
80
75
70
65
60
55
50
Lmax, dB(A)
y = 6.5971ln(x) + 43.043
R² = 0.0392
50
55
60
65
70
75
80
Speed, mph


OBSI Site 2
50 ft. location, Autos only
75
70
65
60
55
50
Lmax, dB(A)
50
55
60
65
70
75
80
Speed, mph
y = 13.718ln(x) + 12.646
R² = 0.2022

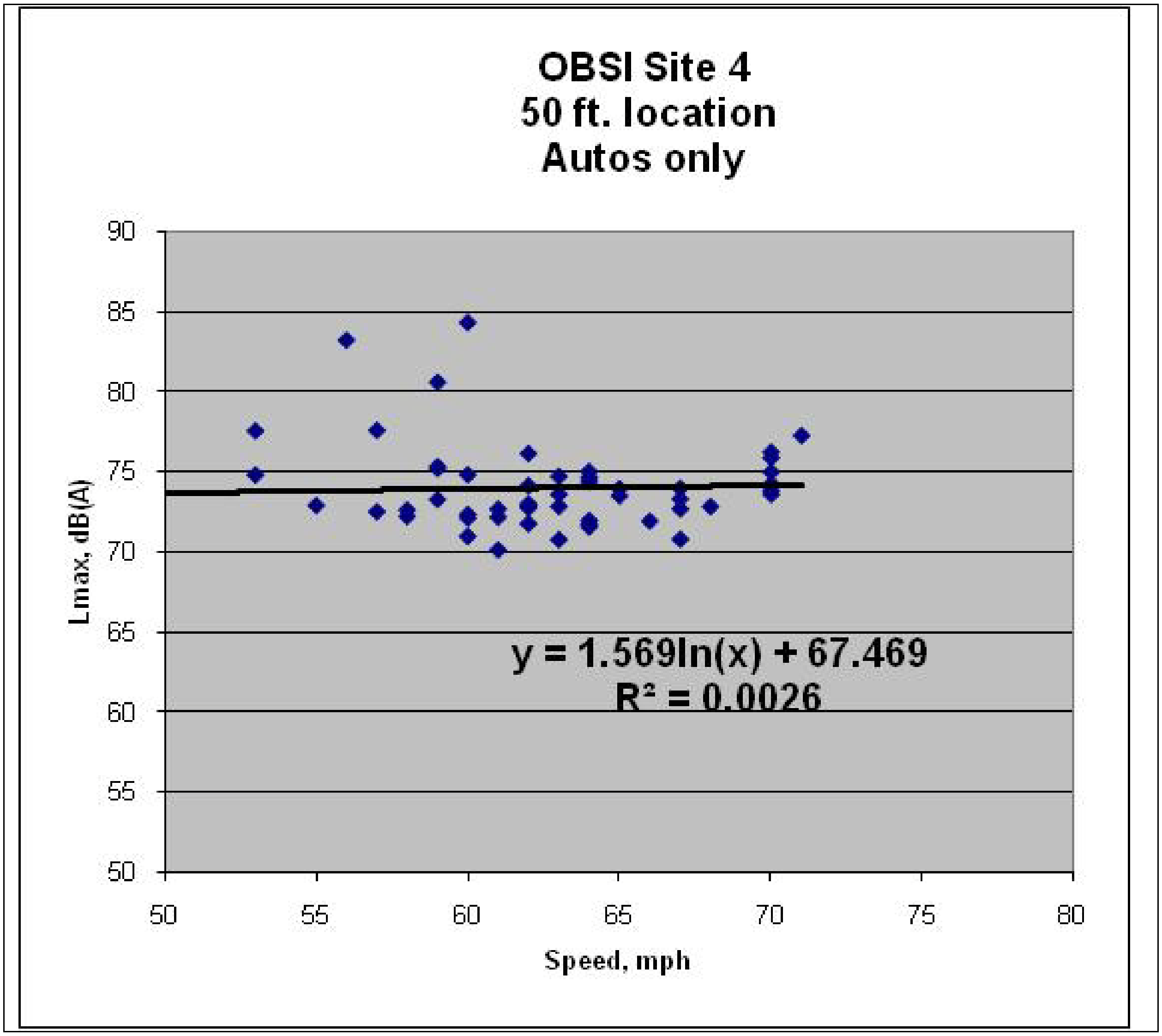

OBSI Site 3
50 ft. location, all vehicles
90
85
80
75
70
65
60
55
50
Speed, mph
y = 4.9242ln(x) + 52.712
R² = 0.011
50
55
60
65
70
75
80
85
90
Lmax, dB(A)



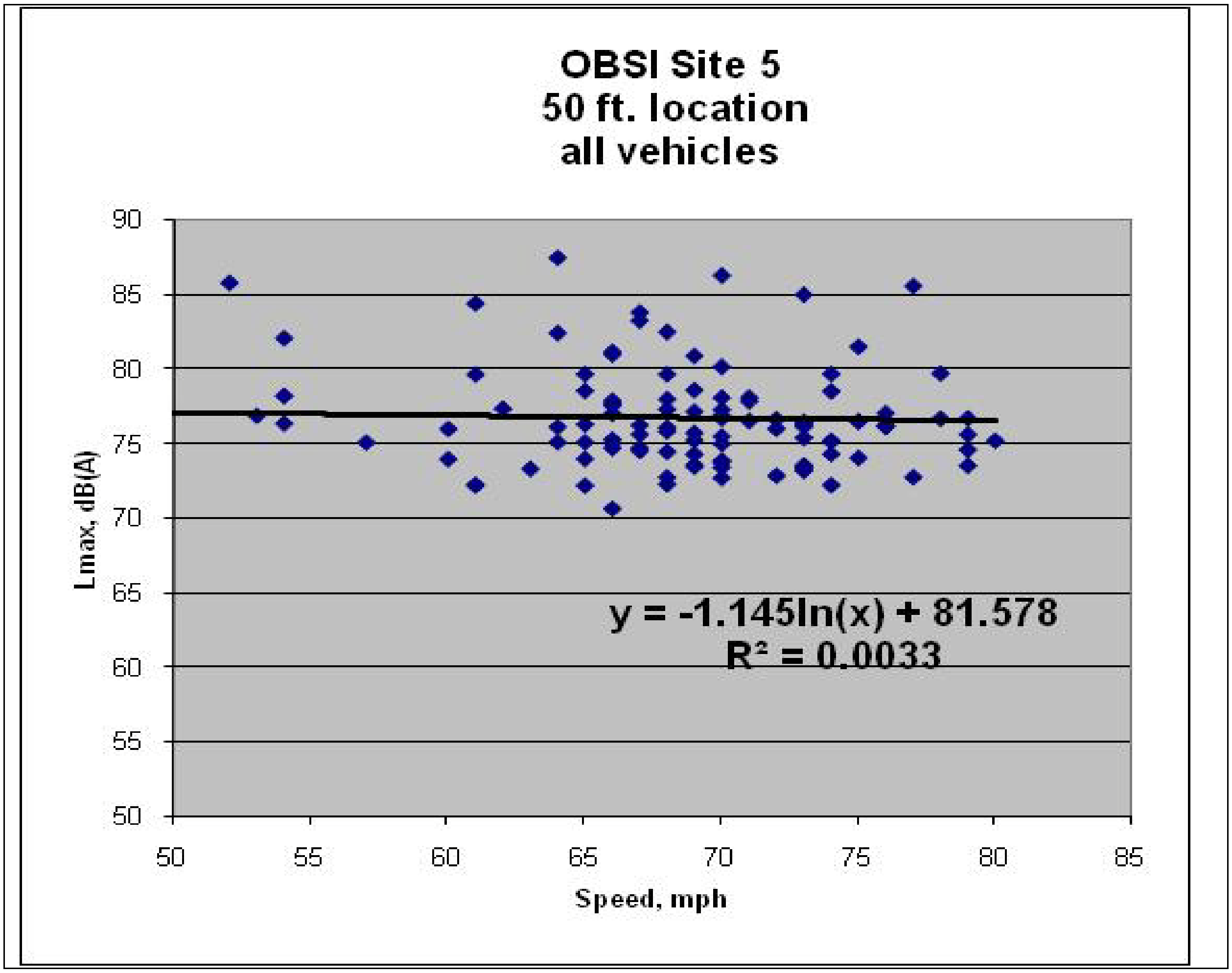
OBSI Site 3
50 ft. location, Autos only
85
80
75
70
65
60
55
50
Lmax, dB(A)
y = -30.7ln(x) + 200.69
R² = 0.014
50
55
60
65
70
75
80
Speed, mph

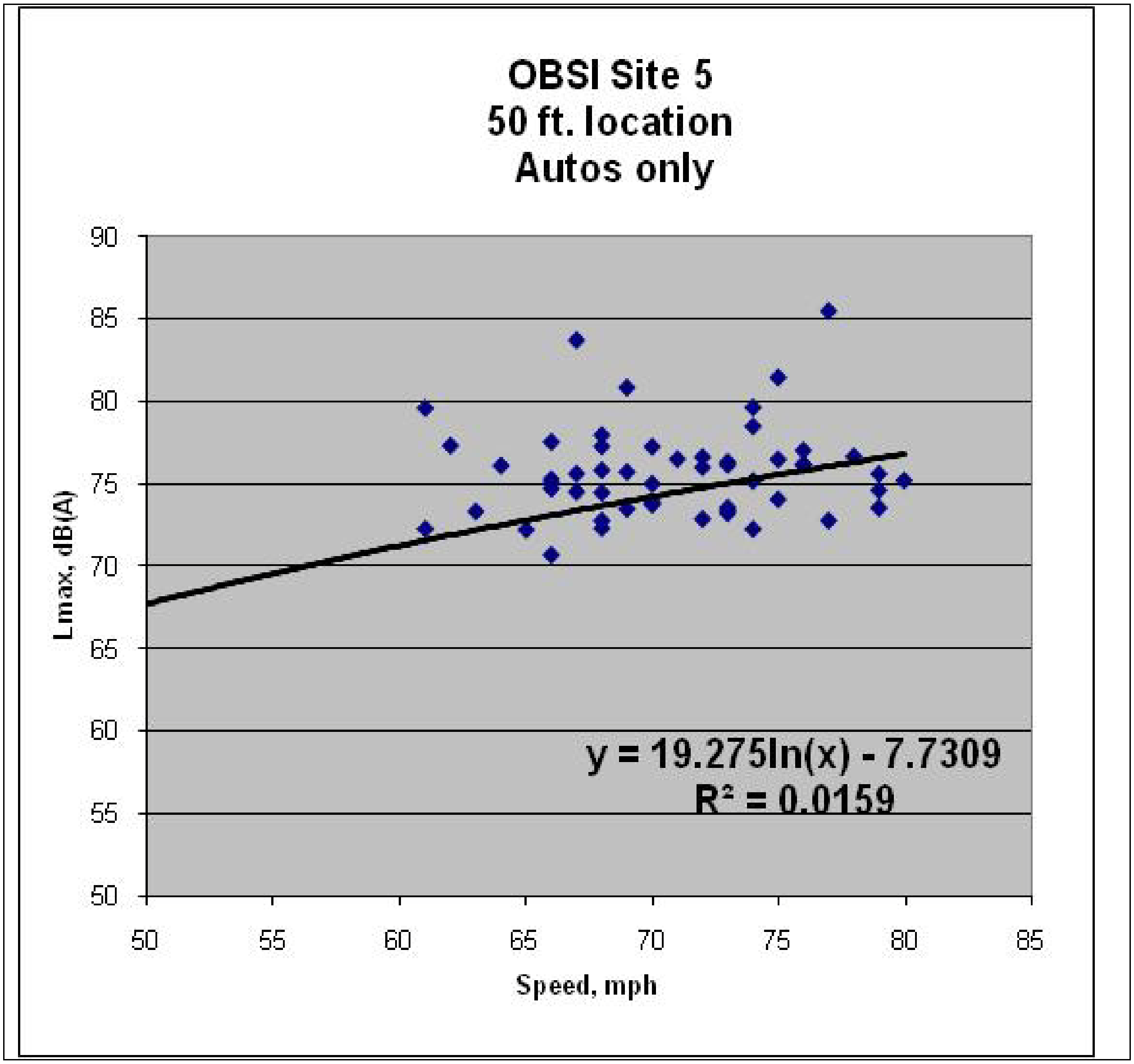


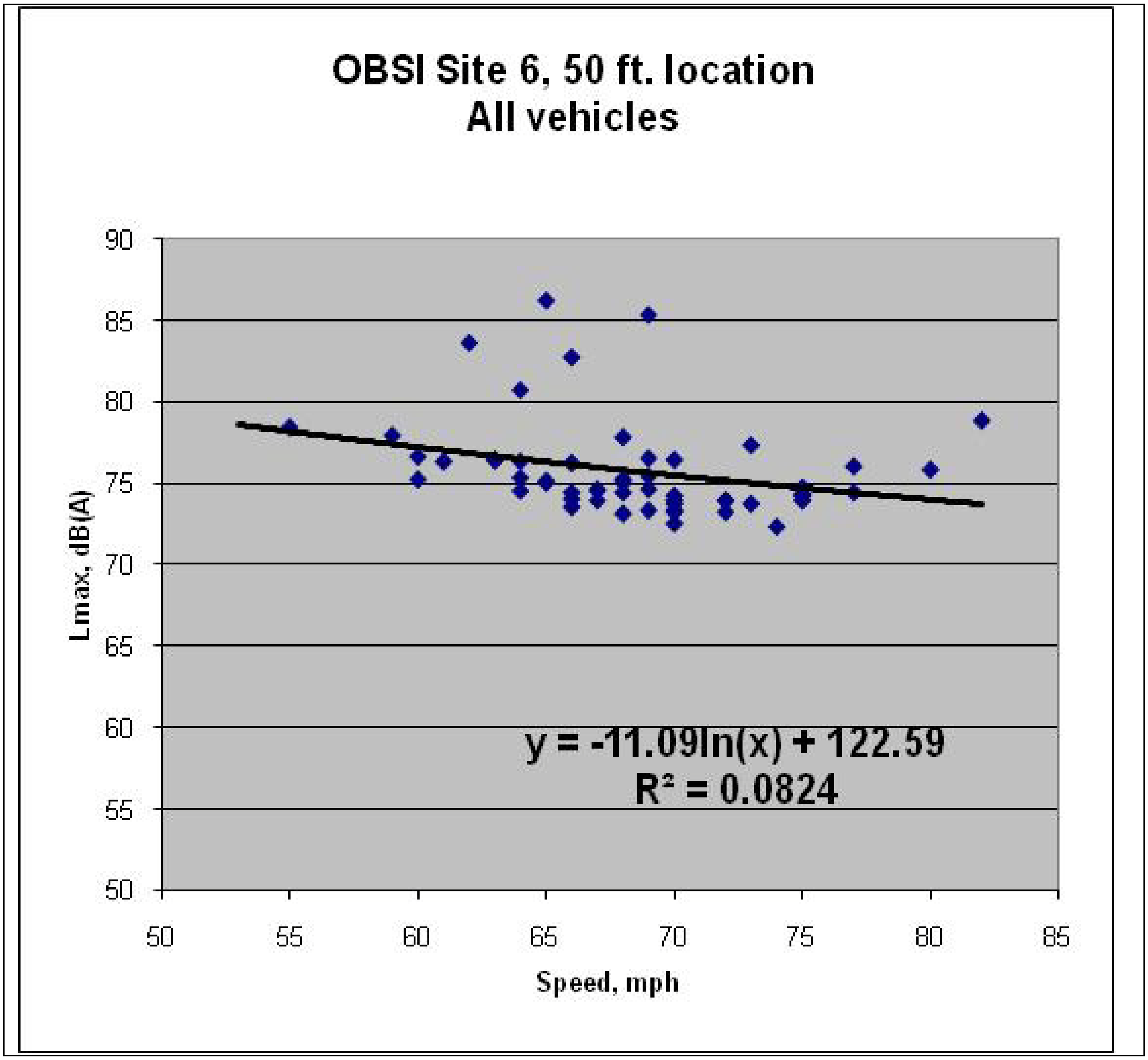
OBSI Site 4
50 ft. location, all vehicles
y = -5.468ln(x) + 97.826
R² = 0.0153
Lmax, dB(A)
Speed, mph
90
85
80
75
70
65
60
55
50
50
55
60
65
70
75
80

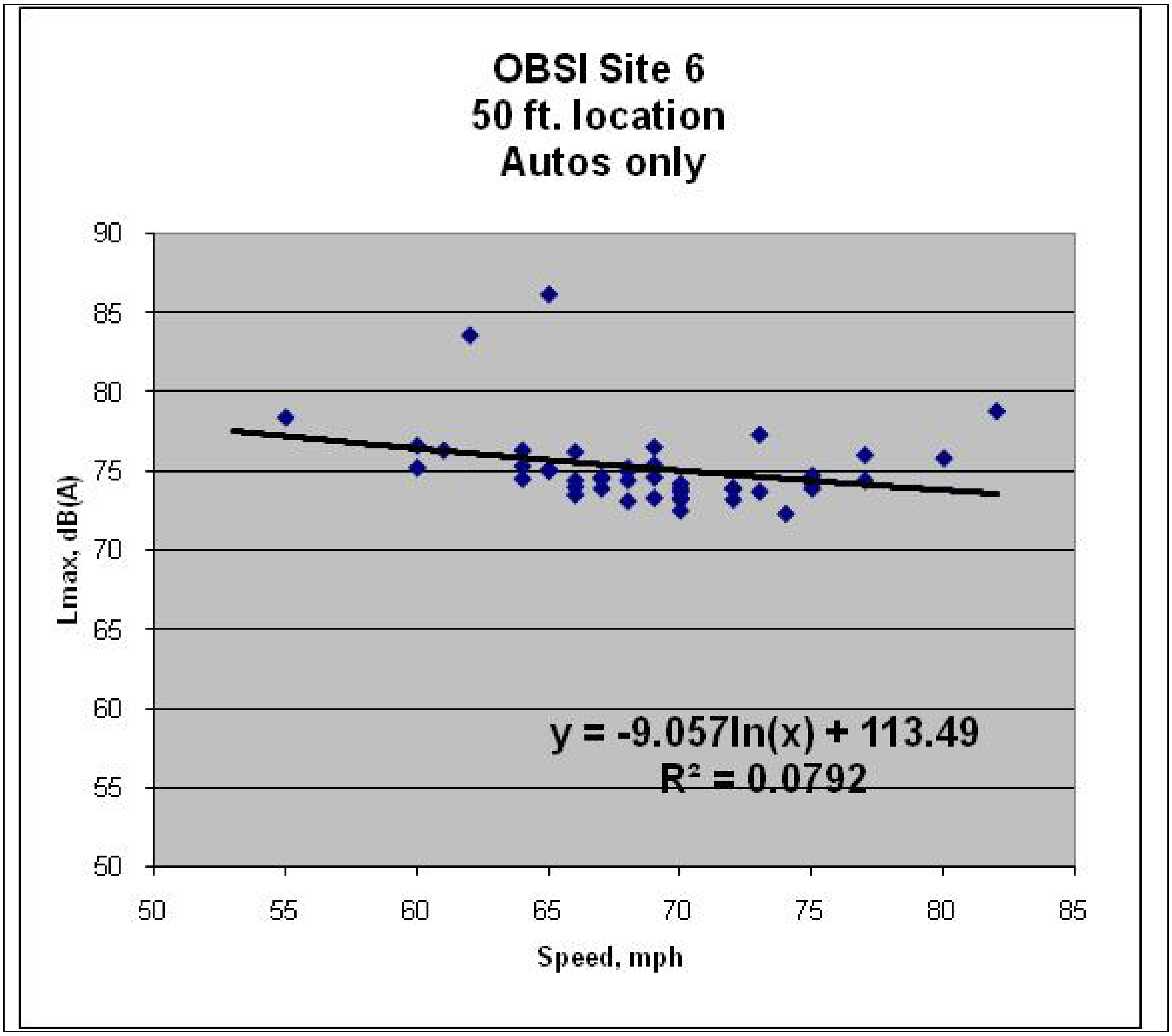


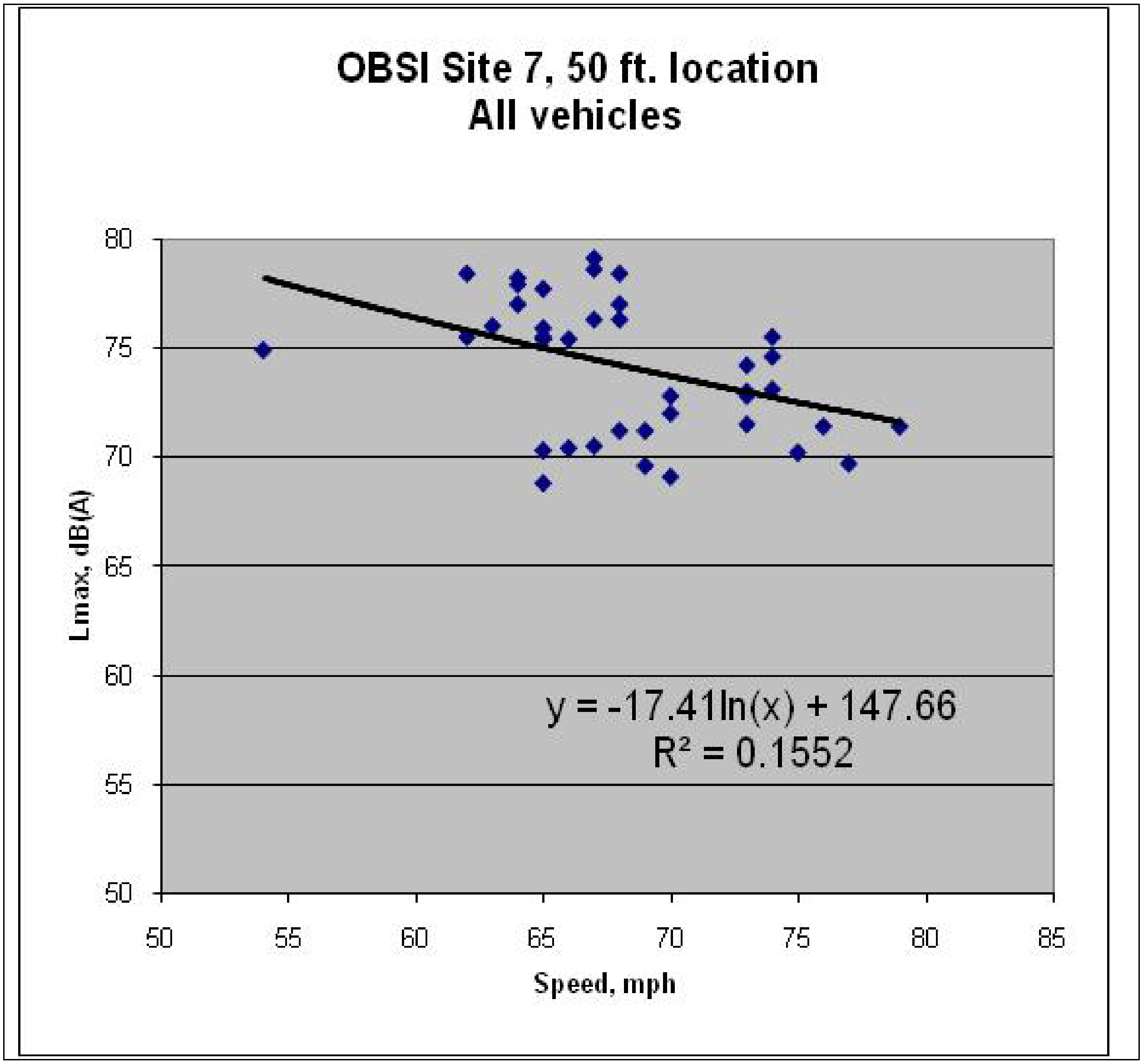
OBSI Site 4
50 ft. location
Autos only
90
85
80
75
70
65
60
55
50
Lmax, dB(A)
y = 1.569ln(x) + 67.469
R² = 0.0026
50
55
60
65
70
75
80
Speed, mph


OBSI Site 5
50 ft. location
all vehicles
Lmax, dB(A)
Speed, mph
y = -1.145ln(x) + 81.578
R² = 0.0033
90
85
80
75
70
65
60
55
50
50
55
60
65
70
75
80
85

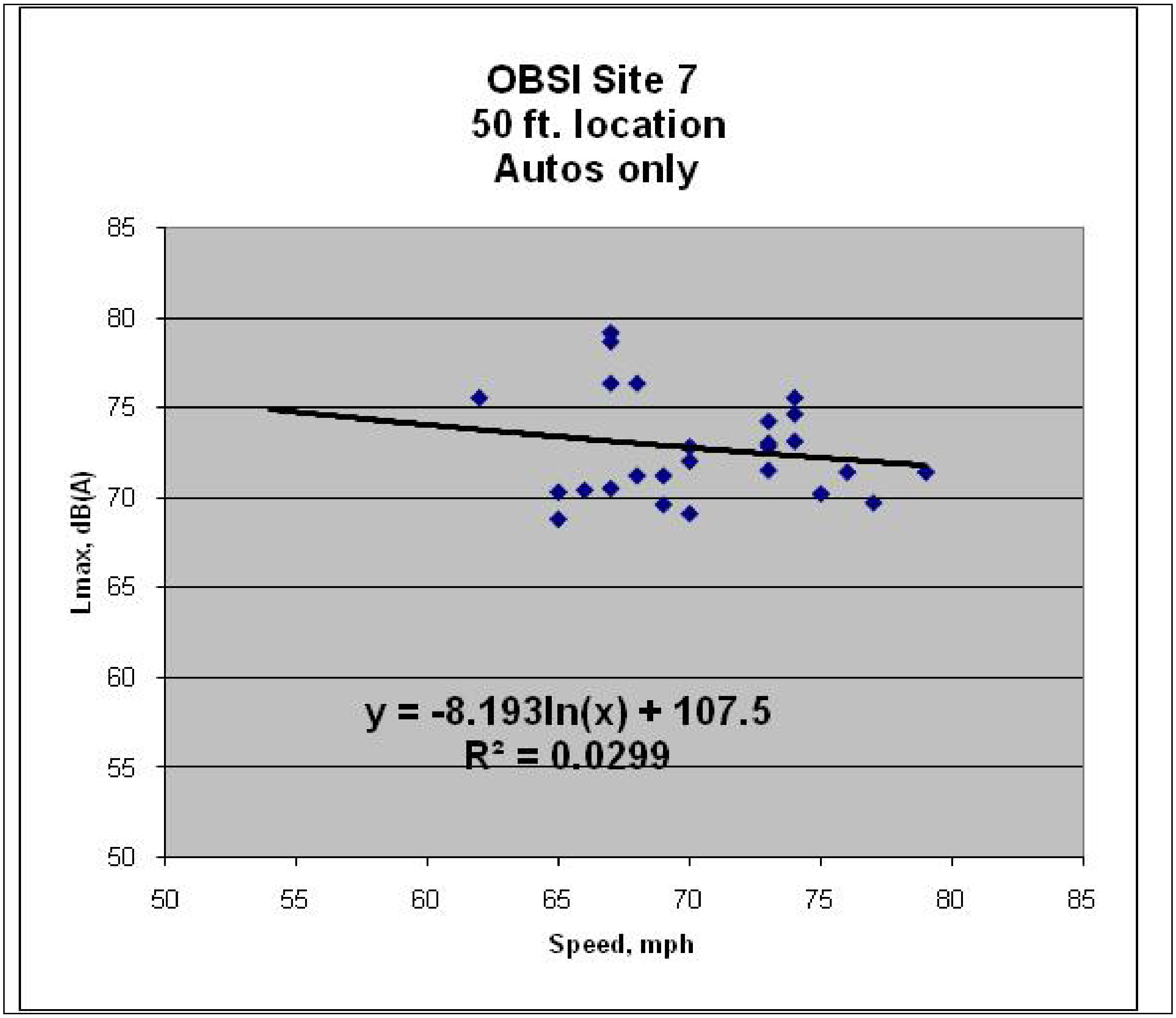

OBSI Site 5
50 ft. location
Autos only
90
85
80
75
70
65
60
55
50
Lmax, dB(A)
y = 19.275ln(x) - 7.7309
R² = 0.0159
50
55
60
65
70
75
80
85
Speed, mph

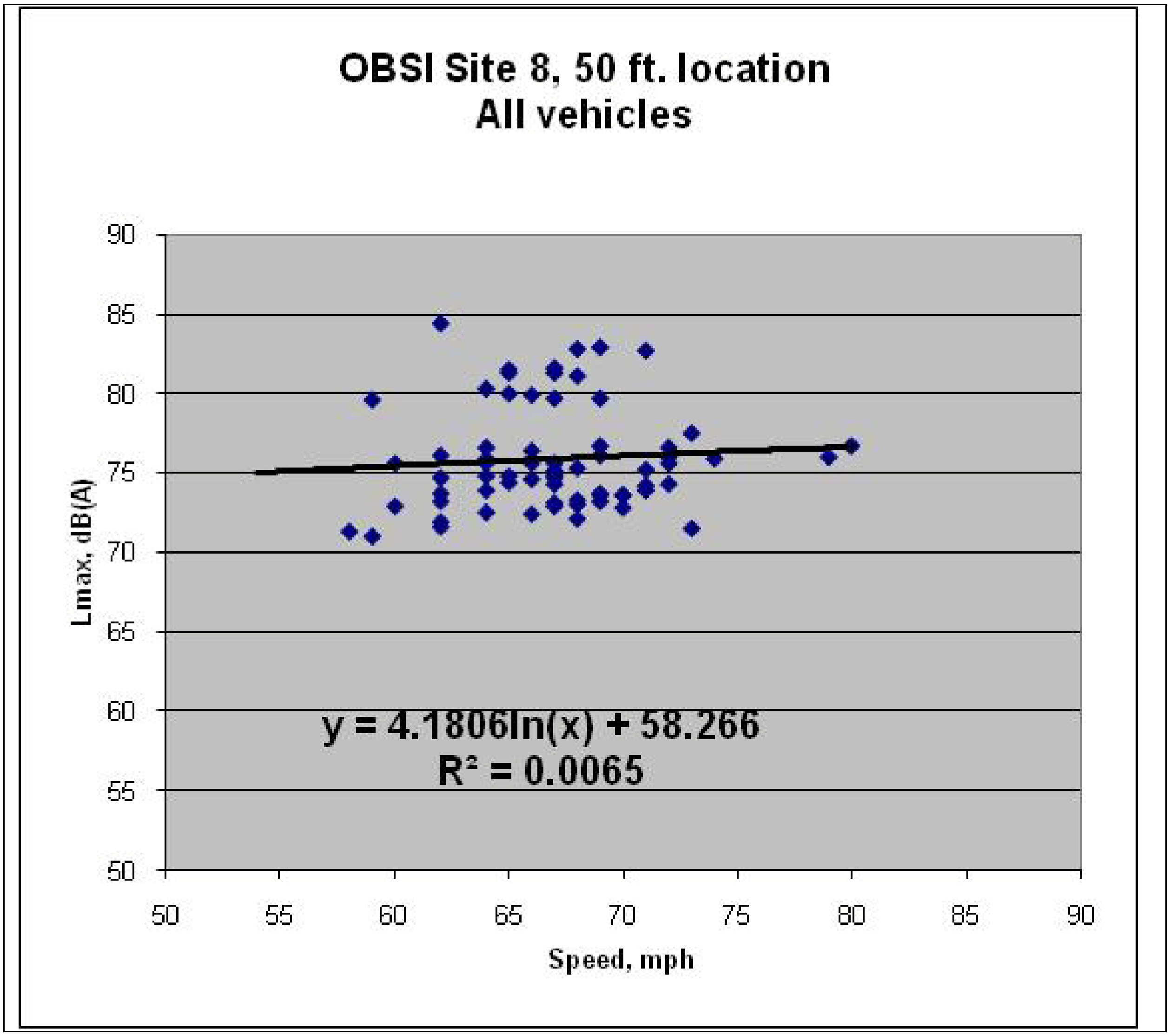

OBSI Site 6, 50 ft. location
All vehicles
Lmax, dB(A)
90
85
80
75
70
65
60
55
50
50
55
60
65
70
75
80
85
Speed, mph
y = -11.09ln(x) + 122.59
R² = 0.0824

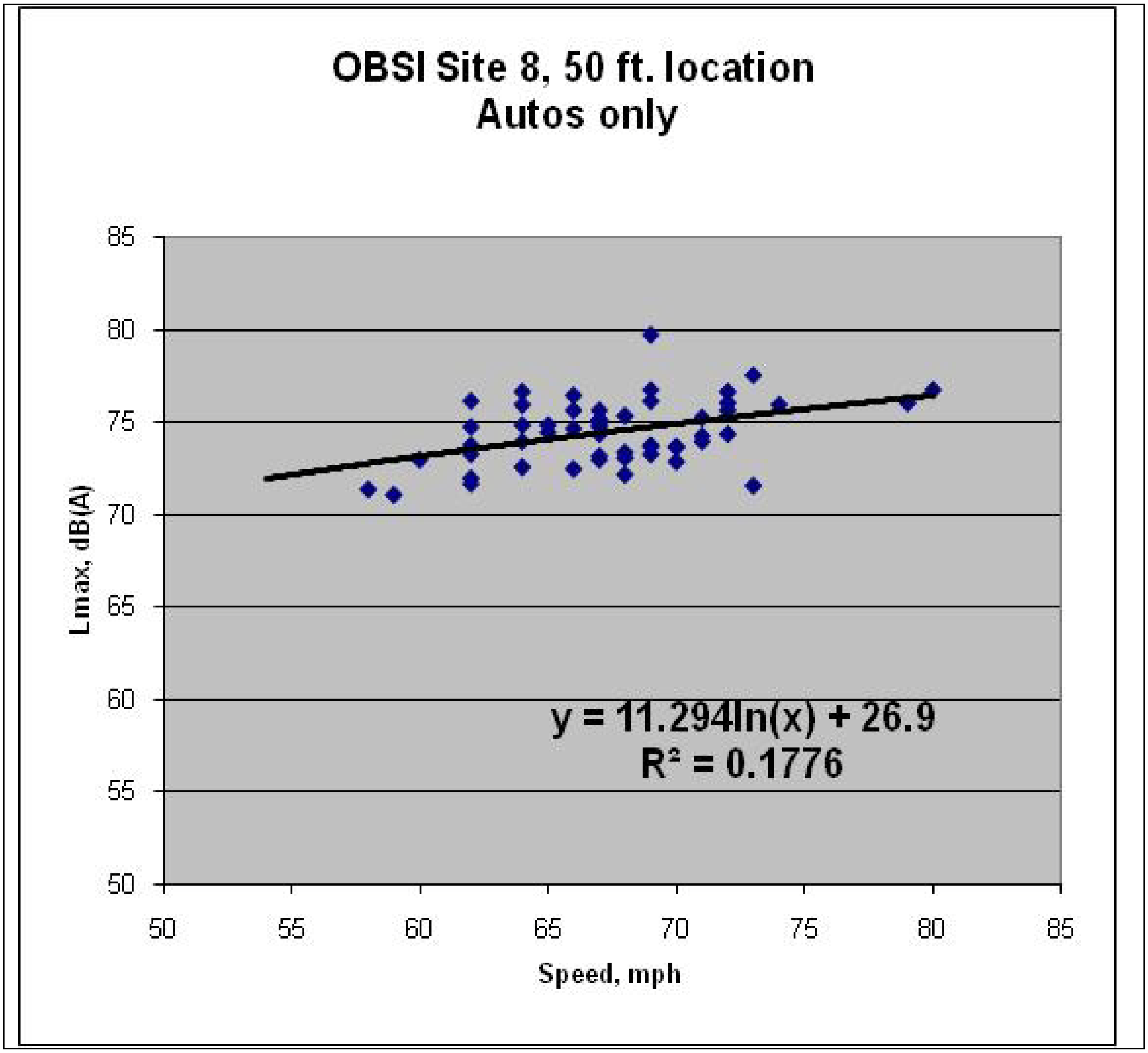

OBSI Site 6
50 ft. location
Autos only
90
85
80
75
70
65
60
55
50
Lmax, dB(A)
y = -9.057ln(x) + 113.49
R² = 0.0792
50
55
60
65
70
75
80
85
Speed, mph



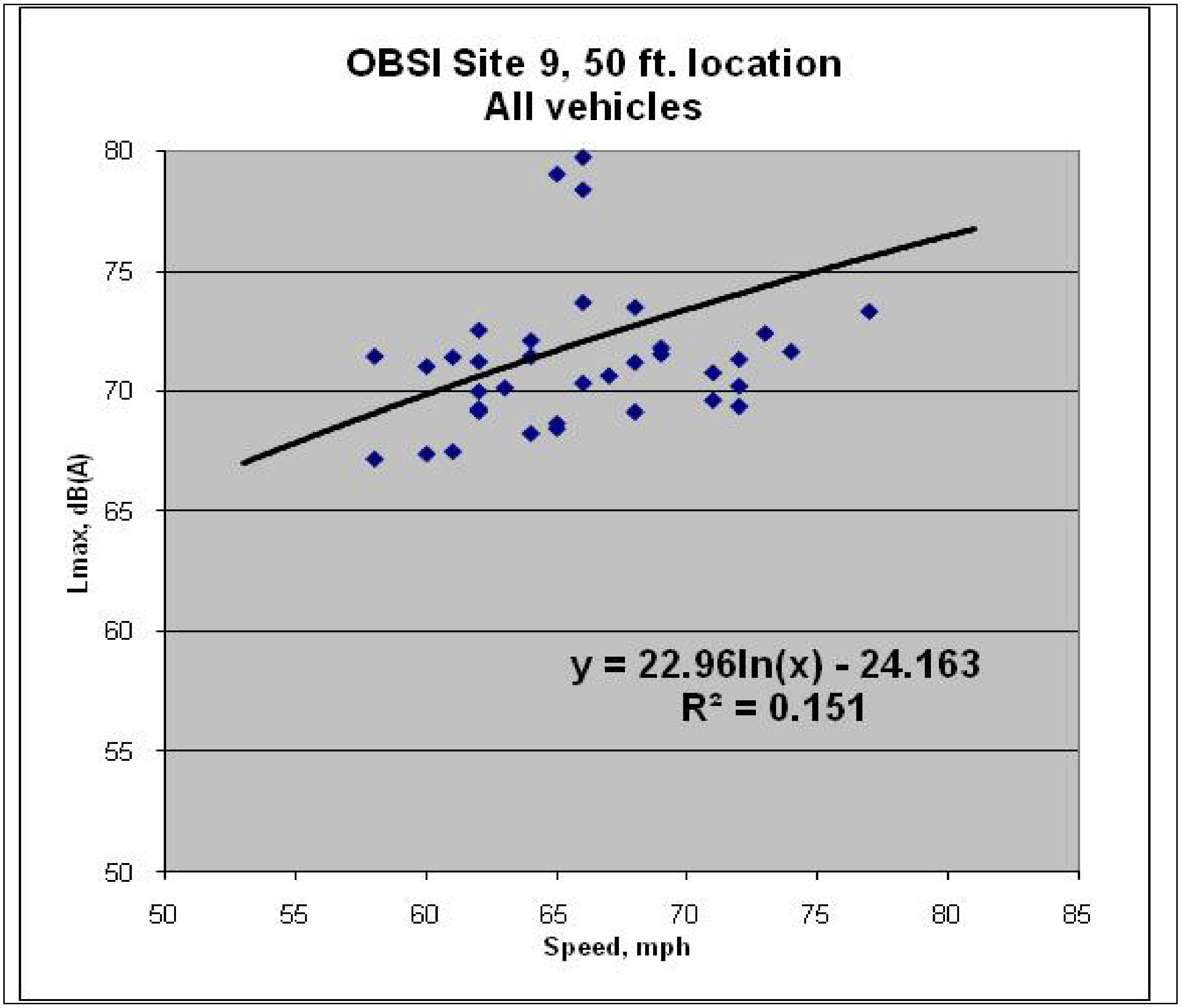
OBSI Site 7, 50 ft. location
All vehicles
80
75
70
65
60
55
50
Lmax, dB(A)
y = -17.41ln(x) + 147.66
R² = 0.1552
50
55
60
65
70
75
80
85
Speed, mph

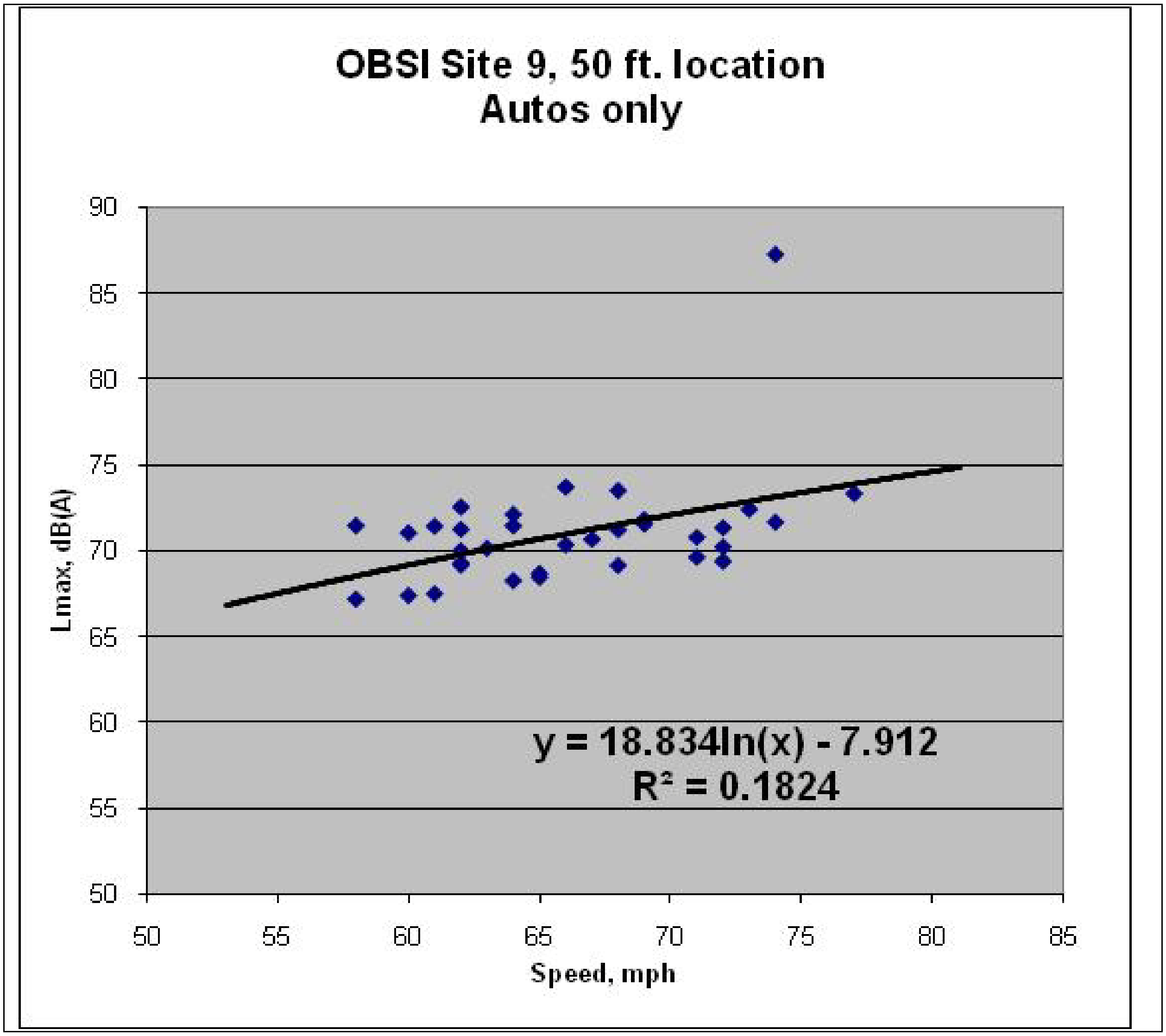

OBSI Site 7
50 ft. location
Autos only
y = -8.193ln(x) + 107.5
R² = 0.0299
Lmax, dB(A)
Speed, mph
85
80
75
70
65
60
55
50
50
55
60
65
70
75
80
85


OBSI Site 8, 50 ft. location
All vehicles
y = 4.1806ln(x) + 58.266
R² = 0.0065
Lmax, dB(A)
Speed, mph
90
85
80
75
70
65
60
55
50
50
55
60
65
70
75
80
85
90

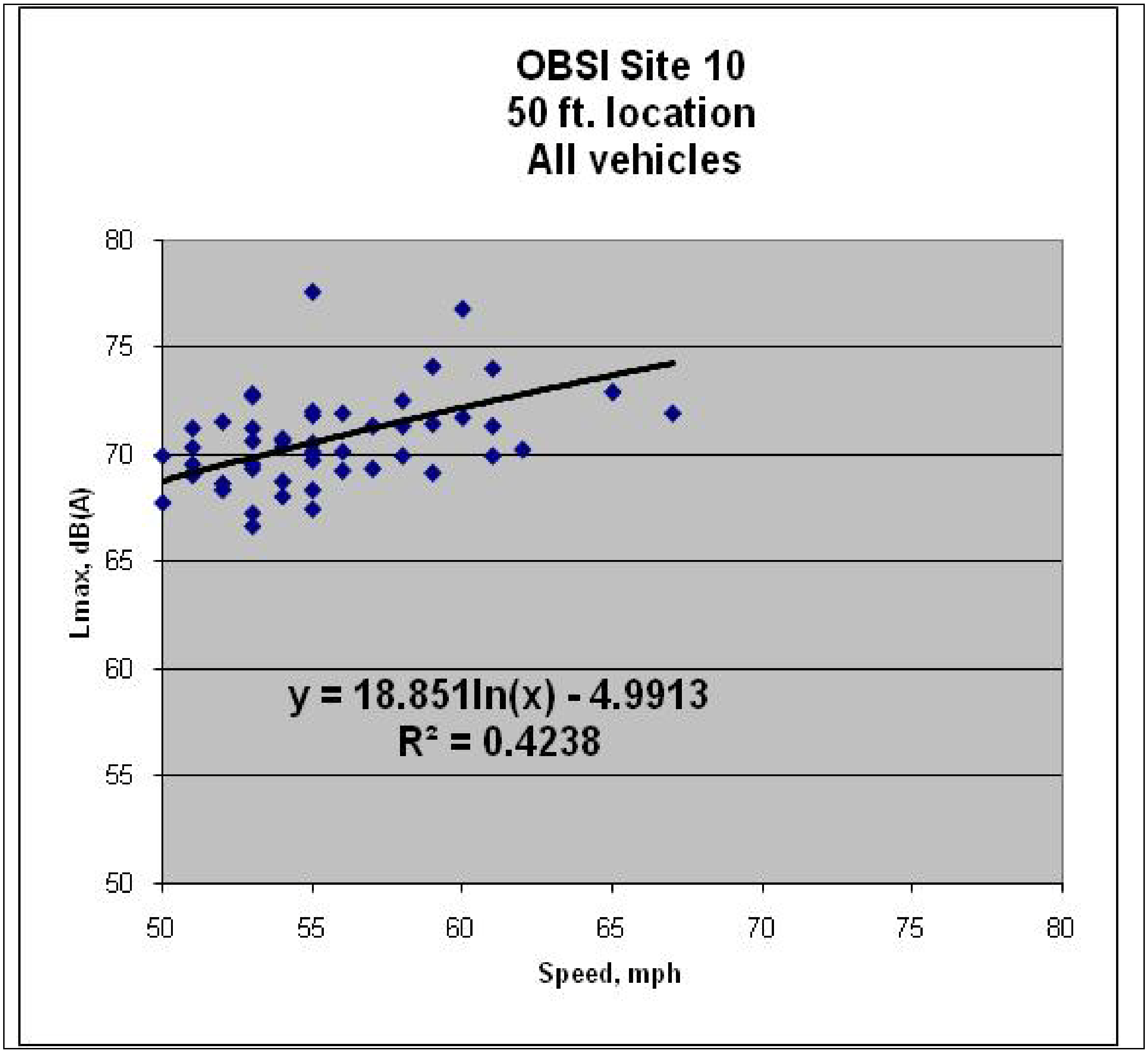


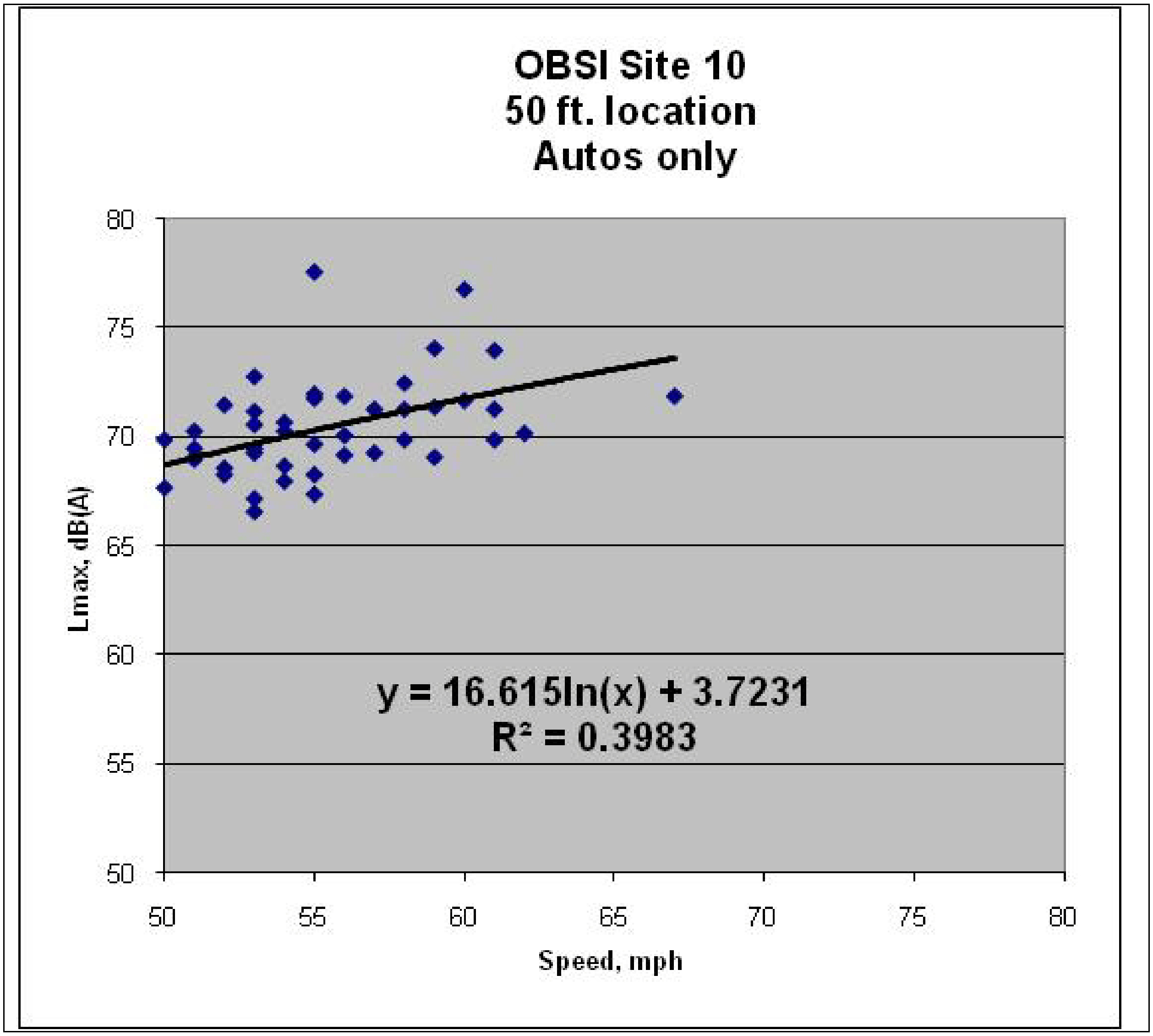
OBSI Site 8, 50 ft. location
Autos only
85
80
75
70
65
60
55
50
Lmax, dB(A)
y = 11.294ln(x) + 26.9
R² = 0.1776
50
55
60
65
70
75
80
85
Speed, mph

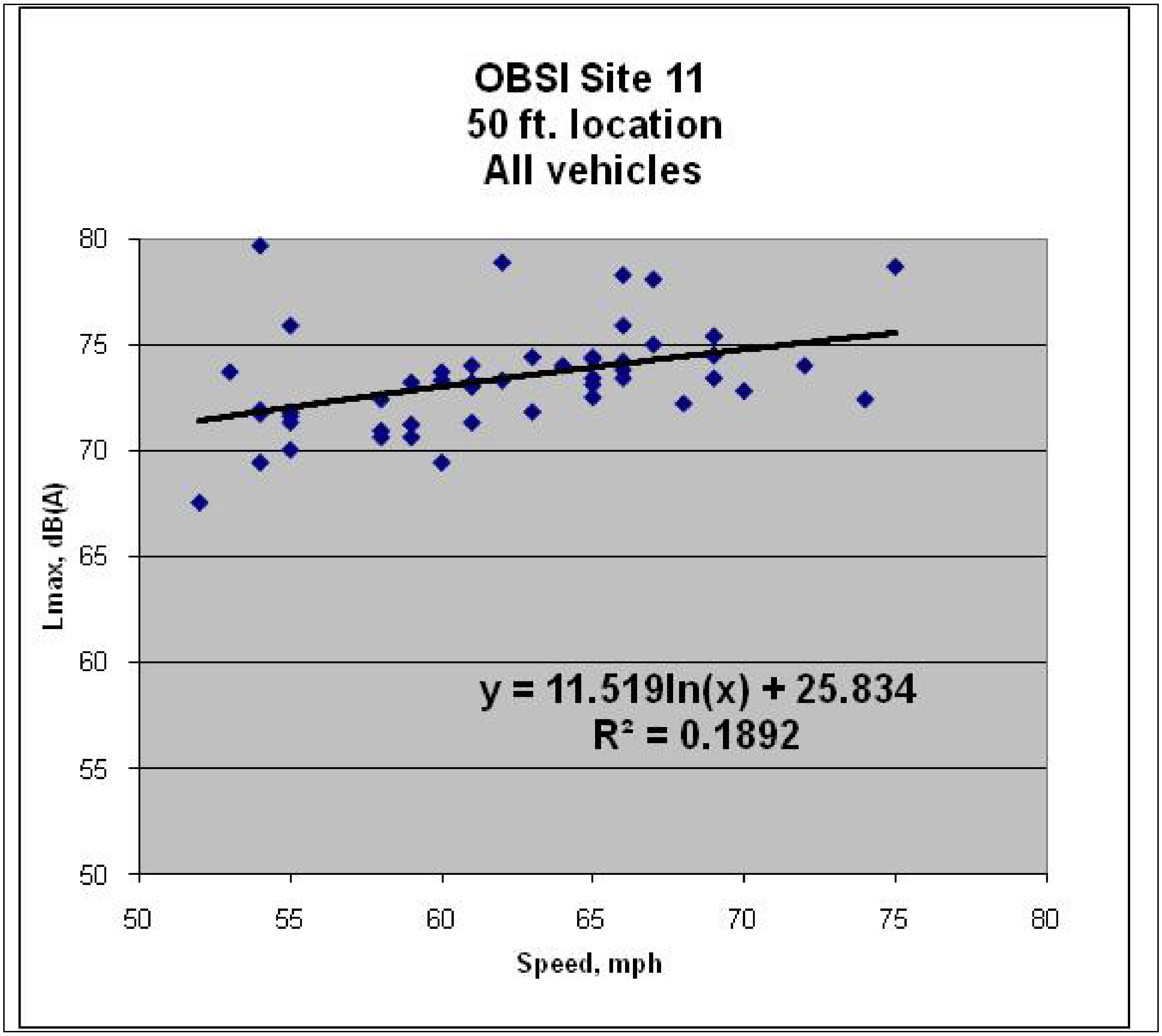

OBSI Site 9, 50 ft. location
All vehicles
Lmax, dB(A)
Speed, mph
80
75
70
65
60
55
50
50
55
60
65
70
75
80
85
y = 22.96ln(x) - 24.163
R² = 0.151

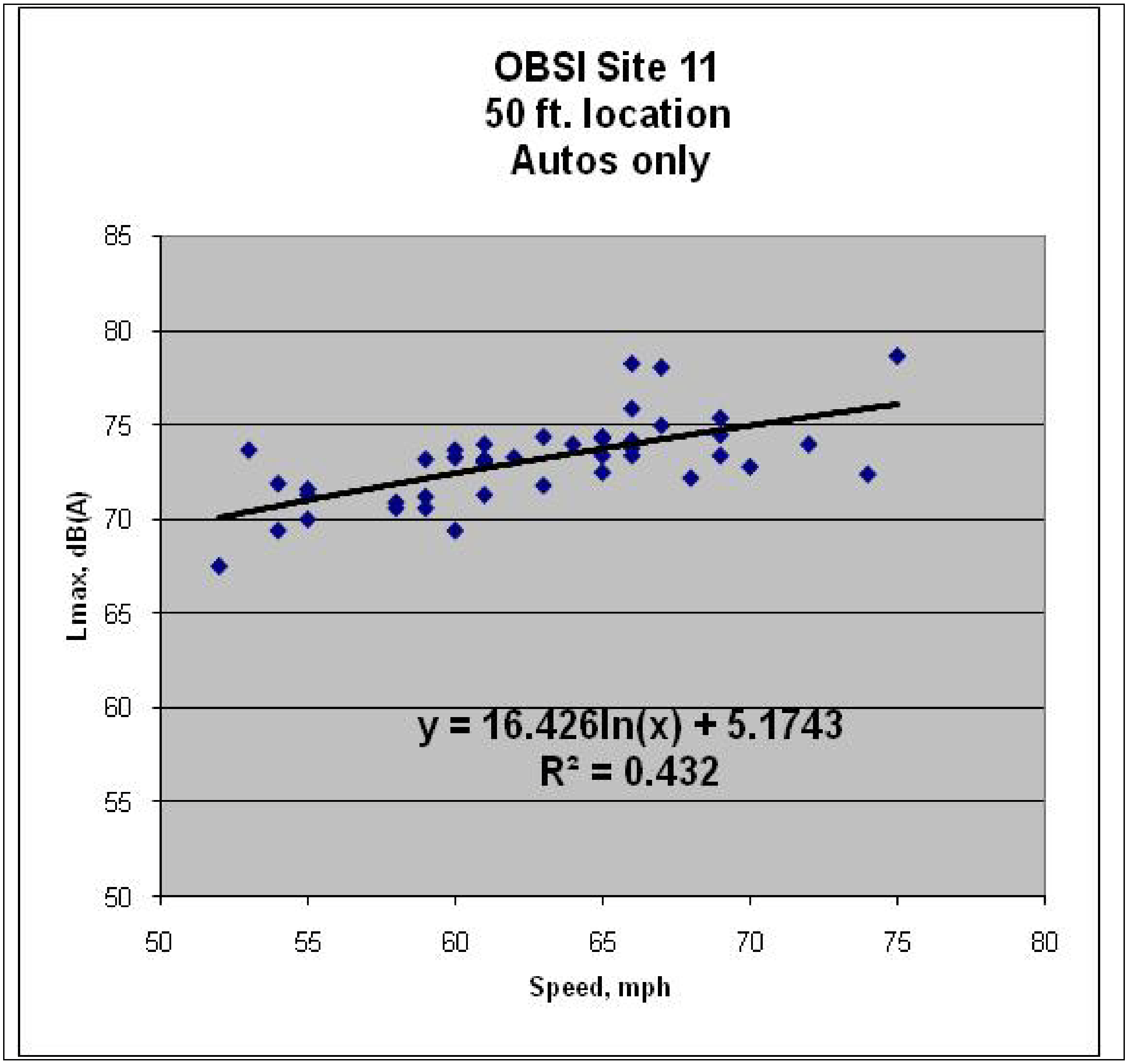


OBSI Site 9, 50 ft. location
Autos only
Lmax, dB(A)
Speed, mph
y = 18.834ln(x) - 7.912
R² = 0.1824
90
85
80
75
70
65
60
55
50
50
55
60
65
70
75
80
85

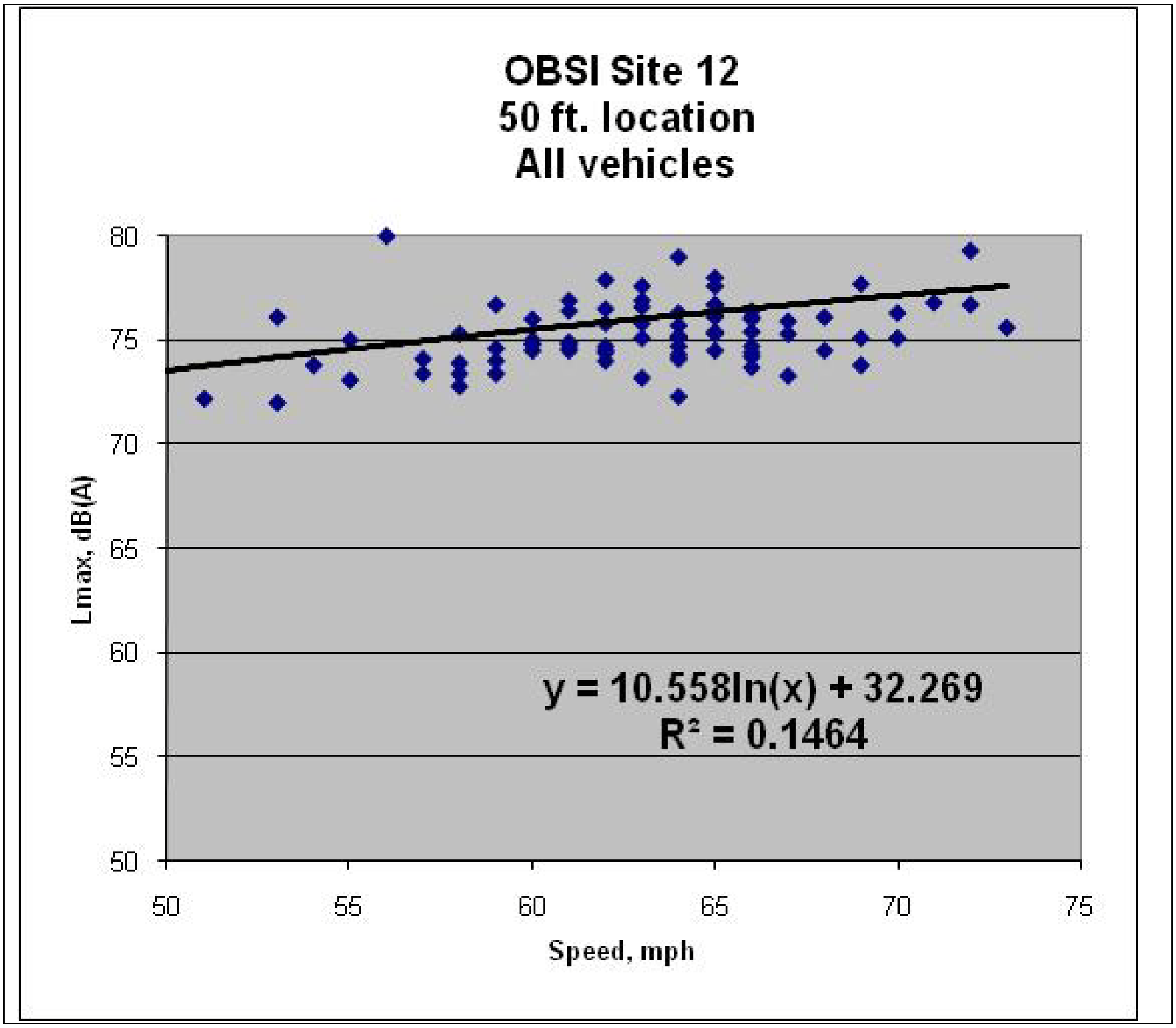

OBSI Site 10
50 ft. location
All vehicles
y = 18.851ln(x) - 4.9913
R² = 0.4238
Lmax, dB(A)
Speed, mph
80
75
70
65
60
55
50
50
55
60
65
70
75
80

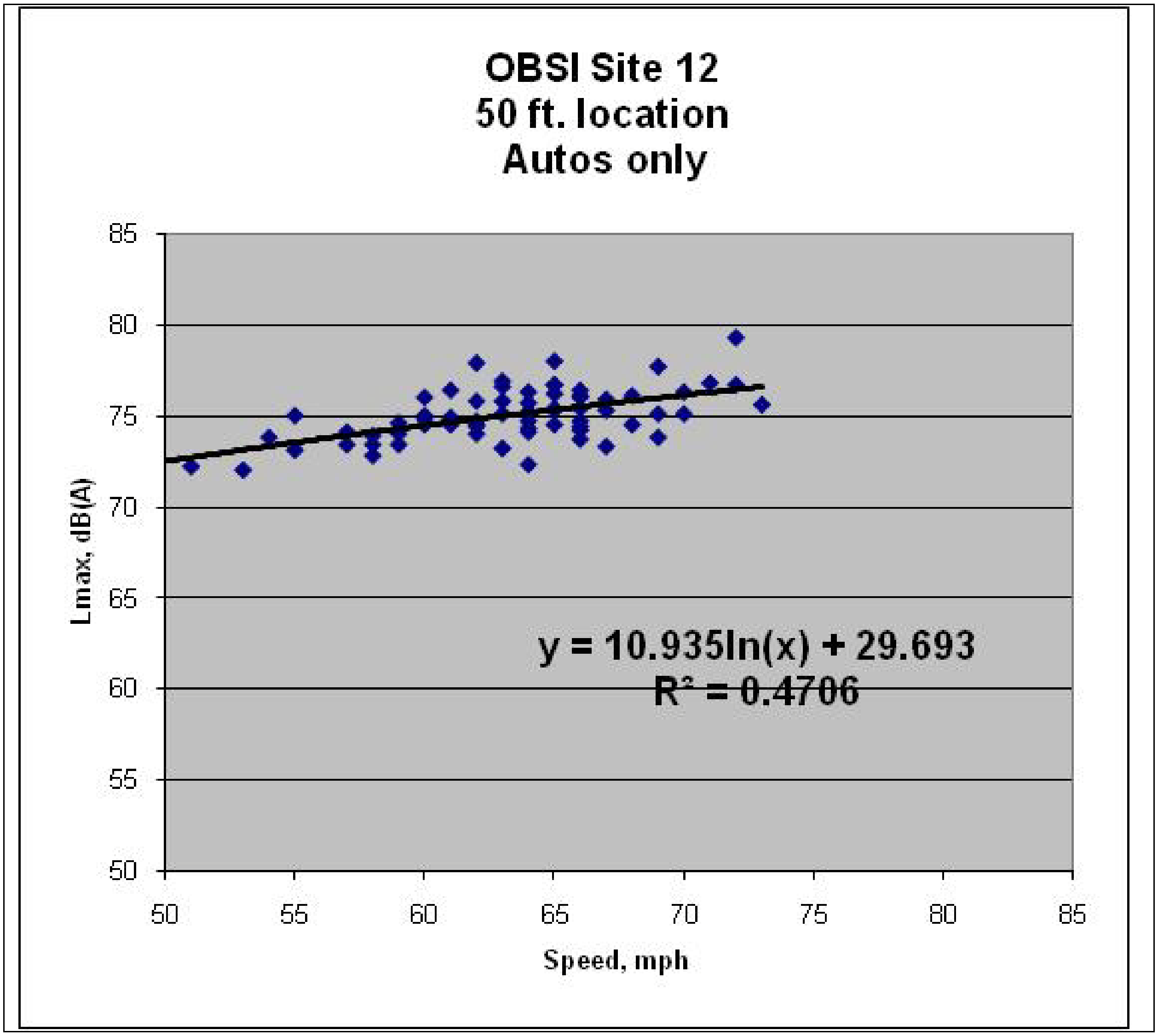

OBSI Site 10
50 ft. location
Autos only
y = 16.615ln(x) + 3.7231
R² = 0.3983
Lmax, dB(A)
Speed, mph
80
75
70
65
60
55
50
50
55
60
65
70
75
80

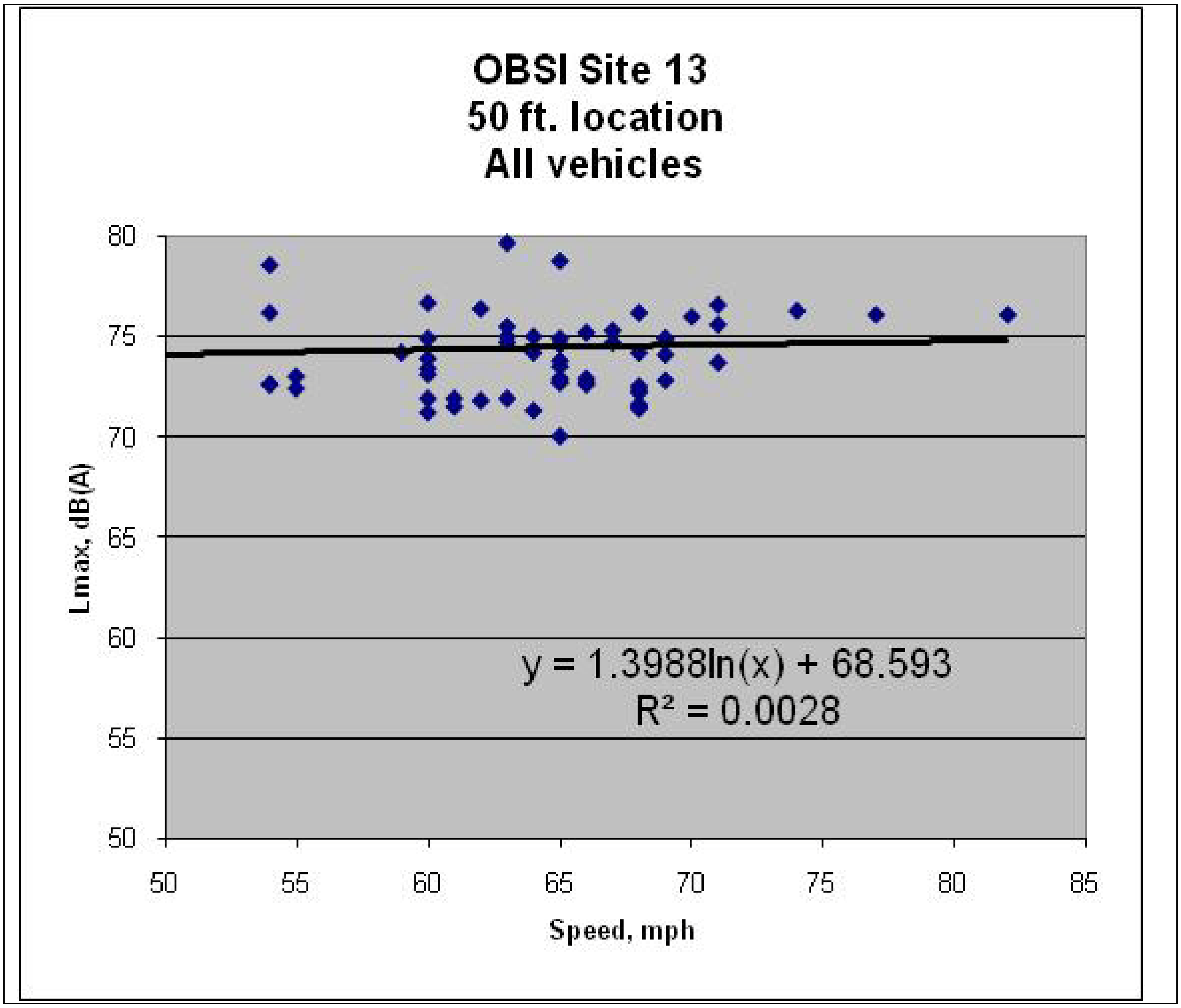

OBSI Site 11
50 ft. location
All vehicles
80
75
70
65
60
55
50
Lmax, dB(A)
y = 11.519ln(x) + 25.834
R² = 0.1892
50
55
60
65
70
75
80
Speed, mph

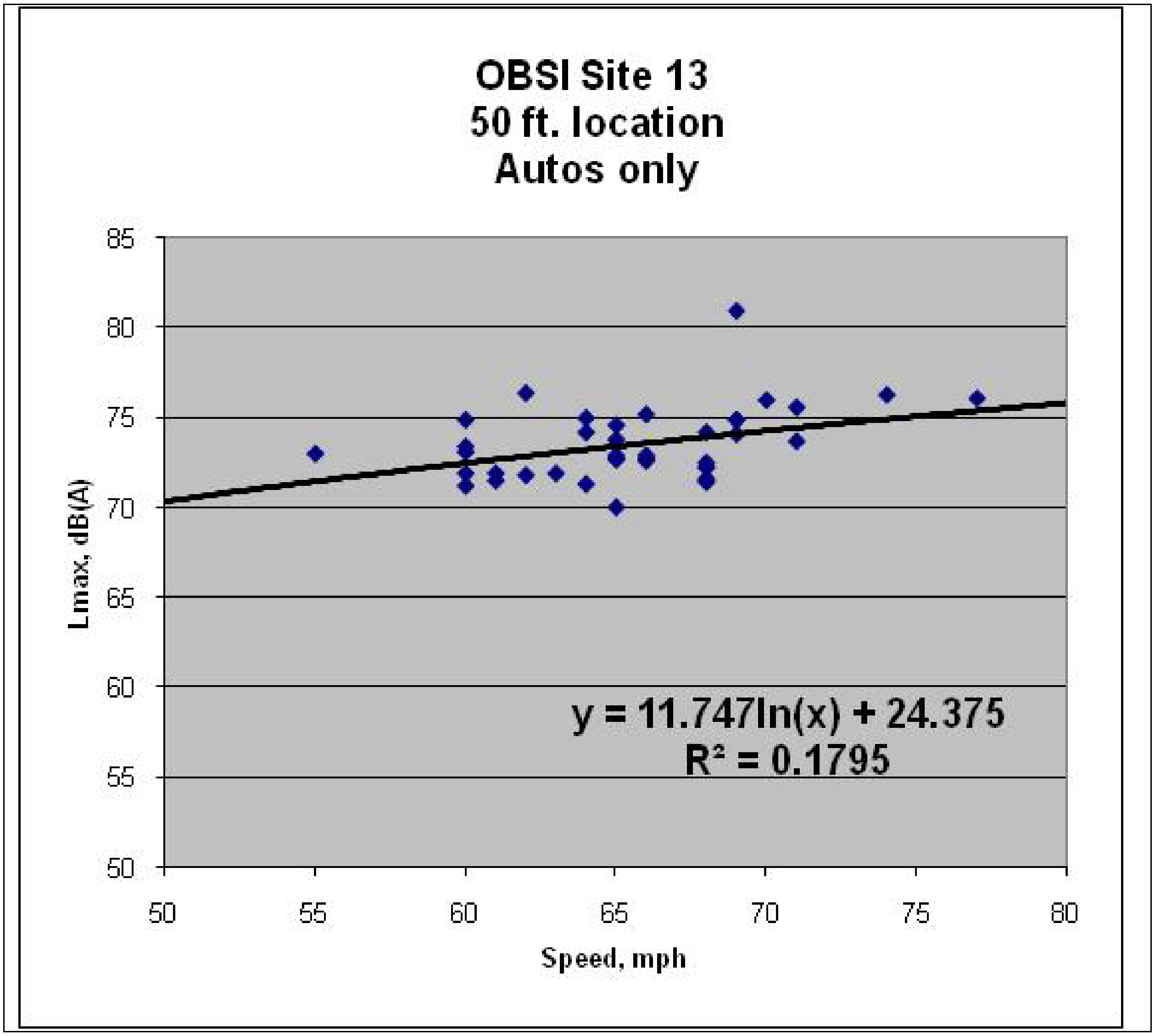


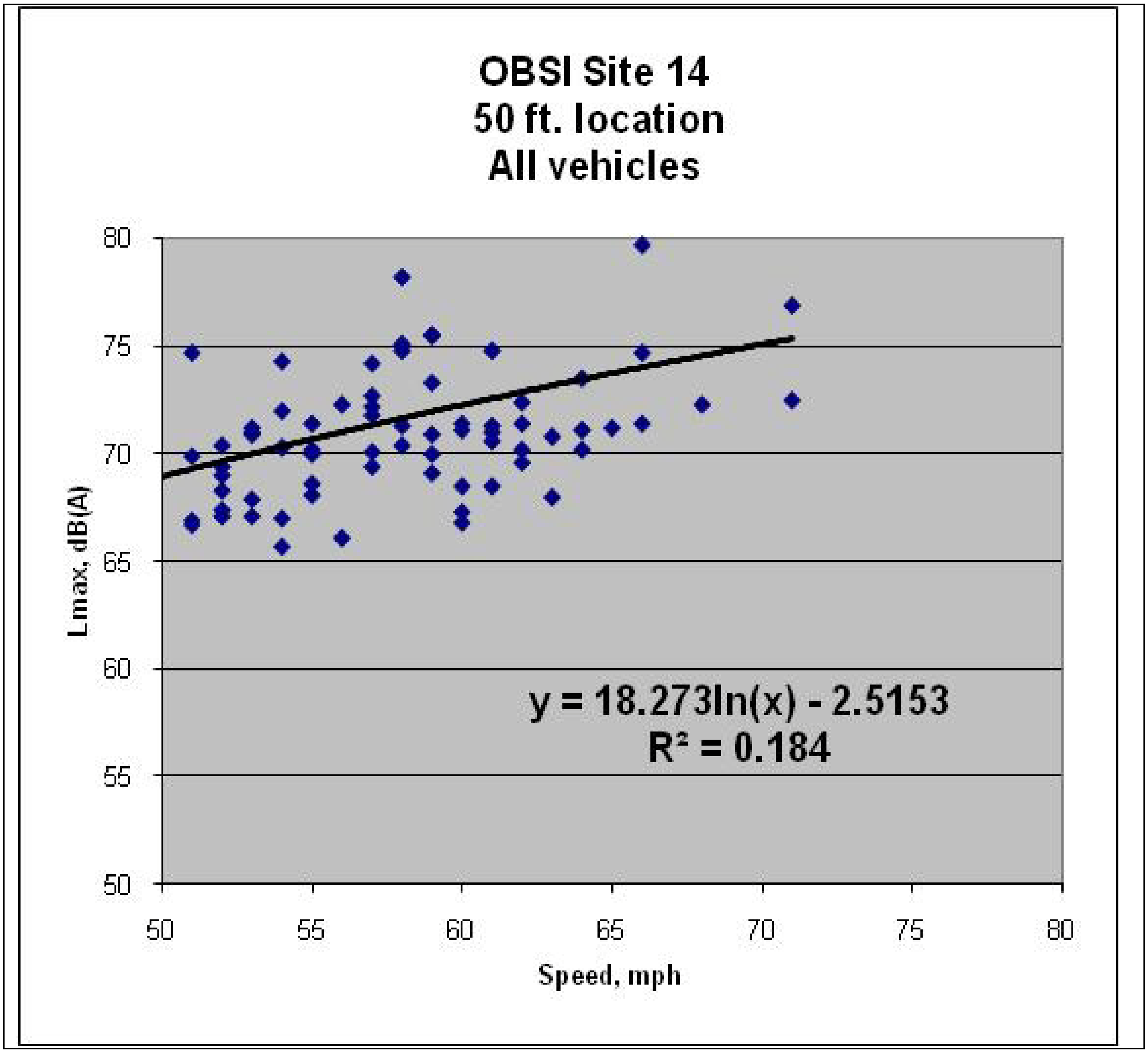
OBSI Site 11
50 ft. location
Autos only
85
80
75
70
65
60
55
50
Lmax, dB(A)
y = 16.426ln(x) + 5.1743
R² = 0.432
50
55
60
65
70
75
80
Speed, mph

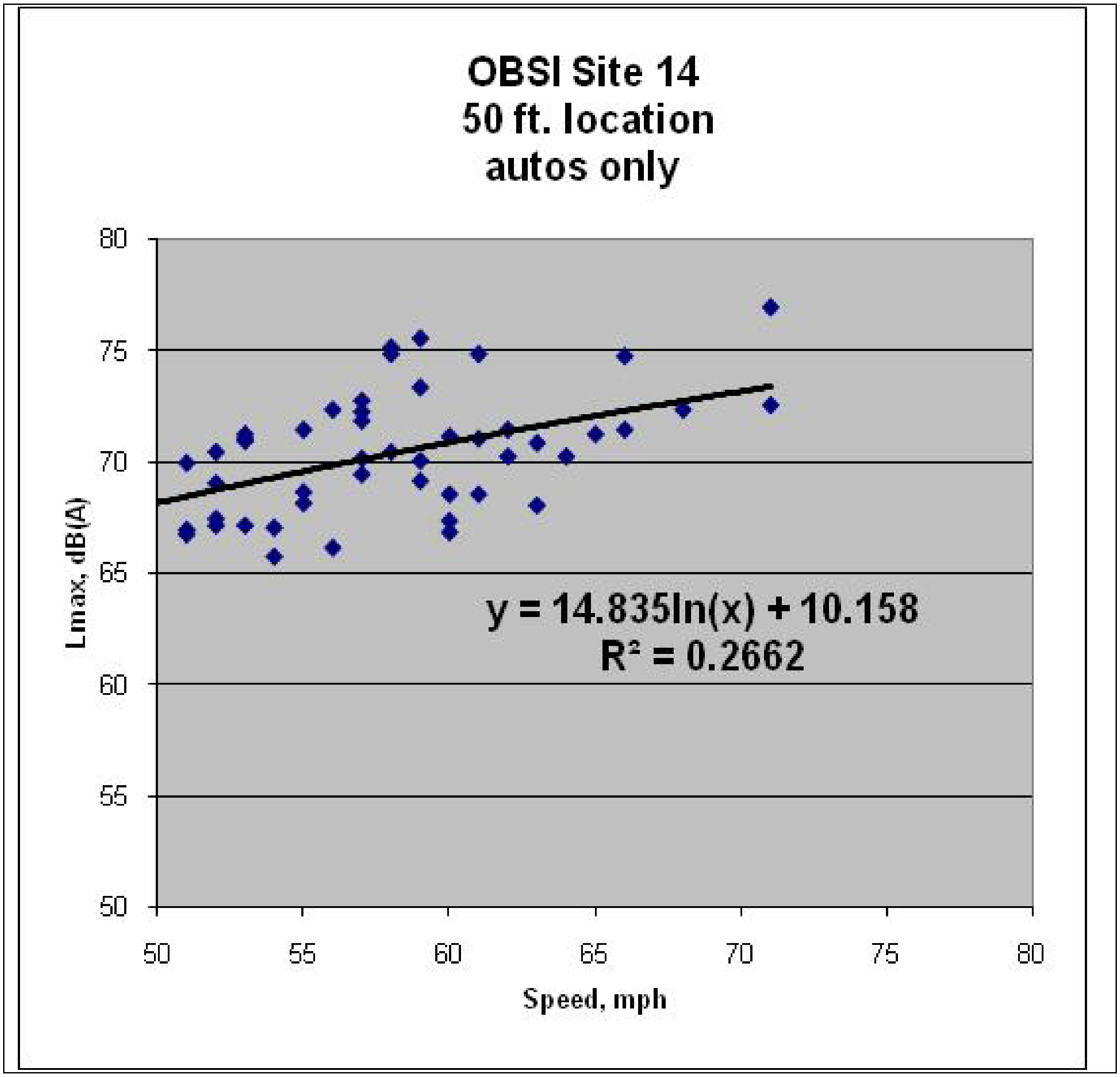

OBSI Site 12
50 ft. location
All vehicles
80
75
70
65
60
55
50
Lmax, dB(A)
50
55
60
65
70
75
Speed, mph
y = 10.558ln(x) + 32.269
R² = 0.1464

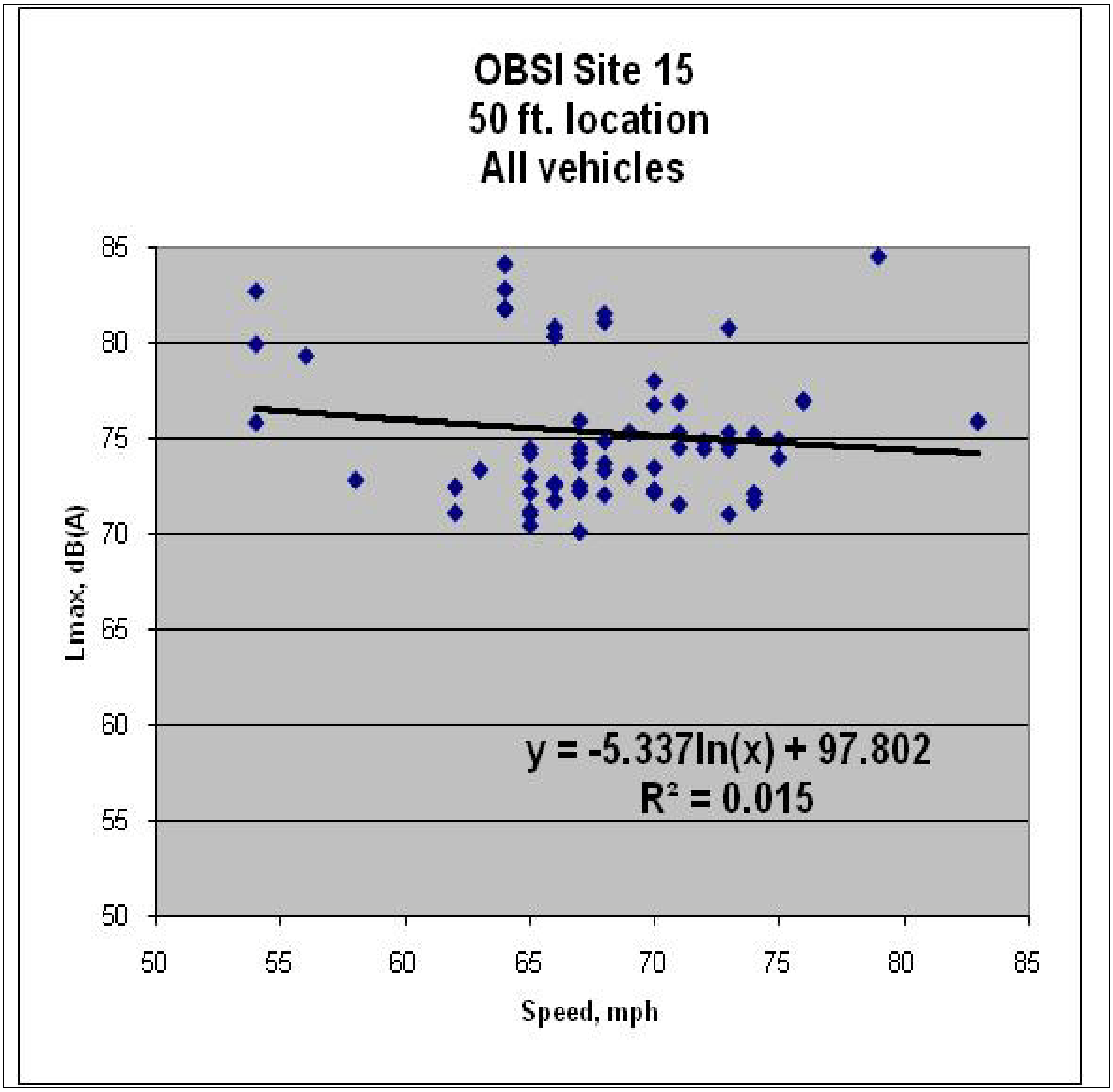

OBSI Site 12
50 ft. location
Autos only
Lmax, dB(A)
85
80
75
70
65
60
55
50
y = 10.935ln(x) + 29.693
R² = 0.4706
50
55
60
65
70
75
80
85
Speed, mph

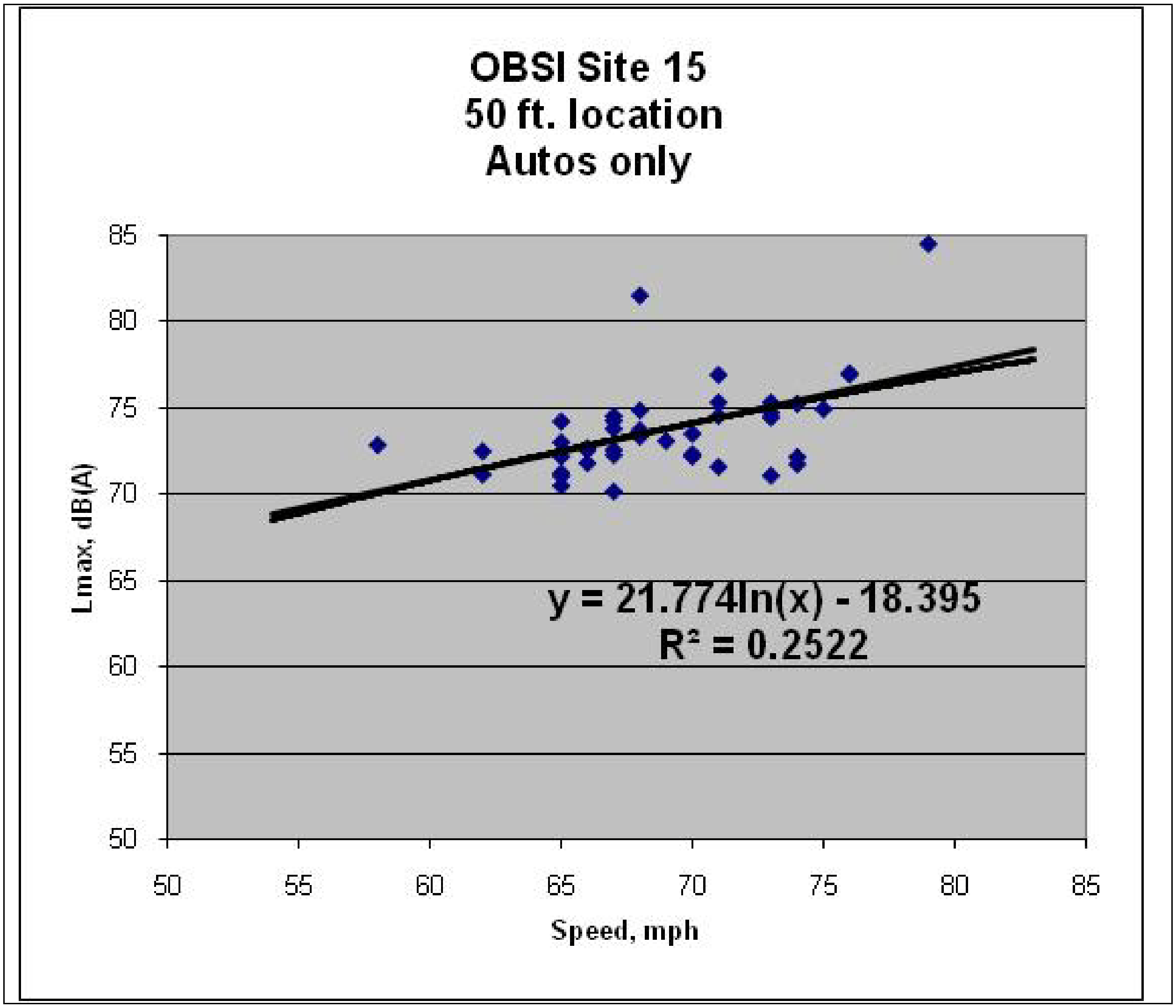

OBSI Site 13
50 ft. location
All vehicles
Lmax, dB(A)
Speed, mph
y = 1.3988ln(x) + 68.593
R² = 0.0028
80
75
70
65
60
55
50
50
55
60
65
70
75
80
85

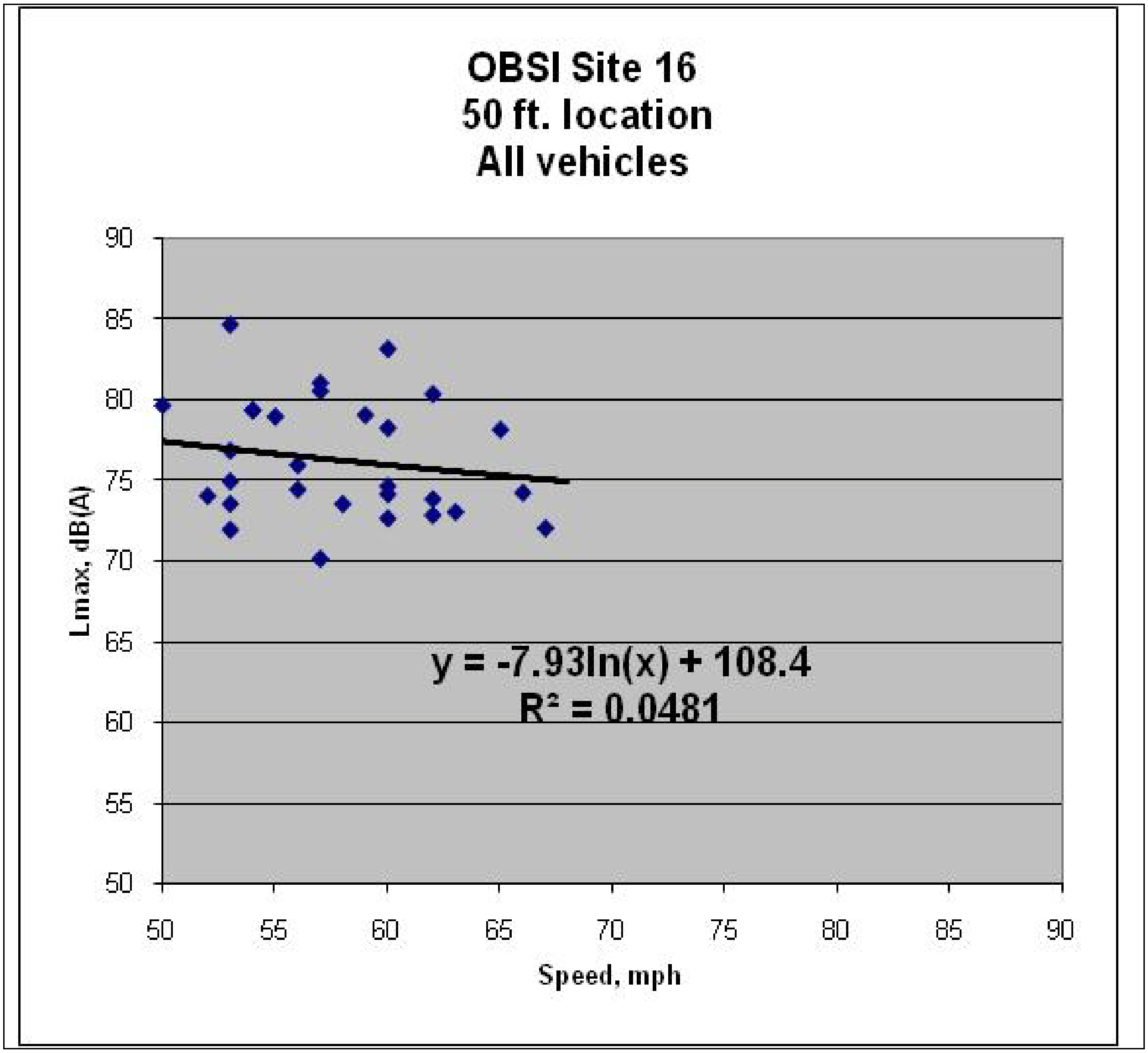

OBSI Site 13
50 ft. location
Autos only
85
80
75
70
65
60
55
50
Lmax, dB(A)
50
55
60
65
70
75
80
Speed, mph
y = 11.747ln(x) + 24.375
R² = 0.1795

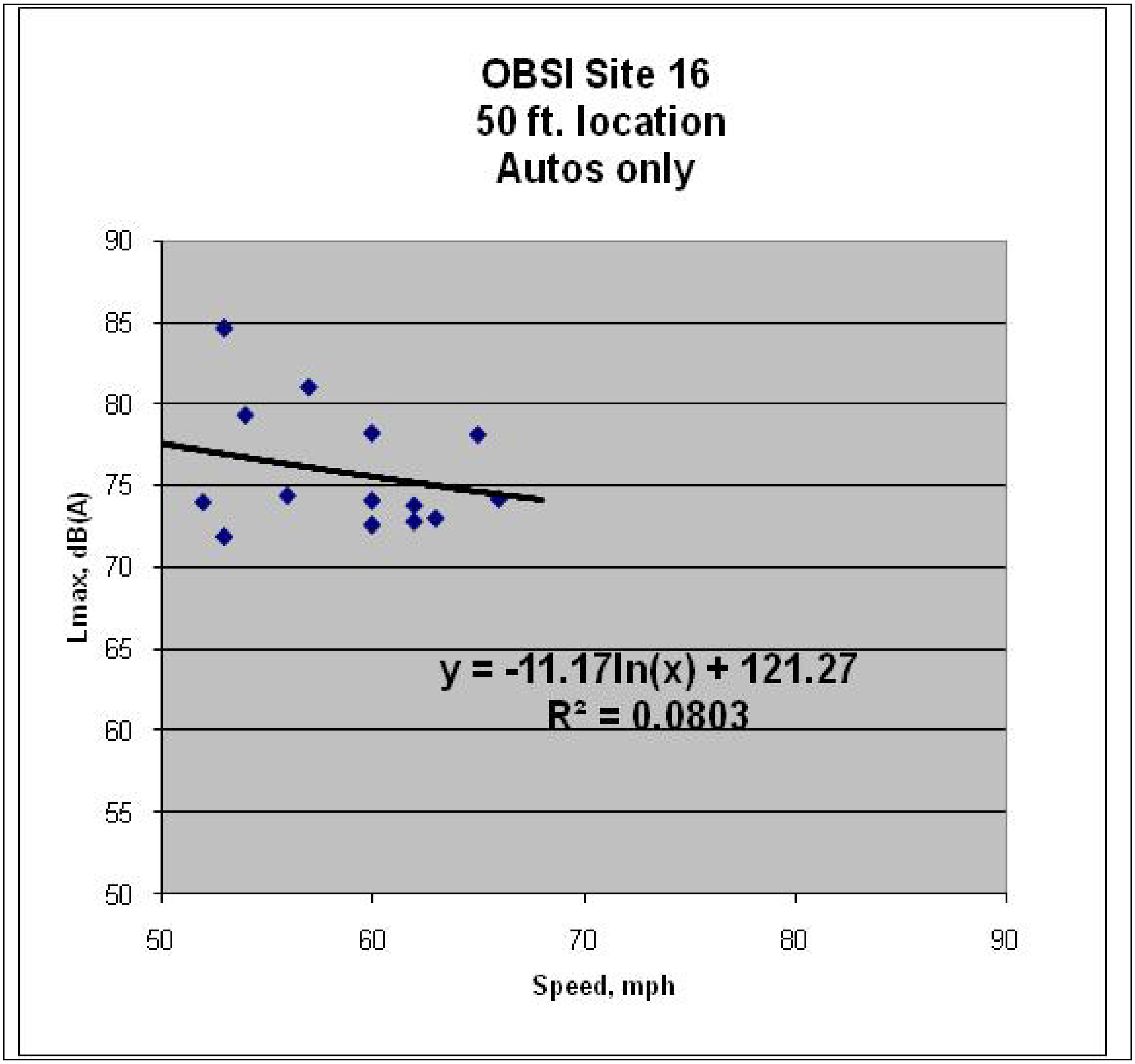

OBSI Site 14
50 ft. location
All vehicles
80
75
70
65
60
55
50
Lmax, dB(A)
50
55
60
65
70
75
80
Speed, mph
y = 18.273ln(x) - 2.5153
R² = 0.184

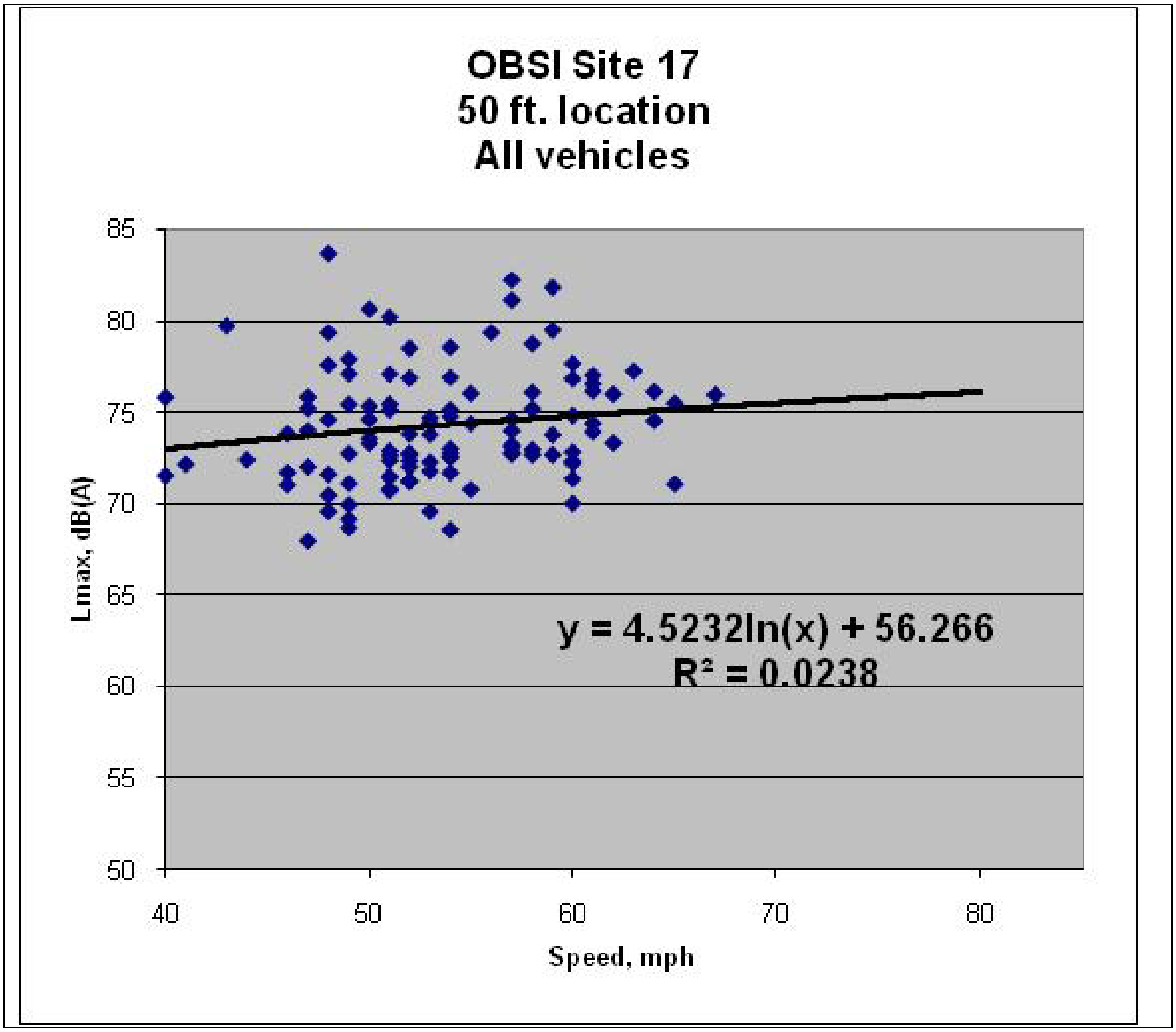

OBSI Site 14
50 ft. location
autos only
80
75
70
65
60
55
50
Lmax, dB(A)
50
55
60
65
70
75
80
Speed, mph
y = 14.835ln(x) + 10.158
R² = 0.2662

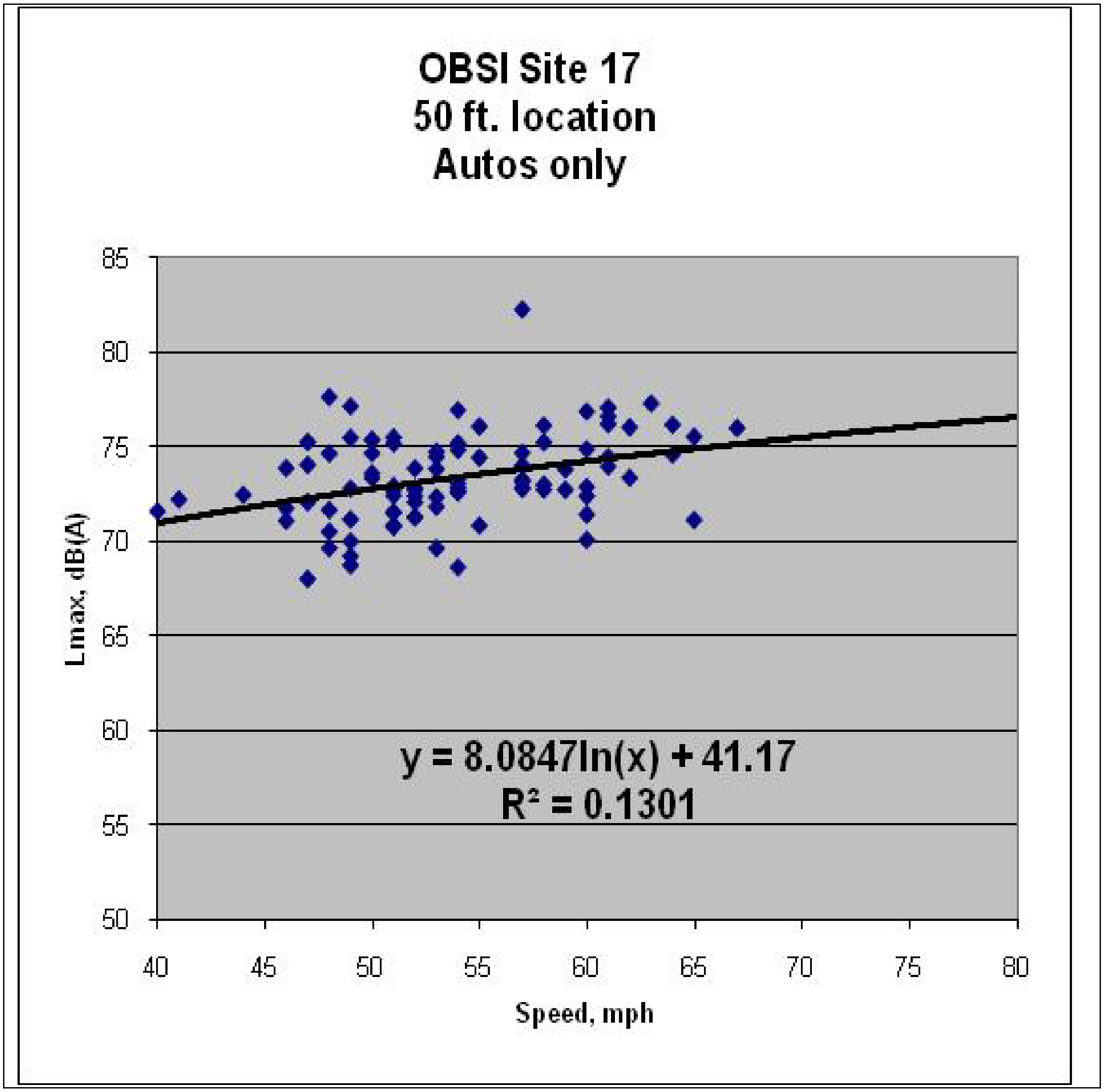

OBSI Site 15
50 ft. location
All vehicles
85
80
75
70
65
60
55
50
Lmax, dB(A)
y = -5.337ln(x) + 97.802
R² = 0.015
50
55
60
65
70
75
80
85
Speed, mph


OBSI Site 15
50 ft. location
Autos only
85
80
75
70
65
60
55
50
Lmax, dB(A)
50
55
60
65
70
75
80
85
Speed, mph
y = 21.774ln(x) - 18.395
R² = 0.2522

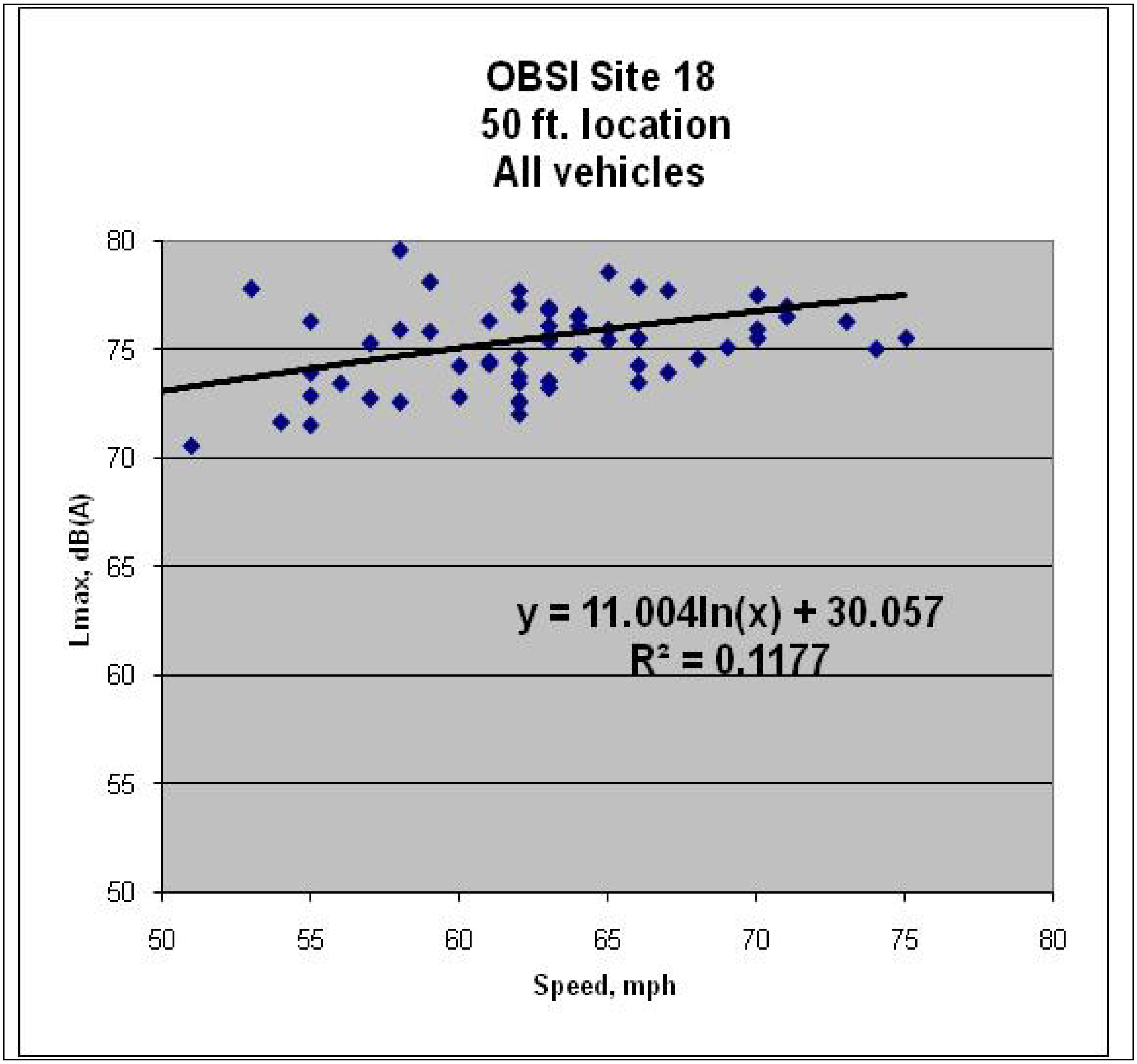

OBSI Site 16
50 ft. location
All vehicles
Lmax, dB(A)
90
85
80
75
70
65
60
55
50
50
55
60
65
70
75
80
85
90
Speed, mph
y = -7.93ln(x) + 108.4
R² = 0.0481

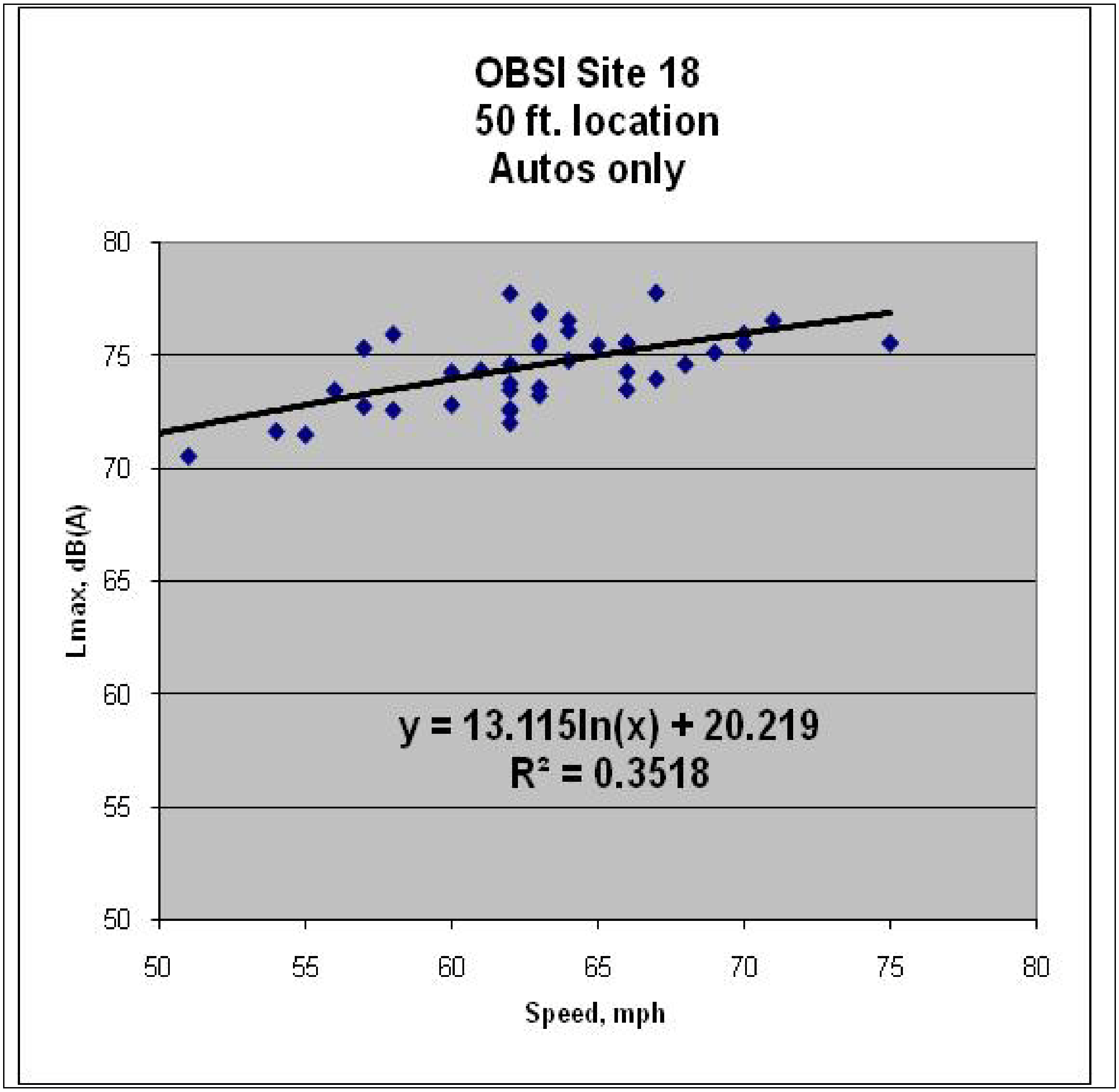

OBSI Site 16
50 ft. location
Autos only
90
85
80
75
70
65
60
55
50
Lmax, dB(A)
y = -11.17ln(x) + 121.27
R² = 0.0803
50
60
70
80
90
Speed, mph

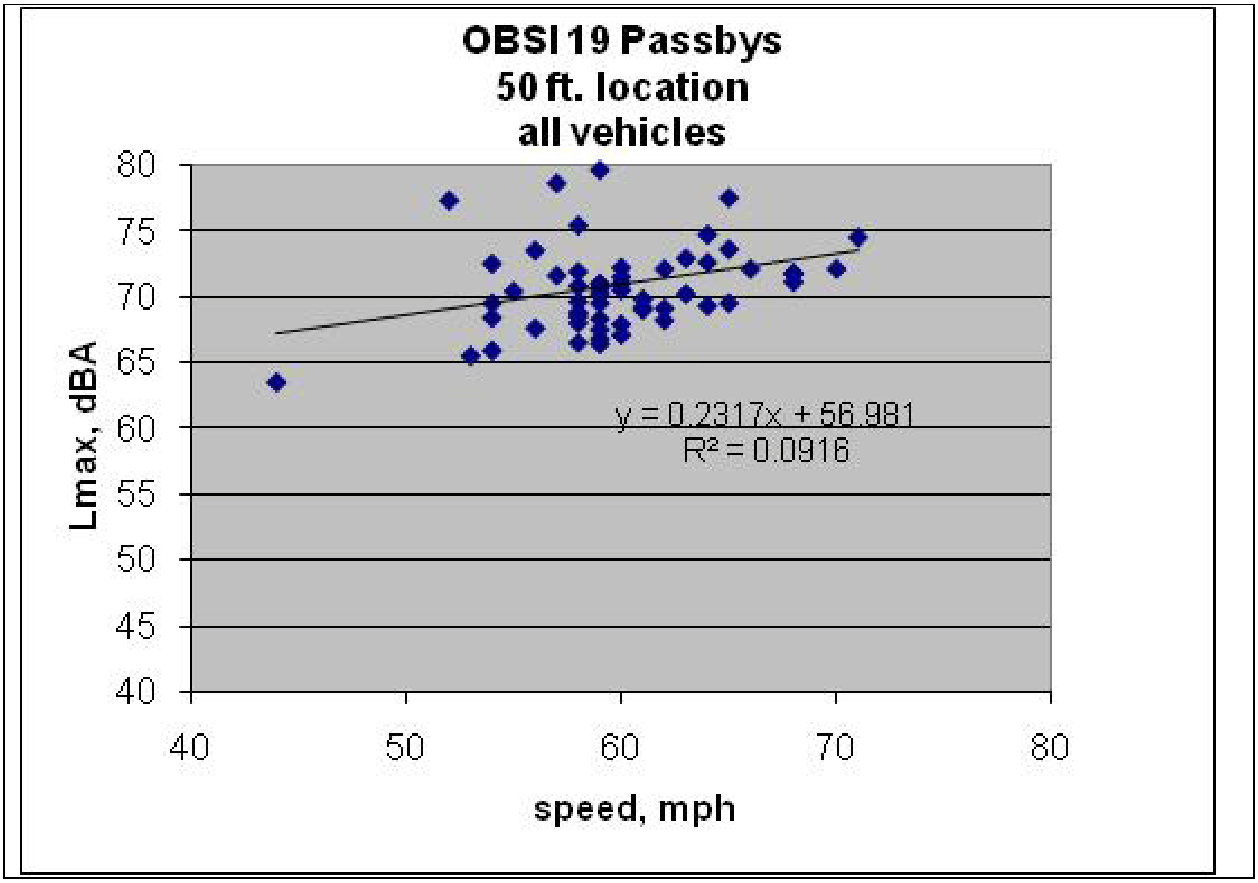

OBSI Site 17
50 ft. location
All vehicles
Lmax, dB(A)
Speed, mph
y = 4.5232ln(x) + 56.266
R² = 0.0238
85
80
75
70
65
60
55
50
40
50
60
70
80

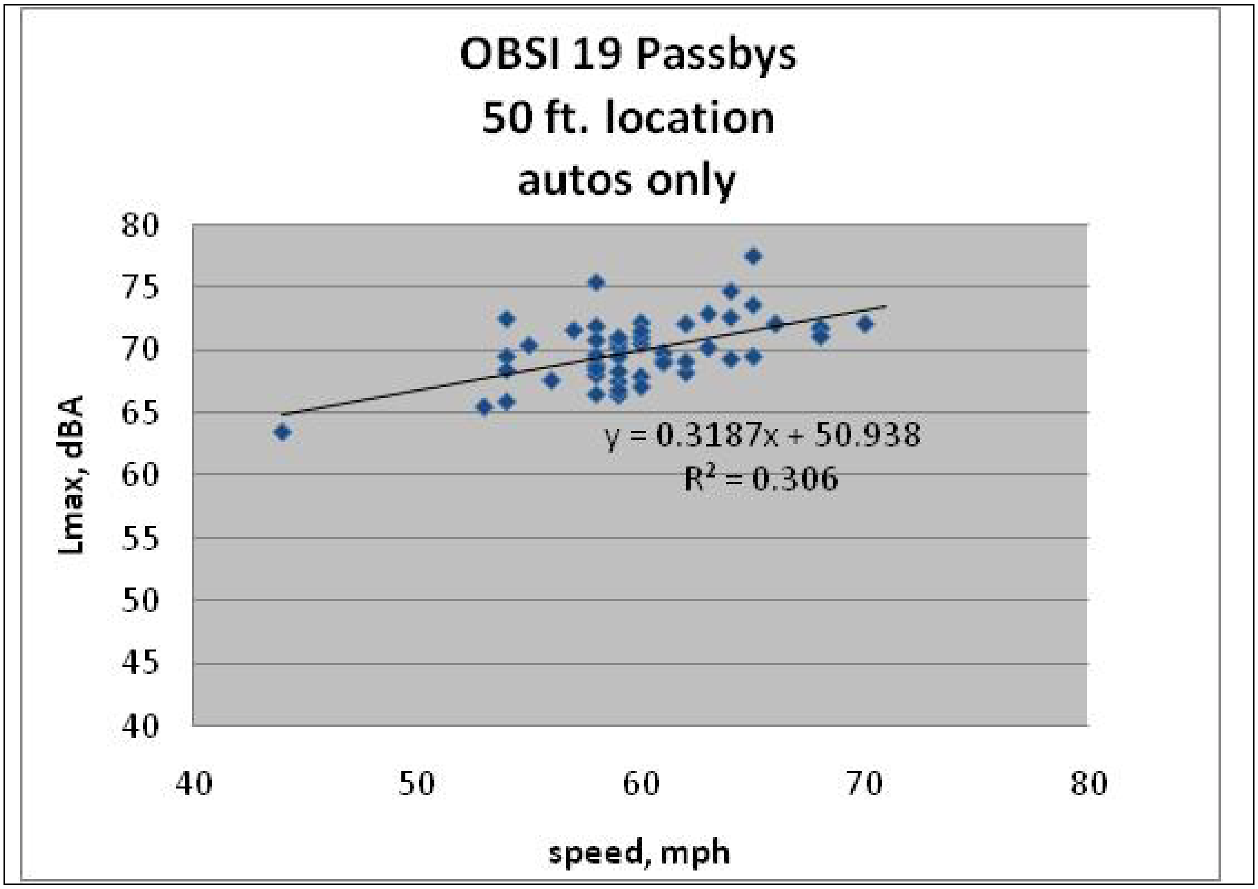


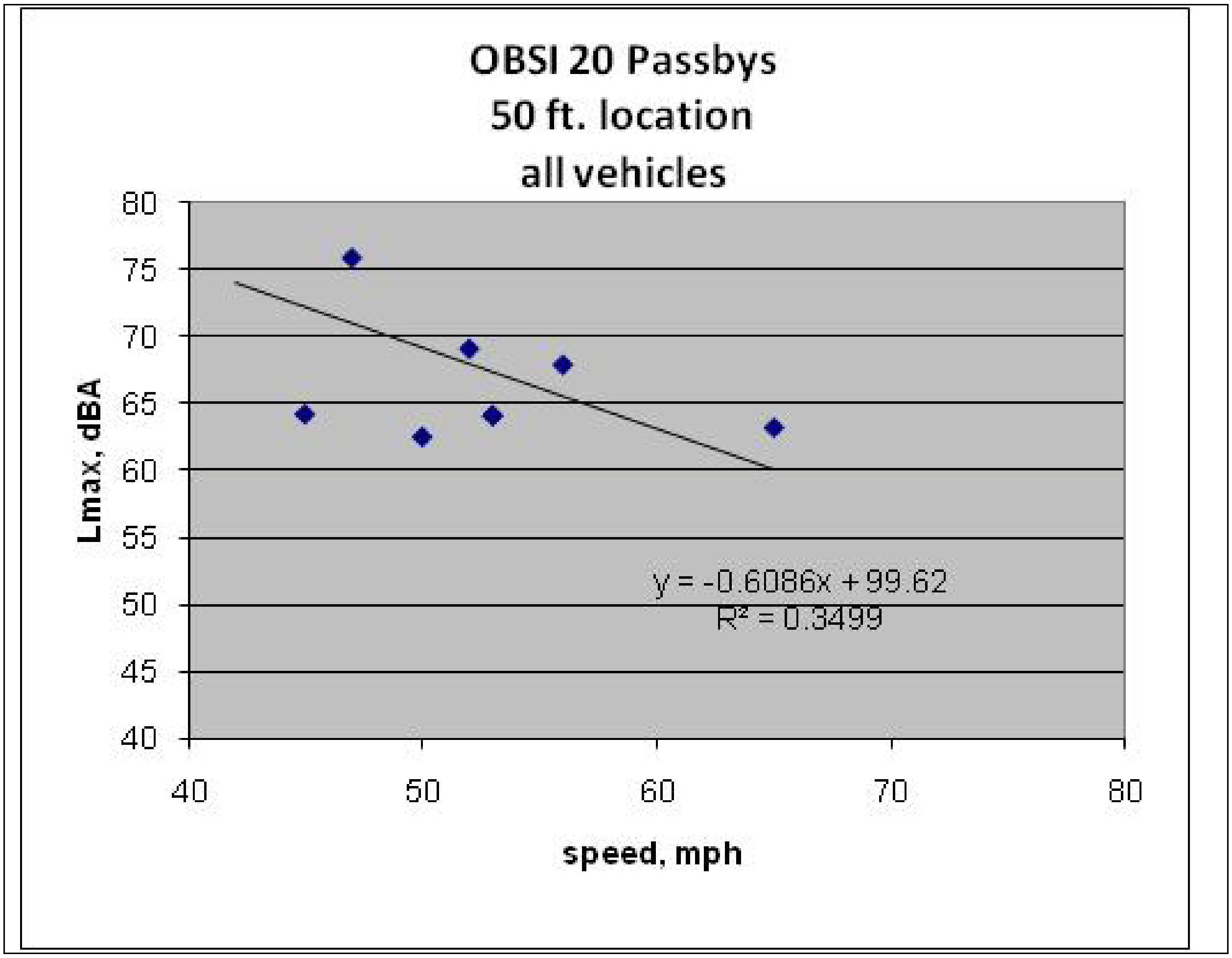
OBSI Site 17
50 ft. location
Autos only
85
80
75
70
65
60
55
50
40
45
50
55
60
65
70
75
80
Lmax, dB(A)
Speed, mph
y = 8.0847ln(x) + 41.17
R² = 0.1301

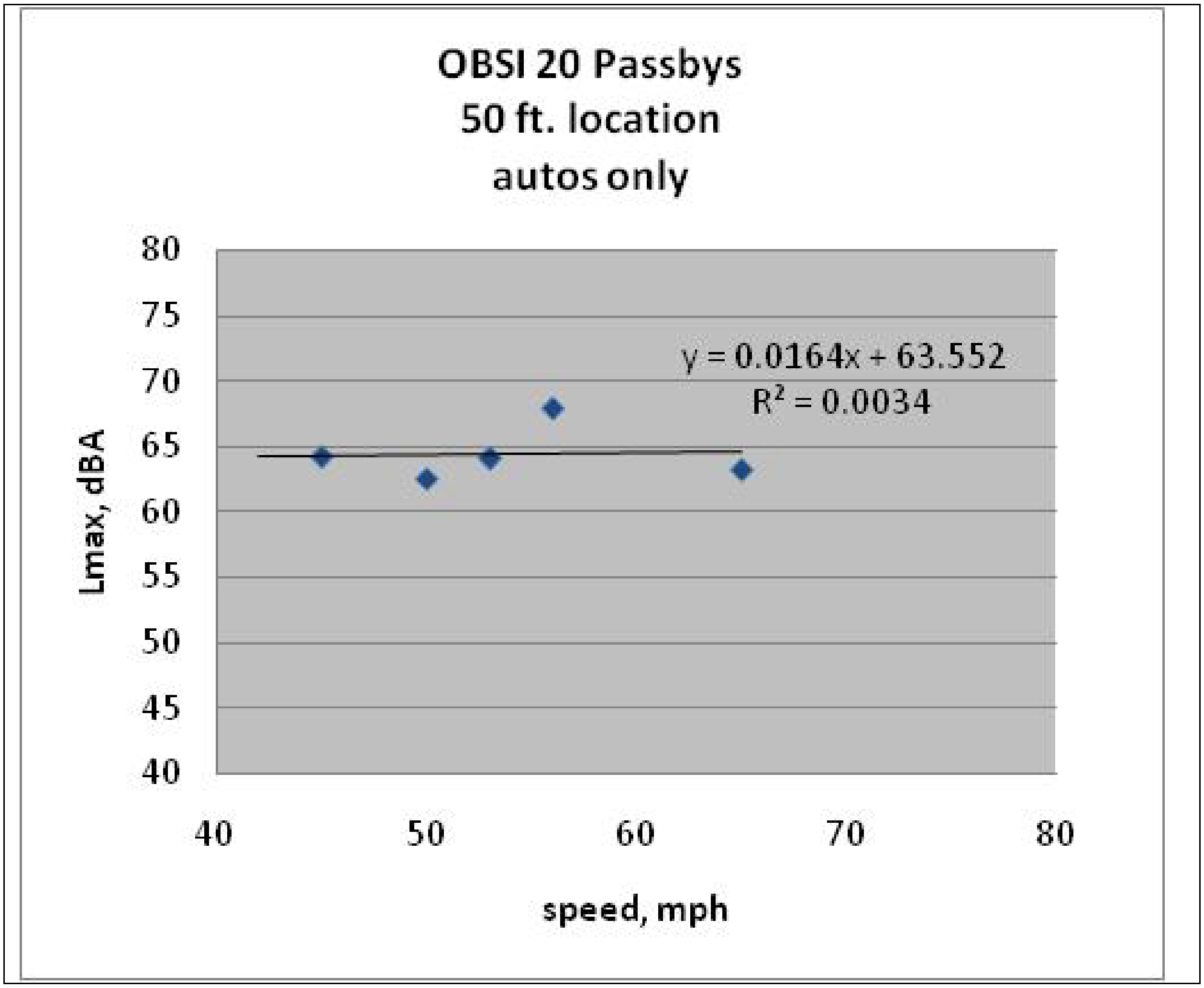

OBSI Site 18
50 ft. location
All vehicles
80
75
70
65
60
55
50
Lmax, dB(A)
50
55
60
65
70
75
80
Speed, mph
y = 11.004ln(x) + 30.057
R² = 0.1177

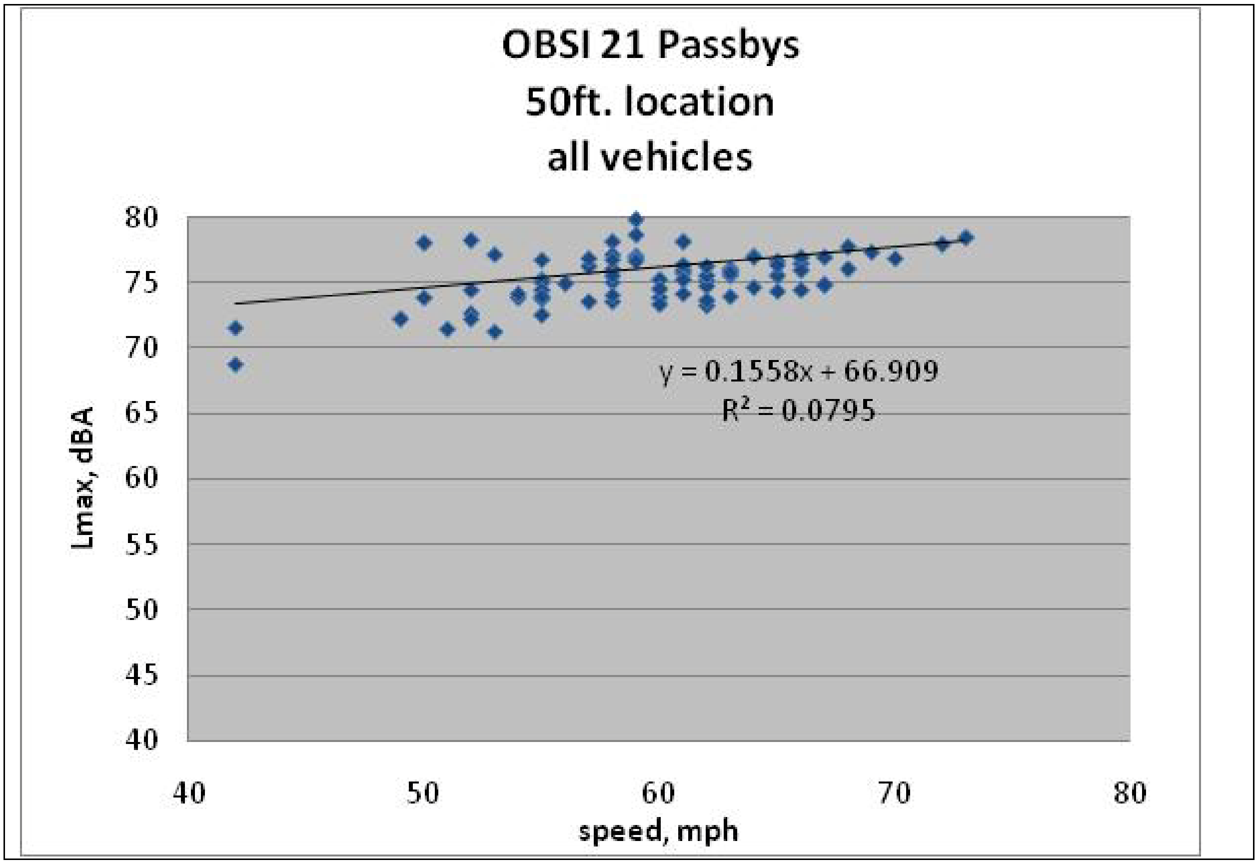

OBSI Site 18
50 ft. location
Autos only
Lmax, dB(A)
80
75
70
65
60
55
50
y = 13.115ln(x) + 20.219
R² = 0.3518
50
55
60
65
70
75
80
Speed, mph

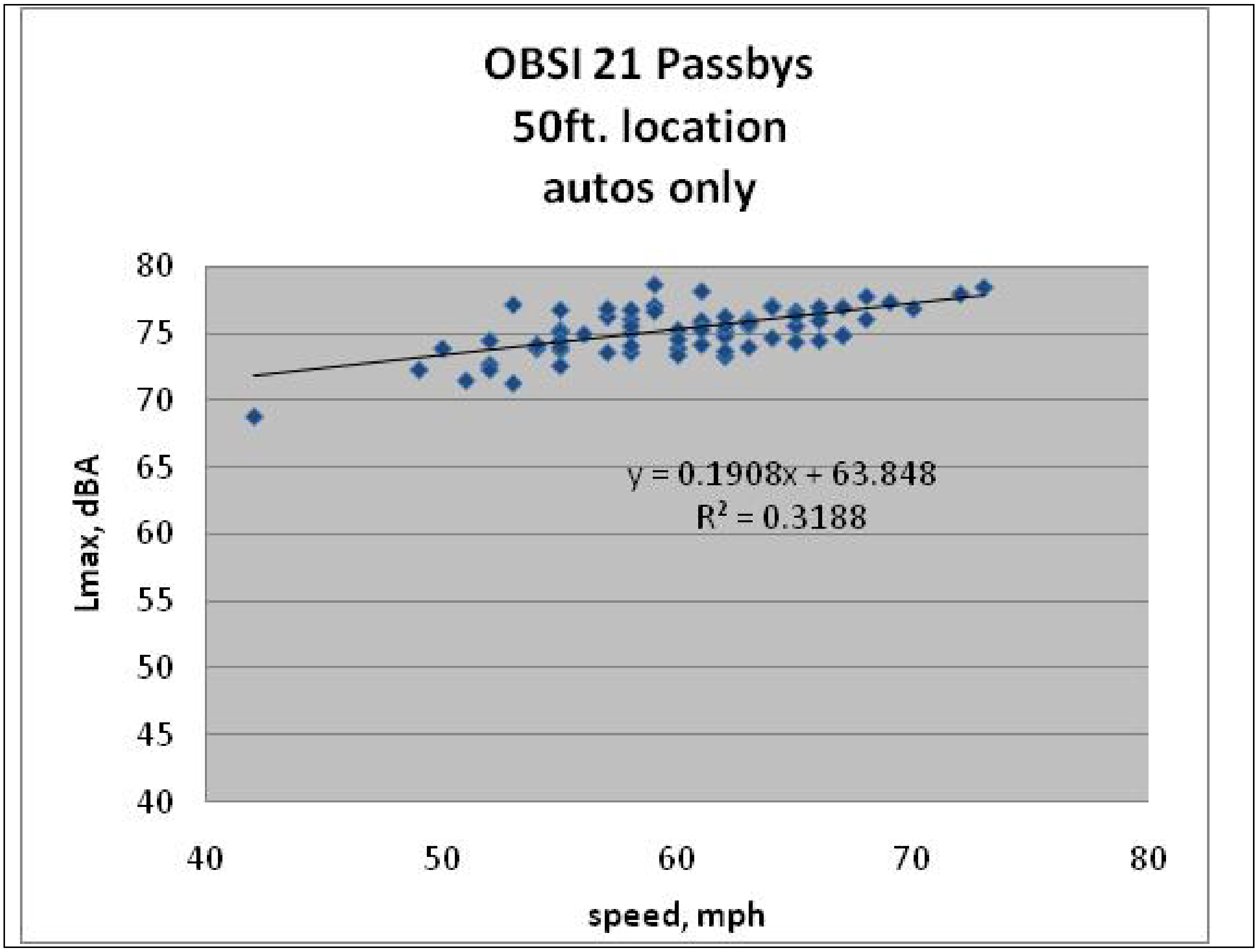

OBSI 19 Passbys
50 ft. location
all vehicles
Lmax, dBA
80
75
70
65
60
55
50
45
40
y = 0.2317x + 56.981
R² = 0.0916
40
50
60
70
80
speed, mph

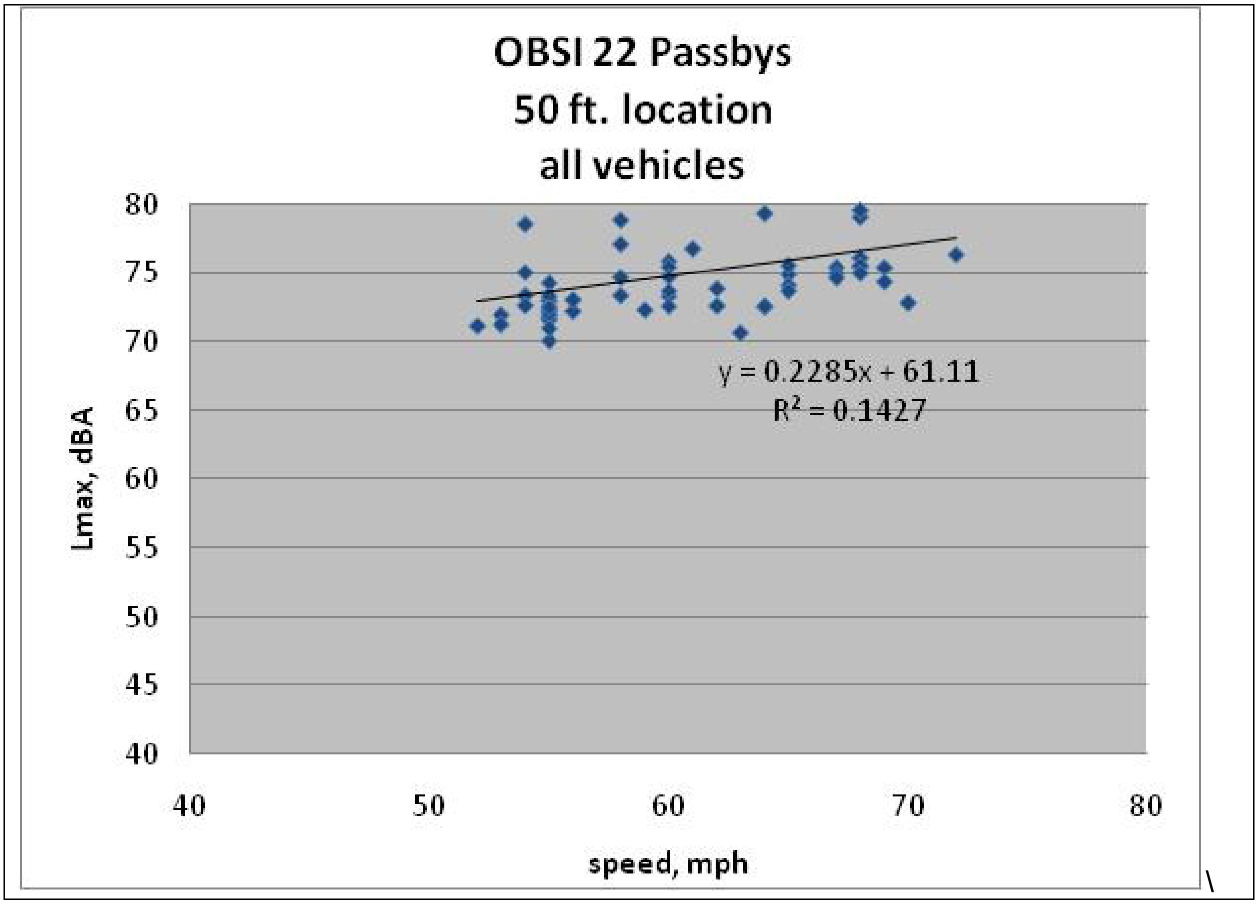

OBSI 19 Passbys
50 ft. location
autos only
Lmax, dBA
80
75
70
65
60
55
50
45
40
40
50
60
70
80
speed, mph
y = 0.3187x + 50.938
R² = 0.306


OBSI 20 Passbys
50 ft. location
all vehicles
Lmax, dBA
80
75
70
65
60
55
50
45
40
y = -0.6086x + 99.62
R² = 0.3499
40
50
60
70
80
speed, mph

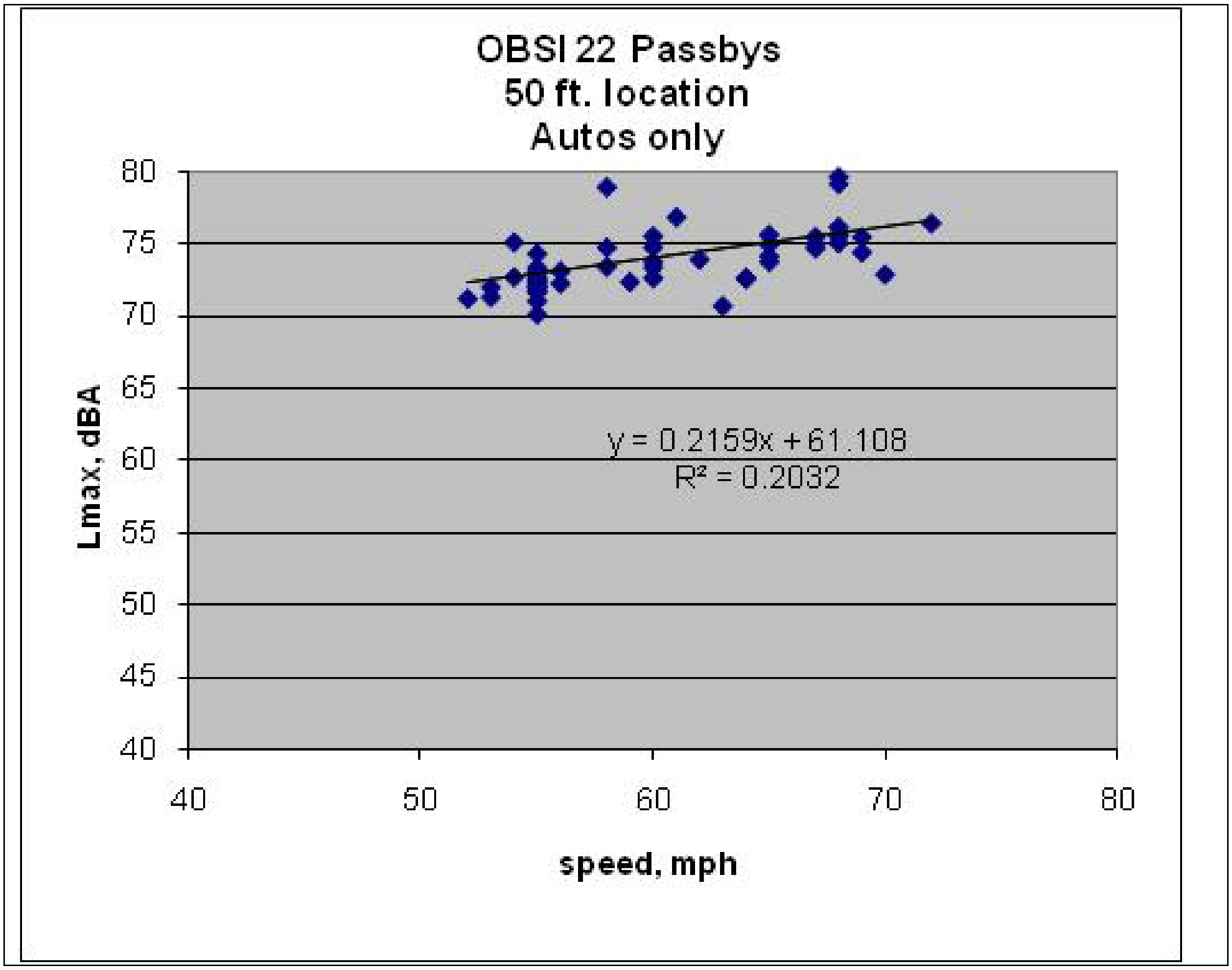

OBSI 20 Passbys
50 ft. location
autos only
y = 0.0164x + 63.552
R² = 0.0034
80
75
70
65
60
55
50
45
40
Lmax, dBA
40
50
60
70
80
speed, mph


OBSI 21 Passbys
50ft. location
all vehicles
Lmax, dBA
speed, mph
y = 0.1558x + 66.909
R² = 0.0795
80
75
70
65
60
55
50
45
40
40
50
60
70
80


OBSI 21 Passbys
50ft. location
autos only
80
75
70
65
60
55
50
45
40
Lmax, dBA
y = 0.1908x + 63.848
R² = 0.3188
40
50
60
70
80
speed, mph



OBSI 22 Passbys
50 ft. location
all vehicles
y = 0.2285x + 61.11
R² = 0.1427
Lmax, dBA
speed, mph
80
75
70
65
60
55
50
45
40
40
50
60
70
80


OBSI 22 Passbys
50 ft. location
Autos only
y = 0.2159x + 61.108
R² = 0.2032
Lmax, dBA
speed, mph
80
75
70
65
60
55
50
45
40
40
50
60
70
80