On-Board Sound Intensity Tire-Pavement Noise Study in North Carolina

By

George Wang, Ph.D., Assistant Professor
Richard Shores, M.Sc., Graduate Research Assistant
Joshua Botts, M.Sc., Graduate Research Assistant
Richard Hibbett, B.Sc., Research Assistant

At
The Department of Construction Management
East Carolina University
Greenville, North Carolina

For the

North Carolina Department of Transportation

<u>Final Report</u>

Project: 2010-13

December 2011

Technical Report Documentation Page

1. Report No. **FHWA/NC/2010-13**	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle **On-Board Sound Intensity Tire-Pavement Noise Study in North Carolina**		5. Report Date **December 2011** 6. Performing Organization Code
7. Author(s) **George Wang, Richard Shores, Joshua Botts and Richard Hibbett**		8. Performing Organization Report No.
9. Performing Organization Name and Address **East Carolina University** **Department of Construction Management** **343B Rawl Hall** **Greenville, NC 27858-4353**		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address **North Carolina Department of Transportation** **Research and Analysis Group** **Raney Building, 104 Fayetteville Street** **Raleigh, North Carolina 27601**		13. Type of Report and Period Covered Final Report **August 2009 to December 2011** 14. Sponsoring Agency Code
Supplementary Notes:		

16. Abstract

This research investigated tire-pavement noise on various types of pavements across North Carolina by using On-Board Sound Intensity (OBSI) method. To mitigate traffic noise, quieter pavement may provide advantages that noise barriers cannot. To reach the ultimate goals of quieter pavement development, for effectively managing traffic noise in support of the NCDOT's function in the FHWA Pooled Fund Study, TPF-5 (135), this research has focused on the most imperative task, i.e., to measure the OBSI noise levels of different types of pavements in North Carolina. A thorough literature review was conducted. OBSI testing equipment with sound intensity measuring process was established at East Carolina University. The OBSI equipment is an important tool for investigating tire-pavement noise and performing traffic noise research in a standard manner so that the data can be shared and compared with other agencies. Sixty one highway sites and 153 test sections around 30 counties for nine types of pavements were investigated. The work of this project is a cornerstone for future determinations of the most cost-effective, durable and technically sound pavement noise abatement means suitable for North Carolina. The data has been proved to be valid and can be used in the FHWA OBSI database or presented to the public. The results indicate that relatively quieter pavements have been used in North Carolina. In the meantime, future work is needed to improve pavement noise levels based on the findings from this project. The OBSI data collected will provide valuable information in future research for quieter pavement development and traffic noise management.

17. Key Words **Tire-Pavement Noise, On-Board Sound Intensity, OBSI, Pavement**	18. Distribution Statement		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 210	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

DISCLAIMER

The contents of this report reflect the views of the authors and not necessarily the views of East Carolina University (ECU). The authors are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the North Carolina Department of Transportation or the Federal Highway Administration at the time of publication. This report does not constitute a standard, specification, or regulation.

ACKNOWLEDGEMENTS

The traffic noise research team at East Carolina University (ECU) acknowledges the North Carolina Department of Transportation (NCDOT) for supporting and funding this project. The team also acknowledges the FHWA Pooled Fund Study TPF-5 (135) for research assistance. The team especially extends our thanks to the current and former project Steering and Implementation Committee members including:

Gregory A. Smith (Chair)

Ernest Morrison (Project Manager)

Mrinmay Biswas

Jerry Blackwelder

Judith Corley-Lay

Jack E. Cowsert

Wiley Jones

The team appreciates Mr. Drew Joyner of the NCDOT for his full support of this project. The team appreciates Mr. Neil Mastin and Mr. Nilesh Surti of the NCDOT for providing the selected pavement inventory information. The team also thanks Mr. Ernest Morrison, the Project Manager of the NCDOT for good communication and assistance throughout the project.

Dr. Paul Donavan of Illingworth & Rodkin, Inc. and Mr. Bruce Rymer of the Division of Environmental Analysis of the California Department of Transportation (Caltrans), provided technical assistance when the team was fabricating the OBSI hardware at ECU for the research.

The assistance of Mr. Walter Gene Oakley of ECU is acknowledged for fabricating microphone mounting fixture.

The assistance of Dr. Keith Sylvester and Mr. Bryan Wheeler of ECU during the illustration and text preparation is also acknowledged.

Without the help of all the above individuals, the project could not have been completed in such a successful manner.

EXECUTIVE SUMMARY

This report summarizes the results of an on-board sound intensity (OBSI) tire-pavement noise study in North Carolina. Based on a thorough literature review and a study of international experience of tire-pavement noise measurement, an OBSI system has been set up by the research team at East Carolina University (ECU), Greenville, North Carolina (NC). The validity of the equipment and OBSI data have been proved by the fourth national OBSI rodeo conducted in Elkin, North Carolina during September 2010. The North Carolina OBSI system used updated software and equipment when compared with similar equipment setups around the nation and world. The equipment will be a useful tool for future traffic noise management and research for the North Carolina Department of Transportation (NCDOT). To date, OBSI data for nine types of pavements on 61 highway sites, 153 test sections in 30 counties have been collected. The data was categorized based on pavement type, age, and testing speed. Quiet pavement types can be adequately identified based on the assessment of tire-pavement noise levels. The results from this research will provide a cornerstone for future utilization and development of quiet pavement and traffic noise management. The results can be used by the NCDOT, local officials and other agencies for traffic noise management. From the results, the best pavement types can be primarily determined for future use near noise-sensitive areas along highways in North Carolina or for development of quiet pavement. The data collected can be presented to the public and also can be used in the Federal Highway Administration (FHWA) OBSI database for nationwide quiet pavement in tire-pavement noise modeling. This database can be used for a future comprehensive study in quiet pavement development and traffic noise mitigation.

This report describes in detail the OBSI process established in NC and a detailed procedure for OBSI operations. The report also presents the results of a literature study and compilation of the relevant literature on traffic noise, which will be a valuable reference for transportation environment managers, engineers and researchers for traffic noise related study and research.

The OBSI data collected from the nine different types of pavements in North Carolina have been presented in the rankings based OBSI pavement noise levels. Based on the comparison between the data collected in NC and those of the similar types of pavements from other states, it can be generally concluded that the highway pavements in NC are relatively quieter than those of some other states, especially in those low volume roads having dense graded asphalt surfaces.

Future OBSI data collection in NC is necessary to enhance the NCDOT OBSI database and increase the sample sizes for each type of pavement. Continuing OBSI data collection can also better monitor the trends of pavement noise changes along the service life of pavements. The changes over time in sound intensity on a particular pavement reflect the tire-pavement

noise ‘deterioration rate’ or ‘reduction rate’. This ‘deterioration rate’ should be different from one pavement type to another. ‘Deterioration rate’ can be used as an evaluation parameter along with the OBSI data collected when the pavement is new. Both of the parameters should be used to comprehensively evaluate and define ‘quiet pavement’.

Future research is necessary to investigate the relationships between tire-pavement noise and natural environment variables such as temperature and moisture. It is also necessary to investigate the relationships between tire-pavement noise, vehicle weight/type, construction, age, and material characteristics. All this information can be included in the tire-pavement noise database. The OBSI equipment can be used as a powerful tool to generate a network map of tire-pavement noise levels in urban or densely populated areas in North Carolina. These results can provide valuable information for traffic noise and pavement management. With continued progress in tire-pavement noise research, future decisions for minimizing traffic noise pollution can be scientifically based and made in North Carolina.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SITES

1.0 INTRODUCTION

In 1976, the US Congress passed legislation requiring the states to provide mitigation for highway noise (considered an environmental impact) as a part of all Type I federal-aid projects at impacted locations where it is reasonable and feasible. The Federal Highway Administration (FHWA) is the designated federal government agency for administering the federal-aid highway program. The FHWA regulation makes a distinction between projects for which noise abatement is considered as a feature in a new or expanded highway and those for which noise abatement is considered as a retrofit feature on an existing highway. The former are defined as Type I projects, the latter as Type II. For Type I projects, the consideration of noise abatement as part of the highway construction project is mandatory if federal-aid funds are to be used and if a traffic noise impact is expected to occur. Type II projects are, however, completely voluntary on the part of the individual states, and such projects compete for funds with all of the other construction needs of the states.

Since the legislation passed in 1976, the traffic noise has become a growing public concern nationwide. In January 2005, the FHWA issued a letter to all state DOTs reiterating that the FHWA policy restricts making adjustments for pavement type in the prediction of highway traffic noise levels and using specific pavement types or surface textures as noise abatement measures. This means the FHWA will not participate in the cost for pavement work done solely for the purpose of reducing noise. In the letter, the FHWA also notes their support in pavement noise abatement research.

In April 2006, as a result of the FHWA Tire-Pavement Noise Strategic Planning Workshop, a Transportation Pooled Fund project (TPF) was hosted by the Washington State Department of Transportation.

Since 2007, the North Carolina Department of Transportation (NCDOT) has been actively participating in the FHWA Tire-pavement Noise Research Consortium, TPF-5 (135), with other states, including California, Kansas, Minnesota, Montana, Ohio, Texas, and Washington. The objectives of the pooled fund study are to (i) provide a forum for states to discuss tire-pavement noise issues; (ii) develop a proposed research plan; and (iii) pool resources and efforts of multiple state agencies and industry to perform tire-pavement noise research in a similar manner of sharing data. The FHWA agreed to consider the use of quieter pavements as a means of traffic noise abatement if, and when sufficient data is presented by the various states that justify such consideration. The NCDOT has been actively involved in activities using and developing quieter pavements and has played a major role in some national activities including: hosting the 4th national OBSI rodeo in Elkin, NC and organizing the Transportation Research Board (TRB) ADC 40 Committee (Transportation-Related Noise and Vibration) Summer Conference in July 2012 in Asheville, North Carolina.

1.1 Traffic Noise and its Mitigation

Traffic noise is a combination of the noises produced by engines, exhaust, tires and aerodynamic noise. It is impacted by traffic volumes, traffic speed and the percentage of trucks in the traffic mix. Tire-pavement noise is defined as the noise emitted from a rolling tire as a result of the interaction between the tire and road surface. Because of this, the tire-pavement noise is highly speed-dependent. When traveling at highway speeds, tire-pavement noise contributes approximately 90%, or the dominant component of the traffic noise. Mitigation of traffic noise has become an increasingly important consideration for highway agencies when constructing new highways or improving the existing systems. Traditionally, construction of noise barriers is the most common method of traffic noise abatement. The design goal for traffic noise barriers in North Carolina is to provide a 7 dBA noise level reduction in equivalent traffic noise levels for the "first row" of noise-sensitive receptors near or adjacent to the highway facility. However, as a 'passive' method, there are limitations to building noise barriers, including (i) high cost, which is between $1.3 and $3 million per mile; (ii) unsuitability for some locations such as hillsides and intersections, and (iii) noise reflections or echoes may occur for two or more opposing or parallel barriers. As an alternative for noise mitigation, quiet pavement may provide advantages that noise barriers cannot. As a result, agencies and researchers seek to investigate tire-pavement noise at the source and further improve pavement surface structure and materials characteristics to reduce traffic noise.

To reduce traffic noise levels, it is critical to accurately capture the tire-pavement noise at its source. This is because, firstly, at highway speeds, tire-pavement noise has been proved to be the dominant component of traffic noise; secondly, if the measuring method is not accurate, i.e., excluding other interfering factors, the data will not be comparable for useful identification of quieter pavements and the mechanism of the causes of tire-pavement noise.

Therefore, it is important to accurately measure the tire-pavement noise levels of different pavements. The results will provide agencies with pertinent information on developing quiet pavement and managing traffic noise. Accurate measurements depend on (i) the selection of the appropriate measuring methods and procedures to capture tire-pavement noise while excluding interfering factors during data collection; (ii) the selection of right pavement candidates for data collection; and (iii) proper data analysis.

The FHWA has released its latest version of Traffic Noise Model (TNM), Version 2.5 in April 2004. This is the first version of the software with major improvements to the acoustics since the original version was released in March 1998. TNM Version 2.5 is an entirely new, state-of-the-art computer program used for predicting noise impacts in the vicinity of highways. The program uses advances in personal computer hardware and software to improve upon the accuracy and ease of modeling highway noise. The current function of the program includes the design of effective, cost-efficient highway noise barriers. Most likely, upon inputting sufficient data from state DOTs, future versions of TNM will allow the use of pavement types in project modeling. Based on the data available from some states in TNM Version 2.5, some pavements are expected to be acoustically "quieter" than the FHWA "average" pavement noise.

1.2 Research Objectives

To support NCDOT's participation of the FHWA pooled fund study, it is imperative to (i) collect the current on-board sound intensity (OBSI) tire-pavement noise data from typical highway pavements in North Carolina; (ii) conduct analysis to determine the quieter pavement type(s) used in North Carolina; (iii) determine the most cost-effective, durable and technical sound pavement noise abatement means suitable for North Carolina; and (iv) to include the information into the nationwide quiet pavement database in traffic noise modeling.

Prior to this project, the NCDOT did not have access to OBSI tire-pavement noise measuring equipment. There was no OBSI tire-pavement noise data collected for North Carolina's road pavement. To better manage traffic noise and identify quiet pavement in NC, the NCDOT needed reliable and valid data for ranking the typical highway pavements in North Carolina based on tire-pavement noise. The data will form a North Carolina OBSI database and be part of the FHWA OBSI database. The data can also answer concerns from vocal groups from densely populated and high traffic volume areas. Residents, motorists, and passengers will enjoy the benefits from quieter pavement defined by OBSI results.

One important objective of this project was to establish the first on-board tire-pavement noise data collection apparatus in North Carolina. This is crucial for any future development of quiet pavement and management of traffic noise in North Carolina. The entire OBSI system including hardware, software, and measurement process needed to be proved valid. The data collected must be accurate and closely correlate to those collected by other DOTs and researchers. During the project, this was accomplished at the 4th OBSI rodeo that was conducted in North Carolina.

The objectives of the project also include:

(i) To collect on-board tire-pavement acoustical noise data on the typical highway pavements in North Carolina;
(ii) To create a database to serve as a baseline for pavement noise study;
(iii) To compare the noise levels of North Carolina highway pavements to other states;
(iv) To develop an OBSI tire-pavement noise measuring and operation procedure for future training purposes;
(v) To conduct a complete literature study on traffic noise to reflect the most current research levels around the world.

To achieve the objectives stated above, it required the research team to make every effort to eliminate the possibility of obtaining imprecise or incomplete information. This included (i) strictly follow the test procedures laid out in the American Association of State Highway Agencies (AASHTO) "Standard Practice for Measurement of Tire-Pavement Noise Using the On-Board Sound Intensity (OBSI) Method", TP 76-11; (ii) validate and calibrate the OBSI system developed by the team; (iii) select the test sections based on the pavement inventory list provided by the Pavement Management Unit and Construction Unit of the NCDOT and the best knowledge on highway pavement and pavement surface characteristics of the team; (iv) eliminate any data that may not be accurate; (v) re-measure any questionable data. The team has carefully and competently gathered and analyzed the data throughout the project.

Another important purpose of this research, upon submitting the sufficient acoustical noise data collected from the pavements in NC, is to obtain the FHWA approval for adding the NC OBSI data into the national OBSI database.

1.3 Research Scope

The scope of this research is implementation of the OBSI program which includes the establishment of an OBSI system, the procedures of operation and the OBSI tire-pavement noise data collection and analysis.

OBSI method was used to measure the tire-pavement noise in this project. This method[1] was proposed by AASHTO and was recently approved in 2011.

As approximately 93% of the pavement in North Carolina is asphalt pavement, emphasis of OBSI data collection has been placed on various asphalt pavements across North Carolina. Several concrete pavement sites were also investigated.

1.4 Outcomes and Benefits

The research team has successfully established the on-board sound intensity measuring program in North Carolina. This is the first OBSI system in North Carolina and reflects the most updated version of OBSI equipment running PULSE® software among other state departments of transportation or universities in the country. The system provides the North Carolina Department of Transportation with a powerful tool for evaluating pavement noise characteristics. It also can be used to investigate various external influencing factors on tire-pavement noise such as different tires, vehicle weight, ambient temperature, driving speed, pavement moisture etc. The system can also be used for monitoring purposes such as urban pavement noise mapping. The OBSI system and the collected data have been proved valid

[1] During the project, the Method was in its proposed stage, it was designated as Standard Method of Test for Measurement of Tire-Pavement Noise using the On-Board Sound Intensity Method (OBSI) – AASHTO Designation: TP 76-10 (Proposed).

by the OBSI rodeo conducted in September 2010 in Elkin, North Carolina and in the subsequent field data collection across North Carolina.

Tire-pavement noise data was collected for the first time in North Carolina, which included nine types of pavements operated and maintained by the North Carolina Department of Transportation. OBSI data collected included typical pavements on interstate, US and NC highways. Pavements investigated included surface courses S9.5 series, S12.5 series, open grade friction course (OGFC), and also concrete pavement with diamond ground textures. Based on the OBSI data, the tested pavements were ranked based on OBSI levels, and quieter pavements were identified.

The overall OBSI results indicated that in the eight types of asphalt pavements tested, the average sound intensity ranged from 98.3 dBA to 99.7 dBA, which are generally lower than those from some other states with similar types of pavements (33). This result can be interpreted that there are 'quieter' pavements used in North Carolina, especially in volume roads. In this project, the highest average noise level captured for a single test section was 105.1 dBA[2], this is also lower than the high values collected in other states from all types of pavements. It has been found that the difference between the lowest average noise level (98.3 dBA) and highest (103.2 dBA) is 4.9 dBA. This proved that quieter pavements have been used consistently in North Carolina in recent years on low volume roads.

OBSI data was also collected for selected pavement sections with various driving speeds to compare the effect of driving speed on the tire-pavement noise levels. Results showed that the relationships between driving speed and sound intensity level followed linear relationship regardless pavement types. For example, for an S9.5B test section, sound intensity ranges from 86.8 dBA at 25 mph to 98.5 dBA at 60 mph. S9.5C followed the same trend.

Based on the findings, recommendations can be made for further research on pavement noise. In this project one to three year old pavements were selected for OBSI measurement. This will make the data comparable to those from other states and the national database. However, it is known that tire-pavement noise levels will be higher as the pavement ages, and the relationships between sound intensity noise level and pavement age ('tire-pavement noise deterioration rate') may be different for different pavement. It is recommended that pavement noise levels at different ages be further investigated in future research. This will provide information on the change rate of pavement noise levels during the entire service life for a particular pavement. It is the authors' opinion of this report that when defining a 'quieter pavement', both factors should be considered, i.e., sound intensity noise level and sound intensity noise deterioration rate.

[2] An average of 105.1 dBA was measured on an OGFC test section in this project. Refer to Chapter 4 for detailed information.

The research results from this project present the NCDOT with a tire-pavement noise database in a format compatible with the pooled fund study. Results and data analysis are in a presentable and comparable format. The data will be valuable for the NCDOT/FHWA for future research on the development of quieter pavement. The results from this project allow for an interesting comparison between the data collected in North Carolina and from other states for various pavement types.

It was the research team's goal to ensure all the data collected and included in the report was accurate in reflecting the actual tire-pavement noise levels when captured, to ensure the OBSI data from North Carolina is identical in terms of measuring procedures with other states. The OBSI data collected to date is valid and reliable for use in establishing a tire-pavement noise database as a baseline, although more OBSI data is needed to enrich the current OBSI database in North Carolina, which is recommended as one of future research areas.

An operation procedure (training manual) has been prepared for training purposes of future OBSI users. The training manual is based on the most current version of B&K PULSE® system, and includes our firsthand experience in calibration, measuring, PULSE® software usage, and field testing related to the OBSI system.

Recommendations drawn from the results include (i) further OBSI data collection is needed to enhance the OBSI data for new pavements (1 to 2 years-old) for enriching the NCDOT OBSI database, and increasing sample sizes; (ii) OBSI data for the entire pavement service life, for example 3 to 20 years, for asphalt pavements, 3 to 30 years for concrete pavement; (iii) tire-pavement noise mapping for urban road networks in densely populated areas for traffic noise management purpose; (iv) various influencing factors on tire-pavement noise level. Detailed recommendations are presented in Chapter 6.

In this report, conclusions on the quieter pavement are given and recommendations for further research on tire-pavement noise, quieter pavement or potential quieter pavement in North Carolina are provided.

1.5 Report Organization

The remainder of the report is organized into chapters that present the project's major areas in detail. Chapter 2 covers the thorough literature study conducted by the team. Chapter 3 introduces the on-board sound intensity measurement program established by the team, B&K PULSE® system installation, hardware and software acquisition, in house and in-situ trial testing, and national OBSI rodeo. Chapter 4 presents the OBSI data collection, including the summary of tire-pavement noise levels for each type of pavement and effect of driving speed on the OBSI noise levels. Chapters 5 and 6 present conclusions for each pavement type with analysis and recommendations on future research in development of quiet pavements.

Chapter 7 presents technology transfer plans of the research project. Chapters 8 and 9 are references cited and appendices for the report.

2.0 LITERATURE REVIEW SUMMARY

As part of Task 1 of this project, at the outset of the research project in August 2009, the research team began collecting all technical literature and relevant documents for the project. The collected literature and documents included information on tire-pavement noise, traffic noise, pavement characteristics, and quieter pavement development. The sources include international journals, conferences and governments publications. Pavement materials and specifications, including typical asphalt pavement types used in North Carolina were also searched.

The above literature and documents were carefully reviewed by the research team. The literature review formed the literature report and a compilation of abstracts related to traffic noise (refer to Appendix 9.1 Compilation of Abstracts related to Traffic Noise). This document contains useful reference material for traffic noise studies.

2.1 Background Information

Noise is defined as an unwanted sound of any sort that affects people's daily life and is detrimental to human health in several respects including widespread psychosocial effects, reduced performance and increased aggressive behavior (1, 2). In the world today, noise has become one of the most pervasive forms of environmental pollution.

Traffic noise is one of the major noise pollution sources. Mitigation of traffic noise can be traced back to 1800's. British road builders used wood blocks and even rubber pneumatic tires at that time to mitigate the noise generated by traffic (3). As more automobiles and trucks took to the highways, traffic noise has become a major issue associated with the design and construction of new highways and improvement of exiting systems.

In 1976, the US Congress passed legislation requiring the states to provide mitigation for highway noise as a part of all federal-aid new, i.e., Type I, highway projects at impacted locations where it is reasonable and feasible (4). For all new projects, it is mandatory to consider noise abatement as part of the highway construction if a traffic noise impact is expected to occur. All states have begun preparing their state-specific policies and procedures, California (Caltrans) is one of the examples (5).

Traditionally, construction of noise barriers is the most common method of traffic noise abatement. The design goal for traffic noise barriers in North Carolina is to provide a 7 dBA noise level reduction in equivalent traffic noise levels for the "first row" of noise-sensitive receptors near or adjacent to the highway facility. However, as a 'passive' method, there are limitations to build noise barriers, including high cost, which is between $1.3 and $3 million per mile (6, 7) and unsuitability for some locations such as hillsides and intersections. Research revealed that tire-pavement noise is the dominant component of traffic noise (8-11) at highway speeds. As a result, civil engineers and acoustic scientists seek to investigate tire-pavement noise at the source and further improve pavement surface structure and materials characteristics to reduce traffic noise.

Traffic noise is a combination of the noises produced by engines, exhaust, tires and aerodynamic noise. It is impacted by traffic volumes, traffic speed and the percentage of trucks in the traffic mix. Tire-pavement noise is defined as the noise emitted from a rolling tire as a result of the interaction between the tire and road surface (12). To improve the noise level of road pavement, it is critical to accurately measure tire-pavement noise level of different types of pavements, which includes (i) the selection of the appropriate measuring methods and procedures to capture tire-pavement noise at the source, (ii) the selection of appropriate procedures that should exclude interfering factors during data collection and (iii) proper data analysis to provide pertinent direction in developing quieter pavement.

2.2 Tire-Pavement Noise Measurement Methods

Considerable research to develop alternative methods for measuring tire-pavement noise at its source has been performed in the last decade. Following are descriptions of the most commonly used methods.

2.2.1 SPB and CPB Methods

The Statistical Passby Method (SPB) was initially used to measure traffic noise and included evaluations of tire-pavement noise. SPB utilizes a random sample of typical vehicles measured individually. The maximum sound pressure level is captured for each passby using a sound measurement system such as a sound level meter which is located 50 ft (15 m) from the center line of the travel lane. The speed and vehicle type of each event is recorded. A statistically significant sample of light and heavy vehicles needs to be collected. The data is used to compute a statistical passby index (SPBI) which is used to compare various pavements. SPB results represent actual traffic noise emissions and provide the best available measurement of the impact of traffic noise on properties adjacent to highways. Since it measures all components of traffic noise alongside the highway, it does not strictly measure only the tire-pavement noise. Control passby (CPB) was then introduced by French National Standard NF S S1 119-2, which is similar to SPB, except that it involves a limited number of controlled vehicles. For CPB, relatively few selected vehicles are driven at a controlled speed past the measurement location. The CPB method takes less time than the SPB method, but it does not account for any variations that might occur in vehicles of the same type. The CPB method has the same site limitations as SPB and requires a light traffic density making it more suited to rural or test track conditions. There is no US standard available for CPB. Figure 2.1 presents a SPB traffic noise measurement (by courtesy of Mr. Gregory Smith of NCDOT).

Figure 2.1 Statistical Passby (SPB) Measurement Apparatus

2.2.2 CPX (Trailer) Method

In the late 1990's, a mobile trailer setup for measuring tire-pavement interface noise was developed in Europe (12, 13). The Close Proximity Method (CPX) was the first to allow focused measurement of tire-pavement interaction noise. A test tire is mounted within a small trailer that is towed by vehicle such as an automobile. Close to the test tire, generally within 4-18 in (100-450 mm), one or more microphones are located. Most trailers have an enclosure around the microphones and test tire in order to provide screening from wind and traffic noise. The noise level is measured as an average over a certain time interval, usually 4-60 seconds. Thus, the measurement can be made along the traffic stream. This method is less sensitive to noise generated by other traffic, and is therefore more reliable for tire-pavement noise measurement. The CPX method has been used in the US, Canada, Korea, South Africa, and European countries for tire-pavement noise measurement (14, 15). Figures 2.2 and 2.3 present the views of the CPX towing vehicle and trailer (by courtesy of Dr. Ulf Sandberg of Swedish Road and Transport Research Institute, VTI).

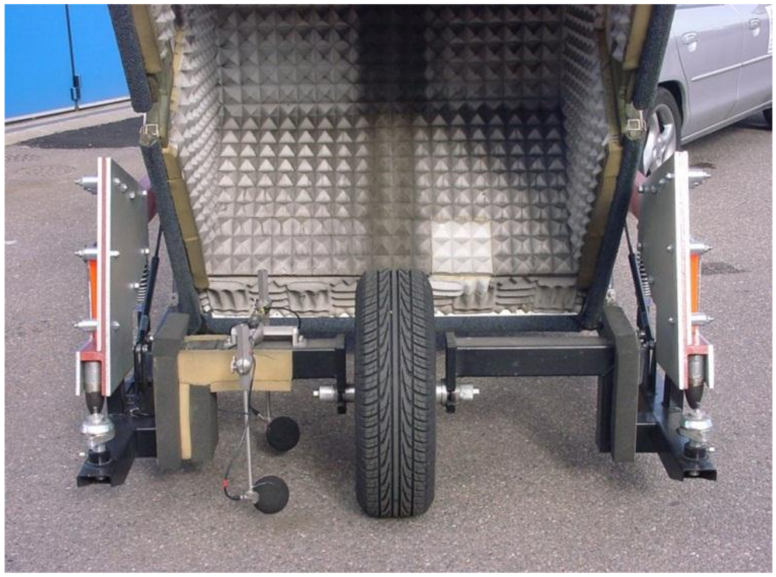


Figure 2.2 Inside View of CPX Trailer

Figure 2.3 CPX Used By the Swedish National Road and Transport Research Institute

2.2.3 OBSI Method

The On-Board Sound Intensity Method (OBSI) was developed by GM for tire sound research. The OBSI measurement hardware consists of a probe (microphone pair) held next to the tire-pavement contact patch by a fixture attached to the wheel studs of the test tire-wheel. The microphone is cabled to the interior of the vehicle where the signals are simultaneously captured on a recorder and processed by a real time-analyzer. The specifically tuned microphones focus on the noise of the tire-pavement interface. Noise from other sources such as wind or other vehicles should not significantly intervene. Figure 2.4 gives the side and top views of the microphone positions in OBSI.

A thorough study has been conducted in the US in recent years to develop and modify a rational test method for measuring tire-pavement noise at the source (16). To select the most appropriate method, two potential methods were initially compared, the CPX and the OBSI. Field testing was conducted to assess the two methods and compare their correlations with controlled passby measurements of a test vehicle. The two at-the-source measurements correlated well with each other, and to a lesser degree, with the passby measurements. Because the results indicated that OBSI data is slightly better correlated to controlled passby data and the CPX results had some distortion in the 1/3 octave band spectra in comparison to both the passby and OBSI results, the OBSI method was selected for further development into an at-the-source tire-pavement noise measuring method.

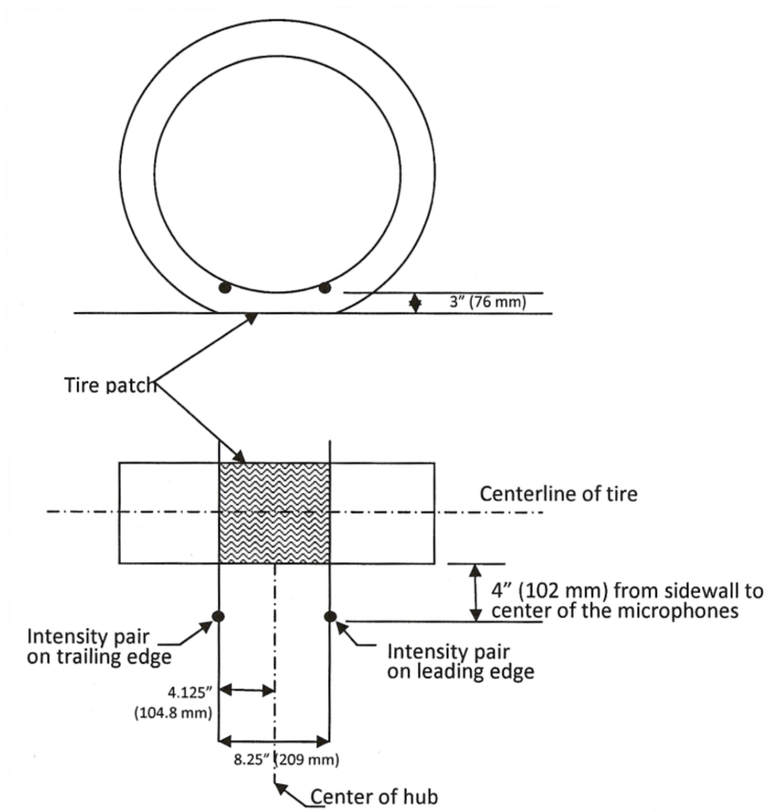


Figure 2.4 Side and Top Views of Microphone Positions

Both the AASHTO Designation TP: Measurement of Tire-pavement Noise Using the On-Board Sound Intensity Method (OBSI) and ASTM WK17029 New Practice for Measurement of Tire-pavement Noise using the On-Board Sound Intensity (OBSI) Method have been approved in 2011.

2.2.4 TPTA (Drum) Method

The Tire Pavement Test Apparatus (TPTA) is a laboratory-based tire-pavement noise measurement that is also used for tire-pavement noise level assessment. TPTA can also be used for testing the durability and friction of pavements (17, 18). The tester contains a drum with a diameter from 1 m to 15 m, motor, gear box, and pulley that drives a steel plate above the drum. Attached to the plate are two arms, with a tire-wheel assembly attached to each. Six curved samples are mounted around the drum. As the steel plate rotates, the two testing tires roll along the outside of the samples. The microphones mounted to the arms capture the tire-pavement noise. Figure 2.5 presents the view of TPTA.

Figure 2.5 View of the Tire-Pavement Test Apparatus (TPTA)

2.3 Considerations in Tire-Pavement Noise Measurement

Any interfering acoustic factors that could affect tire-pavement noise measurements must be considered as soon as the appropriate test method is selected, when pavement sections are chosen and during the noise level measuring process. Errors in sound-intensity measurements can occur for situations in which high-reactive components are present. These components summarized below should be considered.

2.3.1 Speed Effect

Research results indicated that during driving speeds in the range of 55 to 65 mph (88 to 105 kmph), on average, tire-pavement noise increases linearly and at a range of approximately 0.18 dBA for every 1.0 mph (or 0.11 dBA/1.0 kmph) (15). Other research has reached similar conclusions (16, 19).

2.3.2 Pavement related Effects

Research has indicated that noise levels generally increase as pavement ages (20, 21). 'Acoustic longevity' or 'tire-pavement noise deterioration rate' describes how well a pavement retains its original tire-pavement noise level over time. Normally as pavements age, their textures are worn by traffic loading and winter maintenance operations. Their surface features are altered as a result of distress from the environment and traffic. Roughness index (IRI) and friction number also affect tire-pavement noise level (22).

2.3.3 Temperature Effect

Temperature dependency affects tire-pavement noise generation, particularly asphalt surfaces. A separate study on tire-pavement noise indicated that the variation can exceed 0.1 dBA/^{o}C within the range of 5^{o}C and 30^{o}C (23). It is recommended that measured tire-pavement noise levels be corrected to a reference air temperature of 20^{o}C. Season related factors are also reported. Data should be collected during the same time of the year to minimize temperature differences. It is desirable to factor the effects of temperature into the results to improve the accuracy.

2.3.4 Wind Effect

Research found wind can affect noise in two ways: (i) wind noise in the microphones, and (ii) the tendency for wind to carry the sound, changing the effective distance between the tire and microphone (24).

In addition to the above factors, other potential test variables that should be normalized are: tire inflation pressure, test vehicle type and pavement moisture.

2.4 Data Analysis and Current Tire-Pavement Noise Findings

Different analytical tools have been developed for identifying the appropriate practice to assess and mitigate traffic noise. These include the US Federal Highway Administration Traffic Noise Model (TNM); the SoundPLAN model that was developed in Germany (25), and the database by the California Department of Transportation (Caltrans) (21).

TNM has the ability to consider different pavement types in a noise analysis (although it is not allowed by FHWA). In TNM and in the SoundPLAN model, a 3 dBA reduction at the source results in 3 dBA reduction in noise at the receiver. The FHWA has released its latest version of TNM Version 2.5 in 2004. This is the first version of the software with major improvements to the acoustic predictive algorithm since the original version released in

March 1998 (26). Most significantly, it includes the development of regression equations for the resulting reference energy mean emission levels (REMELS) as a function of vehicle speed and vehicle type. TNM uses advances in personal computer hardware and software to improve upon the accuracy and ease of modeling highway noise. The current function of the program includes the design of noise barriers. For design of quieter pavement, further sufficient data is needed.

2.5 Findings of Tire-Pavement Noise Levels

Research conducted around the world has given some qualitative comparison conclusions on different types of pavement or surface treatments. Research conducted in Europe concluded that portland cement concrete (PCC) pavement has higher tire-pavement noise values (1 to 2 dBA) than does dense graded asphalt concrete pavement (reference pavement), and that newly paved open graded asphalt pavement has lower tire-pavement noise values (4 to 5 dBA) than the reference pavement (12). Research conducted in Japan indicates that tire-pavement noise is closely related to the index of porous asphalt pavement surface texture and is reduced in proportion to the increase of total air voids volume per unit area of the asphalt surface (27).

Several states in the US and other countries have conducted research to gain an understanding of tire-pavement noise characteristics. The sound level measurement data collected and analyzed in California by Caltrans indicated that tire-pavement noise levels of dense graded asphalt course (DGAC) are approximately equal to the average pavement sound levels contained in the TNM REMEL data. Open graded friction course (OGFC) is 3 dBA lower and PCC pavement is 2 dBA higher than the TNM average level. Rubber asphalt concrete (RAC) reduced the noise by 5 dBA between 16 months and 6 years after paving. Figure 2.6 presents the two layer OGFC stricture recognized as a quieter pavement structure.

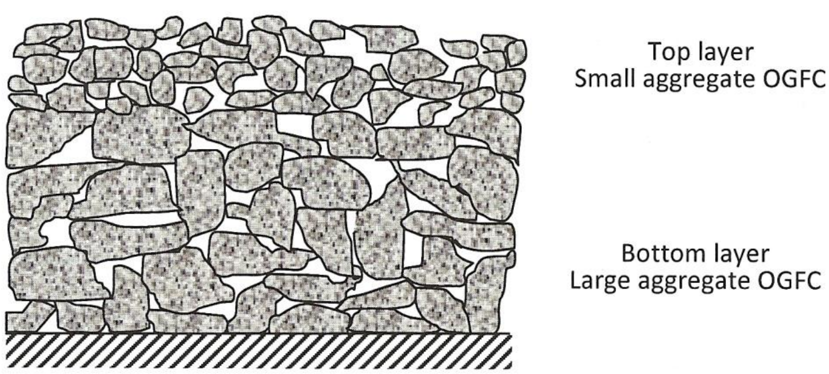


Figure 2.6 Two Layer Open Graded Friction Course

Arizona DOT (ADOT) measured asphalt rubber friction course (ARFC) aged between 3 and 12 years using the CPX method. PCC pavement tining textures were also evaluated. The results indicated that ARFC surfaces typically produced CPX sound levels between 94 and 99 dBA throughout their ten-year design period. The results indicated that the uniform transverse tining produced levels 2 to 3 dBA higher than ARFC's. Diamond grinding of pavement has been found to successfully reduce tire-pavement noise from PCC (17), and presents good acoustic longevity. Research conducted in Kansas and California indicated diamond ground concrete pavement exhibit little or no increase in noise over the first five to ten years after grinding (28).

Research in Texas showed that sound level differences between pavement types ranged to 7 dBA. These results indicate that the noise characteristics of pavement surface types are significant and should be a consideration before selection for highway surfacing (25).

Research conducted in Colorado, Iowa, Michigan, Minnesota, North Dakota and Wisconsin found that if overall noise considerations are paramount, longitudinal tining that provides satisfactory friction may be considered. A spacing of 19 mm uniform tining will provide adequate friction.

Tire-pavement noise levels for Ohio pavement types provide an additional criterion for pavement selection in noise-sensitive areas. There was a difference of 6.7 dBA between the lowest (open graded asphalt) and the highest (random transverse tined concrete).

Other findings include polymer modified hot-mix asphalt (HMA) is quieter than normal control HMA pavement (29). Pavement friction improvement by shot peening (Skidabrader®) did not significantly change the overall noise level, although the noise levels at frequencies of 1600 Hz and above decreased with higher friction (30).

Laboratory-based studies focusing on the sound absorption properties of various pavements were investigated using impedance tube and potable reverberation chamber. PCC and HMA pavement can absorb from 5.0 - 8.5% of sound (31). Construction-related research concluded that compaction methods used can affect the noise level. For example, Marshall compaction produces the most open (most permeable and sound absorptive) voids structure, while rolling wheel compaction produces the least open voids structure (32).

3.0 EQUIPMENT ACQUISITION AND FIELD TEST PREPARATION

3.1 General Information

An important task (Task 2) of this project is to establish an on-board sound intensity system that meets the current and future OBSI measurement needs of the NCDOT. Therefore, to collect necessary information on the OBSI system, including auxiliary equipment and non-standard microphone mounting fixture at the outset of the research, the Principal Investigator (PI, George Wang) visited the California Department of Transportation in Sacramento, CA (Caltrans, Mr. Bruce Rymer) and Illingworth & Rodkin, Inc. in Petaluma, CA (Dr. Paul Donavan) for a consultation of OBSI related issues. The PI also consulted B&K's offices in the US, Canada, and Denmark for technical queries. Following these initial meetings and interactions, the team prepared a list of detailed instrumentation, including parts, fixture, calibration equipment, tools, hardware and software selected for this project. Furthermore, the PI communicated with the Washington Department of Transportation (Mr. Tim Sexton) and Texas Department of Transportation (Mr. John Wirth) about the OBSI apparatus used in the Washington DOT and the Texas DOT respectively. The detailed equipment list was verified again with manufacturers, suppliers, and agencies.

Based on the list of instrumentation, before purchasing, selected suppliers were solicited and their quotations and specifications of the equipment parts were evaluated by the PI. The products were verified to ensure that they were compatible or consistent with the AASHTO standard requirements, and also compatible to those used by other states for tire-pavement noise measurement. The sales engineer from B&K (Mr. Will Kinard), the supplier of the PULSE® analyzer, met with the team on two different occasions for detailed demonstrations of the products.

3.2 OBSI Microphone Mounting Fixture and Fabrication

The microphone mounting fixture is a critical aspect of the system which directly affects the stability of the entire measuring hardware mounted outside of the test vehicle, adjacent to the test tire. The fabricating of the microphone mounting fixture was accomplished through a special machine shop at ECU, based on the shop drawings provided by Dr. Paul Donavan of Illingworth & Rodkin, Inc. The non-standard parts of the mounting fixture are summarized in Table 3.1. The standard parts are summarized in Table 3.2.

Table 3.1 Non-Standard Parts for the Microphone Mounting Fixture

Part No.	Part	Materials	Quantity
SI-2-001	SI Probe Holder	Aluminum	2
SI-2-002	SI Probe Mounting Plate	Aluminum	2
SI-2-003	SI Vertical Back Plate	Aluminum	1
SI-001	Vertical Slide Bar	½ in thick Aluminum	1
SI-002	Vertical Slider – Bearing Holder	Aluminum	1
SI-006	Wheel Mounting Plate	Aluminum	1
SI-008	Sound Intensity Probe	Black Delrin	2
SI-009	Torque Restraint Bracket	0.25 in thick Polycarbonate	1
SI-010	Extended Lug Nut	HT 4140	6

Table 3.2 Standard Parts for the Microphone Mounting Fixture

No.	Part/Description	Size	Quantity
1	Allen Head Screw	¼ - 20 × 3/4	9
2	Allen Head Screw	½ - 13 × 1	2
3	Allen Head Screw (Full Thread)	3/8 – 16 × 2 ¼ or 2 1/2	4
4	Flat Head Screw	¼ - 20 × 3/4	2
5	Lock Nut	½ - 13	1
6	Plastic Tubing	5/16 IN × 12 (7/16 OD)	1
7	Threaded Rod	5/16 – 18 × 12	1
8	Lock Nut	5/16 - 18	1
9	Lock Nut	3/8 - 16	4
10	Washers	3/8	8
11	Washers	1/4	4
12	Washer	3/4	1
13	Nut	5/16 - 18	1
14	Plastic Shaft. Collar (Grainger)	Stock No. 1F496, ¾ in dia.	2
15	Mounted Ball Bearing (Grainger)	Stock No. 1F548-0, ¾ dia.	2

3.3 Hardware Acquisition and PULSE® System Installation

Task 2 started at the same time as Task 1, and continued for approximately five months. When the acquisition of the OBSI parts, including Standard Reference Testing Tire (SRTT), was completed, the OBSI system was installed on the selected test vehicle. For this research project, a 2008 Chevrolet Impala LS passenger vehicle was used. The Impala is one of the preferred passenger cars for OBSI testing (others include Chevrolet Malibu, Toyota Camry, Hyundai Sonata). The OBSI system was set up and adjusted to the requirements needed for OBSI tire-pavement noise data collection. Trial testing for sound intensity noise capturing was conducted in-house at ECU in January 2010.

A PULSE® system training was conducted at the end of January 2010 by an application engineer (Mr. Joe Chou) from B&K's Atlanta Office. The PI and graduate research assistants attended the training session conducted in the OBSI research room at ECU. Again, the system was verified and calibrated during the training process.

The entire OBSI system was calibrated, verified and ready for trial field testing in late March 2010. Formal OBSI data collection started in June 2010. The data collected from June 2010 to mid-September, i.e., before the OBSI rodeo, was saved separately and carefully examined for accuracy after the OBSI rodeo.

For the OBSI measuring system, the selected sound intensity analyzer and software is a Brüel & Kjǽr (B&K) system. The microphones are G.R.A.S.'s Class 1 ANSI S1.9 amplitude response and phase matched. The sound intensity calibrator is G.R.A.S.'s model and the microphone calibrators are Larson Davis 369 calibrators. All instruments (or equivalent) used in this project meet ANSI Type I specifications (ANSI S1.16/IEC 61672-1). The major acoustical equipment includes 3050-A-040 PULSE® mini-frame with 4-ch input module LAN-XI 51.2kHz; sound intensity calibrator and corresponding software. The test tire used in this study is a 16 inch ASTM Standard Reference Test Tire (SRTT) P225 60R16 97S (per ASTM F 2493-06). The SRTT was manufactured in September 2008. It was first used on March 26, 2010. Mileage used on the SRTT is recorded on each testing. A detailed list of the instrumentation with brief specifications and descriptions is given in Table 3.3.

Figures 3.1 to 3.14 present detailed images of the major parts which formed the OBSI system and were used in this research.

Table 3.3 Major Hardware and Software in OBSI System used in the Research

No.	Equipment Item Type	Specification and Description	Quantity
	Hardware		
1	Hardware Mount	mics 4" from the tire wall (±0.25"); mics 3" in above ground (±0.25"); mics separation distance on probe = 0.63" (±0.04");between center of diaphragms); spacing between two probes = 8.25", 4.125 on each; side of center hub (±0.25")	1
2	Test Tire	Uniroyal (BF Goodrich) P225/60R 16 97S Tiger Paw AWP (5 ribs); Groove depth on SRTT should be > 0.314" (7.97 mm)	1
3	Wheel	6.50 ± 0.5 in wide steel wheel (16 × 6.5 J wheel); open wheel well	1
	Calibrator and Measuring Tools		
4	Durometer	Type A durometer confirming with ASTM D2240 specifications, measuring within a month of test	1
5	Radar Gun	Accurate to ±1 mph	1
6	Met Station	Accurate to 2.0^{o}F and 0.75 in Hg (±25^{o} mbar); Measure air temperature pressure during the course of measurements, report in hourly; Measure barometric pressure during the course of the measurements	1
7	Pavement Temperature Gun	Accurate to 2.0^{o}F pavement temperature hourly	1
8	Tire Tread Depth Gauge		1
9	Tire Pressure Gauge	Inflate to 30 ± 2 psi cold	1
10	Acoustic calibrator	Class 1 ANSI S1.40 Done after manufacturer specified "warm up" period 1 h before and 1 hour after measurements	1
11	Sound Intensity Calibrator		1
	Acoustical Equipment		
12	Microphone Pairs (ideally includes 2 back up pairs)	Class 1 ANSI S1.9 Amplitude response and phase matched	4
13	Preamps (ideally includes 4 pack up preamps)	Phase matched and gain matched The Type 4178 mics need external polarization	4
14	Microphone Extension Cables		
15	Power Supply		
16	Windscreens	Open-cell-structure foam, spherical, 3.3-3.6 in in diameter	
17	4-Channel Analyzer	Class 1 ANSI S1.9 Sound intensity level in 1/3 octave, 200 – 10,000 Hz 400 - 5,00 Hz (required), A-weight, Overall sound intensity level; sound intensity vector direction; LAN-XI hardware interfacing via an Ethernet connection to a PC 3560-B-010 – PULSE® Mini-Frame with 4ch Input (LEMO)	1
18	7771-N4	PULSE® CPB Analysis, 1-4 Channel Node-locked License	1
	M1-7771-N4	PULSE® CPB Analysis Software; provides real-time sound intensity calibrations via 1/1 octave, 1/3rd octave, 1/12th octave, 1/24th octave, and/or FFT. frequency analysis techniques	1
19	7708-N5	PULSE® Time Data Recorder	1
20	M1-7708-N5	PULSE® Time Data Recorder Software	1
21	7789-N	PULSE® Time Node-Locked Software	1
22	M1-7789-N	Software	1
23	3599	Sound Intensity Probe Kit	1
24	4297	Sound Intensity Calibrator	1
25	QB-0048	Rechargeable Battery	2
26	Laptop PC	Dell XT2 Touchscreen, anti-Glare, low voltage processor	1

Figure 3.1 shows the microphone mounting hardware fabricated at ECU Physics Instruments Machine Shop. The fixture was made based on the blueprints provided by Dr. Paul Donavan of Illingworth & Rodkin, Inc. Some modifications had made to secure the microphone during field testing which are presented in Chapter 5. Figure 3.2 shows 4-ch Input Module LAN-XI 51.2 kHz (Mic, CCLD, V) B&K Type 3050-A-040 Analyzer and Type 2831 Battery Module for LAN-XI.

Figure 3.1 OBSI Microphone Mounting Fixture Parts Fabricated at ECU

Figure 3.2 B&K PULSE® Type 3050-A-040 Analyzer and Battery

Figure 3.3 shows the two pairs of G.R.A.S. ½" condenser microphones for sound intensity measuring. Figure 3.4 shows the sound calibrators, a 1 kHz, 94 and 114 dBA, sound intensity calibrator (Type 51 AB, by G.R.A.S.), and type one durometer.

Figure 3.3 Two Pairs of G.R.A.S. ½ in. Microphones

Figure 3.4 Calibration Equipment for Microphone, Sound Intensity and Tire

Figure 3.5 shows the ½ inch microphone preamplifier connected to the LEMO-1B, 7pin wiring installed on the mounting fixture in the OBSI case. Figure 3.6 shows the Standard Reference Testing Tire which is to be mounted on P225/60R16 97S steel rim.

Figure 3.5 Microphones on the Fixture with 7-pin Cables in the Case

Figure 3.6 P225/60R16 Standard Reference Testing Tire (SRTT)

Figure 3.7 shows the test vehicle used in this project, 2008 Chevrolet Impala LS. This is one of the typical test vehicles used for OBSI with a wheel size of 225/60/16. It was rented from ECU motor fleet. Additionally the team found it is necessary to add a suspension stiffening bracket onto the test vehicle for reducing suspension movement during testing. Figure 3.8 shows the Dell Laptop PC used in this project, a processor for the data transferred from the PULSE® analyzer. It has a Core 2 Duo 2.66 GHz Processor, 15.4 in Ultra Sharp Display, and 4GB RAM.

Figure 3.7 Test Vehicle, 2008 Chevrolet Impala LS

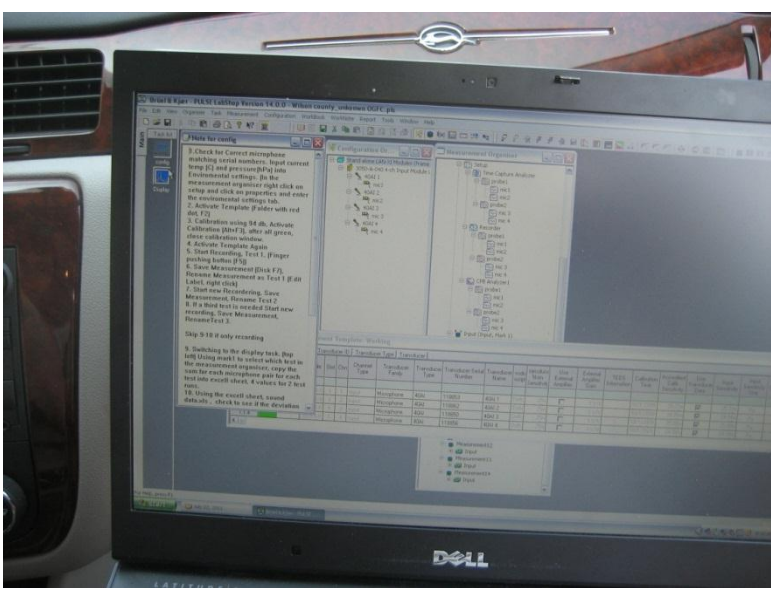


Figure 3.8 Dell Laptop PC

Figure 3.9 shows the PULSE® Analyzer connected to the microphones and laptop PC which was placed in the test vehicle. Figures 3.10 and 3.11 show the tool cases containing all parts, materials, tools, measuring and calibration equipment needed during the test. The tool cases, OBSI equipment case, and SRTT perfectly fit in the trunk of the test vehicle as seen in Figure 3.11.

Figure 3.9 PULSE® Analyzer in the Backseat of the Test Vehicle

Figure 3.10 Tool Cases

Figure 3.11 OBSI Cases in the Trunk of the Test Vehicle

Figure 3.12 shows the first time installation of the measuring equipment on the test vehicle in March 2010 for the trial test. Figures 3.13 and 3.14 show the OBSI equipment installed on the test vehicle ready for the trial OBSI data collection.

Figure 3.12 Installation of the OBSI System for the First Field Trial Testing

Figure 3.13 Microphones with Windscreens, Mounting Fixture and Cables

Figure 3.14 OBSI Test Vehicle and Microphone Mounting System

3.4 Trial Field Testing

3.4.1 PULSE® System Training

As planned and indicated in the project proposal, one of the important steps to successfully operate the required OBSI equipment was in-house training prior to the trial field testing. The in-house training included self-training and external training.

3.4.1.1 Self-Training

Between November 2009 and January 2010, the team members conducted self-training. During the self-training process, the PI assigned the training work to the team members. The self-training included perusal of the literature in three parts:

- Study of the basics and fundamentals of sound and vibration. This included five major references, i.e., (i) Tyre/Road Noise Reference Book, by Ulf Sandberg; (ii) Noise and Vibration Control, by Malcolm J. Crocker; (iii) Acoustics and Noise Control, by B. J. Smith, R. J. Peters and S. Owen; (iv) Acoustics for Engineers, by Jens Blauert and Ning Xiang; (v) Environmental Noise report by B&K.
- Study of the recent publications, training materials, standard specifications on tire-pavement noise. This mainly included (i) Tire-Pavement Noise 101 – an Introduction to Tire-Pavement Noise, A Federal Highway Administration Workshop; (ii) AASHOT Designation: TP 76-11 - Standard Method of Test for Measurement of Tire-Pavement Noise Using On-Board Sound Intensity (OBSI) Method; (iii) National Cooperative Highway Research Program (NCHRP) Report 630: Measuring Tire-Pavement Noise at the Source; (iv) Tire-Pavement Noise: Measurement and Modeling US DOT Volpe Center; (v) Traffic Noise Analysis, Caltrans.
- Review of Instruction Manuals supplied by the equipment manufacturers, for example, PULSE® system instruction manuals by B&K.

The self-training also included: (i) assembling the microphone mounting fixture; (ii) understanding the connections of the fixture, microphones, batteries, analyzer, computer; (iii) the in-house operation of the PULSE® system.

3.4.1.2 External training

The self-training was an excellent preparation for the external training by the equipment manufacturers and suppliers. B&K PULSE® system training took place on January 28, 2010 and administered by B&K's application engineer (Mr. Joe Chou) at ECU in the OBSI Research Room located in Rawl Building 341 at East Carolina University. The training included:

- Review of the PULSE® system and detailed functions of the program;
- Verification of the settings and calibrations conducted for the system;

- Demonstration of the instruments, connections, operations, and sound intensity measurements;
- Trouble shooting section;
- Questions section.

This training was one of the important activities in Task 2. During the PULSE® system training, the team members familiarized themselves with the analyzer and the software operating systems and had questions answered by the PULSE® application engineer. The training was an excellent preparation for in-house practice and in-situ noise measurement. The training was videotaped which can be used for future review purposes, and will also be a good reference for preparing an OBSI training manual. Figure 3.15 shows the demonstration given by the B&K application engineer in the PULSE® training session. Figure 3.16 presents the one on one question answer session by the B&K application engineer.

Figure 3.15 PULSE® System Training by B&K at ECU

Figure 3.16 PULSE® System Training by B&K at ECU

3.4.2 Preparation for the Trial Field Testing

During February and March 2010, the team practiced OBSI installation and operation before the trial testing. The practices took place in the ECU parking lot, and on local roads. The practices included:

- Switching the testing tire/wheel onto the test vehicle; checking balance, tire pressure and hardness, etc.;
- Mounting the microphone fixture onto the tire without microphones;
- Driving the test vehicle on roads in the vicinity of the ECU campus from lower speeds to the maximum testing speed of 60 mph to check for any vibration observed, and if so, the severity of the vibration and make necessary adjustments of the fixture/hardware;
- As the field trial progressed, the threaded rod was cut approximately six inches to fit the test vehicle to reduce vibration and the chance of apparatus failure.

Preparation also included the design of two forms for OBSI field testing by the research team. Table 3.4 presents the NCDOT-ECU OBSI Data Collection Task Check List which had been used throughout the testing. All actual field information was recorded on the forms. Table 3.5 presents the NCDOT-ECU Standard Reference Testing Tire (SRTT) Use Record used for recording purposes. The mileages of the SRTT for OBSI testing including warming up were recorded on this form. All digital field information was verified with the hard copies of the filed record after each OBSI data collection trip from the field.

From January to March, 2010, the research team also continued focusing on in-house setup of the PULSE® system and hardware adjustment.

3.4.3 Field Trial Testing

The field trial testing was divided into three steps: (i) to verify the microphone mounting hardware without microphones and to make adjustments if necessary; (ii) to verify the stability of the fixture with microphones, preamps, probes, and cables connected to the analyzer while keeping the microphone above the required ground distance (3 inches) for safety reasons[3]; (iii) to conduct OBSI data collection with all standard settings for practice purposes. Steps 1 and 2 were conducted during March and April 2010. Step 3 was conducted in May 2010.

In March, several trial tests were conducted as part of Step 3 as mentioned above. The main purpose of these trial tests was to test the microphone mounting fixture and minimize vibrations when driving at full speed of 60 mph. During this time, other quality control activities were also practiced such as recording field information onto the newly designed forms while monitoring and controlling driving speeds. Figure 3.17 presents a driving test with the microphone mounting fixture fixed on the test wheel, without microphones. The purpose of the driving test was to make sure the hardware perfectly fit the test wheel and the driving speed did not produce significant vibration. When this driving test was conducted, the microphone probes were installed.

After Steps 1 and 3 of the trial tests, on March 26, 2010, the research team first installed the entire OBSI system onto the test vehicle and conducted a trial data collection. However, as mentioned above, for safety reasons, this trial test allowed the microphones to be placed above the standard distance above ground (larger than 3 inches) for OBSI measuring. In the meantime, the research team was getting familiar with the testing procedures. This included using the radar gun to check speed, monitoring the temperature, calibrating the microphones; recording the site information on the designed forms. Figure 3.18 presents a research assistant checking the speed of the test vehicle. Figure 3.19 presents a trial test on NC 11 near East Carolina University on March 26, 2010. It is noted that the microphones were slightly higher than 3 inches. The threaded rod was cut 6 inches shorter at a later date.

[3] In these trial tests, the probe was kept approximately twice the distance from the ground (6 inches).

Table 3.4 NCDOT-ECU OBSI Data Collection Task Check List

OBSI Task Check List

Organization : East Carolina University OBSI Research Team				
Date:				
Date and time of equipment calibration:				
Test site data				
Location:				
Year Constructed:	Lane location:			
Station Number:	Pavement Type:			
Environmental Conditions (Data taken Every 60.)				
	Recorded 1	**Recorded 2 (if needed)**	**Retarded** 3 (if **needed)**	
Air Temperature				
Road surface Temperature				
Tire Temperature				
Wind Speed				
Weather Condition				
Time				
Humidity				
Barometric Pressure				
Was any moisture present (Y/M]				
Pre trip **check** list				
Tire condition/ inflation			Yes	No
Cold tires should be inflated to 30 psi. ± 2psi			X	
Drive for 15 min. to get tires to normal operating temps.			X	
Drive for extra 10 miles, since SRTT Is new.			NA	
OBSI apparatus on vehicle				
3 inches from the pavement			X	
4 inches from the tire			X	
level and in constant spot on car			X	
Test Data				
Vehicle Speeds Tested within ± 1 mph		Run 1	Run 2	Run 3
	Speed of vehicle			
Noise level measured in dBA		Run 1	Run 2	Run 3
	dB			
Mic Calibration/ Gain adjust value		Start reading	End reading	
Gain adjust values taken 1 hour before each test run and within one hour after each test run.	Mic 1			
	Mic 2			
	Mic 3			
	Mic 4			
Operators on site		Duties for test site		

Table 3.5 NCDOT-ECU Standard Reference Testing Tire (SRTT) Use Record

Standard Reference Testing Tire (SRTT) Use Record				
Date (DD/MM/YYYY)	Location	Mileage (Start)	Mileage (End)	Total Mileage

Figure 3.17 Field Test of the Microphone Mounting Fixture

Figure 3.18 presents that a research assistant was checking the driving speed of the test vehicle by using a radar gun (Bushnell® Velocity™ Speed Radar Gun). In the meantime, the research assistant communicated with the driver to adjust the speed within 60 mph ± 1 mph. The driver also checked the differences among the readings from the speedometer of the car, GPS and the radar gun.

Figure 3.18 Checking the Driving Speed of Test Vehicle during the Trial Test

Figure 3.19 presents the test vehicle with OBSI system installed collecting OBSI data during the trial test. This initial trial test was to verify the entire system to ensure it was working properly. The data collected was not included in the database for the project.

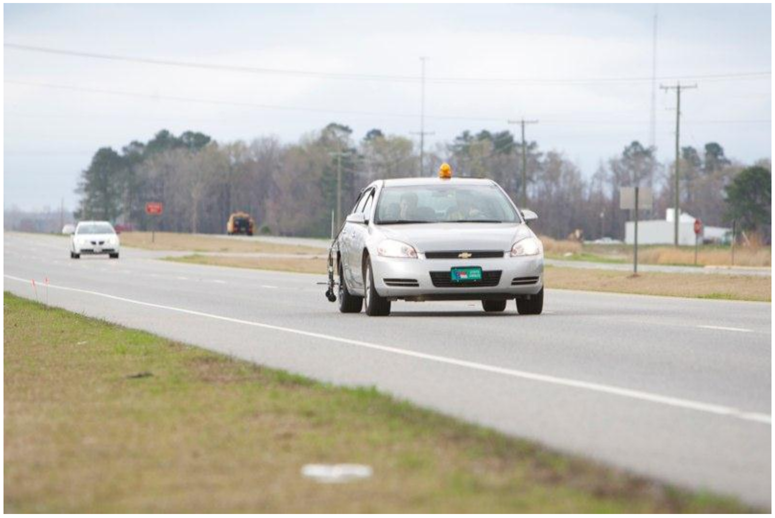


Figure 3.19 Trial Test on NC 11 on March 26, 2010

Figure 3.20 presents the team laying out the test sections before the trial test. The setup took place after the team visually inspected the entire highway pavement section selected for the trial testing.

Figure 3.20 Laying-Out the 440 Feet Testing Section

Figure 3.21 shows the OBSI test vehicle being driven at a speed of 60 mph and the research assistant checking the speed.

Figure 3.21 OBSI Trial Testing in Eastern North Carolina in March 2010

3.5 OBSI Rodeo in North Carolina

From March to June 2010, the research team conducted numerous trial tests to collect OBSI data, compare the data, and check the repeatability of the data and to ensure the data collected was valid and accurate. The results from this period of time were for the system verification purposes and were not part of the OBSI database of the project.

The formal OBSI data collection started on June 23, 2010 after all of the trial testing data was repeated perfectly and the research team received an inventory list of typical asphalt pavements in North Carolina from the Pavement Management Unit of the NCDOT on June 16, 2010.

The OBSI data collected from June to September 2010, i.e., prior to the OBSI rodeo, was saved as a separate folder for re-examination after the upcoming OBSI rodeo in September 2010. The OBSI rodeo was an important step to learn from other OBSI teams and verify the accuracy and validity of the data collected by the ECU research team.

3.5.1 Background Information

The NCDOT (Mr. Gregory Smith) and the FHWA Pooled Fund Study, TPF-5 (135), organized the 4th On-Board Sound Intensity Rodeo on September 14 and 15, 2010. This rodeo was held in Yadkin County, near the town of Elkin, North Carolina. The ECU research team with four other organizations: Rutgers University, the US DOT Volpe Center/FHWA, the American Concrete Pavement Association (ACPA), and Illingworth & Rodkin, Inc. (I&R) participated in the rodeo.

The measurements were performed on twelve different pavement sections of several highways in the vicinity of Elkin, NC. All testing was done following the current American Association of State Highway Agencies (AASHTO) provisional test procedure: (Standard Practice for Measurement of Tire-pavement Noise Using the On-Board Sound Intensity (OBSI) Method", TP 76-11, American Association of State Highway and Transportation Officials, 444 North Capitol Street N.W., Suite 249, Washington, D.C. 20001).

3.5.2 Pre-OBSI Rodeo In-House Verification and Calibration

Prior to the start of rodeo on September 14th, 2010, Dr. Paul Donavan, the technical advisor of TPF-5 (135) visited ECU OBSI equipment and research facilities on September 12, 2010. Physical inspections, verification and calibration of the hardware and software were made. A review of the data collected from March 26 to August 2010 was conducted. The results verification and equipment setups and calibration were satisfactory and the ECU team was ready for the rodeo. Figures 3.22 and 3.23 present the pre-rodeo verification of OBSI facilities at ECU in the OBSI research room. Figure 3.24 shows the sound intensity calibration before the rodeo at ECU.

Figure 3.22 Pre-Rodeo OBSI System Verification and Calibration

Figure 3.23 Pre-Rodeo Equipment Verification

Figure 3.24 Sound Intensity Calibration

3.5.3 Test Procedures and Sites

All of the OBSI testing followed the AASHTO Standard Method of Test TP 76-10[4] (proposed). Prior to the start of testing on September 14th, physical inspections of each

---

[4] The Method is approved in 2011 and now it is AASHTO Standard TP 76-11.

team's setup was conducted for dimensional accuracy with respect to the distance from the tire, height above the pavement, and microphone separation. To avoid any site biases, each vehicle was measured in the same parking stall. The dimensions of all teams were within the ± 0.25 inch tolerance specified in the procedure. Also prior to testing, the tire durometer measured hardness, tread depth, and inflation pressure were measured by one operator and one gage. The two rear tires of each vehicle were weighed on the portable scales with and without the operators in the vehicle. Larson Davis Model CAL200 acoustic calibrators were used after being verified to produce the same calibration sound level. The test sections included in the rodeo were located to the north and east of Elkin, NC, on US 21 Bypass, Interstate I-77, and State Route 268 Bypass (CC Camp Road). The test circuit defined a loop about 6½ miles in length with a typical transit time of 7 minutes. Within the loop, 12 test sections were defined on both hot mix asphalt (HMA) and Portland cement concrete (PCC).

Figure 3.25 shows the ECU team beginning to install the test tire at the rodeo. Figure 3.26 presents the team members installing the microphones onto the mounting fixture while checking the level and distance to the ground and the wall of the SRTT.

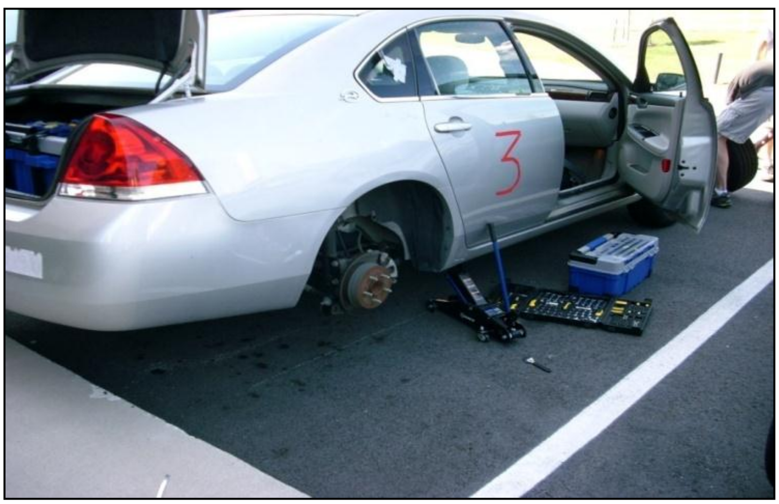


Figure 3.25 Preparation for Installing the SRTT

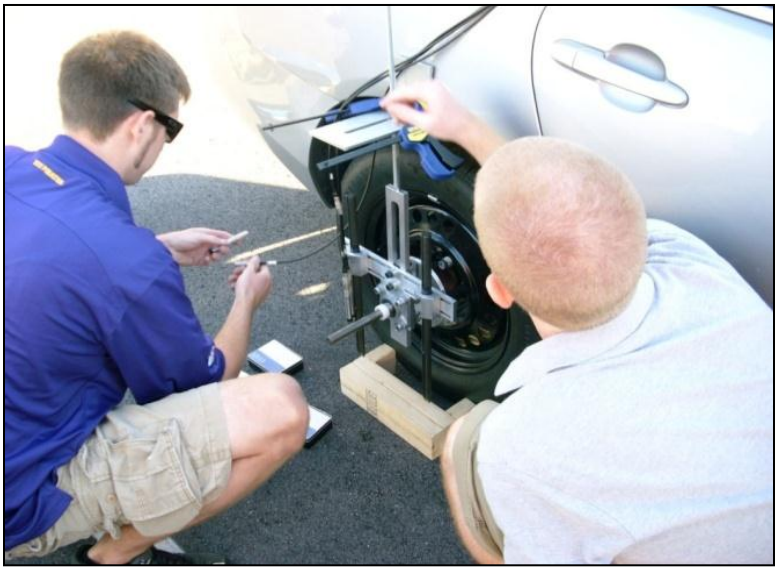


Figure 3.26 Checking the Positions of Microphones

Figure 3.27 shows the weight of the test vehicle was checked and recorded as part of the information at the rodeo. The ECU test vehicle tire weight was approximately 820 lb. throughout the project.

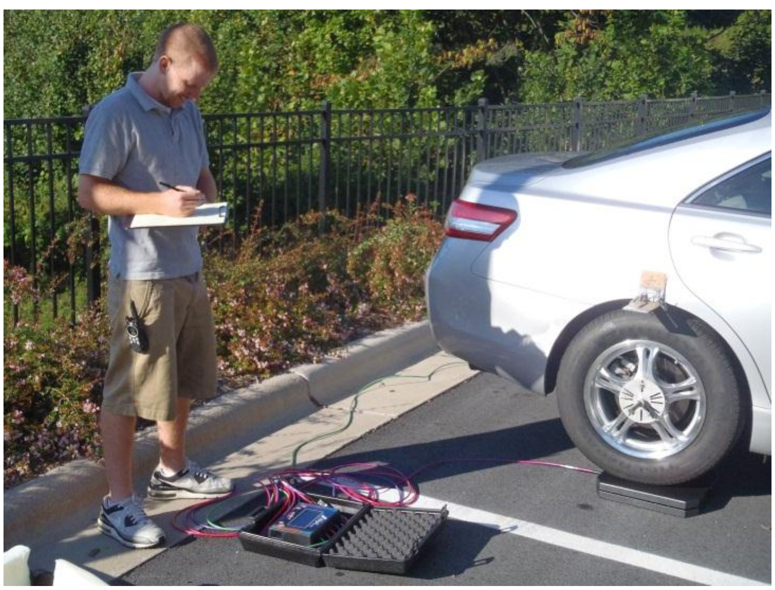


Figure 3.27 Measuring the Weight of the Test Vehicle

Figure 3.28 shows that the ECU test vehicle with the entire OBSI system was installed and ready for rodeo testing.

Figure 3.28 OBSI System Installed on the Test Vehicle Ready for Testing

Figure 3.29 shows ECU OBSI test vehicle (Number 3) in the rodeo test near Elkin, NC. Figure 3.30 shows the ECU research team members in the OBSI rodeo.

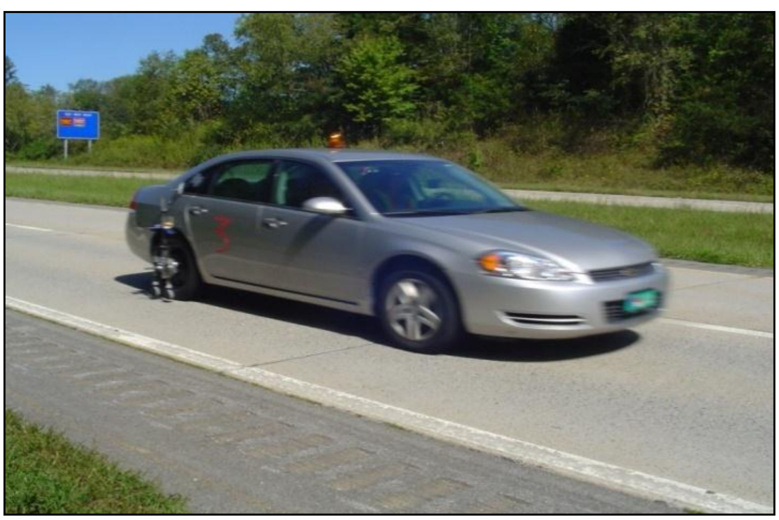


Figure 3.29 ECU OBSI Test Vehicle on Rodeo Test

Figure 3.30 The ECU OBSI Rodeo Team

3.5.4 Test Results and Comparison

Throughout the rodeo, the run-to-run variation in overall A-weighted OBSI level for each team was low. The average variation was 0.2 to 0.3 dBA for each of the teams with standard deviations about those averages of only 0.1 to 0.2 dBA (34).

Comparison of the overall OBSI levels for Volpe, ECU, Rutgers, and IR as measured initially for the first testing on September 14^{th}, 2010 indicated the average difference between teams on each of the pavements was 1.2 dBA with a standard deviation of 0.5 dBA. The difference in levels for the individual sites spans from 0.3 dBA at Site 3 to 2.3 dBA at Site 5A. For comparison, the results from the three test teams in the Texas Rodeo of February 2009 found a maximum range of 2.0 dBA with an average range of 1.3 dBA. The 2008 Mesa Rodeo saw a maximum range of 2.2 dBA between four teams with an average range of again 1.3 dBA on nine pavement surfaces (35). Two-team rodeos at Yuma and NCAT both saw average ranges of 1.3 dBA with maximum ranges of 2.1 dBA and 2.9 dBA, respectively. Figure 3.31 presents a comparison of sound intensity data for 12 pavement sites during the 2010 OBSI rodeo. A comparison indicates that the ECU OBSI performed well and the data was close to the mean of the data from all teams in the overall 12 sites testing.

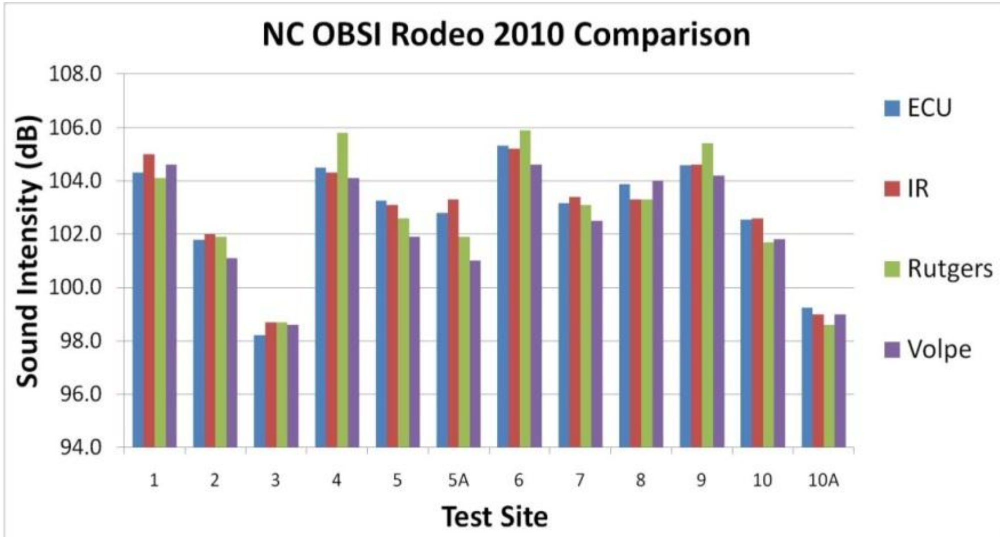


Figure 3.31 A Comparison of OBSI Data for 12 Pavement Sites in 2010 OBSI Rodeo

OBSI rodeo field work was completed on September 15, 2010. Data analysis and summary were presented in the report titled Comparative OBSI Testing in North Carolina: The North Carolina Rodeo (34). The analysis showed that ECU's data was consistent and comparable to other team's data. The collected data was very close to the mean measurement of each testing site.

The rodeo results indicated that the OBSI system and data collection process used in North Carolina was valid. After the rodeo, a systematic OBSI data collection was continued. The data collected prior to the rodeo from June 23, 2010 was also verified and formed part of the OBSI database.

4.0 TIRE-PAVEMENT NOISE MEASUREMENT AND OBSI DATA COLLECTION

Once the pavement inventory list was received from the Pavement Management Unit of the NCDOT (Mr. Neil Mastin, Pavement Management System Engineer, for typical surface asphalt courses, open grade friction course (OGFC) and ultra-thin bonded wearing course (UTBWC)), and later by Construction Unit of the NCDOT (Mr. Nilesh Surti, for concrete (diamond grinding) pavement (DGCP)), the team started the OBSI data collection. The formal OBSI data collection in North Carolina started on June 23 2010, shortly after the successful completion of the trial noise measurement from March to May 2010. Table 4.1 presents an overview of pavement types provided by the NCDOT and the OBSI testing status of each type of pavement.

Table 4.1 Major Pavement Types in the Study

	Typical Asphalt Pavements Used in North Carolina							**Special Pavements**		
Pavement Types	SF9.5A	S9.5A	S9.5B	S9.5C	S9.5D	S12.5C	S12.5D	OGFC	UTBWC	DGCP
OBSI Data Collection	Tested	Tested	Tested	Tested	Tested	Not tested	Tested	Tested	Tested	Tested

OBSI data for all types of pavements in Table 4.1 was collected except for Type S12.5C. S12.C was not measured primarily due to accessibility difficulties encountered at the locations and limited numbers of site locations.

4.1 Test Equipment, Procedures, and Site Selection

4.1.1 Test Equipment

As indicated in Chapter 3, B&K PULSE® analyzer and software was used in the project. Table 4.2 presents the parameters of the test vehicle used in this project. The tire load measured represents the approximate load when the OBSI testing was conducted. Two researchers were normally in the test vehicle during data collection, one was driving and the other one was operating the PULSE® system. Table 4.3 presents the information of the SRTT used in the project (values collected in September 2010) including hardness and tread depth.

Table 4.2 Test Vehicle Parameters

Test Vehicle Type	Test Tire Load (lbs.)	Bolt Circle Diameter
Chevrolet Impala LS 2008	~820	115 mm

Table 4.3 Test Tire Information

Tire	Build Date	Durometer Hardness Number	Tread	Relative OBSI Level
SRTT	Week 36 2008	66.2	8.0 mm	0.1 dBA

4.1.2 Test Procedures

All OBSI testing followed the AASHTO Standard Method of Test TP 76-11. Prior to the data collection on each day, as indicated in Appendix 9.2, Procedures of Operating OBSI and PULSE® System were strictly followed including:

- Check the test sections laid out prior to the test;
- Calibrate the microphones prior to and after the test on each day;
- Check cold tire inflation pressure;
- Conduct warm-up runs for the SRTT (approximately 10 miles);
- Record environmental conditions, including temperature (air, pavement and tire) and air pressure[5].

4.1.3 Test Section Selection

Prior to each test, a visual site survey was normally conducted by the PI and/or a team member(s). The purpose of this site visit was to conduct a visual survey of the geometric shapes in the pavement and pavement surface characteristics to ensure that the pavement surface was smooth, with no aggregate segregation, no patches and potholes and no cracks or other surface defects of any type. During the site visit, a 440 feet test section was selected with approximately 1,000 ft. before and after the test section. Table 4.4 presents the selection criteria for the test sections. The pre-test visit and pre-selected test sections made the OBSI data collection efficient and safer.

[5] The OBSI rodeo conducted in September 2010 showed that the ECU team put the actual values of temperature and barometric pressure in the PULSE® system at the time of testing. The other four teams used the default values (20°C and 1013.25 hPa). Although the deviation was small (from 0.05 to 0.13 dBA) and it was suggested, no corrections were applied to the results. The ECU research team continued to input the actual parameters throughout the project.

Table 4.4 **Pavement Test Section Selection Criteria**

Pavement Condition Category	Visual Observation
Pavement Surface Characteristics	Smooth, no transverse or longitudinal cracks observed
Materials Properties	No surface segregation and asphalt bleeding observed
Geometry	Straight driving lane, no uphill, downhill, for approximately 1500 ft., (440 ft. or 135 m for test section for 60 mph)[6]

The typical pavement types found in North Carolina for this study were mainly those surface courses with 20 years of design life, and with various traffic volumes: < 0.3 million ESALs[7] (SF9.5A, S9.5A); 0.3 to 3 million ESALs (S9.5B); 3 to 30 million ESALs (S9.5C); > 3 million ESALs (S9.5D, S12.5D). The pavements tested also included newly resurfaced surface courses. Surface treated pavements are not commonly used in North Carolina, and were not tested.

4.2 Asphalt Pavement

Typical asphalt pavements used in North Carolina were provided by the NCDOT Pavement Management Unit (Mr. Neil Mastin, Pavement Management Systems Engineer) on June 16, 2010. The asphalt pavements were located in approximately 40 counties across North Carolina and included nine different types of asphalt pavements, which were SF9.5A, S9.5A, S9.5B, S9.5C, S9.5D, S12.5C, S12.5D, open grade friction course (OGFC), and ultrathin bonded wearing course (UTBWC). Eight out of the nine types of asphalt pavements had been investigated. The selected pavements were 1 to 3 years old for better comparison purposes[8].

Table 4.5 shows the particle size distribution requirements for S9.5 series and S12.5 series of dense graded surface courses. Table 4.6 presents the Superpave mix design criteria of the selected asphalt pavement types.

[6] If OBSI data were collected for various driving speeds, the distance of the section will vary for 5 seconds of noise capturing. The PULSE® system and driving speed will control the actual test distance.
7 ESAL stands for Equivalent Single Axle Load.
[8] This is because the age of the pavement can impact its OBSI noise level.

Table 4.5 Aggregate Particle Size Distribution Criteria

Standard Sieves	**Percentage Passing Criteria – Mix Type (Nominal Maximum Aggregate Size)**			
	9.5 mm (for S9.5 Mixes)		12.5 mm (for S12.5 Mixes)	
(mm)	Min.	Max.	Min.	Max.
19.0			100.0	
12.5	100.0		100.0	90.0
9.5	90.0	100.0		90.0
4.75		90.0		
2.36	32.0 (60.0)[9]	67.0 (70.0)[10]	28.0	58.0
0.075	4.0	8.0	4.0	8.0

It is noted that in Table 4.5, for SF9.5A mix, the percentage passing 2.36 mm sieve shall be a minimum of 60% and maximum of 70%. This means that the particle size of SF9.5A is slightly finer than that of S9.5A. It will be seen later that this did not make differences for the OBSI noise level of SF9.5A and S9.5A.

Table 4.6 Superpave Mix Design Criteria

	Design	**Binder**	**Compaction Levels in Lab**			**Volumetric Properties (c)**			
Mix	ESALs	PG				VMA	VTM	VFA	% Gmm
Type	Millions	Grade	No. Gyrations @		Max. Rut Depth	% Min.	%	Min. – Max.	@ N_{ini}
			N_{ini}	N_{des}	(mm)				
SF9.5A	<0.3	64-22	6	50	11.5	16.0	3.0-5.0	70-80	≤91.5
S9.5B	0.3-3	64-22	7	75	9.5	15.0	3.0-5.0	65-80	≤90.5
S9.5C	3-30	70-22	8	100	6.5	15.0	3.0-5.0	65-76	≤90.0
S9.5D	>30	76-22	9	125	4.5	15.0	3.0-5.0	65-76	≤90.0
S12.5C	3-30	70-22	9	100	6.5	14.0	3.0-5.0	65-75	≤90.0
S12.5D	>30	76-22	9	125	4.5	14.0	3.0-5.0	65-75	≤90.0

In Table 4.6, the design ESALs is based on 20 year design traffic. The vast majority of S9.5 mixes is designated as SF9.5A as that is what most NCDOT divisions use for lower ADT resurfacing. The S9.5A is much rarely used now.

4.2.1 SF9.5A

SF9.5A and S9.5A are dense graded surface courses used on low volume roads in North Carolina. Compared to S9.5A, SF9.5A is more commonly used. Table 4.7 summarizes the sites tested for SF9.5A. Appendix 9.5 provides the detailed site information including

[9] The number in parentheses is for SF9.5A mix.
[10] The number in parentheses is for SF9.5A mix.

accurate locations, satellite maps, GPS locations and sound intensity tire-pavement noise levels. Figures 4.1, 4.2 and 4.3 summarize the results for SF9.5A. The data was broken into two graphs due to the large number of roads measured. The average sound intensity for SF9.5A was 99.1 dBA, which was the second lowest out of the nine pavements investigated in the project, including both asphalt and concrete pavements.

Table 4.7 Summary of SF9.5A Sites[11] for OBSI

Test Date	County	Highway
February 9, 2011	Edgecombe	SR 1105
February 9, 2011	Edgecombe	SR 1523
February 16, 2011	Martin	SR 1501
February 16, 2011	Martin	SR 1420
February 16, 2011	Martin	SR 1002
February 23, 2011	Nash	SR 1945
February 23, 2011	Nash	SR 1733
February 23, 2011	Nash	SR 1134
February 23, 2011	Nash	SR 1124
February 23, 2011	Nash	SR 1105
March 18, 2011	Washington	SR 1125
March 18, 2011	Washington	SR 1180
March 18, 2011	Washington	SR 1127
April 15, 2011	Franklin	SR 1425
April 15, 2011	Franklin	SR 1456
April 15, 2011	Franklin	SR 1001
April 15, 2011	Franklin	SR 1611
April 15, 2011	Warren	SR 1300
April 15, 2011	Warren	SR 1335
April 15, 2011	Warren	SR 1634
April 15, 2011	Warren	SR 1620
April 15, 2011	Vance	SR 1518
April 26, 2011	Hyde	SR 1104
April 26, 2011	Hyde	SR 1114
April 26, 2011	Hyde	SR 1304
April 26, 2011	Hyde	SR 1305

[11] Refer to Appendix 9.5 Site Information and OBSI Data for detailed test sections and road surface data.

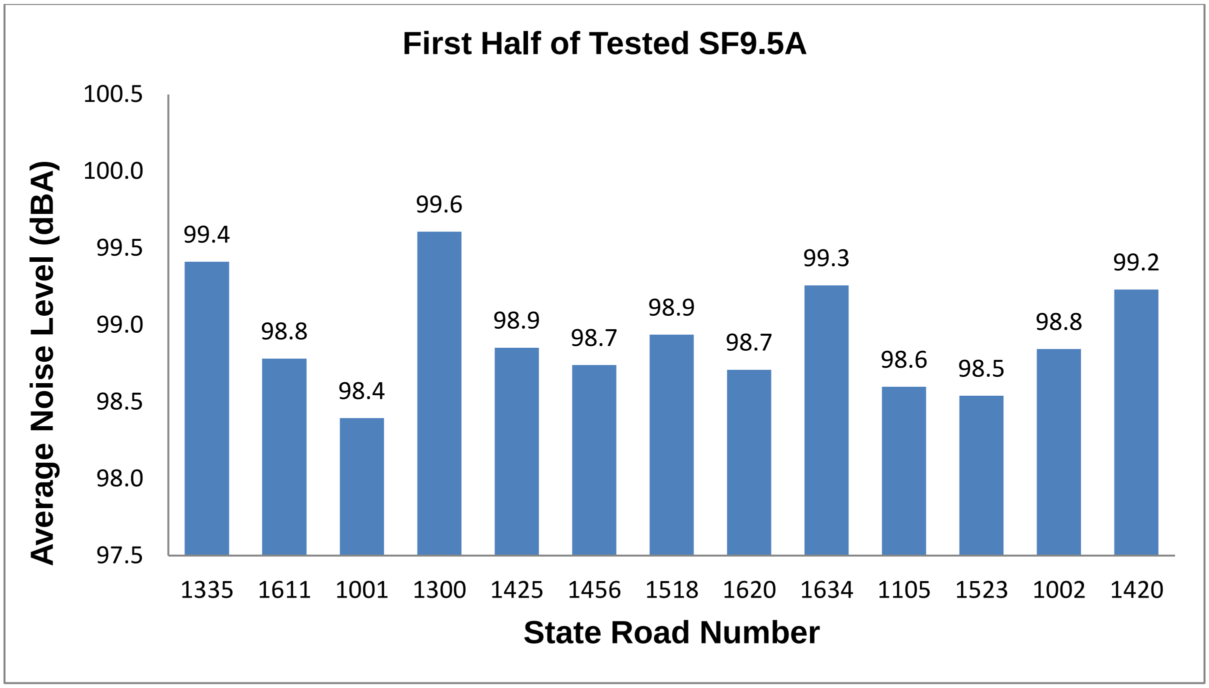


Figure 4.1 Average Sound Intensity for Various SF9.5A Sites – Part I

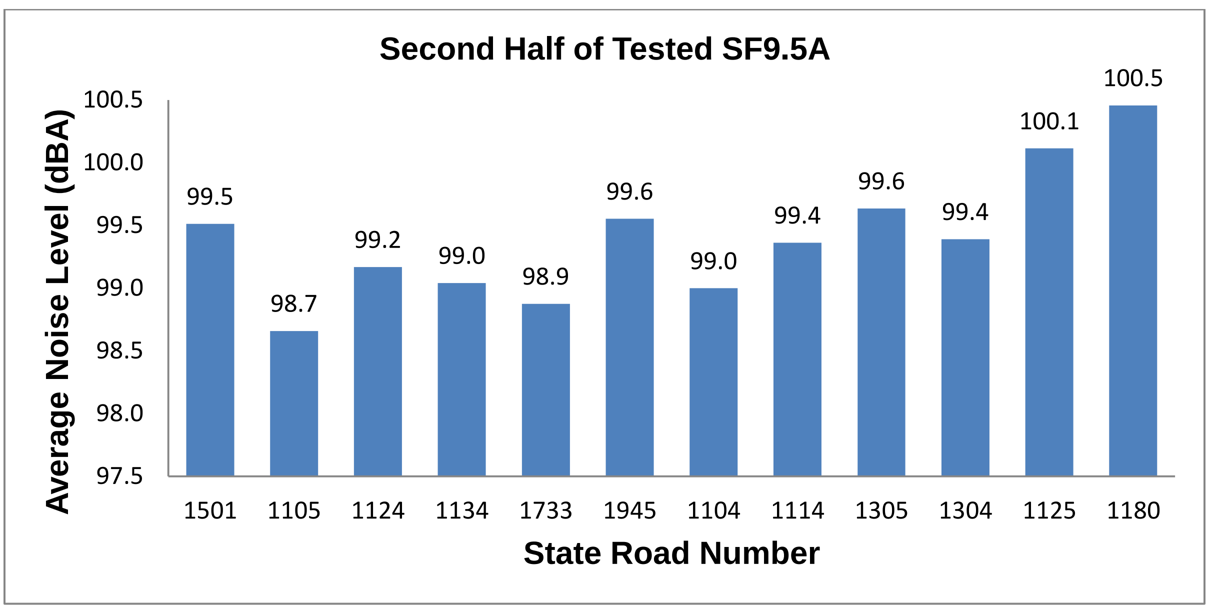


Figure 4.2 Average Sound Intensity for Various SF9.5A Sites – Part II

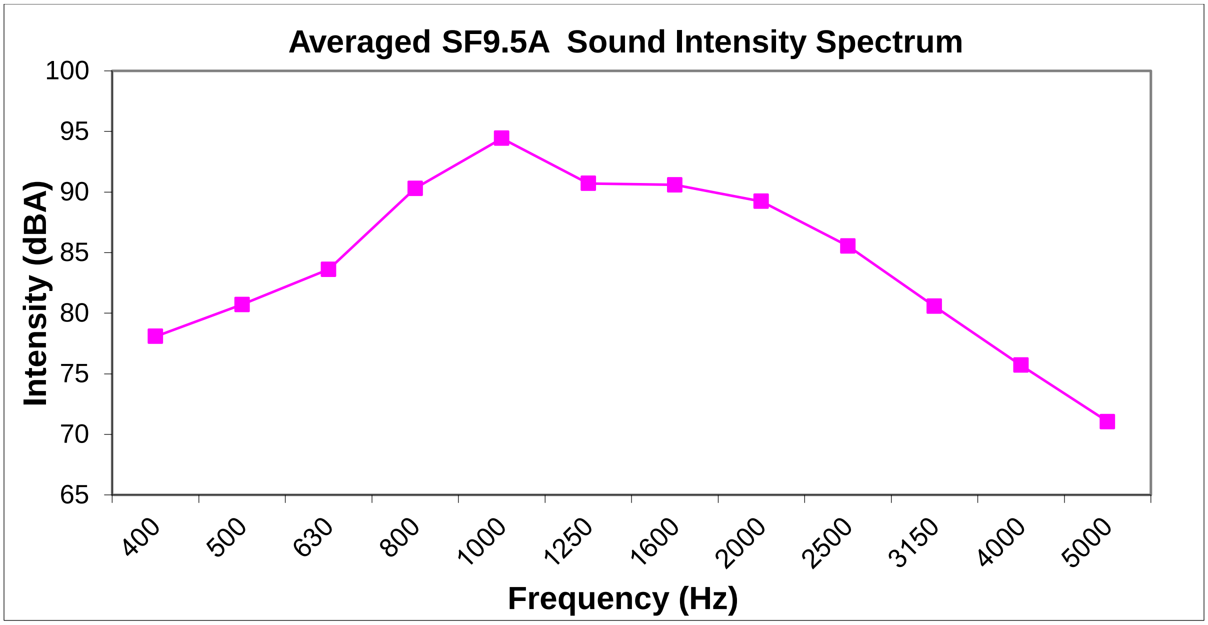


Figure 4.3 Sound Intensity Spectrum from 400 to 5,000 Hz Frequency

4.2.2 S9.5A

S9.5A is also a surface course which is used on very low volume roads in North Carolina, but it is not as commonly used in NC as SF9.5A currently. Table 4.8 summarizes the sites tested for S9.5A. Figures 4.4 and 4.5 summarize the results for S9.5A. The average of sound intensity levels for S9.5A is 99.1 dBA which is the same as SF9.5A. Appendix 9.5 provides the detailed site information, including accurate location, satellite map, GPS location and sound intensity tire-pavement noise level.

Table 4.8 Summary of S9.5A Sites for OBSI

Test Date	County	Highway
February 11, 2011	Johnston	SR 1525
February 11, 2011	Johnston	SR 1168
February 11, 2011	Johnston	SR 1162

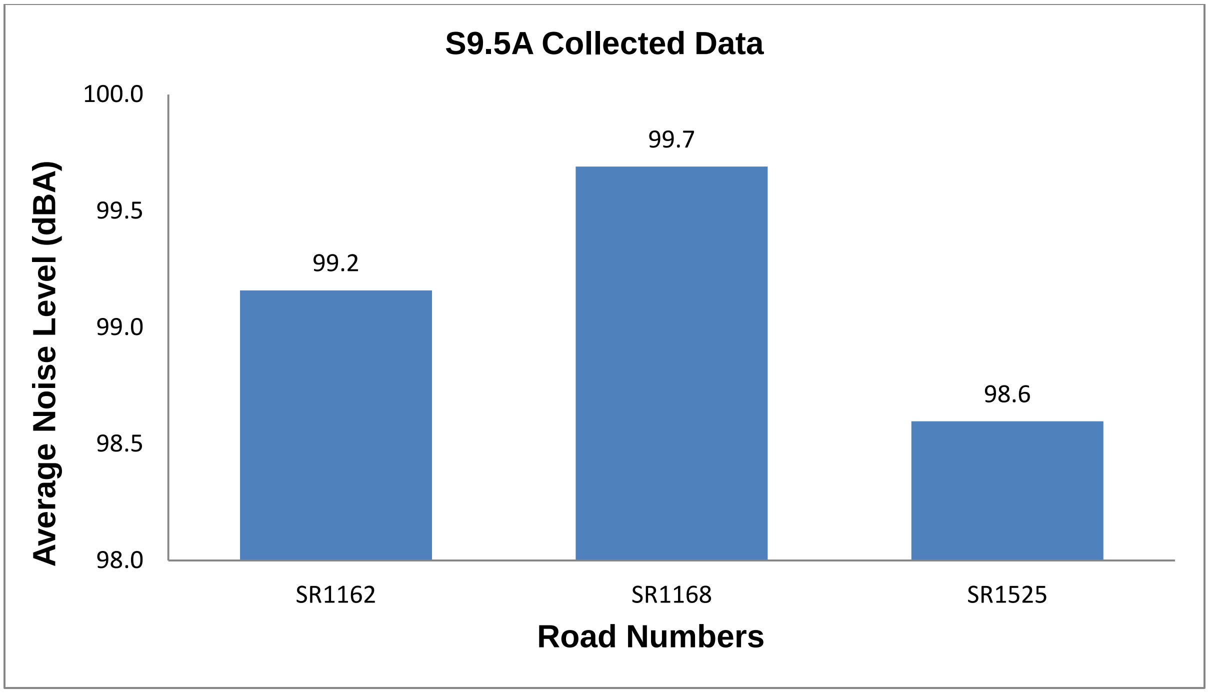


Figure 4.4 Average Sound Intensity Tire-Pavement Noise for Various S9.5A Sites

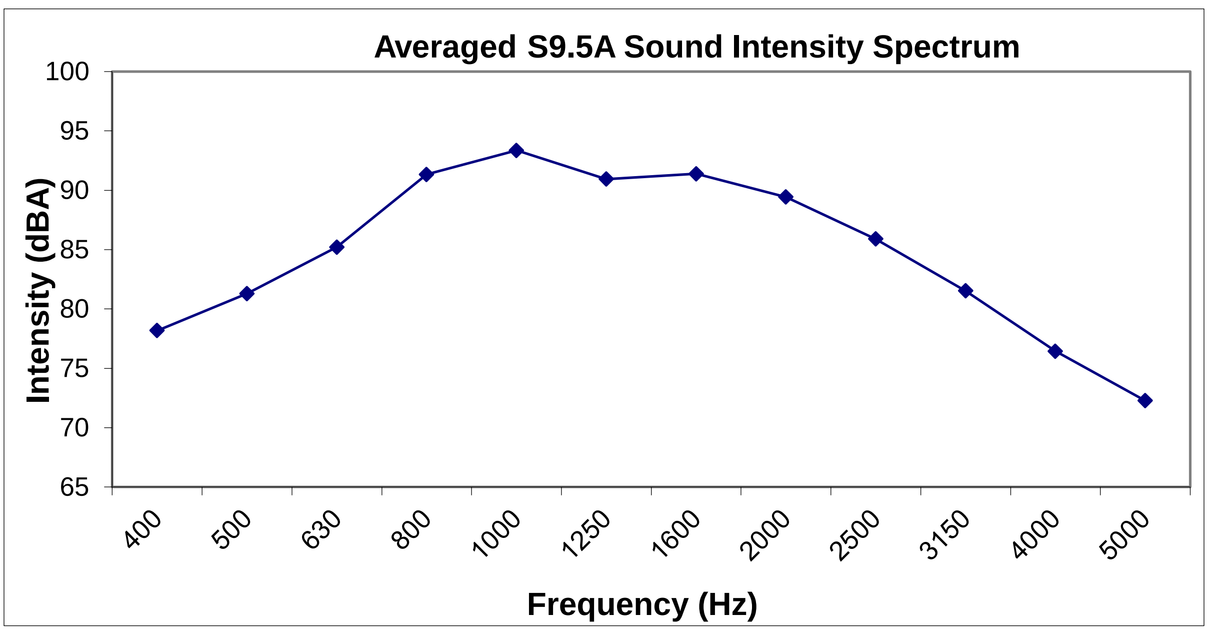


Figure 4.5 Sound Intensity Spectrum from 400 to 5,000 Hz Frequency

4.2.3 S9.5B

S9.5B is a surface course used in North Carolina, which carries average daily traffic (ADT) approximately 0.3 to 3.0 million ESALS. Figures 4.6 and 4.7 summarize the OBSI results for S9.5B. The average of sound intensity levels for S9.5B is 98.4 dBA. Although this is the lowest in this project, it is very close to other dense graded surface courses. Table 4.9 summarizes the sites tested for S9.5B. Appendix 9.5 provides the detailed site information, including accurate location and satellite map, GPS location, and sound intensity tire-pavement noise level.

Table 4.9 Summary of S9.5B Sites[12] for OBSI

Test Date	County	Highway
June 23, 2010	Pitt	NC 118 EB
June 23, 2010	Pitt	NC 118 WB
June 24, 2010	Lenoir	NC 8 NB
June 24, 2010	Lenoir	NC 58 SB
July 1, 2010	Nash	NC 43 SB
July 1, 2010	Nash	NC 43 NB
July 1, 2010	Nash	NC 43 NB[13]
July 29, 2010	Tyrrel	NC 94
February 11, 2011	Johnston	SR 1182
February 18, 2011	Craven	NC 101
February 18, 2011	Craven	NC 118
February 18, 2011	Craven	NC 306
April 6, 2011	Green	NC 58
April 6, 2011	Lenoir	NC 58

[12] Refer to Appendix 9.5 Site Information and OBSI Data for detailed test sections and road surface data.
[13] Eight testing speeds were used for this site: 25, 30, 35, 40, 45, 50, 55, 60 mph.

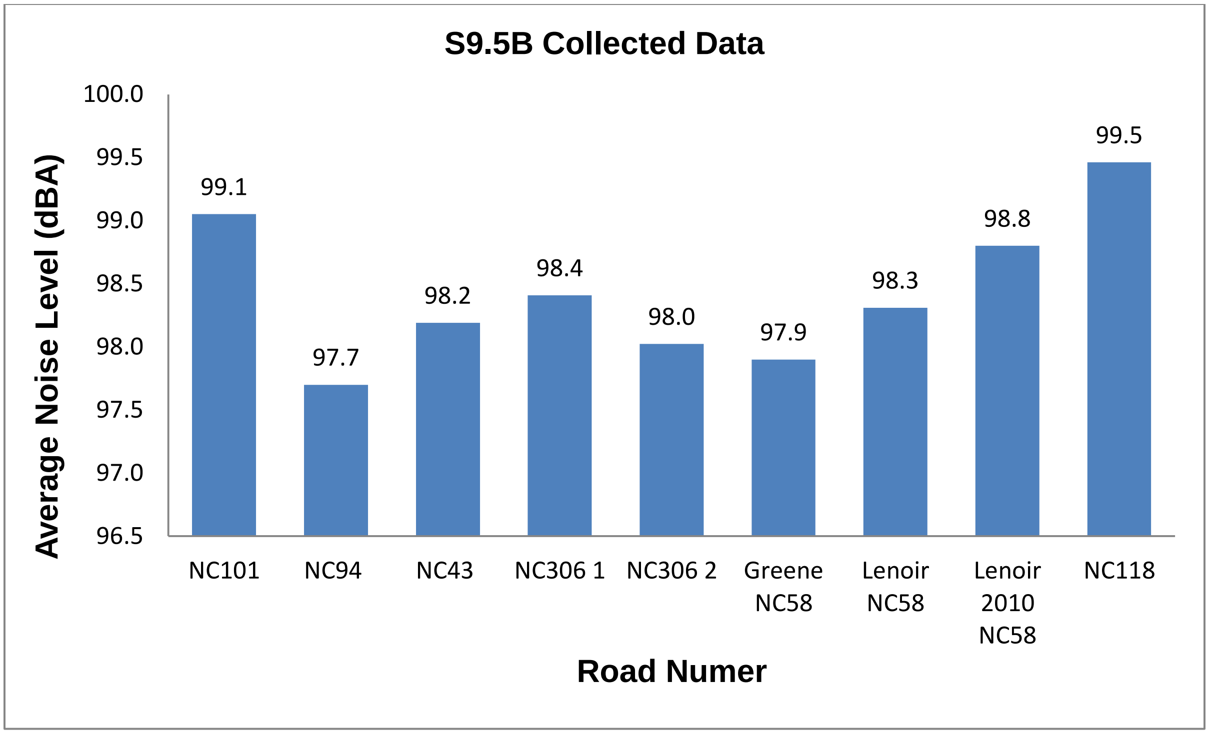


Figure 4.6 Average Pavement Noise for Various S9.5B Sites

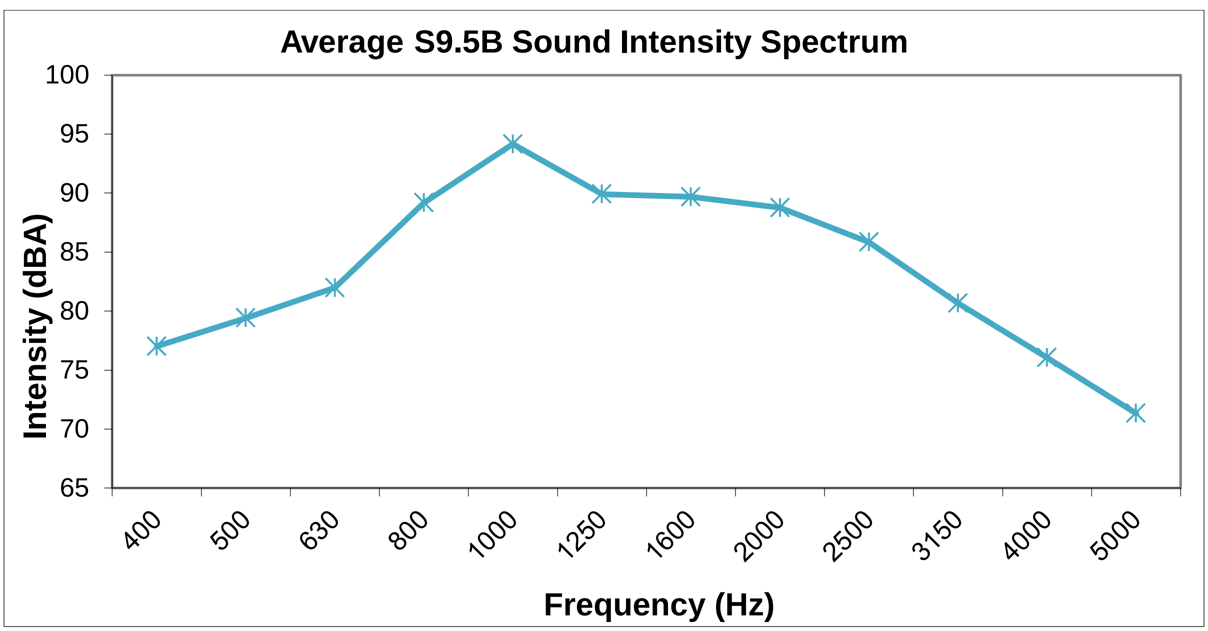


Figure 4.7 Sound Intensity Spectrum from 400 to 5,000 Hz Frequency

4.2.4 S9.5C

S9.5C is an HMA surface course used in North Carolina. Table 4.10 summarizes the sites tested for S9.5C. Figures 4.8 and 4.9 summarize the results for S9.5C. The average of sound intensity levels for S9.5C is 99.3 dBA. Appendix 9.5 provides the detailed site information, including accurate location, satellite map, GPS location, and sound intensity tire-pavement noise level.

Table 4.10 Summary of S9.5C Sites for OBSI

Test Date	County	Highway
June 23, 2010	Pitt	NC 118 WB
June 23, 2010	Pitt	NC 118 EB
June 23, 2010	Pitt	NC 11 SB
June 23, 2010	Pitt	NC 11 NB
June 23, 2010	Pitt	NC 11 SB[14]
March 25, 2011	Duplin	NC 24
March 25, 2011	Duplin	US 421
March 25, 2011	Sampson	US 421
April 6, 2011	Lenoir	NC 118
February 18, 2011	Pamlico	NC 55

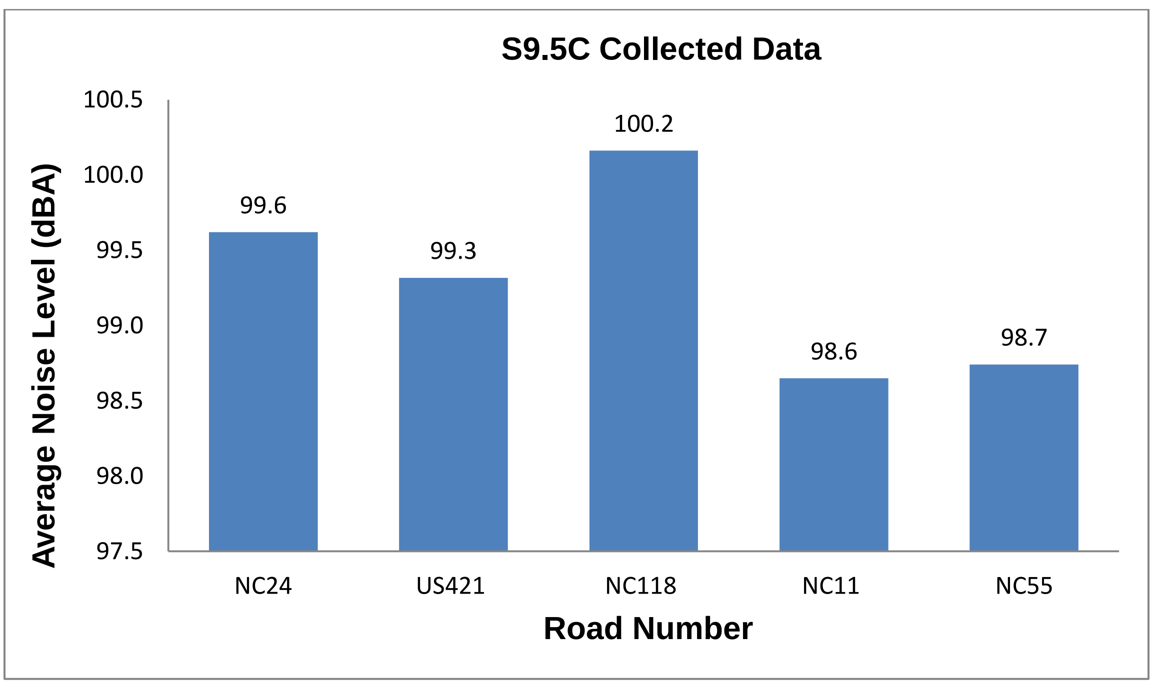


Figure 4.8 Average Sound Intensity Tire-Pavement Noise for Various S9.5C Sites

[14] Six testing speeds were used for this site: 35, 40, 45, 50, 55, 60 mph.

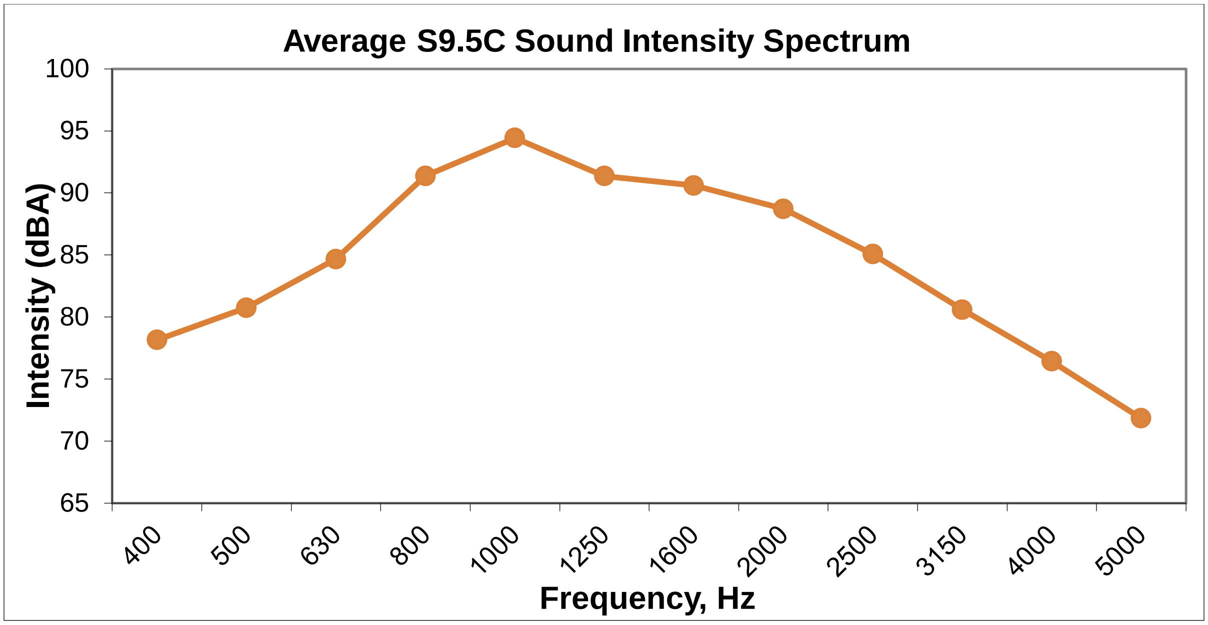


Figure 4.9 Sound Intensity Spectrum from 400 to 5,000 Hz Frequency

4.2.5 S9.5D

S9.5D is a surface course used in North Carolina for high volume roads. Table 4.11 summarizes the sites tested for S9.5D. Figures 4.10 and 4.11 summarize the results for S9.5D. The average of sound intensity levels for S9.5D is 99.5 dBA. Appendix 9.5 provides the detailed site information, including accurate location, satellite map, GPS location, and sound intensity tire-pavement noise level.

Table 4.11 Summary of S9.5D Sites for OBSI

Test Date	County	Highway
May 26, 2011	Orange	I-40
May 26, 2011	Alamance	I-40
May 26, 2011	Guilford	I-40

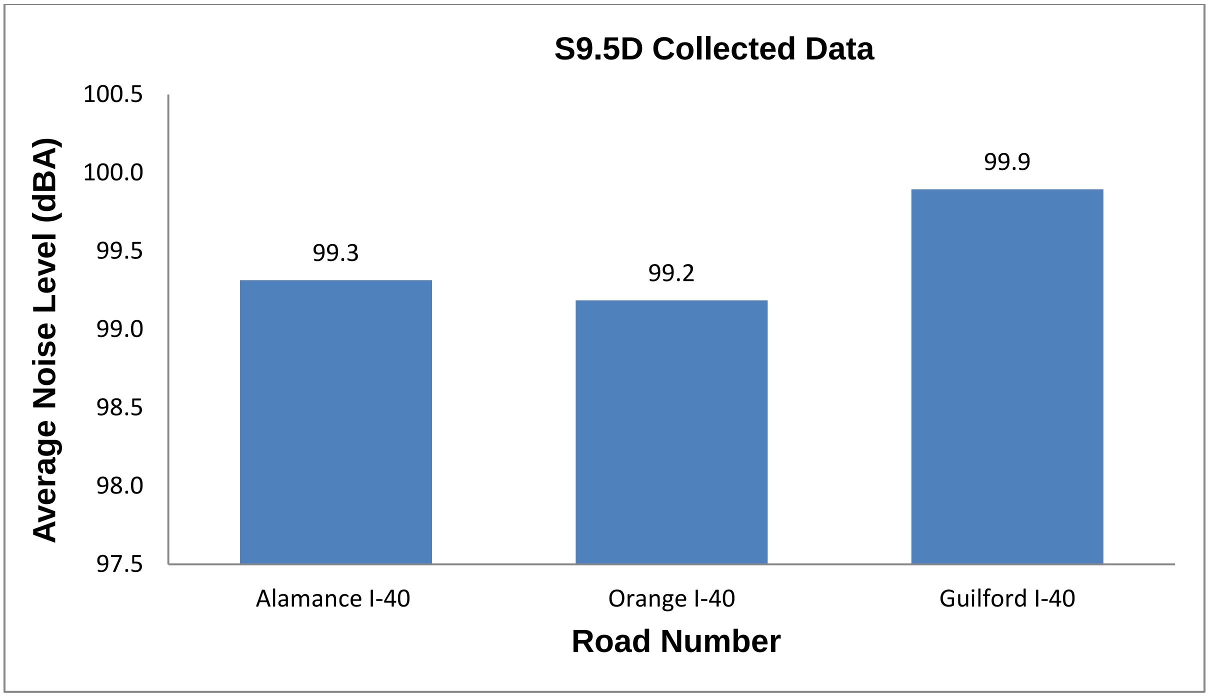


Figure 4.10 Average Sound Intensity Tire-Pavement Noise for Various S9.5D Sites

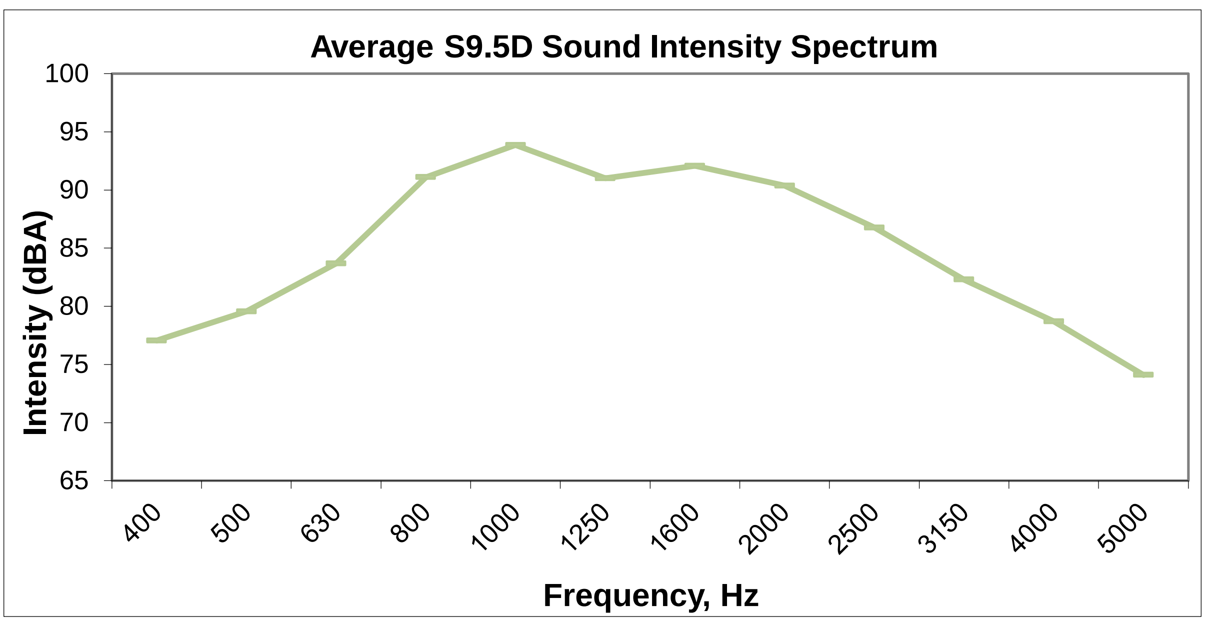


Figure 4.11 Sound Intensity Spectrum from 400 to 5,000 Hz Frequency

4.2.6 S12.5D

S12.5D is a dense graded surface course used on high volume roads in North Carolina and the average daily traffic (ADT) is larger than 30 million ESALs. Table 4.12 shows the site tested for S12.5D and the sound intensity levels for the test sections are shown in Figures 4.12 and 4.13. The average sound intensity level for S12.5D is 99.7 dBA. Appendix 9.5 provides the detailed site information, including accurate location, satellite map, GPS location, and sound intensity tire-pavement noise level.

Table 4.12 Summary of S12.5D Sites for OBSI

Test Date	County	Highway
June 23, 2011	Robeson	I-95

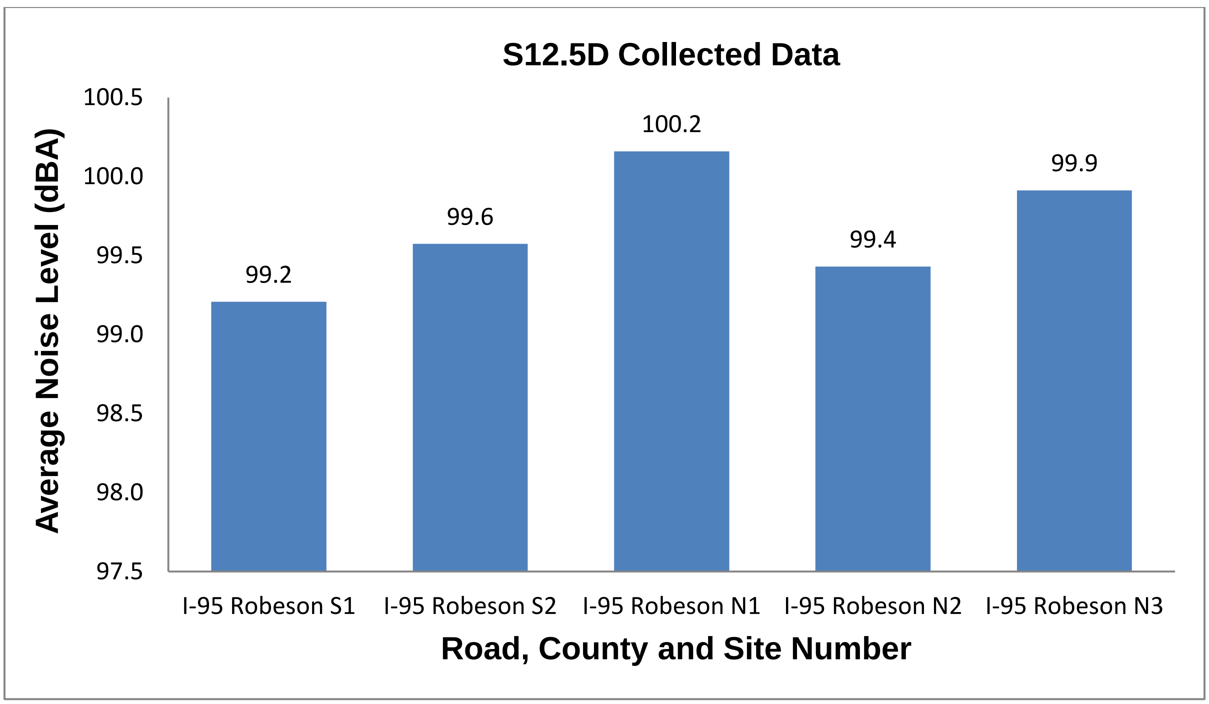


Figure 4.12 Average Sound Intensity Tire-Pavement Noise for Various S12.5D Sites

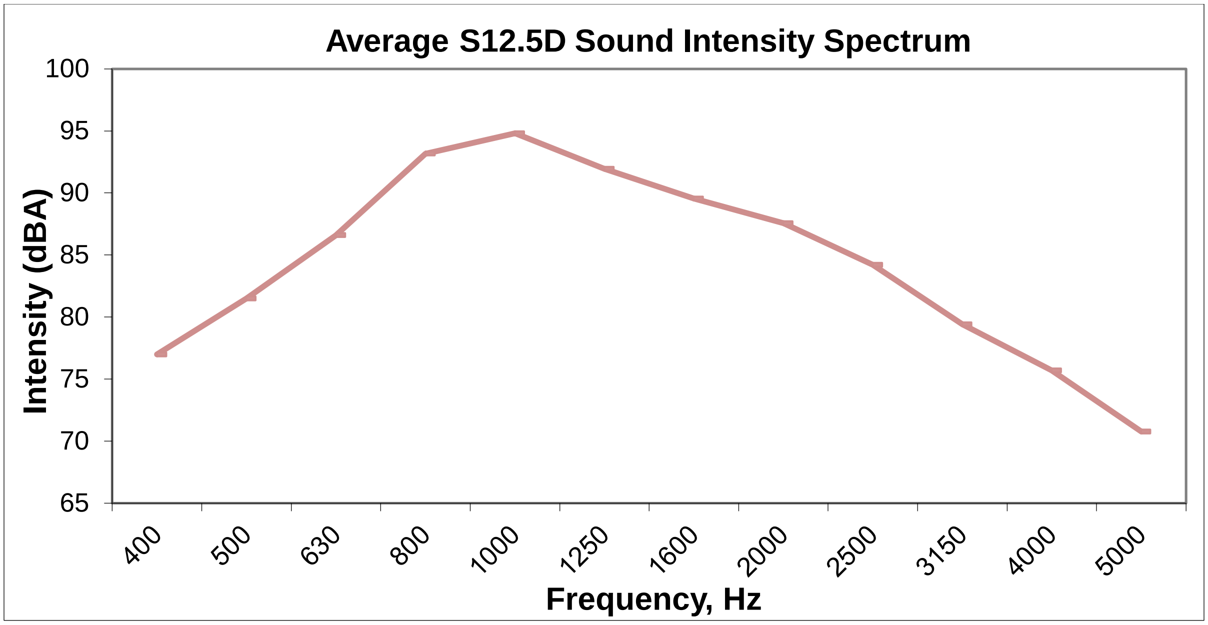


Figure 4.13 Sound Intensity Spectrum from 400 to 5,000 Hz Frequency

4.2.7 Open Grade Friction Course (OGFC)

Open Graded Friction Course (OGFC) is a surface course commonly used in North Carolina. Various OGFC have been used since 1950 in different parts of the US to improve the frictional resistance of asphalt pavements. However, the experience of states with this kind of mix has been widely varied. While many states have reported good performance, many other states have stopped using OGFC due to low durability or loss of the voids (36). However, many improvements have been made during the last few years in the way OGFCs are designed and constructed. Table 4.13 summarizes the sites tested for OGFC. Figures 4.14 and 4.15 summarize the results for OGFC. The average of sound intensity levels for OGFC is 103.2 dBA. Appendix 9.5 provides the detailed site information, including accurate location, satellite map, GPS location, and sound intensity tire-pavement noise level.

Table 4.13 Summary of OGFC Sites for OBSI

Test Date	County and Site	Highway
June 29, 2010	Sampson 1	I-40 EB
February 11, 2011	Sampson 2	I-40 EB
February 11, 2011	Sampson 2	I-40 WB
May 27, 2011	Forsyth	I-40 Bus.
May 27, 2011	McDowell	I-40
May 27, 2011	Burke	I-40
May 28, 2011	Haywood	I-40 Border of TN/NC
May 28, 2011	Polk[15]	I-26
May 28, 2011	Polk[16]	I-26
May 28, 2011	Henderson[17]	I-26
May 28, 2011	Henderson[18]	I-26

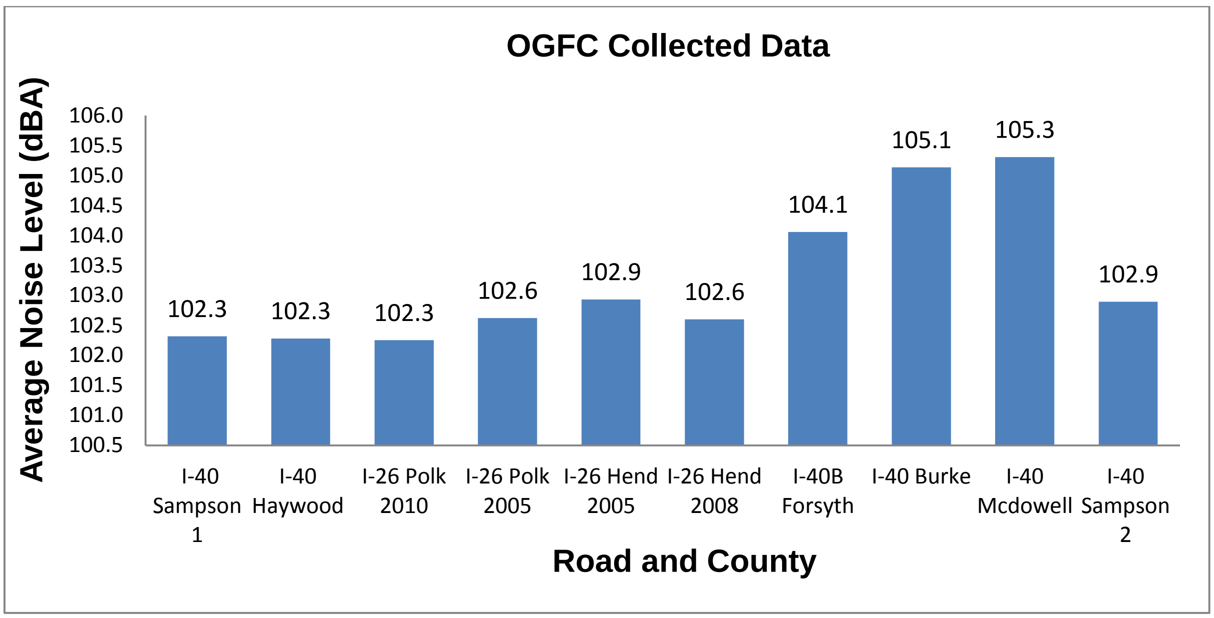


Figure 4.14 Average Sound Intensity Tire-Pavement Noise for Various OGFC Sites

[15] This site was constructed in 2005.
[16] This site was constructed in 2010.
[17] This site was constructed in 2005.
[18] This site was constructed in 2010.

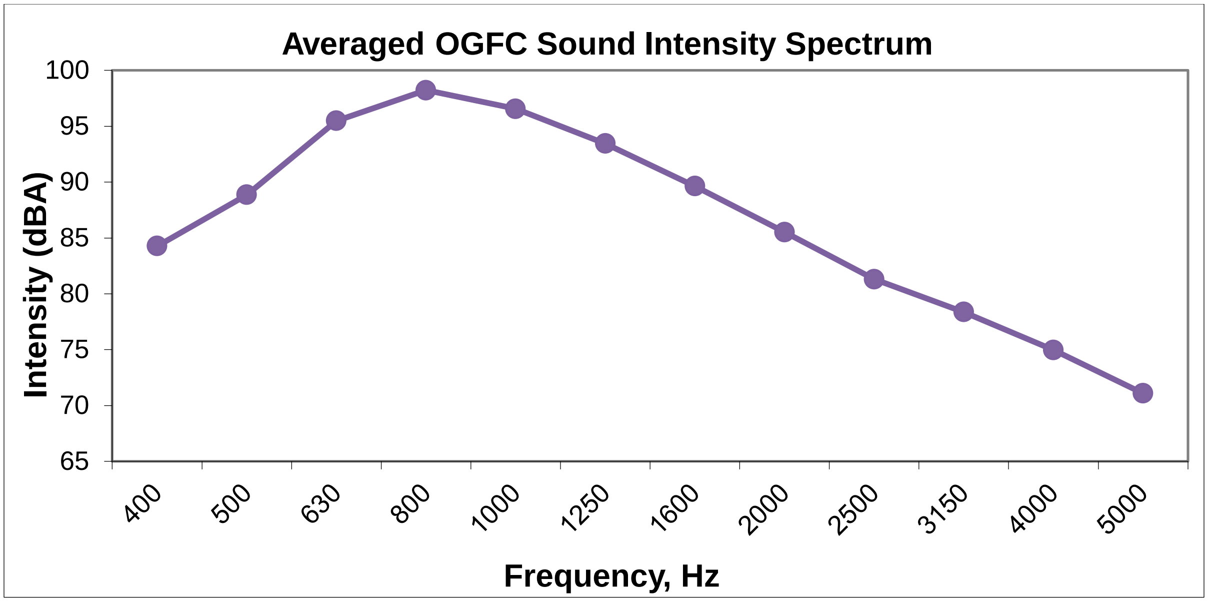


Figure 4.15 Sound Intensity Spectrum from 400 to 5,000 Hz Frequency

4.2.8 Ultra-Thin Bonded Wearing Course (UTBWC)

Use of an ultra-thin bonded wearing course (UTBWC) is reported on as a pavement preservation strategy for jointed plain concrete pavements. UTBWC is a special treatment surface course recently used in North Carolina. Construction of UTBWC is the application of a warm polymer modified emulsion membrane followed immediately with an ultra-thin wearing course. Hot mix asphalt composed of about 6% asphalt binder of PG 70-28. Depending on the 3/8 inch gap graded coarse aggregate in the mix, the binder content slightly varied from 6% binder content to meet the mix design. UTBWC can be used on both urban and rural sections. One of the benefits of the UTBWC is that the elevation change is small, typically 5/8 inch. Expenses associated with thick overlays, such as adjustments to signs, guardrails, bridge clearances, and shoulders are minimized (37). The effectiveness of the UTBWC in improving ride quality and extending pavement life is evaluated for five projects (37). Table 4.14 summarizes the sites tested for UTBWC. Figures 4.16 and 4.17 summarize the results for UTBWC. The average of sound intensity levels for UTBWC is 101.8 dBA. Appendix 9.5 provides the detailed site information, including accurate location, satellite map, GPS location, and sound intensity tire-pavement noise level.

Table 4.14 Summary of UTBWC Sites for OBSI

Test Date	County	Highway
June 23, 2011	Cumberland	I-95
June 23, 2011	Harnett	I-95

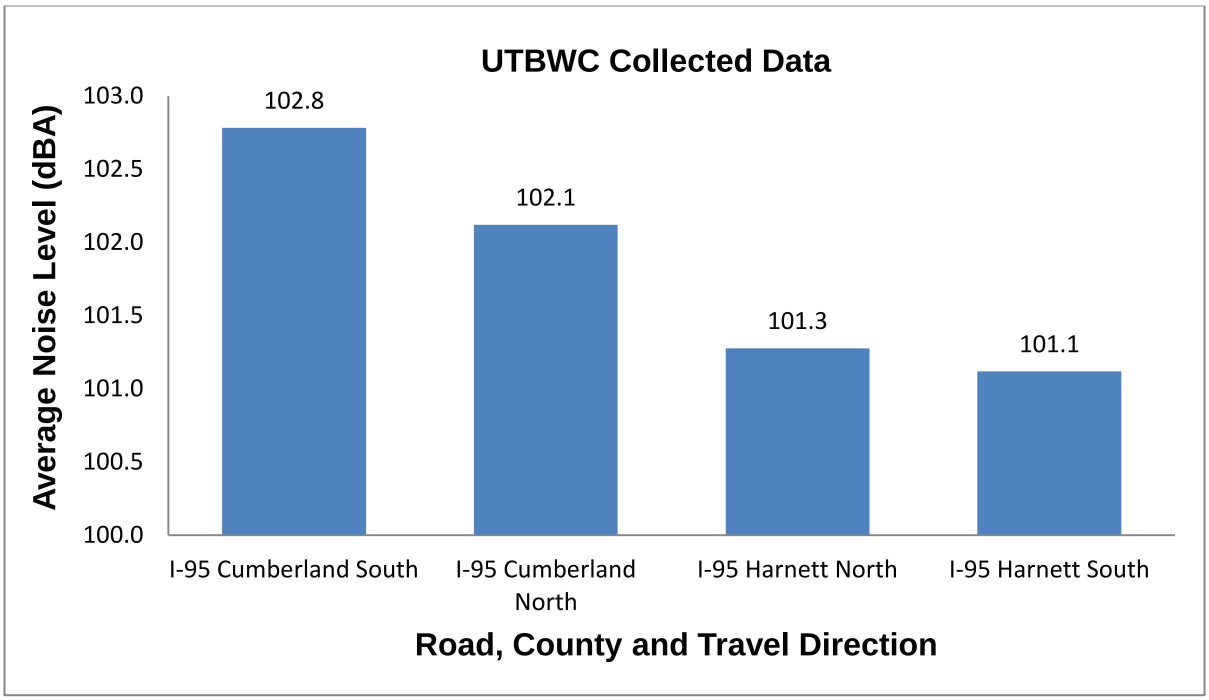


Figure 4.16 Average Sound Intensity Tire-Pavement Noise for Various UTBWC Sites

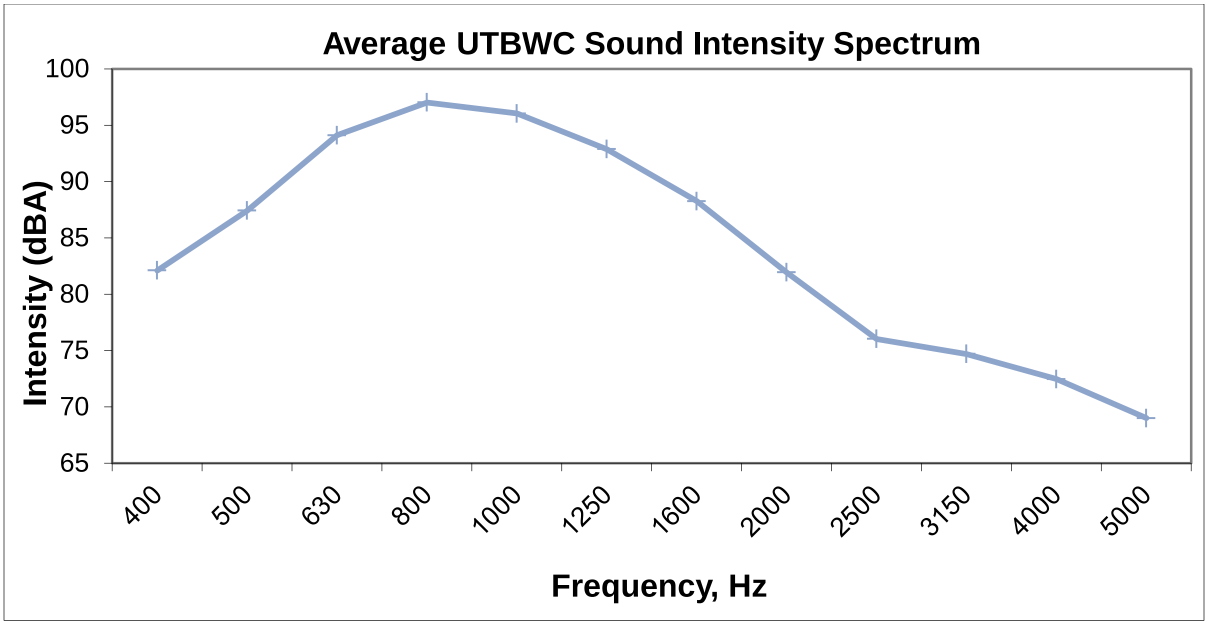


Figure 4.17 Sound Intensity Spectrum from 400 to 5,000 Hz Frequencies

4.2.9 Effect of Driving Speed on the Sound Intensity Tire-Pavement Noise Level

Two test sites were selected to verify the effect of driving speed on sound intensity levels. The test sites are summarized in Table 4.15. Table 4.16 shows the linear relationship for the two sites investigated. 'Y' stands for OBSI level, while 'X' stands for driving speed. The two results are almost perfectly matched in terms of sound intensity and driving speed. Figure 4.18 presents a view of the NC 11 Southbound site tested to verify the effect of driving speed on the sound intensity.

Table 4.15 The Sites for Various Driving Speed

Test Date	County	Highway	Driving Speeds (mph)
June 23, 2010	Pitt	NC 11 SB	35, 40, 45, 50, 55, 60
July 1, 2010	Nash	NC 43 NB	25, 30, 35, 40, 45, 50, 55, 60

Table 4.16 Linear Relationships between Sound Intensity and Driving Speed

Site	Linear Relationship between Driving Speed and OBSI Level
NC 11 Southbound Lane	Y= 0.3024 X+79.895, R^2 = 0.9940
NC 43 Northbound Lane	Y = 0.3324 X + 78.501, R^2 = 0.9913

Figure 4.18 A Site View of NC 11 Southbound

4.3 Concrete Pavement

Concrete has been used to build some of the long-lasting highway pavements, airports, roadways, and other pavements in the world. Many of these pavements are carrying significantly more traffic, including larger trucks carrying heavier loads than engineers originally intended. Across the US, there are concrete highways and roads that were designed to last 20 years, but have lasted 30, 40, or 50 years.

4.3.1 Concrete Surface Texture Treatment

Concrete pavements may receive various surface texture treatments which can affect the tire-pavement noise. The textures can include burlap drag, astro-turf, uniformly and random transverse tined, longitudinally tined, and both profile and whisper diamond grinding processes. More recently, longitudinal and transverse tining and diamond grinding are commonly used. Tining can be exposed aggregate, dimpled or imprinted texture, combination of longitudinal and transverse, sprinkled aggregate (e.g. aggregate broadcast onto the surface), and drag textures. Transverse tining has often been promoted due to its advantage for draining the roadway quicker, and for higher friction values. Figure 4.1 indicates random spaced transverse tining (courtesy by Mr. Larry Scofield of ACPA).

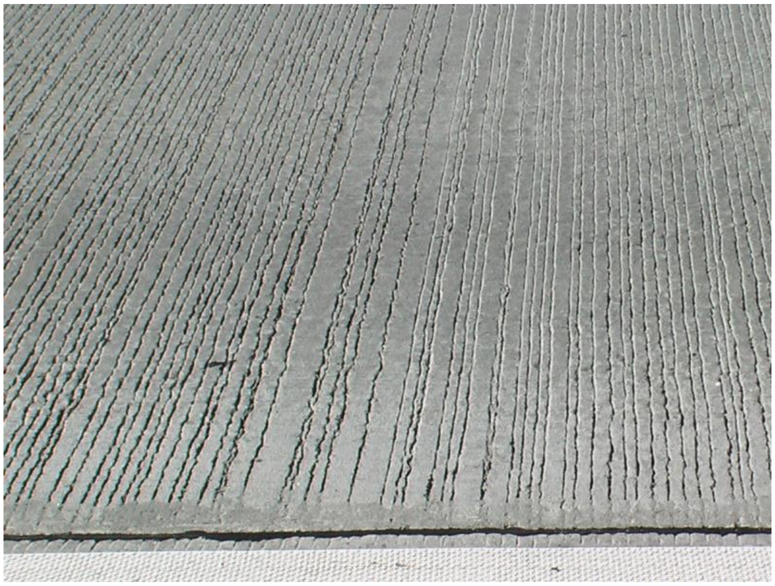


Figure 4.19 Random Spaced Transverse Tining

Diamond grinding was typically used for restoring profile or making concrete pavement smoother. A typical surface texture resulting from diamond grinding is shown in Figure 4.20 (courtesy by Mr. Larry Scofield of ACPA). It is reported that diamond grinding can produce the smoothest and quietest surfaces while also enhancing the friction characteristics. A typical diamond grinding pavement after trafficking might have a “ridge” height of 1 - 2 mm and is separated by 1/16 to 1/8 inch grooves.

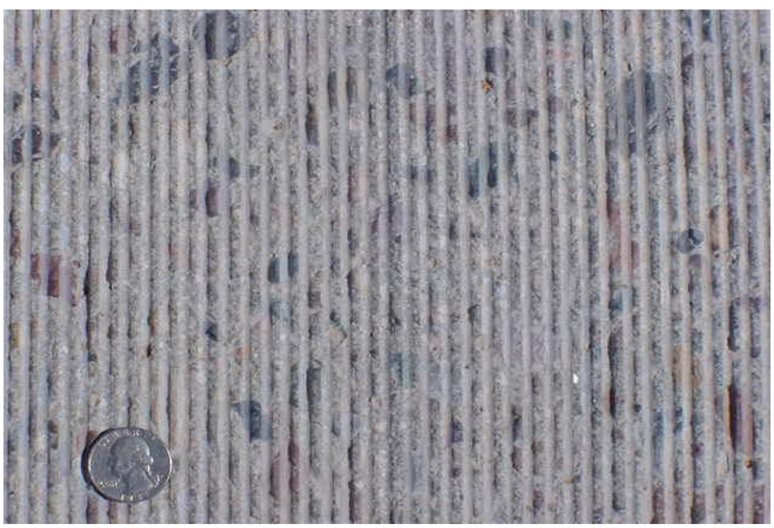


Figure 4.20 A typical Diamond Ground Surface

In North Carolina during the testing period, there was very few new concrete available to be measured. Several concrete pavement sections were tested on the recommendation of the NCDOT (Mr. Gregory Smith) and the collected data is presented in the next section.

4.3.2 Diamond Ground Concrete Pavement (DGCP)

Diamond Ground Concrete Pavement (DGCP) is a surface course used in North Carolina. Table 4.17 summarizes the sites tested for DGCP. Figures 4.21 and 4.2 summarize the results for DGCP. The average of sound intensity levels for DGCP is 102.8 dBA. I-77 and US 1 presented uniform diamond ground surfaces. However both I-73 and I-85 had non-uniform ground sections which increased measured noise levels. Appendix 9.5 provides the detailed site information, including accurate location, satellite map, GPS location, and sound intensity tire-pavement noise level.

Table 4.17 Summary of DGCP Sites for OBSI

Test Date	County	Highway
June 29, 2010	Wake	US 1 Longitudinal Diamond Ground
October 15, 2010	Greensboro	I-73 Longitudinal Diamond Ground
October 15, 2010	Greensboro	I-85 Longitudinal Diamond Ground
September 15 2010	Yadkin	I-77 Longitudinal Diamond Ground

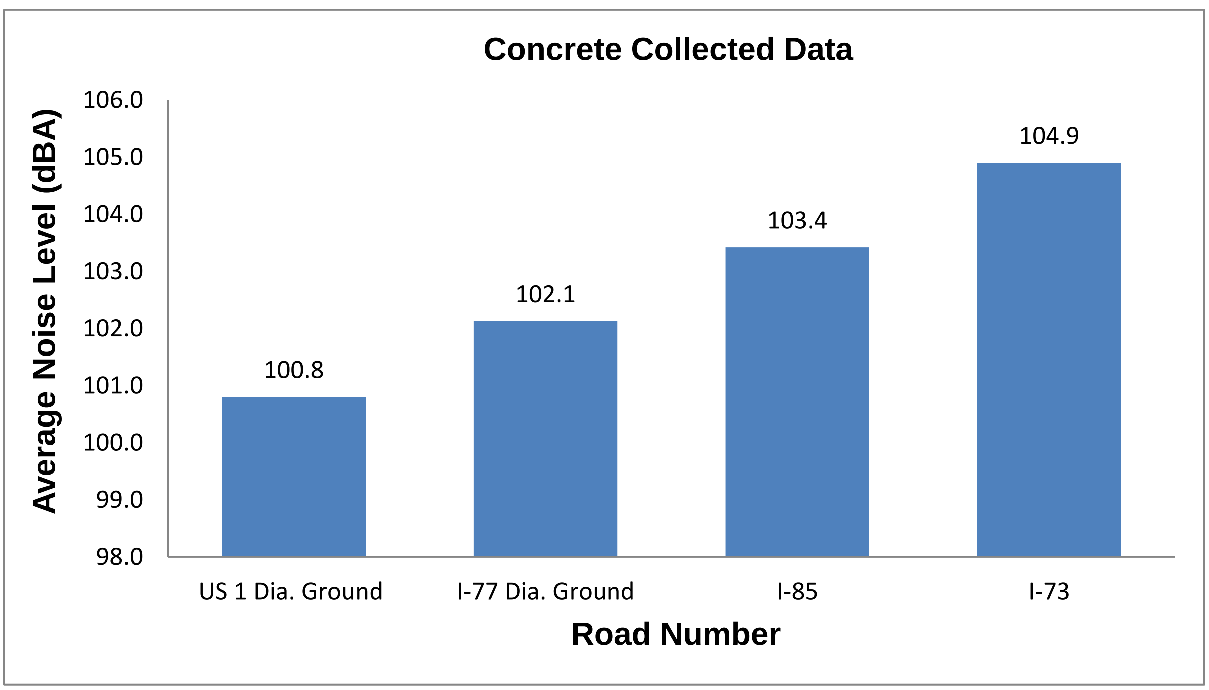


Figure 4.21 Average Sound Intensity Tire-Pavement Noise for Various Concrete Sites

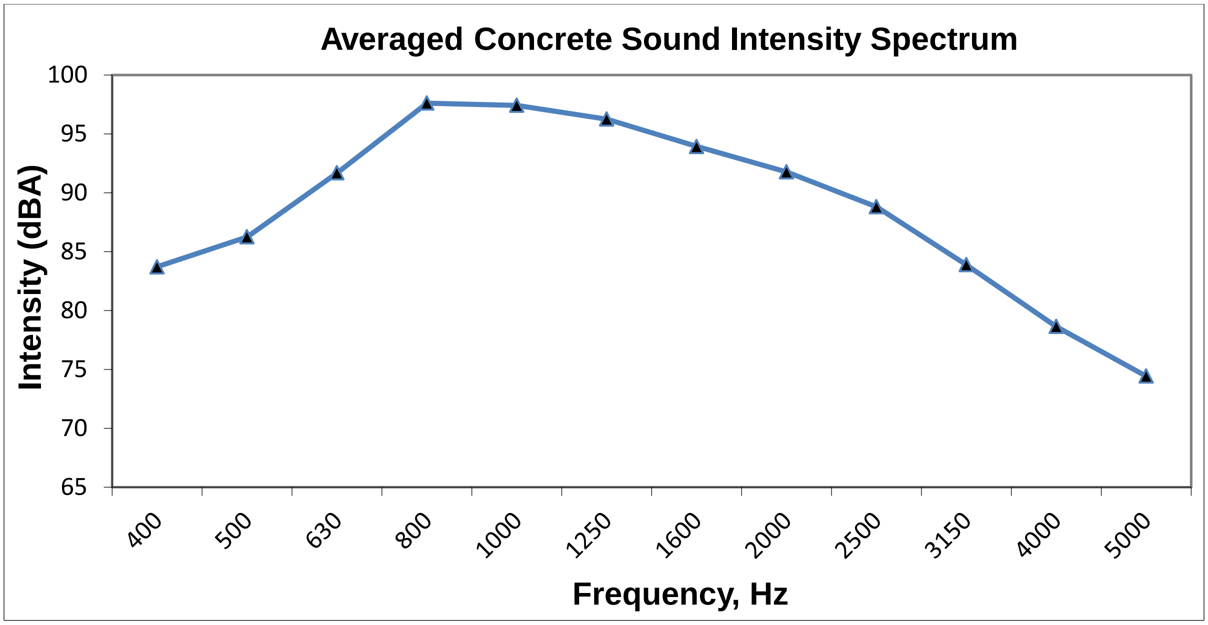


Figure 4.22 Concrete Sound Intensity Spectrum from 400 to 5,000 Hz Frequency

4.4 Findings

Pavement noise results from eight types of asphalt pavement and diamond ground concrete pavement are summarized in the following sections and figures. Figure 4.23 presents the summary of sound intensity levels for nine types of pavements. Figure 4.24 presents the average of sound intensity spectrum for the individual types of pavements. Figure 4.25 presents ranges of sound intensity levels for nine types of pavements. Figure 4.26 presents the sound intensity with two standard deviation spread.

4.4.1 Typical Dense Graded Asphalt Pavement

It was found that the six typical dense graded friction courses tested, i.e. S9.5A, S9.5B, S9.5C, S9.5D, SF9.5A, and S12.5D, had very close sound intensity tire-pavement noise levels. The lowest average number is 98.4 dBA for S9.5B, while the highest is 99.7 dBA for S12.5D. This indicates the difference of the sound intensity among the typical asphalt pavements in North Carolina is very low, which is 1.3 dBA based on the OBSI data obtained.

4.4.2 Special Asphalt Pavements

4.4.2.1 OGFC

It was found that the OGFC tested in the project had the highest measured noise level with an average sound intensity of 103.2 dBA. This number is slightly higher than the average of OGFC reported in some states. However, there can be various reasons. This is discussed in Chapter 5 - Conclusions.

4.4.2.2 UTBWC

The two highway sites (I-95) were two years old when tested. The average OBSI level is 101.8 dBA, from 101.2 to 102.5 dBA. This is in the higher levels of the OBSI levels of the pavements investigated in the project. However, this is an acceptable level for thin overlays. The reasons for the sound intensity values are discussed in Chapter 5 - Conclusions.

4.4.3 Concrete Pavement

The overall average OBSI level of the concrete is 102.8 dBA, from 100.8 to 104.9 dBA. This range is in the lower level as compared with other data from different states. The detailed texture should be further investigated from the construction plan to verify the reason.

4.4.4 The Effect of Driving Speed

Figure 4.27 presents the sound intensity levels for different driving speeds. Two linear equations which are almost perfectly fitted were found. This is further discussed in Chapter 5 – Conclusions.

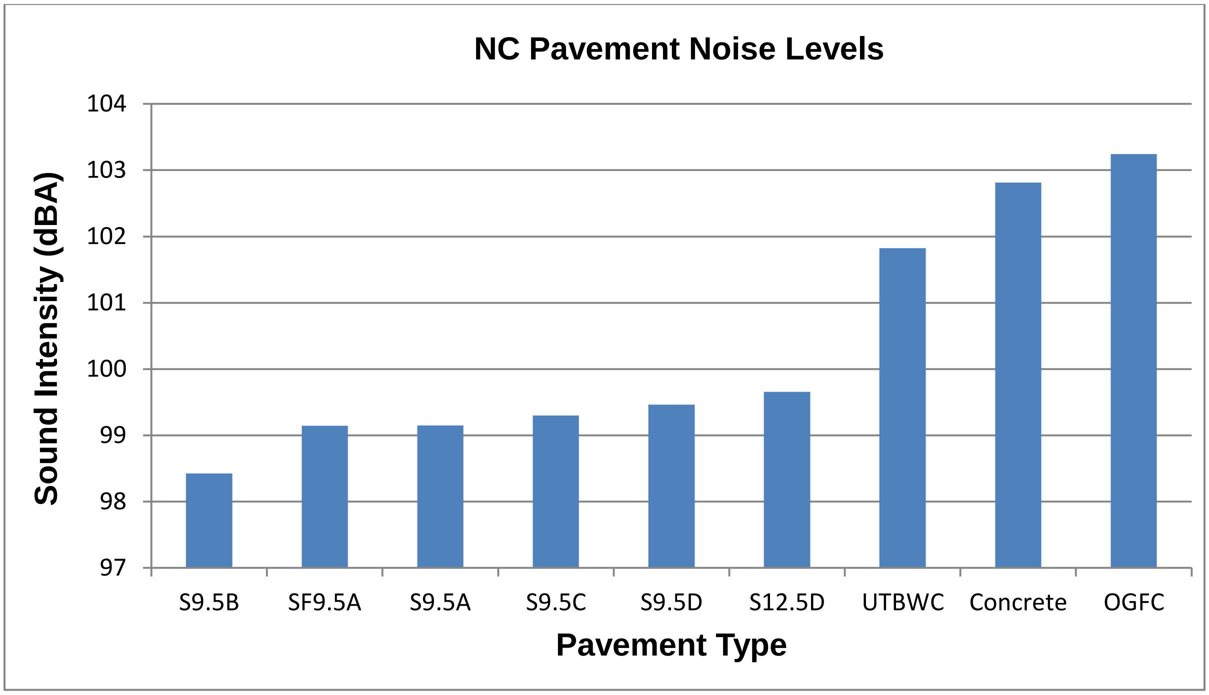


Figure 4.23 Sumamry of Sound Intensity Levels for Nine Types of Pavments

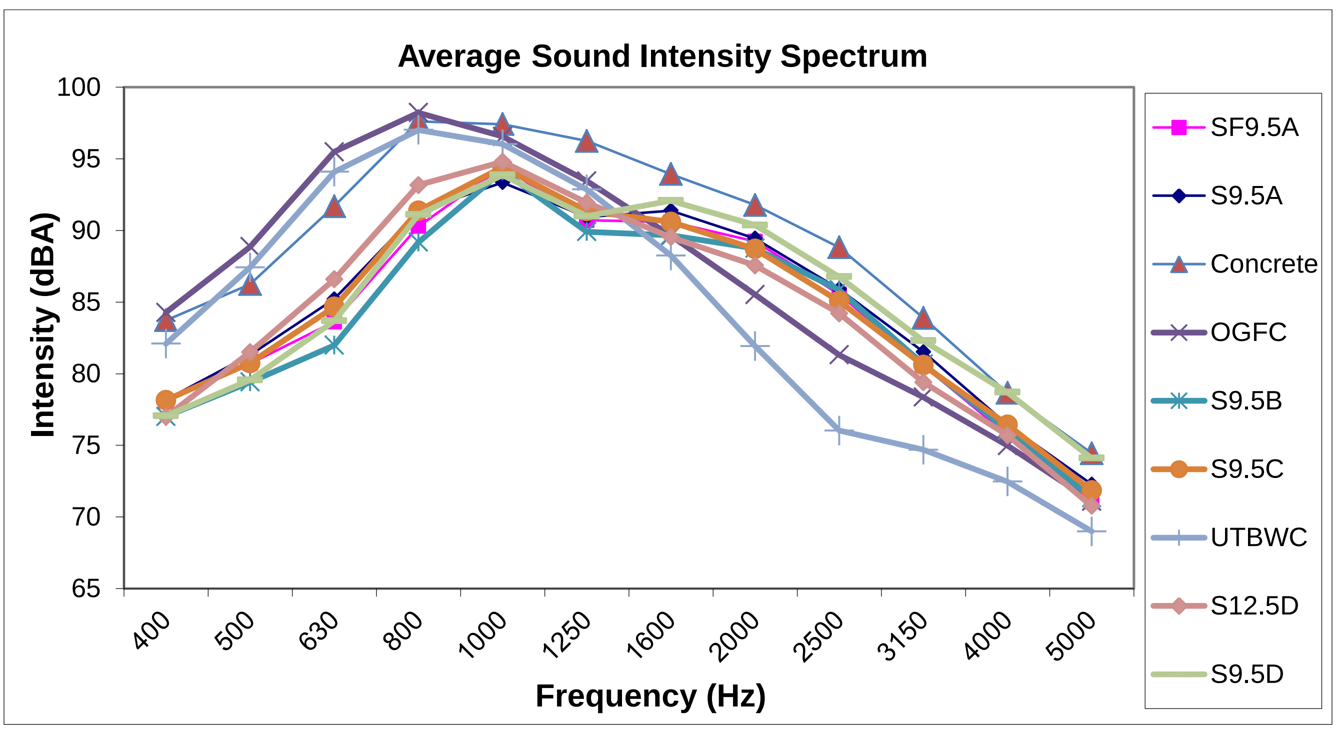
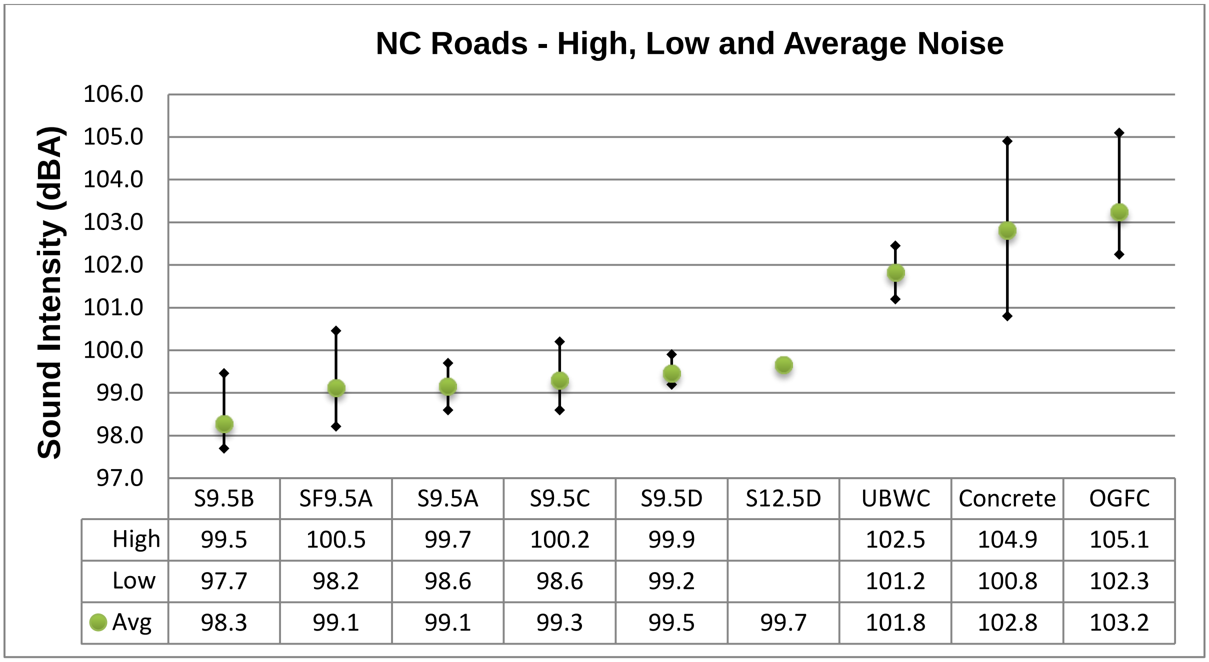


Figure 4.24 Average of Sound Intensity Spectrum for Nine Types of Pavements



	S9.5B	SF9.5A	S9.5A	S9.5C	S9.5D	S12.5D	UBWC	Concrete	OGFC
High	99.5	100.5	99.7	100.2	99.9		102.5	104.9	105.1
Low	97.7	98.2	98.6	98.6	99.2		101.2	100.8	102.3
Avg	98.3	99.1	99.1	99.3	99.5	99.7	101.8	102.8	103.2

Figure 4.25 Ranges of Sound Intensity Levels for Nine Types of Pavements

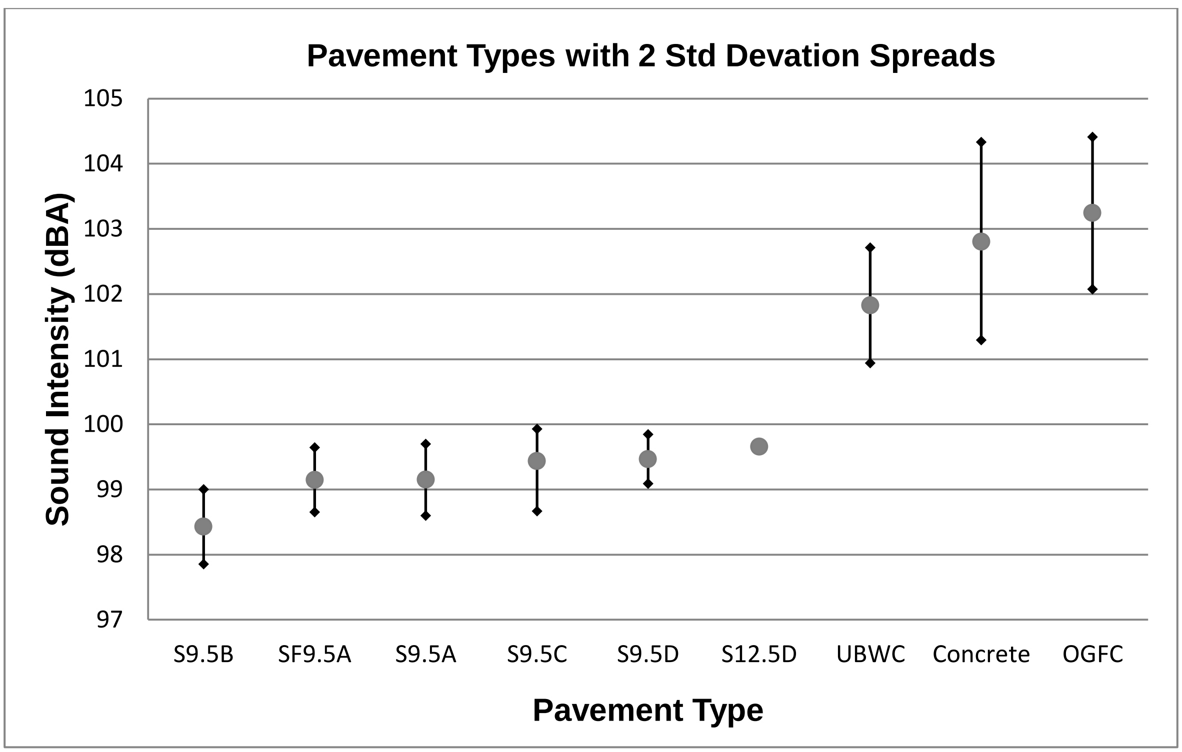


Figure 4.26 Sound Intensity with two Standard Deviation Spread

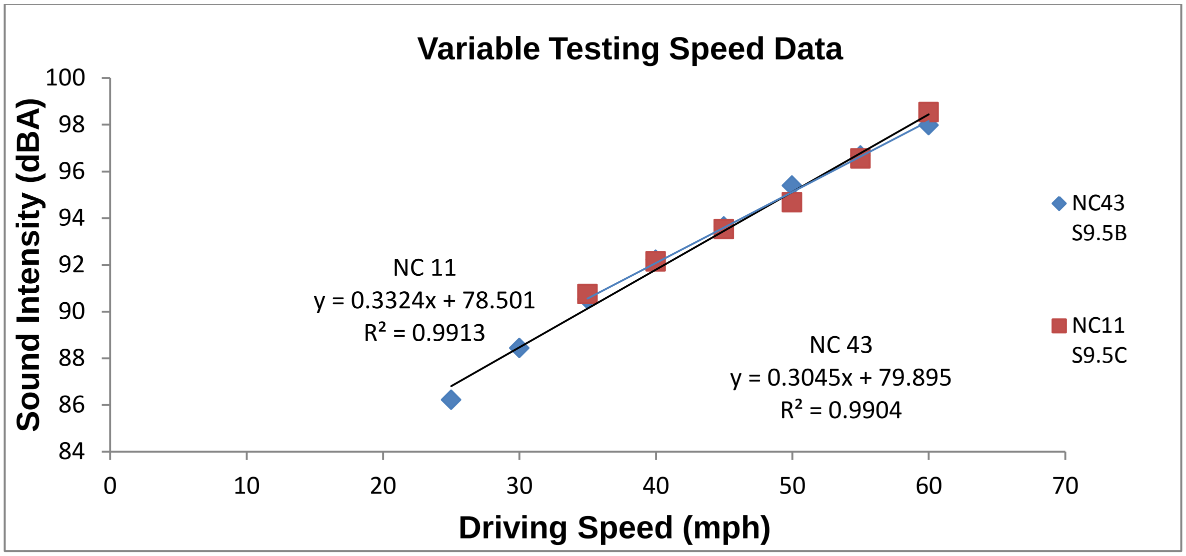


Figure 4.27 Sound Intensity Levels for Different Driving Speeds

5.0 CONCLUSIONS

This research investigated tire-pavement noise on various types of pavements across North Carolina by using an On-Board Sound Intensity (OBSI) method. Based on a thorough literature review, a measurement system using OBSI equipment was established at East Carolina University. The OBSI system will be an important tool to investigate tire-pavement noise and related influencing factors for years to come. Sixty-one highway pavements from 30 counties for nine types of pavements were investigated. The work of this project is a cornerstone for future determination of the most cost-effective, durable and technical sound pavement noise abatement means suitable for North Carolina. The data have been proved to be valid and can be used in the FHWA OBSI database or presented to the public. The results indicate that, at least in recent years, some ‘quieter pavements’ have been used on low volume roads in North Carolina.

5.1 OBSI System Established in North Carolina

The OBSI system established in this project has been proved to be valid by internal, external verifications and calibrations, and also by the 4^{th} OBSI rodeo. The OBSI system in NC meets the requirements for OBSI measurements and future needs of the NCDOT. The OBSI equipment in NC represents a unique and updated version of similar equipment in the nation and the world. The team has accumulated firsthand experience on the non-standard fixture fabrication, hardware and software installation and operation of the system in the process of OBSI data collection. The firsthand experience of the team is included in the “Procedures of Operating OBSI PULSE® system” in Appendix 9.2.

The assessment of tire-pavement noise levels at the source is necessary to adequately identify and develop quieter pavement types. The OBSI method allows researchers to quickly measure and compare pavement acoustics in great detail and has proven to be a reliable method for tire-pavement noise measurement throughout this project. For quieter (or louder) pavement identification and quieter pavement development purposes, a reliable standard measuring method should be identified and maintained so that the data can be compared nationally and internationally.

The OBSI method can be used for general OBSI data collection to enhance the tire-pavement noise database in NC and to increase the sample sizes of each type of pavement. The equipment is also a power tool to conduct research and investigate various influencing factors that affect tire-pavement noise, which include the effects of temperature, moisture, vehicle driving speed, weight of vehicle, and age of pavement. It can be used to map tire-pavement noise distributions in densely populated or noise sensitive areas for traffic noise management purpose. With this equipment, the NCDOT can perform tire-pavement noise investigations and research in a similar manner with other agencies and be able to share data with other agencies.

The data collected by the NC OBSI equipment has been validated and compares closely to the data collected by the participating members in the national OBSI rodeo.

5.2 Typical Asphalt Pavement

Six types of typical asphalt pavement surfaces have been investigated for tire-pavement noise levels. The pavements investigated were SF9.5A, S9.5A, S9.5B, S9.5C, S9.5D, and S12.5D. The six typical pavements cover from very low volume traffic to very high volume traffic. The results of OBSI data indicate that the tire-pavement noise levels of these six types of pavements are in a lower range, from 98.2 to 99.6 dBA, comparing with other dense graded surface friction courses in other states[19]. The difference between the lowest (S9.5B) and highest (S12.5D) is 1.4 dBA. The pavement selected for this project is approximately 1 to 3.5 years old (2.5 years difference). Research by others (33) for the OBSI values changes due to the age of the pavements indicate that for a three year difference, the OBSI value changes in the ranges of between -0.6 dBA to +2.0 dBA (positive sign means the OBSI values increase with longer life). In the research conducted by Colorado for 34 pavements, the maximum OBSI change in three years was 2.6 dBA (33). Therefore, for the eight asphalt pavements investigated in this project, the age difference, i.e. approximately 2.5 years can be one of the reasons that contribute to the OBSI difference (1.4 dBA) between the lowest and highest noise levels.

Broken down by types, the average OBSI value for surface course S9.5B was 98.2 dBA; the average values for SF9.5 A and S9.5 A are very close which was 99.1 dBA; S9.5 C and S9.6D are very close, which was 99.5 dBA; and S12.5D is slightly higher which was 99.6 dBA. The standard deviations of the data were low, which proved the validity of the data.

Comparing the data with OBSI data from other states, it can be concluded that the typical friction mixes in North Carolina are quieter than some other mixes in other states. For example, in Colorado, OBSI data were collected on 34 pavement sections for three years, i.e., 2006, 2007, and 2009 (both asphalt and concrete). All the data (approximately 100 OBSI measurements), was above 100.4 dBA in three years (33). In Washington State, sound intensity measurement for ½ inch HMA in September, October and December 2009 for 10 test sites indicated that one site is 98.2 dBA, and the rest (9) were from 100.3 to 104.6 dBA (38). It also can be concluded that the typical pavements, S9.5 series and S12.5 series are very consistent in terms of tire-pavement noise levels.

[19] In Arizona, SAM and ARFC have noise levels of 99.6 dBA and 101.4 dBA (36); in Colorado, for ten asphalt pavement sites, OBSI levels range from 101.4 to 104.3 dBA (33).

However, some quieter pavements were observed for some special pavements in other states. These quieter pavements include asphalt rubber friction course (ARFC) in California and Arizona, which were in the ranges of 96.6 to 97.8 dBA and dense grade asphalt friction course (DGAC) in California, which were in the range of 96.7 to 99.0 dBA (39). It can be concluded that there is room to improve the tire-pavement noise level of the pavements in NC. To further investigate the root causes, it is necessary to extract pavement cores from the pavements to conduct a mix design study, including aggregate shape, gradation, asphalt content (AC), and air voids (AV).

5.3 Special Asphalt Pavement

Two special asphalt pavements were investigated in this project, i.e., open grade friction course (OGFC) and ultrathin bonded wearing course (UTBWC).

5.3.1 Open Grade Friction Course (OGFC)[20]

Eleven sites were tested for OGFC. The average of the sound intensity value was 103.2 dBA (102.3 to 105.1 dBA). This result indicated that the OGFC tested in the project had 3.6 dBA differences (higher). This is somewhat different from the reports from other states (38). This may come from the following reasons, (I) the mix designs of OGFC can be very different, for instance, in Washington State, most of the OGFCs contain asphalt rubber and SBS modified asphalt binder (38); (ii) the age of the OGFC investigated in this project is approximately four years or older which may cause a couple of decibels loss; (iii) the detailed mix design, and other parameters of the OGFCs, especially aggregate characteristics is not clear and there is no comparison among the OGFCs at this stage. Therefore, more information is needed to identify the cause of the higher noise level of OGFC in the highways tested.

5.3.2 Ultrathin Bonded Wearing Course (UTBWC)

OBSI data was collected for UTBWC in Cumberland and Harnett Counties on Highway I-95. The pavement was two years old when tested. The average noise level was 101.8 dBA, from 101.2 to 102.5 dBA. This was on the higher side of the pavements investigated in the project. The reasons for this may come from (i) the conditions and type of old pavement overlaid was unknown; (ii) the gap graded, angular coarse particles (no fine aggregate) may cause higher noise level. There is not much literature regarding tire-pavement noise level for UTBWC. Further research on UTBWC mix designs is needed to improve the pavement noise level for UTBWC.

5.4 Concrete Pavement

OBSI data were collected on US 1 in Wake County, I-77 in Yadkin County, I-73 and I-85 near Greensboro. The overall average OBSI level is 102.8 dBA, from 100.8 to 104.9 dBA. Seven sites on I-73 were tested and the values ranged from 100.8 to 105.6 dBA; three sites

[20] OGFC is designated as open grade asphalt concrete (OGAC) in some literature.

were tested on I-85, the values ranged from 104.8 to 105.4 dBA. However, the overall average, 102.8 dBA, is a promising number compared to those of concrete pavement from some other states (39).

5.5 Relationships between Sound Intensity and Testing Speed

From the results indicated in Section 4.2.9, it can be seen that the linear relationships exist between sound intensity level and driving speed:

For NC 11 Southbound lane, the relationship between driving speed (X) and noise level (Y) is given by the following equation Eq. 1:

$$Y= 0.3024\,X+79.895,\ R^2 = 0.9940 \qquad \text{Eq. 1}$$

For NC 43 Northbound lane, the relationship between driving speed (X) and noise level (Y) is given by the following equation, Eq. 2:

$$Y = 0.3324\,X + 78.501,\ R^2 = 0.9913 \qquad \text{Eq. 2}$$

This finding is similar to the reports in other literature (15, 16, and 19). From the two equations in Section 4.2.9, the slopes of linear equations are 0.30 and 0.33 respectively, it indicated that if driving speed is reduced by 10 mph, the sound intensity can drop 3.0 to 3.3 dBA. This may be a factor to consider reducing traffic noise in populated urban areas.

6.0 RECOMMENDATIONS

6.1 General Recommendations

NCDOT should consider utilizing the NC OBSI system as a powerful tool to investigate, monitor and manage traffic noise in the future. The equipment has been well maintained to date by the team at ECU. This equipment represents one of the newest OBSI systems in the country and the world. An intensive use of the equipment at its 'current value' in North Carolina within the near future is imperative to enhance the OBSI database. This equipment will not only be able to serve North Carolina, but may also allow other states to collect unique OBSI data.

Setting up a short term utilization plan, for the next three years, for instance, is necessary for the NCDOT to fully utilize the data collection potential of the equipment. This may include:

- Routine OBSI data collection to enhance the current OBSI database;
- For future research, as indicated in next section;
- Organize workshops for demonstrations to various NCDOT divisions, local agencies, and the public who are concerned about traffic noise;
- Conduct OBSI testing in other states or countries for a particular quiet pavement, followed by detailed mix design and field material sampling, and investigation. This will help quieter pavement development from material and mix design aspects;
- Utilize the opportunity in July 2012 at the TRB ADC 40 Annual Meeting in Asheville, NC to make the participants and guests aware of the OBSI equipment in NC and further serve the Pooled Fund Study TPF-5 (135) group.

6.2 Future Research

Data analysis should be strengthened in the relationships between OBSI data and pavement properties. Identified pavement types, locations, ages, mix designs, materials characteristics and construction methods should be included in the tire-pavement noise database. Combination of laboratory-based studies and OBSI data can play an important role in quiet pavement development. Continued research is crucial considering the current OBSI equipment; both hardware and software are in excellent condition.

6.2.1 Tire-Pavement Noise Mapping for Urban Road Network

It is possible to conduct noise level mapping for major roads in noise-sensitive areas of NC. A proposed team can collect OBSI data in the selected highways for the urban communities and noise sensitive areas that are experiencing growing levels of annoyance from traffic. This Noise-Mapping project can include a visualization of changes in noise levels along a particular road for ease in understanding pavement noise related problems. The series of maps will allow local government officials to better manage traffic noise and plan future urban development. With multiple years of data collection, the project can involve developing an optimization model for determining the most efficient program for implementing low volume pavements to ensure the maximum reduction of impact for residents within a city. This could involve the application of a number of models, including, noise prediction, network optimization and cost benefit analysis.

By using this well established OBSI system, NCDOT can determine pavements noise levels for roads in the major cities of NC. The tire-pavement map can be updated every 2 to 3 years. Transportation environment managers, planners and city officials can use this information for future planning, selecting highway geometric design, highway pavement types, and answering public concerns.

This research will be highly beneficial for NCDOT to: (i) obtain pavement acoustical data from likely complaint areas, (ii) mitigate noise in densely populated areas. (iii) enrich the OBSI pavement noise database. This research will provide useful information to further develop noise-compatible pavement types for use in urban areas.

6.2.2 Further Investigation of OGFC and UTBWC Tire-Pavement Noise

OGFC with gap graded coarse aggregate is used in a few interstate highways in NC. UTBWC is a special surface treatment for both asphalt concrete pavements which has been used in NC in recent years. The OBSI data collected in this study for seven OGFC sites is not quieter than the typical dense graded asphalt surface course, i.e., S9.5 and S12.5 series as identified in this study. The OBSI noise data for UTBWC is higher than the conventional surface courses. The reasons for the higher noise levels can be due to different reasons such as: material selection, mix design parameters, asphalt rubber, and rubber fiber addition in other states. It is critical for NCDOT to improve the sound intensity level for OGFC in NC. This study will include the initial mix design and materials review, examination, field sample recovery and laboratory testing, and may include OBSI field testing. It is expected that, from this study, the noise level of OGFC and UTBWC can be improved.

6.2.3 Effect of Surface Texture of Concrete Pavement on Pavement Noise

In this project it is not possible to conclude the effect of texture types on concrete tire-pavements noise due to the small sample size of the concrete textures tested. To use and produce quieter concrete pavements, it is necessary to investigate the pavement noise levels of all concrete textures used in NC. These textures may include burlap drag textures; broom textures, diamond grooving, longitudinal and transverse tining, Astro-Turf texture, random spaced transverse tining, exposed aggregate and diamond grinding (whisper grinding). It should include pervious concrete. The shapes and dimensions of construction/expansion joints should be included in this study. Noise study results combined with considerations of skid resistance will provide useful information for the NCDOT and other agencies in selecting appropriate concrete surface textures.

6.2.4 Study on the Effect of the Vehicle Weight on Noise level

Increasing test vehicle weight may cause more noise. However, the relationships between the weight of vehicle and pavement noise level OBSI are not reported by other researchers. This study will be highly beneficial for the NCDOT to: (i) obtain pavement acoustical data due to heavy vehicles; (ii) to compare the data with the light passenger car data. This research will provide useful information for future development of noise-compatible pavement types for use in urban areas and high volume roads.

6.2.5 Tire-Pavements Deterioration Rate for Different Types of Pavements

It will be beneficial to conduct a deterioration rate study for certain pavements - a proposed team can collect tire-pavement noise data from pavements with a service life of 1 to 20 years for asphalt pavement and 1 to 30 years for concrete pavements. The relationships will be established and the deterioration rates will be given for the selected pavements. The results will be fundamental and important in the future to accurately define a 'quiet pavement'.

In this project, pavements selected for OBSI data are generally one to three years old. It is known that the noise level will increase along with the increase of pavement life; however the rate of noise increase is varied. Some pavements may have zero loss within 3 years in terms of sound intensity, some pavements may have 2 to 3 dBA loss within the same time. The deterioration rate is not clear for long term period. When selecting or defining a 'quieter pavement', deterioration rate' or 'reduction rate' (the sound intensity change trend) is another factor to be considered, along with the OBSI data obtained when the pavement is newly paved. In this study, tire-pavement noise data will be collected from pavements with service life of 1 to 20 years for asphalt pavement and 1 to 30 years for concrete pavements. The results will be fundamental and important for future accurately defining a 'quiet pavement'. The changes of sound intensity of a particular pavement reflect the tire-pavement noise 'deterioration rate'. This 'deterioration rate' can be different from one pavement to another. 'Deterioration rate' can be used as an evaluation parameter along with the OBSI data collected when the pavement is new. The two parameters should be used to comprehensively evaluate and define 'quieter pavement'.

6.2.6 Comparison Study of Sound Intensity Pavement Noise Level

It is necessary to investigate the effect of construction related factors on tire-pavement noise. This study will focus on several parameters which may affect pavement noise from construction. The parameters include the pavement smoothness (IRI) at each stage and micro texture, material/surface segregation. It also compares the deterioration rate of IRI and OBSI. The NCDOT's various units can use the results in project specifications as quieter pavement considerations. It will be highly beneficial for the NCDOT to obtain pavement acoustical data with different surface characteristics parameters. The research will provide useful information to further improve construction and development of noise-compatible pavement types.

7.0 IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN

During the two year research period of time, the team leader and PI, Dr. George Wang:

- Visited the California Department of Transportation (Caltrans) Environment Department in Sarcomata, CA, and interacted with Mr. Bruce Rymer, Senior Manager and Analyst in the Division of Environmental Analysis, (in June 2009);
- Visited Illingworth & Rodkin., Inc., in South Petaluma, California, and interacted with Dr. Paul Donavan, technical expert of FHWA Pooled Fund Study, TPF-5 (135), (in June 2009);
- Attended 2009 ADC 40 meeting in Dayton, OH, and met with FHWA Pooled Fund Study TPF-5 (135) participants (in July 2009);
- Attended Inter-Noise 2009 in Ottawa, Canada, and interacted with Dr. Ulf Sandberg of Swedish National Road and Transport Research Institute, VTI (August 2009);
- Attended TRB 2010 Winter meeting, ADC 40 meeting in Washington, D.C. (in January 2010);
- Attended Asia Pacific Transportation Development Conference in Tainan, Taiwan, and presented a tire-pavement noise literature review paper (in May 2010);
- Attended 2010 ADC 40 meeting in Denver, CO (July 2011);
- Attended 2011 TRB meeting in Washington, D.C. (January 2011);
- On March 30th and April 8th, 2011, attended the Webinar on Concrete Pavement Surface Characteristics and Noise Measurement Seminar sponsored by FHWA Project TPF-5 (135) (March – April 2011).
- Attended TRB ADC 40 meeting in Portland, OR, and submitted a paper for including in the Proceedings and presentation (in July 2011);
- Joined TRB ADC 40 Committee as a 'friend' member.

7.1 Research Products

The research project has produced research products in four major areas: (i) development of OBSI system in North Carolina; (ii) development of the detailed operation procedures and preparation of the detailed instruction manual for OBSI; (iii) the first OBSI database was established in NC, and therefore the baseline and database of tire-pavement noise in NC; (iv) a thorough traffic noise literature review and compilation of the abstracts. The research products include:

- A well maintained OBSI system, one of 2-3 most updated version of the similar system among 6 other agencies;
- All auxiliary equipment for OBSI operation;
- A literature review and compilation report;
- NC OBSI database in a format compatible with the pooled fund study and FHWA;
- OBSI operation instruction manual;

- Three papers submitted to peer-reviewed journals or conferences:

  G. Wang, G. Smith, Y. Wang, (2010), “Review of tire-pavement noise measurement and quieter pavement development”, *The 8th Asia-Pacific Transportation Development Conference,* Tainan, Taiwan, May 27-30.

  G. Wang, G. Smith, R. Shores, J. Botts, (2011) “Preliminary tire-pavement noise study and measurement in North Carolina”, *NOISE-CON 2011 and TRB ADC 40 Conference*, Portland, Oregon, July 25-27.

  G. Wang, G. Smith, R. Shores, (2011), “Review of tire-pavement noise measurement and quieter pavement development”, *Journal of Transportation Research Part D: Transport and Environment,* to be submitted.

7.2 Research Product Users

The following groups within the NCDOT can apply the research products to inform and improve their decisions and policies:

- Human Environment Unit
- Pavement Management Unit
- Materials and Tests Unit
- Construction Unit
- Transportation Planning Branch, and
- Strategic Planning Office

The FHWA Pooled Fund Study, TPF-5 (135), can use the OBSI data as part of the national tire-pavement noise database in the latest version of Traffic Noise Model (TNM) in the efforts of development of quieter pavement in the nation.

In addition, the research products can be useful to other departments of transportation, the FHWA, and consultants interested in the areas of highway materials, pavements, and traffic noise management. The research products can be interesting to international researchers and government agencies.

The authors plan to send the OBSI PULSE® data, upon approval by the Research Project Manager and Steering Committee Chairman, to the Pooled Fund Study, TPF-5 (135), to be added into the OBSI database.

Local officials, planners, and designers can also use the research in public hearings. The data collected can be used to present information about quieter pavements in general in the country and understand the major traffic noise contributor, tire-pavement noise levels.

7.3 Research Products Applications

The NCDOT can use the well-established, calibrated and validated OBSI system as a powerful tool to investigate, monitor and manage traffic noise in the future. The equipment has been well maintained by the team at ECU. This equipment is one of most updated versions available with the same configuration in the country, and probably in the world. An intensive use of the 'current value' of the system in the near future in North Carolina to enhance the OBSI database is imperative. This equipment will not only be able to serve North Carolina, but may also be utilized in other states. The utilization may include: (i) routine OBSI data collection to enhance the current OBSI database; (ii) for future research applications as previously mentioned; (iii) organize workshops, make demonstrations to NCDOT Divisions, local agencies, and the public who are concerned traffic noise; (iv) for quieter pavement development, as a comparison study; conduct OBSI testing in other states, or countries for a particular quieter pavement(s), followed by detailed mix design and field material sampling, ultimately to improve sound intensity levels of the pavements in NC; (v) utilize the opportunity in July 2012 of the TRB ADC 40 Annual Meeting in Asheville, NC to make the participants and guests be aware of the OBSI equipment in NC, and further better serve the Pooled Fund Study TPF-5 (135) groups.

Data from this project (digital data are not included in this report, but available in a digital PULSE® or excel file) are in a presentable format such as bar graphs and tables. The data represents the relationship between tire-pavement noise and various pavement surfaces, types, speed, and frequencies. The team is confident that the results from every site are accurate and can be included in a national database for purposes of comparison and quieter pavement development. The data will be valuable for the NCDOT/FHWA for future research on development of quieter pavements.

The NCDOT can use the information to identify the quieter pavements in NC and determine the best pavement that is suitable for use near noise-sensitive areas along highways, which is an immediate benefit to the public in terms of tire-pavement noise level, durability and safety.

Ultimately, it is hoped that the collected information will be used to develop pavements that are acceptable to the FHWA as viable traffic noise abatement measures in TNM in lieu of expensive noise barriers. The NCDOT can use the data and all technical information of the research study for publication, presentation, and training purposes.

A draft training manual (OBSI Operation Procedure) has been prepared for possible training with the NCDOT. The NCDOT can use the procedure, with the OBSI equipment for organizing workshops, making demonstrations and for public concern of traffic noise, and training for NCDOT Divisions and local agencies.

Clearly, the data collected has led up to the following two results in identifying quieter pavement in North Carolina: the ‘quietest’ pavement in North Carolina; and the rankings of noise level of the pavements in North Carolina to allow the NCDOT to improve the noise levels of the pavements.

The significance of this study also includes providing the NCDOT with tire-pavement acoustical noise data for comparison with similar data from other states, and for inclusion in a nationwide quieter pavement database for future comprehensive research. This study involves development of noise-compatible pavement types for use in urban areas and that may be used as a cost-effective means of traffic noise abatement. The NCDOT can further use the information to determine the best suitable pavement for use near noise-sensitive areas along highways as an immediate benefit to the public in terms of tire-pavement noise levels, durability and safety. Ultimately, it is the NCDOT’s desire to develop the collected data and analytical results to develop future “quieter” pavements that are acceptable to the FHWA as viable traffic noise abatement measures in lieu of expensive noise barriers to reduce mitigation costs, and for use in future training and informational endeavors. The NCDOT will use the data and all technical information of the research study for publication, presentation, and training purposes.

8.0 CITED REFERENCES

1. World Health Organization (WHO), "Occupational and Community Noise", WHO Fact Sheet No. 258. Geneva, 2001.
2. S. Stansfeld, M. Haines and B. Brown, "Noise and Health in the Urban Environment", Review of Environmental Health, 15(1-2), 43-82, 2000.
3. Arizona Milepost, "Sound Barriers and Noise Control", Arizona Milepost, Spring 2003.
4. FHWA, "Highway Traffic Noise in the United States - Problem and Response", US Department of Transportation, Federal Highway Administration, FHWA-HEP-06-020, 2006.
5. Caltrans, "Traffic Noise Analysis Protocol", Division of Environmental Analysis, Caltrans, 2006.
6. S. Rawool and R. Stubstad, "Effect of Diamond Grinding on Noise Characteristics of Concrete Pavements in California", Available on http://pdfcast.org/cache/effect-of-diamond-grinding-on-noise-characteristics-of-concrete-pavements-in-california (accessed on March 12, 2010).
7. W. Jones, "Highway Noise Control with HMA", Asphalt, Fall Issue, 2002.
8. S. Punnamee and L. Dai, "Road and Tire Noise Emission Assessment with Closed Proximity Method on an Asphalt Rubber Concrete Pavement", Transportation Association of Canada Fall Meeting, Saskatoon, Saskatchewan, 2007.
9. D. Holzman, "EU Ramps Up Road Improvements", Environmental Health Perspectives, 112(11), 614, 2004.
10. P. Calamia, V. Busch, J. Ilene, T. Turen and M. McNerney, "On the Use of Pavement Surfaces to Attenuate Traffic Noise", Journal of Acoustical Society of America, 101(5), 3076, 1997.
11. U. Sandberg, "Road Traffic Noise - the Influence of the Road Surface and its Characterization", Applied Acoustics, 21(2), 97-118, 1987.
12. U. Sandburg and J. Ejsmont, "Tyre-Road Noise Reference Book", Informex, Harg, Sweden, 2002.
13. ISO 11819-II, "Acoustics – Measurement of the Influence of Road Surfaces on Traffic Noise – Part II: The Close Proximity Method", International Organization for Standardization, Geneva, Switzerland, 2000.
14. D. Cho and S. Mun, "Study to Analyze the Effect of Vehicles and Pavement Surface Types on Noise", Applied Acoustics 69, 833-843, 2008.
15. T. Bennert, D. Hanson, A. Mahe and N. Vitillo, "Influence of Pavement Surface Type on Tire-Pavement Generated Noise", Journal of Testing and Evaluation; March 2005, 33 (2), 1-7, 2005.
16. P. Donavan and D. Lodico, "Measuring Tire-Pavement Noise at the Source", NCHRP Report 630, 2009.

17. T. Wulf, T. Dare and R. Bernhard, “The Effect of Grinding and Grooving on the Noise Generation of Portland Cement Concrete Pavement”, Proceedings of Acoustics 08, Paris, 2008.
18. R. Bernhard and R. Wayson, “An Introduction to Tire-Pavement Noise”, Purdue University, SQDH 2005-1, 2005.
19. S. Mun, D. Cho, C. Dae and C. Muk, “Influence of Pavement Surface Noise: The Korea Highway Corporation Test Road”, Canadian Journal of Civil Engineering, 34, 809-816, 2007.
20. H. Bendsten, E. Kohler and Q. Lu, “Acoustic Aging of Asphalt Pavements - A California Danish Comparison”, Road Directate, Danish Road Institute, Report 171, 2009.
21. Ongel and J. Harvey, “Investigation of Noise, Durability, Permeability, and Friction Performance Trends For Asphalt Pavement Surface Types: First and Second Year Results”, Caltrans Report: USPRC-SR 2008-01, 2008.
22. L. Khazanovich and B. Izevbekhai, “Implication of Time-Dependent Texture-Degradation on Pavement On-Board Sound Intensity Patterns In MNROAD Test Cells”, Proceedings of the International Noise Conference, Dearborn, Michigan, July 2008.
23. L. Anfosso and Y. Pichaud, “Temperature Effect on Tire-Road Noise”, Section Acoustique Routie`re et Urbaine, LCPC Centre de Nantes, BP 4129, 44341 Bouguenais cedex, France, 2006.
24. J. Chalupnik and D. Anderson, “Roadside Tire Noise”, Washington State Department of Transportation, WA-RD 329.1, 1994.
25. M. McNerney, B. Landsberger, T. Turen and A. Pandelides, “Comparative Field Measurements of Tire-Pavement Noise of Selected Texas Pavements”, the University of Texas at Austin, Center for Transportation Research, Federal Highway Administration, RR-2957-2, 2000.
26. G. Anderson, C. Lee, G. Fleming and C. Menge, “FHWA Traffic Noise Model User’s Guide”, FHWA Final Report FHWA-PD-96-009, Washington, D.C., 1998.
27. T. Inoue and T. Ihara, “Study of the Effect of Surface Texture of Porous Asphalt on Tire-Pavement Noise”, SURF 2004, Toronto, 2004.
28. L. Scofield, “Evaluation of Acoustic Longevity of Diamond Ground Surfaces”, Proceedings of TRB 2010 Annual Meeting, January 10-14, 2010, Washington, D.C., 2010.
29. Washington State Department of Transportation, “Evaluation of Long-Term Pavement Performance and Noise Characteristics of Open Grade Friction Courses”, WDOT Experimental Feature Report Contract 7134, I-5, 2008.
30. B. Rymer, P. Donavan and E. Kohler, “Tire-Pavement Noise Levels Related to Roadway Friction Improvement”, Proceedings of TRB 2010 Annual Meeting, January 10-14, 2010, Washington, D.C., 2010.

31. M. Ahammed and S. Tighe, "Sound Absorption Characteristics of Typical Pavements: an Ontario Study", Proceedings of TRB 2010 Annual Meeting, January 10-14, 2010, Washington, D.C., 2010.
32. Q. Lu, S. Luo and J. Harvey, "Compaction of Noise-Reducing Asphalt Mixture in the Laboratory", Proceedings of TRB 2010 Annual Meeting, January 10-14, 2010, Washington, D.C., 2010.
33. R. Rasmussen, "Tire-Pavement and Environmental Traffic Noise Research Study", Colorado Department of Transportation, DTD Applied Research and Innovation Branch, January 2011.
34. P. Donavan, "Comparative OBSI Testing in North Carolina: the North Carolina Rodeo", Illingworth & Rodkin, Inc., March 2011.
35. P. Donavan, "Comparison of OBSI Measurements for Four Research Teams: the Mesa Rodeo", Prepared for California Department of Transportation, Sacramento, California, November 2008.
36. H. Smith, "Performance Characteristics of Open-Graded Friction Courses". In NCHRP Synthesis of Highway Practice 180, TRB, National Research Council, Washington, D.C., 1992.
37. J. Corley-Lay, J. Mastin *et. al*., "Ultrathin Bonded Wearing Course as Pavement Preservation Treatment for Jointed Concrete Pavements", Serial: Transportation Research Record: Journal of the Transportation Research Board, Issue Number: 2005, Publisher: Transportation Research Board, ISSN: 0361-1981.
38. M. Russell, J. Uhlmeyer, T. Sexton *et. al.*, "Evaluation of Long-Term Pavement Performance and Noise Characteristics of OGFC" – Project 3, June 2010.
39. B. Rymer, "Caltrans Division of Environmental Analysis - Quieter Pavement Summary Sheet", 2007

9.0 APPENDICES

9.1 Compilation of Abstracts Related To Traffic Noise

<u>Anderson, S., Lee, S., Fleming, G. and Menge, W. (1998): "FHWA Traffic Noise Model, Version 1.0, Users Guide"</u>

This User's Guide is for the Federal Highway Administration's Traffic Noise Model (FHWA TNM), Version 1.0 – the FHWA's computer program for highway traffic noise prediction and analysis. Two companion reports, a Technical Manual and a data report, respectively, describe the acoustics and the vehicle noise- emissions data base within TNM. The User's Guide first lists TNM's hardware/ software requirements, instructs how to install the program and an optional digitizer, and discusses TNM's file structure. Next it provides definitions of commonly used terminology. Finally, it details each TNM menu item, including overviews of all TNM procedures: setup, input, calculate, barrier analysis, parallel barriers, and contours. Also included are the following appendices: FWHA policy, details of all input types, input- error messages, comparison of TNM with STAMINA 2.0/ OPTIMA, certified output for the official TNM test case, and REMEL Database.

<u>Anderson, W., Pierce, M., Uhlmeyer, S. and Weston, J. (2008): "Evaluation of Long-Term Pavement Performance and Noise, Characteristics of Open-Graded Friction Courses"</u>

This experimental project is being conducted as a part of WSDOT's effort to produce pavements that reduce the noise generated at the tire-pavement interface. Experimental sections of open-graded friction courses (OGFC) were built using asphalt rubber (AR) and styrene-butadiene-styrene (SBS) polymer modified asphalt binders. A section of conventional Class ½ inch hot mix asphalt (HMA) serves as the control section for the two experimental sections. Sound intensity measurements were conducted using the On Board Sound Intensity (OBSI) methods immediately after construction and monthly, weather permitting, for a year following construction. OBSI readings immediately after construction indicated that the OGFC-AR and OGFC-SBS sections were 2.8 to 3.8 decibels, respectively, quieter than the Class ½ inch HMA control section. Data from one year later showed that the AR and SBS modified sections were 1.5 to 3.3 decibels quieter, respectively, that the control section. Sound intensity reading taken between wheel paths are at levels similar to the initial readings after the sections were constructed indicating that studded tire wear is having a negative effect on the sound absorbing qualities of the open-graded mixes.

<u>Anfosso-Ledee, F. and Pichaud, Y. (2006): "Temperature Effect On Tyre-Road Noise". Section Acoustique Routie`re et Urbaine, LCPC centre de Nantes, BP 4129, 44341 Bouguenais cedex, France</u>

Tyre–road noise emission decreases when the outdoor temperature increases, with a variation that can exceed 0.1 dBA/^{o}C. This effect depends on tyre-road combination, but semi-generic corrections can improve the accuracy of tyre-road noise measurements. In this paper, the variation of pass-by noise level of a passenger car at 90 kmph with temperature is investigated, on seven types of road surfaces, under different temperature conditions. A good correlation between air, road surface and tyre temperature is outlined. A linear relationship between noise level and air temperature variations is observed for bituminous pavements, of about 0.1 dBA/^{o}C, but reduced to 0.06 dBA/^{o}C for pavements having porosity. No temperature effect is observed on cement concrete pavements. A spectral analysis shows that the temperature effect is highest in low and high frequency range, what can be explained by generating mechanisms rather than propagation.

<u>American Association of State Highway and Transportation Officials (AASHTO), (2011): "Standard Method of Test for: Measurement of Tire-Pavement Noise Using the On-Board Sound Intensity (OBSI) Method, TP 76-11."</u>

This test method describes the procedures for measuring tire-pavement noise using the on-board sound intensity (OBSI) method and the procedures for verification of the measurement system. The test method provides an objective measure of the acoustic power per unit area at points near the tire-pavement interface. The on-board sound intensity measurement method described herein permits the tire-pavement sound intensity to be measured directly and allows various pavements and textures to be directly compared. This method is expected to be subject to revision as experience increases and research results are implemented. This standard may involve hazardous materials, operation, and equipment. This standard does not purport to address all of the safety concerns associated with its use. It is the responsibility of the user of this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

<u>Ashammed, M. and Tighem S. (2009): "Sound Absorption Characteristics of Typical Pavements: An Ontario Study"</u>

Traffic noise is a growing problem throughout the world. Pavement with high acoustic absorption capabilities can significantly reduce the roadway traffic noise. The durability of such acoustically absorptive pavements is however major concern for highway application. The sound absorption capabilities of typical Portland cement concrete (PCC) pavements that were surface texture in different configurations and different asphalt concrete (AC) pavements, typical to Ontario, Canada, were measured in the Centre for Pavement and Transportation Technology (CPATT) laboratory at the University of Waterloo, Ontario using the CPATT impedance tube and a custom designed portable reverberation chamber. On average, regular Superpave (SP), stone mastic asphalt (SMA) and fin graded SP mixes were shown to absorb 6.3%, 7.5%, and 8.5% of sound, respectively. Textured PCC surfaces were shown to absorb 5% to 6% of the sound. The varying thickness has shown no significant effect on the variation of sound absorption of conventional AC and PCC pavements. The variation of bulk relative density (BRD) was shown to affect significantly the sound absorption capabilities of conventional dense AC pavements. However, the effect of the air void contents in the dense AC pavements was shown to be insignificant or minimal for the variation of sound absorption capabilities of the tested AC pavements.

Barrett, D. and Johnston, T. (2010): "Port Columbus International Airport Southwest Noise Berm/ Wall Project: Comparison of General Prediction Method and ISO 9613-2 Computations".

The Columbus Regional Airport Authority (CRAA) plans to relocate Runway 10R-28L at Port Columbus International Airport (CMH) in Columbus, Ohio 702 feet south of its existing location. This action would require the acquisition and removal of 35 houses to meet Federal Aviation Administration (FAA) airport design standards. The Airport's most recent Federal Aviation Regulations (FAR) Part 150 Noise Compatibility Plan (NCP) includes an approved noise abatement measure to construct a noise berm/wall to help reduce noise and minimize the visual impacts caused by removal of the houses. The CRAA retained Harris Miller Miller & Hanson Inc. (HMMH) to conduct a noise mitigation study to determine the final location, length, height, and composition of the berm/wall. In addition, the study sought to confirm whether the proposed measure would comply with FAA noise reduction standards, thereby making it eligible, as an approved NCP measure, for FAA funding. HMMH conducted the evaluation using the General Prediction Method (GPM) as implemented in the SoundPLAN® computer model. On previous projects, HMMH has used SoundPLAN®'s implementation of ISO Standard 9613-2. For this project, however, the authors found the GPM to provide results that were more uniform and also in closer agreement with prior measured and predicted results than those computed by ISO 9613-2. This paper provides a comparison of relevant aspects of the two standards and suggests explanations for the differing results.

Bekhor, S. and Iscovitch, O. (2010): "A Model to Minimize Road Traffic Noise in the Planning Phase of a New Neighborhood"

Noise is an environmental problem that affects people's lives. Negative noise effects include annoyance, sleep disturbance, and reduction of property values. A dominant source of environmental noise in urban areas is the motorized vehicle traffic flow of the transportation network. The purpose of this paper is to determine, for given noise level limits and total trip demand, the optimal trip distribution in the planning phase of a new neighborhood. An algorithm to solve the combined traffic assignment and noise problem is developed. A key feature of the algorithm is a method to find the equivalent maximum traffic volume for each road segment without exceeding the noise criterion for each of the designated receivers. The results of the process are a modified OD matrix which could be used for neighborhood planning. The paper shows an implementation of the algorithm for a real case.

Bendtsen, H., Kohler, E., Lu, Q. and Rymer, B. (2010): "Californian and Danish Study on Acoustic Aging of Road Pavements". TRB 2010 Annual Meeting.

It is the experience by noise technicians that the traffic noise emission of a given asphalt pavement changes over time. Knowledge on acoustical aging is important for road administration when developing policies and strategies for noise abatement. It is important to know how noise reducing as well as "normal" pavements performs over time. Acoustical aging is important information in order to achieve good accuracy when noise is predicted with methods like the American TNM method or the Nordic NORD2000 method or the like. Noise performance models for road pavements are necessary if noise is to be integrated as an active parameter in Pavement Management Systems. The purpose of this current paper is to contribute to the ongoing international development in the field of acoustical aging by performing a comprehensive analysis of four existing Californian and Danish results from long time noise measurement series on asphalt pavements. For porous pavements (built in air void over around 15%) it is a known phenomenon that the voids of the pavements tend to clog and that this increases the nose generated from air pumping. But for other dense and open graded (but not real porous) pavement types there is not much knowledge on which changes in the surface structure that cause this increase in noise in the period in between when the bitumen film is worn off and when the pavements begins to deteriorate with distresses like raveling, cracking etc. The objective is to analyze and compare trends in the development of noise over time. A comparison of the actual nominal noise levels is not the main objective of this study but rather the change in levels over time. The development of the noise spectra over the years is also analyzed in order to investigate which mechanisms of noise generation might be changed over time. The increase of noise has normally been analyzed in relation to the age of pavements. In this paper this is supplemented by also using the traffic load as well as an artificial indicator defined as the change of noise predicted as combination of actual physical age and traffic load.

Bendtsen, H., Kohler, E., Lu, Q. and Rymer, B. (2011): "Tire Road Noise Measurements and Temperature"

The On Board Sound Intensity (OBSI) method is used by University of California Pavement Research Center (UCPRC) as well as by other researchers and consultants in the USA to perform detailed measurements of tire noise emission from road pavements. In Europe the Close Proximity method (CPX) is currently used. International experiences indicate that the temperature is a factor which has some influence on the results of measurements of road traffic noise. The objective of this paper is to analyze how the temperature affects the OBSI results. The results presented here are also relevant to the CPX method because the Standard Reference Test Tire (SRTT), which is the test tire for the OBSI, is being studied as a possibility for the CPX method. The analysis is based on a unique series of detailed noise measurements performed on the California Department of Transportation (Caltrans) test sections with 5 different pavements at highway LA138 in the Mojave Desert in Southern California. The measurements were carried out in the desert within three consecutive days in the wintertime where the variation of the air temperature over the day was from to 2 to 22°C. This ensures that the primary variable parameter during these measurements is the temperature. Based on this project the air temperature correction factor of -0.027 dB/°C for asphalt pavements can be suggested for the SRTT tire used in the OBSI method and other noise measurement methods using this tire. The temperature mainly influences the noise at frequencies above 1000 Hz; therefore it could be relevant to apply frequency dependent correction factors.

<u>Bennett, T., Hanson, D., Maher, A. and Vitally, N. (2005): "Influence of Pavement Surface Type on Tire-Pavement Generated Noise" Journal of Testing and Evaluation; March 2005, Vol. 33 Issue: Number 2 p1-7, 7p.</u>

Pavement noise evaluations were conducted on 42 pavement surfaces in New Jersey using the Close Proximity Method (CPX) via the NCAT Noise Trailer. The CPX Method is a current ISO Standard that measures sound levels of the tire-pavement interface, thereby providing a method to evaluate solely the influence of pavement surface on traffic noise. The surfaces were comprised of both hot mix asphalt (HMA) and Portland cement concrete (PCC). The HMA surfaces consisted of dense-graded asphalt mixes (DGA), open-graded friction course (OGFC) with and without crumb rubber, stone-mastic asphalt (SMA), Nova Chip®, and a micro surfacing slurry mix. The PCC surfaces, pavements and bridge decks, had varying surface treatments consisting of transverse tining, saw-cut tining, diamond grinding, and broom finish. The main focus of the research was to: 1) Evaluate how different pavement surfaces influence the generation of tire-pavement noise, 2) Evaluate the effect of vehicle speed on the tire-pavement generated noise, and 3) Provide guidance as to the repeatability of the CPX method and optimal test distance on the roadway to aid in maximizing testing efficiency. Results of the testing indicated that the asphalt-based surfaces provided the lowest tire-pavement noise levels. Of the HMA surfaces tested, the OGFC mixes modified with crumb rubber provided the lowest noise levels (96.5 dBA at 60 mph (96.5 km/h)). However, not only were these mixes modified with crumb rubber, but they also had the finest aggregate gradation. The loudest HMA surface was a 12.5 mm SMA mix (100.5 dBA at 60 mph (96.5 kmph)). The PCC surfaces had the highest noise levels. Of all PCC surfaces tested, the transverse tined surface obtained the loudest noise levels (106.1 dBA at 60 mph (96.5 kmph)). It was found that if the PCC surface was diamond ground, the noise levels could be comparable, and sometimes lower, than typical HMA pavement surfaces. Typical noise levels of the diamond ground PCC surfaces were approximately 98.7 dBA at 60 mph (96.5 kmph). To evaluate the effect of vehicle speed, noise measurements were conducted at 55, 60, and 65 mph (88.5, 96.5, and 104.6 kmph). Test results within this range indicate that on average, the tire-pavement noise increases linearly and at a rate of approximately 0.18 dBA for every 1.0 mph (1.6 kmph). The Nova Chip®

mixes were less susceptible to the increase in vehicle speed (0.15 dBA increase for every 1.0 mph (1.6 kmph) increase), while the PCC broom finish (no treatment) surfaces were affected the greatest by vehicle speed (0.29 dBA increase for every 1.0 mph (1.6 kmph) increase). The CPX method was found to be repeatable; with an average standard deviation of approximately 0.13 dBA, as long as the test distance was greater than 0.2 miles (0.32 km). This is most likely due to the sensitivity of the test method being influenced by the ability to track the identical wheel-path in successive test runs.

<u>Bernard J. and Sandberg, U. (2005): "Tire-Pavement Noise, Where Does It Come From?". TR News 240 September - October 2005.</u>

Highway traffic noise is generated from four vehicle sub sources: the engine- drivetrain, the exhaust system, the aerodynamics, and the interaction of the tires with the pavement. Tire pavement interaction is the predominant subsource of noise from properly maintained automobiles traveling at speed above 30 kilometers per hour (20 miles per hour). For properly maintained trucks without engine compression brakes, tire pavement interface noise is similarly predominant, but at higher speeds. Pavements that produce less noise from the tire interface are a strategic solution for addressing highway noise. The interaction of the tire with the pavement generates sound that radiates away from the tire in the near field, the acoustic transition zone surrounding the source. Tire-pavement noise is complex, and different mechanisms prevail on different pavements surfaces. At the tire-pavement interface, several mechanisms create energy that radiates as sound. These are called sound generation mechanisms. In addition, some characteristics of the tire- pavement interface cause the energy to be converted to sound and to radiate efficiently. These characteristics are called sound enhancement mechanisms.

<u>Bowlby, W., Wayson, R., Chiguluri, S. Martin, M. and Herman, L. (1997): "Interrupted Flow Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model"</u>

During the period November 1994 through January 1996, the U.S. Department of Transportation, Research and Special Programs Administration, John A. Volpe National Transportation Systems Center (Volpe Center), Acoustics Facility, in support of the Federal Highway Administration (FHWA) and 25 sponsoring State transportation agencies, conducted the National Pooled Fund Study (NPFS), SP&R 0002-136, titled "Highway Noise Model Data Base Development". This report presents the results of one portion of that study- the measurement, data reduction, and analysis of individual vehicle sound level and speed data for interrupted flow traffic (accelerating from stop signs, toll booths, and on-highway ramps). Also presented is the development of regression equations for the resulting Reference Energy Mean Emission Levels (REMELs) as a function of vehicle speed and vehicle type. These REMELs are part of the data base that is the foundation around which the acoustical algorithms in the FHWA's Traffic Noise Model, Version 1.0 (FHWA-TNM) are being structured.

Calamia, P., Busch-Vishniac, I., Turen, T. and McNerney, M. (1997): "On the Use Of Pavement Surfaces To Attenuate Traffic Noise" The Journal of the Acoustical Society of America, 101 (5)

Efforts to limit the propagation of traffic noise tend to focus on the use of noise barriers and their associated insertion loss. Bearing in mind that the source which contributes most to roadside automobile noise at highway speeds is tire-pavement interaction, an investigation into the use of ‘‘quiet’’ pavements to reduce tire-pavement interaction noise, and thus attenuate traffic noise at the source, has been undertaken. Using the trailer method, onboard and roadside measurements have been made of tire-pavement interaction noise on various pavements currently in use in the state of Texas, as well as in the Western Cape and Gauteng provinces, South Africa. Preliminary results obtained with a test-vehicle speed of 60 mph show that reductions in roadside noise levels from 4 to 15 dBA can be achieved with ‘‘quiet’’ pavements.

Chalupnik J. D. and Anderson D. S. (1994): "Roadside Tire Noise", Washington State Transportation Center (TRAC)

This study investigated the noise produced by a single passenger vehicle tire heard at the roadside. This report presents the study's equipment and the development of the data reduction techniques. To choose test sites, selection criteria were applied that would prevent extraneous artifacts from influencing the results of the study. Special care was taken to minimize microphone wind noise caused by the high-speed turbulent flow of the measurement process. Measurements were taken on both old and new Class B asphalt, Class D asphalt, and Portland cement concrete pavement. The results are presented in graphical form. The results indicated that the class D asphalt surfaces measured in this study did not produce lower roadside tire noise, and these surfaces were no more acoustically absorbent than the other road surfaces.

Cheng, H., Harris, R. and Yin, M. (2010): "Using Micro Data to Assess Traffic Noise Impact on Residential Property Value; an Application of the Hedonic Model"

This research examined the impact of highway traffic noise on residential property values. Micro level data were used to control for the characteristics of the properties, and FHWA TNM V2.5 was used to calculate the traffic noise level for each selected sample. Hedonic methods were employed to decompose property value to its base characteristics. Linear regression models were constructed to estimate the Noise Depreciation Sensitive Index (NSDI). By applying the data from Jefferson County, Kentucky, a correlation coefficient of -0.0034 was obtained for the traffic noise variable, which means a unit increase in the traffic noise level (dBA in Leq) will cause a depreciation of a property by 0.34% of its sale price. The procedure presented in this research could thus provide state transportation agencies with hard data for establishing cost criteria for noise barrier construction decisions.

<u>Dae S., Cho. and Mun, S. (2008): “Study to Analyze the Effects of Vehicles and Pavement Surface Types on Noise”</u>

The effects of vehicles and pavement surface types on noise have been investigated at the Korea Highway Corporation’s Test Road along the southbound side of the Jungbu Inland Expressway, South Korea. The study was conducted in 2005 and 2006 through field measurements at nine surface sections of asphalt concrete and Portland cement concrete pavements using eleven vehicles. For the road noise analysis, the sound power levels (PWLs) of combined noise (e.g., tire-pavement interaction noise and power-train noise together) and tire-pavement interaction noise using various vehicles were calculated based on the novel close proximity (NCPX) and pass-by methods. Then, the characteristics of the PWLs were evaluated according to surface type, vehicle type, and vehicle speed. The results show that the PWLs of vehicles are diversely affected by vehicle speed and the condition of the road surface.

<u>Donavan, P. (2010): “The Acoustic Radiation from Pavement Joint Grooves Between Concrete Slabs.” TRB 2010 Annual Meeting</u>

The sound generation and radiation from grooves in the joints between concrete slabs were modeled using relationships previously established for tire groove resonances and groove air pumping. Resonance behavior was clearly established from both in-lab and on-road on-board sound pressure level data. The strength of the noise source was found to be proportional to 20 times the logarithm of the groove cross-sectional area. This relationship along with the accounting of residual texture, background noise was found to replicate that measured in the lab testing. The model was then calibrated using the lab results and extended in speed range using a theoretical calculation of the sound radiation from the end of the joint groove. The predicated level produced by an isolated joint of specified dimension was then used to model the average sound intensity level for a pavement with a user specified distance between joints, vehicle speed, and pavement texture generated level. For smaller groove cross sectional areas (~0.25 in^2), the contribution of joint grooves was found to be on the order of 1 dBA for quieter pavement textures. For larger cross sectional areas, such as a groove width of ½ in and depth of 1 in, the contribution increases almost 3 dBA.

Donavan, P. (2008): "Acoustics2008/1818: Evaluation of the ASTM Standard Reference Test Tire for Purposes of Standardized Measurement of On-Bound Tire-Pavement Noise"

Currently in the US, efforts are underway to develop standard methods for on-board sound intensity (OBSI) measurement of tire-pavement noise. Up until recently, the default standard tire was the Goodyear Aquatred 3 tire originally selected due to its apparent similarity to Tire a specified in the ISO CPX procedure. Because of longer-term availability, the ASTM Standard Reference Test Tire (SRTT) is the primary candidate for replacement of the Aquatred 3. Issues of concern for the SRTT include tire-to-tire variation, the relation of the SRTT to preciously used reference tire, and the "break-in" period required for stable test tires. To address tire-to-tire variability, six SRTT's were tested on variety of asphalt (AC) and Portland cement concrete (PCC) surfaces. These included four new tires and two that had been in use for some time. Two of the new tires were retested with increasing use to examine any break-in period effect. For comparison, the older Aquatred 3 was also tested on these same surfaces using both OBSI and controlled pass-by measurements. The results of these measurements are presented along with their implication to for reference tire selection.

Donavan, P. (1993): "Tire Pavement Interaction Noise Measurement under Vehicle Operating Conditions of Cruise and Acceleration", General Motors Noise and Vibration Center May 1993 Document Number: 931276

In previous literature, sound intensity has been used to quantify the strength of tire-pavement interaction noise sources very near an operating tire under non-driven, cruise conditions as measured on trailers or actual vehicles. In the current investigation, the relationship between such on-board sound intensity data and coast-by sound pressure levels measured 7.5 meters away from the centerline of vehicle travel were examined. When compared either in terms of overall A-weighted levels or 1/3 octave band spectra, there data demonstrate a strong correlation between the two types of measurements. Given this correlation, the sound intensity technique was then used to quantify the tire-pavement interaction noise for the driven tires of a passenger car under accelerating conditions such as those specified in the ISO 362/SAE J1470 or SAE J986 passby noise procedures. These data indicate that in some cases, the strength of the tire-pavement noise produced under acceleration on an overall A-weighted sound pressure level basis can be as much as 9 dBA higher than those measured under cruise conditions. This effect has been investigated for several different tiers covering several different acceleration rates in the speed range from 48 to 80 kmph. The results of this study are examined in detail with attention given to differences in performance between tires and to exterior passby noise contributions.

Donavan P. R., Schumacher R. F. and Stott J. R. (1998): “Assessment of Tire-Pavement Interaction Noise under Vehicle Pass-By Test Conditions Using Sound Intensity Measurement Methods”, the Journal of the Acoustical Society of America, Vol. 103(5)

Over the past several years, sound intensity measurement methods have become an increasing valuable tool in isolating tire-pavement interaction noise when a vehicle is tested under full throttle acceleration conditions such as the ISO 362 R15 procedure. Several investigations have been conducted and reported which demonstrate the relationship between ‘‘on-board’’ sound intensity measured close to a tire contact patch and the sound pressure level measured by a stationary microphone 7.5 m away from the line of travel of the vehicle. Using these relationships, the contribution of tire-pavement noise can be assessed relative to other noise sources associated with a vehicle under acceleration as measured at 7.5 m. In this application, it has been determined that some tires can produce significantly higher noise levels under the torque of acceleration than under cruise conditions. Sound intensity has also been used to separate sound propagation from sound generation effects in the assessment of test surfaces such as those specified by SAE and ISO. This paper reviews the various applications of sound intensity in the assessment of tire-pavement interaction noise issues related to vehicle passby noise, the implication of recent findings on noise reduction strategies, and the potential for standardization of sound intensity techniques.

Donavan, P. R. and Lodico, D. M. (2009): “Measuring Tire-Pavement Noise at the Source”, NCHRP Report 630

Tire-Pavement noise has become an increasingly important consideration for highway agencies. However, there are no widely accepted procedures for measuring solely tire-pavement noise under in-service conditions. As a result, this research was undertaken to evaluate potential noise-measuring procedures and identify or develop appropriate procedures applicable to light and heavy vehicles and all paved surfaces. Such procedures will provide highway agencies with an appropriate means for (1) measuring and rating tire-pavement noise levels on existing pavements, (2) evaluating new pavements incorporating noise-mitigating features, and (3) identifying design and construction features associated with different noise levels. The objectives of this research were to (1) develop rational procedures for measuring tire-pavement noise at the source and (2) demonstrate the applicability of the procedures through testing of in-service pavements. To achieve these objectives, (1) a literature search was conducted to gain understanding of what approaches have been used in the past to quantify tire-pavement noise source levels, (2) evaluation testing was conducted to assess candidate methods and select the most promising one, (3) the effect of test parameters of the selected method were examined to develop parameter limits, and (4) field test were performed on in-service pavements to demonstrate the applicability of the proposed measurement method for different pavement types. This report presents the results of the research, the information obtained, implications for developing a rational test procedure, and the proposed test method.

Donavan, P. (1997): “An Assessment of the Tire Noise Generation and Sound Propagation Characteristics of An ISO 10844 Road Surface”, SAE document from http://www.sae.org/technical/papers/971990. Document Number: 971990

A road surface complying with the new International Standards Organization (ISO) specification was installed at an Arizona test facility (DPG site) in the winter of 1995/96. As part of the acoustic qualification of this site, comparative tests were conducted between this new surface, a Society of Automotive Engineers (SAE) sealed asphalt surface and an existing ISO surface in Michigan (MPG site). Initial testing with one vehicle and tire combination indicated that the new ISO surface produced ISO 362-1994 passby and coastby levels about 2 dBA lower than sealed asphalt. Relative to the Michigan surface, the levels for the new Arizona ISO surface were 3 to 3 and 1/2 dBA lower. These differences were much greater than expected based on previously published studies of these two test surface types. Since the new surface was constructed to the ISO specification and meets the physical requirements for sound absorption coefficient, porosity, and surface texture, further investigation was conducted to determine if sound propagation or tire noise generation differences accounted for the differences. Experimental work to understand this difference included the use of on-board sound intensity measurements to isolate tire noise generation under both acceleration and coast and static sound propagation tests to isolate surface reflective properties. Analytically, a sound reflection model was developed to predict differences in attenuation based on measured surface impedance data. Taken together, the results of this investigation support the conclusion that a majority of the differences observed are due to tire noise generation. However, in comparing the new ISO surface to the SAE, a significant portion was also found to be attributable to sound propagation differences.

Donavan, P. (2003): “Assessment of Highway Pavements for Tire/Road Noise Generation”, From SAE website http://www.sae.org/technical/papers/2003-01-1536. Document Number: 2003-01-1536, Illingworth and Rodkin Inc.

With the growing recognition that pavement selection can be an effective traffic noise abatement tool, there has been increased need for developing methods to characterize tire/road noise generation for existing and experimental highway surfaces. To address this need, sound intensity measured on-board a test vehicle has been developed as an alternative technique to wayside, passby, or trailer methods. As part of this development, the relationship between sound intensity measured close to a moving tire contact patch and coast by sound pressure data measured at stationary point 7.5 meters away has been demonstrated for different tires and road surfaces. A protocol for sound intensity measurement on existing highways in traffic has also been developed. Using these, a library of the tire/road noise levels has been assembled for California State Highways and experimental highway test sections. The goal of this work is to aid in the decision process for determining when and how effective pavement selection can be used to reduce highway noise levels. In this paper, data relating the sound intensity and coast by measurements, data from a range existing highway pavement surfaces, and data from experimental test sections are presented. From these, the potential for using "quiet" pavements to abate noise and the effect of pavement parameters such as surface texture and porosity are examined.

Donavan, P. (2009): "Use of the ASTM Standard Reference Test Tire as a Benchmark for On-Bound Tire/ Pavement Noise Measurement", located at the SAE website: http://www.sae.org/technical/papers/2009-01-2108. Document Number: 2009-01-2108, Illingworth and Rodkin Inc.

There is a growing interest in using a standard reference tire for both assessing changes in test track pavement over time and rank ordering of the performance of different highway pavements. Because of longer-term availability, the ASTM Standard Reference Test Tire (SRTT) is the primary candidate for these applications. Issues of concern for the SRTT include tire-to-tire variation, the relation of the SRTT to other tires currently in use, and the "break-in" period required for stable test tires. To address tire-to-tire variability, seven SRTT's were tested on variety of asphalt concrete (AC) and Portland cement concrete (PCC) surfaces on two occasions. These included five new tires and two that had been in use for some time. Two of the new tires were re-tested with increasing use to examine any break-in period effect. For comparison to other tires currently in use, on-board sound intensity (OBSI) and controlled pass-by measurements were conducted with the SRTT and compared to pass-by levels measured for light vehicles operating on actual highways. To further evaluate the SRTT for use as a reference tire in OBSI measurements, its sensitivity to variations in temperature, tire inflation pressure, test vehicle type, perturbations in test speed, and load were also measured. Based on the evaluations performed, the SRTT appears to be well suited to be used as long-term reference tire for tracking pavement changes and comparing different roadway surfaces.

Donavan, P. (2005): "The Effect of Pavement Type on Low Speed Light Vehicle Noise Emission", located at SAE website: http://www.sae.org/technical/papers/2005-01-2416. Document number: 2005-01-2416, Illingworth and Rodkin Inc.

At speeds of 50 kmph or greater, the exterior noise emission of light vehicles is typically dominated by tire-pavement noise for operating conditions of cruise and moderate acceleration. At a test speed of 56 kmph, it has been found that pavement type can create a 10 dBA or more variation in tire-pavement noise. This has significant implications for both community noise and vehicle noise emission testing. In this paper, the results of tire-pavement noise measurements for over 80 different pavements in Europe and the United

States are reported. These pavements include research surfaces, existing roadways, and ISO 10844 passby test surfaces. Measurements were conducted using an on-board sound intensity methodology that has been correlated to cruise-by noise levels. These results are discussed in terms of the revisions being considered for the ISO 362 passby test procedure and the ISO 10844 test surface specification. Additionally, a case history of community traffic noise reduction achieved by use of a quieter pavement is reviewed to demonstrate the importance of the pavement in low-speed vehicle noise emissions.

Donavan, P. (1995): "Sound- Intensity Measurement Errors in the Presence of Large Pressure to Intensity Ratios", located at SAE website: http://www.sae.org/technical/papers/951334. Document number: 951334, General Motors Corp.

Errors in sound-intensity measurements are examined for situations in which a high-reactive component is present. This occurs when the indicated sound-intensity level is much smaller than the sound-pressure level. In these situations, significant errors in the sound-intensity measurement can occur for even very small phase mismatch between microphone channels. High-reactive components may be encountered in the near field of an extended source such as a body panel, when the intensity vector does not coincide with the sensitive axis of the probe, or when measurements are made in the presence of high background noise, reverberant sound fields, air flow, or standing waves. Expressions for calculating sound intensity error due to phase mismatch with high-reactive components present are developed and examples of calculated error for common instrumentation are provided. Cases of sound-intensity measurements with known amounts of phase mismatch are also examined.

Donavan, P. and Rymer, B. (2010): "Effects of Aging on Tire-Pavement Noise Generation for Concrete Pavements of Different Textures"

Between 2003 and 2010, research on the changes in tire-pavement noise generation over time was conducted on eleven different textures applied to Portland cement concrete (PCC). The initial textures included longitudinal tining, burlap drag, and longitudinal broom. Additional texturing was applied to these surfaces in the form of longitudinal grooving of varying depth and spacing and diamond grinding with varying spacer dimensions as well as a combination of the two. Since their application, these sections have been routinely monitored for tire noise performance using the on-board sound intensity (OBSI) method. As originally measured in June 2003, the range in level between the surfaces was relatively small at 2.7 dBA. At 5 years, the range is slightly smaller at 2.3 dBA. Over the total 7½ years of the study, the overall noise performance has increased at an average rate of about 0.10 dBA per year. Considering different frequency ranges, the change in noise level has displayed some variation with the lower frequency levels actually decreasing for some pavements with time while the higher frequencies were found to increase at a rate higher than the overall levels for all pavements. For the higher frequencies, findings suggest that the increased noise is due to polishing the surfaces. For the lower frequencies, the reduction in noise level is less pronounced with more variability between textures. For the ground surfaces, some evidence was found indicating that the reduction may be linked to some loss of larger scale texture as the surfaces are worn down.

Donavan, P. (2010): "Tire Noise Generation and Propagation Over Porous and Non-Porous Asphalt Pavements"

Acoustic measurements were made on a number of asphalt test pavements at the National Center for Asphalt Technology Test Track including five porous pavements. On-board sound intensity (OBSI) measurements were taken to quantify the tire-pavement noise source strength as function of pavement parameters. The OBSI results fell into three pavement groupings based on spectral shape. More than other parameters these groupings were determined by whether the pavement was porous or not and whether it was new or older. The OBSI results also indicate that porous single porous layer pavements are particularly effective at reducing tire-pavement noise source strength at frequencies above 1250 Hz for designs 18 to 33 mm thick. For a thicker, double layer porous pavement, source strength reductions extended down to 630 Hz. Porous pavements were also found to be effective in reducing the source strength of the tire-pavement interaction by reducing some tire noise mechanisms and by reducing the sound power level of the source through local sound absorption. Testing was also conducted to evaluate the additional attenuation for sound propagating over porous, sound absorbing pavements compared to non-porous pavements. From the propagation measurements, all of the porous pavements produced additional sound attenuation over that produced by the non-porous pavements. The additional attenuation also increased with distance from the source.

Fakhri, M. and Naderi A., "The Role of Porous Asphalt Pavement in Reducing Noise and Improving Driving Safety in Urban Areas", Tehran, Iran

One of the important factors to design modern urban roads is prediction of road traffic noise and reducing it to an acceptable standard level. The major type of asphalt concrete pavement which has been widely used in urban and non-urban roads in Iran is dense graded asphalt. In this research a comparative study was carried out by the authors to investigate the effects of porous asphalt in reducing the traffic noise in an urban area where a heavy traffic road pass through overpopulated region of the city of Amoul in north of Iran. In this road geometric design, vehicle type and environment was the same while the asphalt pavement was different, one with dense graded, the other with porous asphalt. The result of this study showed that porous asphalt improving driving safety in wet weather as well as reducing the traffic noise.

De Fortier S., Prozzi, J. and Bianchini, A. (2010): "Evaluation of the OBSI Method", TRB paper: 10-3599. TRB 2010 Annual Meeting.

This paper reports the results of sound pressure and intensity measurements collected at the National Center for Asphalt Technology (NCAT) Test Track. For evaluation of the on-board sound intensity (OBSI) method, the sound intensity measurements are compared to corresponding sound pressure measurements. The Test Track comprises a variety of different hot-mix asphalt (HMA) surface mixtures including dense graded Superpave and open- graded friction course mixtures that were evaluated as part of the noise study. Sound testing was done using the NCAT close proximity (CPX) noise trailer and the OBSI method was used to measure sound intensity levels with different vehicles and tires. All the noise testing was done at a speed of 72 kmph (45mph). An analysis of variance (ANOVA) was done to determine the significance of mixture type, vehicle and test tire on the noise levels. It was found that each of these statistically significantly influenced the noise levels. The analyses identified and quantified the differences between sound intensity and pressure levels on the different asphalt mixtures evaluated allowing a ranking of these in terms of noise performance. The data suggest that the type of vehicle used to measure sound intensity is not as critical as the tire used.

Fleming, G. and Rickley, E. (1994): "Performance Evaluation of Experimental Highway Noise Barriers"

During the period October 1986 through April 1994, the U. S. Department of Transportation, Research and Special Programs Administration, John A. Volpe National Transportation Systems Center, in support of the Federal Highway Administration and 17 sponsoring State transportation agencies conducted the National Pooled Fund Study (NPFS), HP&R 0002-136, "Evaluation of Performance of Experimental Highway noise Barriers". The first publication supporting the NPFS, FHWA-RD-90-105, Parallel Barrier Effectiveness, Dulles Noise Barrier Project, presented the results for parallel barriers subject to controlled traffic conditions. The second publications, FHWA-RD-92-068, Parallel Barrier Effectiveness Under Free-Flowing Traffic Conditions, presented the results for parallel barriers located along Interstate 495 in Montgomery County, Maryland. This report is the third and final publication supporting the NPFS. In addition to presenting the results of additional analyses of previously collected data, it summarizes the findings of the multi-year study.

Giorjao C., Tatiana, C., Andrae, M. and Yoneda, R. (2005): "Tire Contribution for Pass-By Noise." located at the SAE website: http://www.sae.org/technical/papers/2005-01-4165. Document number: 2005-01-4165

A major concern on product development is to meet local markets legal requirements. Pass-by noise (PBN) test is standardized and is used to homologate vehicles. Main contributors are powertrain, exhaust, air intake system and tires. The objective of this paper is to show tires contribution in final results of pass-by noise measurements. Tests were done using tires of different suppliers (brand), origins and specifications.

Golebiewski, R., Makarewicz, R., Nowak, M. and Preis, A. (2003): "Traffic Noise Reduction Due to the Porous Road Surface", Applied Acoustics 64 (2003) 481–494

Porous road surfaces reduce road traffic noise. A new method of noise reduction assessment is proposed. The noise generated by a few vehicles was measured two times: on an old surface with the dense asphalt and on a new surface with the porous asphalt. Subjective assessments of drive-by noise suggest that the sound exposure and the road surface coefficient can be used as the acoustical characteristics of a road surface. Their average values, with the average number of vehicles passing the receiver during a day or night, makes it possible to predict the equivalent continuous A-weighted sound pressure level for the new road surface. This is the main objective of this paper. # 2003 Elsevier Science Ltd. All rights reserved.

Haider, S., Chatti, K., Baladi, G. and Sivaneswaran, N. (2010): "The Impacts of Pavements Monitoring Frequency on Pavement Management Decisions"

Pavement performance monitoring is an essential part of a pavement management system (PMS). Therefore, highway agencies collect pavement condition data, containing various structural and functional distresses, on a regular basis. However, the frequencies of pavement condition data collection vary among highway agencies. This study explores the effect of pavement monitoring frequency on pavement performance prediction and its consequence at the network level PMS decisions. A statistical methodology was developed to investigate the impact of monitoring frequency on the performance prediction using different model forms. The results of the analyses showed that performance predictions are impacted by the monitoring interval. Furthermore, different types of distress to be collected may need different monitoring intervals because of their unique growth over time and associated uncertainty in prediction. When cost consequences and prediction uncertainties are combined, it seems that monitoring cracking (image-based) at 1-year interval will be more appropriate while for roughness (sensor-based) a monitoring interval of 1 to 2-year could be suitable. The results of network level analyses demonstrated that monitoring interval may significantly impact the short- and long-term network conditions for various preservation strategies. Increasing the monitoring interval may have a consequence on the PMS decisions. Longer intervals for crack monitoring (image-based) may cause an overestimation of an agency costs for pavement repair at the network level. On the other hand, longer intervals for IRI monitoring (sensor-based) will results in an underestimation of repair costs at the network level.

Inoue, T. and Ihara, T., "Study of the Effect of Surface Texture of Porous Asphalt on Tire-pavement Noise"

Porous asphalt has been well known as a noise reduction surface course compared to a conventional one. Air void content of porous asphalt also contributes to the reduction of noise generation due to tire-pavement interaction. It is important to understand effect of the surface texture of porous asphalt on noise reduction and which index of surface texture is appropriate. This paper presents an adequate index of surface texture which is obtained after numerous noise measurements on an experimental pavement made of different maximum size of coarse aggregate produced from the same source. This experimental pavement has several porous asphalt surface sections both given thicknesses and air void contents. Mean Texture Depth, Mean Profile Depth, Standard Deviation of Surface Profile and Ratio of accumulated length of 2 mm Texture Depth (hereafter RAL2) are examined as an index of surface texture. As a result of this examination, RAL2 is found to be an effective index for noise generation measured by CPX method. This index has been verified in the existing porous asphalt pavements, which were made of different aggregate resources. Noise reduction is maximized as RAL2 approaches 1.0. We found a good correlation among these RAL2 of coarse aggregate, laboratory specimen and actual pavement surface. Therefore, using this method it is possible to predict a noise generation value at the porous asphalt mix design stage. We recognized that the difference in surface texture affects the analysis results of sound pressure level of noise and PSD of surface profile texture appears in the wave number less than 200 c/m. And an analysis of the correlation between sound pressure level of 1/3 octave band and PSD of 1/3 octave band of texture profile has shown that wave number from 20 to 250 c/m has positive effect in noise reduction on the sound pressure level within 200 to 800Hz. This result of analysis has also demonstrated that the index of RAL2 is adequate for evaluation of noise generation. When thickness and air void content of porous asphalt are different from the above value, it is necessary to add the factor of total air volume per unit area. This modification also demonstrated the effectiveness of evaluation of noise generation for other type of hot asphalt mixture such as dense graded and SMA.

International Organization for Standardization, (2003): "Tyres-Coast-By Methods for Measurement of Tyre-to-Road Sound Emission", ISO 13325, 1st edition

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization. International Standards are drafted in accordance with the rules given in the

ISO/IEC Directives, Part 2. The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75% of the member bodies casting a vote. Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. ISO 13325 was prepared by Technical Committee ISO/TC 31, Tyres, rims and valves.

Iwao, K. and Yamazaki, I. (1995): "A Study on the Mechanism of Tire-Road Noise." Vehicle Research Laboratory, Nissian Research Center, Nissian Motor Co. Ltd. Natsushima-cho l. Yokosuka-shi. Kanagawa. 237 Japan

This paper describes the mechanism of generating tire/ road noise. Which contributes very much to the vehicle exterior noise, by dividing the factors of the tire/ road noise into exacting force, vibration characteristics and acoustic radiation characteristics? In addition, it show the effectiveness of suppressing the distinctive tread vibration mode, which is the main mode of vibration radiation noise of around 1 kHz with a high sound pressure level in radial tires for passenger cars.

Jones, W. (2008): "Highway Noise Control with HMA", The Journal of the Acoustical Society of America; May 2008, Vol. 123 Issue: Number 5 p3390

Tire-pavement noise is a major contributor to traffic noise at highway speeds. Tire & pavement noise is affected by different pavement properties. A study conducted in California measured the noise levels of different mix types and the mix characteristics affecting noise levels. In this study, tire & pavement noise was measured using the on-board sound intensity (OBSI) method. Data was collected on four different types of pavement mixes: conventional open graded asphalt concrete (OGAC), rubberized asphalt concrete that are open graded (RACO), rubberized asphalt concrete that are gap graded (RACG), and dense graded asphalt concrete mixes (DGAC). A total of 72 field pavement sections were included in the study, all of which were less than 8 years old at the time of the measurements. This paper evaluates the pavement characteristics affecting noise levels using principal components regression. This technique was used due to the multicollinearity found among the variables. Two principal components were extracted from the measured parameters such as air void content, gradation properties, pavement roughness, age, and pavement surface condition.

(2008): "Evaluation of the ASTM Standard Reference Test Tire for purposes of standardized measurement of on-board tire-pavement noise", the Journal of the Acoustical Society of America; May 2008, Vol. 123 Issue: Number 5, p3390

Currently in the US, efforts are underway to develop standard methods for on-board sound intensity (OBSI) measurement of tire & pavement noise. Up until recently, the default standard tire was the Goodyear Aquatred 3 tire originally selected due to its apparent similarity to Tire a specified in the ISO CPX procedure. Because of longer-term availability, the ASTM Standard Reference Test Tire (SRTT) is the primary candidate for replacement of the Aquatred 3. Issues of concern for the SRTT include tire-to-tire variation, the relation of the SRTT to previously used reference tire, and the "break-in" period required for stable test tires. To address tire- to- tire variability, six SRTT's were tested on variety of asphalt (AC) and Portland cement concrete (PCC) surfaces. These included four new tires and two that had been in use for some time. Two of the new tires were retested with increasing use to examine any break in period effect. For comparison, the older Aquatred 3 was also tested on these same surfaces using both OBSI and controlled pass-by measurements. The results of these measurements are presented along with their implication to for reference tire selection.

(2008): "Low Speed Exterior Vehicle Noise and the Effect of Pavement Type", The Journal of the Acoustical Society of America; May 2008, Vol. 123 Issue: Number 5 p3133

For operating conditions of cruise and moderate acceleration, the exterior noise emission of light vehicles is typically dominated by tire & pavement noise at speeds of 50 kmph or greater. At a test speed of 56 kmph, it has been found that pavement type can create a 10 dBA or more variation in tire & pavement noise. This has significant implications for both community noise and vehicle noise emission testing. In this paper, the results tire & pavement noise measurements for over 40 different pavements in Europe and the United States are reported. These pavements include research surfaces, existing roadways, and ISO 10844 passby test surfaces. Measurements were conducted using an on-board sound intensity methodology that has been correlated to cruise-by noise levels. These results are discussed in terms of the revisions being considered for the newly revised ISO 362 passby test procedure and the ISO 10844 test surface specification. Additionally, a case history of community traffic noise reduction achieved by use of a quieter pavement is reviewed to demonstrate the importance of the pavement in low speed vehicle noise emissions.

(2008): "Evaluation of effects of pavement characteristics on the OBSI levels using Principal", the Journal of the Acoustical Society of America; May 2008, Vol. 123 Issue: Number 5 p3390

Tire-pavement noise is a major contributor to traffic noise at highway speeds. Tire-pavement noise is affected by different pavement properties. A study conducted in California measured the noise levels of different mix types and the mix characteristics affecting noise levels. In this study, tire-pavement noise was measured using the on-board sound intensity (OBSI) method. Data was collected on four different types of pavement mixes: conventional open graded asphalt concrete (OGAC), rubberized asphalt concrete that are open graded (RACO), rubberized asphalt concrete that are gap graded (RACG), and dense graded asphalt concrete mixes (DGAC). A total of 72 field pavement sections were included in the study, all of which were less than 8 years old at the time of the measurements. This paper evaluates the pavement characteristics affecting noise levels using principal components regression. This technique was used due to the multicollinearity found among the variables. Two principal components were extracted from the measured parameters such as air void content, gradation properties, pavement roughness, age, and pavement surface condition.

(1996): "Light Vehicle Exterior Noise: Measurement, Regulation, Tires, And Pavement", the Journal of the Acoustical Society of America; April 1996, Vol. 99 Issue: Number 4 p2508-2529, 22p Title: ISSN: 00014966; 15208524

Exterior noise is the only acoustic attribute regulated for passenger cars and light trucks. The primary procedure used to quantify this noise is an outdoor passby test conducted under full- throttle acceleration. Unless specified noise levels are met under this procedure, a vehicle may not be sold in a given market jurisdiction. Recent reduction of European regulatory limits by 3 dBA has reinforced many of the technical challenges faced in designing and testing vehicles to meet these new requirements. These challenges include: better understanding and control of test and environmental variables, more accurate methods of noise prediction, and improved techniques for isolating and reducing individual source contribution. In recent investigations, sound intensity has been employed to isolate tire-pavement interaction noise for vehicles under passby conditions. This has led to the determination that tires can produce significantly higher noise levels under the torque of acceleration than under cruise conditions. As a result, tires are often the major noise source when the total vehicle noise approaches the new regulatory limits. This paper reviews the variables associated with the passby test procedure, the effects of vehicle acceleration on tire-pavement interaction noise, and the needs for improved predictive methods.

Khazanovich, L. and Izevbekhai, B. (2008): "Implication of Time-Dependent Texture-Degradation on Pavement On- Board-Sound-Intensity Patterns in Mnroad Test Cells", http://www.mrr.dot.state.mn.us/research/pdf/all_mnroad_reports.html

Pavement texture is an important parameter in tire-pavement-interaction-noise (TPIN). As pavements carry traffic load over the years measurable degradation occurs in texture. As the pavement is exposed to environmental and traffic elements, changes occur in ride quality measured by the International Roughness index (IRI) as well as the Surface Rating (SR). Research investigated the correlation between TPIN measured with the On-Board Sound intensity (OBSI) Protocol, Estimated Single Axle load (ESAL); SR and age of pavement in

MnROAD test cells. General observation shows decrease of OBSI with respect to traffic evident in the relative values of driving and passing lane in the rigid pavements and conversely an increase in OBSI in the bituminous segments with time. An initial overall model of all the cells was not feasible as various pavement types exhibited unique characteristic residuals. This led to the development of individual models for each surface type. Although hysteretic effects are implicated in both parameters, no tenable relationship between Friction Number (FN) and TPIN was yet established. TPIN exhibited non-linear characteristics with respect to the Pavement age ESALS IRI and SR using the universal Levenberg –Marquardt hybrid of steepest-descent and least-squares non-linear model fitting technique.

<u>Kowalski, K., Dare, T., McDaniel, R., Olek, J. and Bernhard, R. (2010): "Exploration of a Laboratory Technique for Tire/ Pavement Assessment of Hot Mix Asphalts (HMAs)</u>

Experimental techniques to measure tire-pavement noise generation from asphalt pavements in the laboratory have been limited. Pavement samples are typically constructed from different materials from those used in the field, or else construction is so time-consuming that only one or two asphalt samples are constructed. A series of experiments were conducted to determine if Purdue University's Tire-Pavement Test Apparatus (TPTA) could be used to overcome these limitations. One porous friction course mixture, one stone matrix asphalt mixture, and four Superpave dense-graded asphalt mixtures were designed and fabricated using a specially developed compaction procedure. Although the produced samples had low on-board sound intensity levels, their also had higher than design values of the air voids. The elevated levels of the air voids were a direct consequence of the inability of the compaction method used in this study to produce the required compaction levels. Despite these difficulties, the sample technique and the TPTA testing protocol were shown to offer effective approach for of quick laboratory assessment of tire-pavement noise characteristics.

<u>Kuemmel, D. Jaeckel, J. Satanovsky, A., Shonber, S. and Dobersek, M. (1996): "Noise Characteristics of Pavement Surface Texture In Wisconsin." Transportation Research Record; January 1996, Vol. 1544 Issue: Number 1 p24-35, 12p</u>

Twelve Portland cement concrete pavement (PCCP) test sections were constructed to compare with standard PCCP and asphaltic concrete pavement (ACP) to quantify the effects of the pavement surface texture on noise, safety, and winter maintenance. Asphalt pavements studied included a Strategic Highway Research Program asphalt, stone matrix asphalt (SMA), and Wisconsin standard asphalt. A dependency between the pavement textures and their noise characteristics was observed. Noise measurements indicated that uniformly transverse tined PCCP created dominant noise frequencies that were audible adjacent to the road and inside the test vehicles. Careful design and construction of transversely tined PCCP can reduce tire-road noise. No significant acoustical advantages of open-graded asphalts over the standard dense asphalt were found. The results of this research are preliminary and have not yet been approved by the Wisconsin Department of Transportation Council on Research.

Lee, C. and Fleming G. (1996): "Measurement of Highway-Related Noise", National Technical Information Service, Springfield, Virginia

The U.S. Department of Transportation, Research and Special Programs Administration, John A. Volpe National Transportation Systems Center (Volpe Center), Acoustics Facility, in support of the Federal Highway Administration (FHWA), Office of Environment and Planning, has developed the "Measurement of Highway-Related Noise." This document reflects significant improvements and changes in noise measurement technologies that have evolved since the 1981 FWHA publication, Sound Procedures for Measuring Highway Noise. This report documents the recommended procedures for the measurement of (1) existing noise; (2) vehicle noise emissions; (3) barrier insertion loss; (4) construction equipment noise; (5) noise reduction due to buildings; and (6) occupational noise exposure.

Lodico, D. M. and Donavan, P. (2009): "Evaluation of Test Variables for Onboard Sound Intensity (OBSI) Measurements", Transportation Research Board Annual Meeting 2009 Paper #09-3261

As a portion of the overall research work for the National Cooperative Highway Research Program (NCHRP) 1-44 Project, an examination of test variables and measurement uncertainties was conducted for the on-board sound intensity (OBSI) method of measuring tire-pavement noise at the source. The intent of this investigation was to provide guidance on test variables in order for users to determine the control limits needed to implement the OBSI procedure. Based on an extensive review of literature regarding on-board tire noise measurement methods, pertinent variables were identified that could affect the repeatability and reproducibility of the measurements. The sensitivity of OBSI results to variations in pavement temperature, the configuration of the OBSI measurement fixture, tire inflation pressure, test vehicle type, test speed, and load were measured. The testing was done on both asphalt and cement concrete pavements using two different test tires; the ASTM Standard Reference Test Tire (SRTT) and the implement the OBSI procedure. Based on an extensive review of literature regarding on-board tire noise measurement methods, pertinent variables were identified that could affect the repeatability and reproducibility of the measurements. The sensitivity of OBSI results to variations in pavement temperature, the configuration of the OBSI measurement fixture, tire inflation pressure, test vehicle type, test speed, and load were measured. The testing was done on both asphalt and cement concrete pavements using two different test tires; the ASTM Standard Reference Test Tire (SRTT) and the Dunlop SP Winter Sport M3 tire (Dunlop). The investigation found that OBSI measurements were most sensitive to vehicle speed, tire loading, tire inflation pressure, and probe distance from the pavement. This paper summarizes the evaluation and results of the test parameter investigation, the information obtained, and the implications for developing a rational test procedure.

Lu, Q., Luo, S. and Harvey, J. (2009): "Compaction of Noise-Reducing Asphalt Mixtures in the Laboratory"

In recent years, significant amount of research effort has been spent by engineers worldwide to develop alternative asphalt surface mixtures that are quieter, safe, and durable. These mixtures typically have very high air-void contents, placed in thin layers, and compacted in a way different from conventional dense-graded asphalt mixtures. Different compaction methods have been applied to fabricate specimens in laboratory studies. The effect of compaction on mix performance has not been sufficiently studied. This paper investigates the impact of compaction methods on the performance of quiet (porous) asphalt mixtures. Four different compaction methods are included: Marshall Impact, Hveem kneading, Superpave gyratory and rolling wheel compaction. The rolling wheel compaction is selected as a surrogate for field compaction. Specimens of four different porous mixtures with nominal maximum aggregate sizes varying from 4.75 mm to 19.0 mm are compacted by the four methods, and are tested for various performance indices, including permeability, sound absorption, moisture sensitivity, and resistance to raveling. It is found that each compaction method has its own advantages and disadvantages. The effect of compaction methods also varies with the aggregate gradation. Mix performance indices also have different sensitivities to the compaction method.

Menge, C. and Barrett, D. (2010): "Reflections from Highway Noise Barriers and the Use of Absorptive Materials in the U.S., and Why Small Increases in Noise Levels May Deserve Serious Considerations"

For decades, many U.S. Departments of Transportation (DOTs) have followed widely-accepted guidance that single reflections of noise from noise barriers to the opposite side of highways are "generally one to two dBA or less, and therefore not perceptible to the average human ear." Increases in the average noise level are undoubtedly small in such cases, yet the outcry from residential communities subject to reflected noise can be quite significant, depending upon various physical and political circumstances. Such outcry has resulted in significant effort and money spent researching the magnitude of sound level increases both near and far from reflective noise barriers along highways. In some cases, DOTs have added absorptive materials to barriers after construction. Other DOTs have long-standing practices of using barriers with absorptive surfaces wherever there is noise-sensitive land use on the opposite side of the highway, specifically to avoid any perception of increased highway noise due to the barriers. The paper presents historical information on the study of reflections from noise barriers in the U.S., human perception of changes, and also how reflective noise barriers may change the character of noise from highways as heard in communities opposite the barriers. Although such changes may be small, they may be interpreted as sound-level increases, and result in the conclusion that the affected residents are being treated unfairly by the DOT. The authors draw two conclusions from having performed the research for this paper: 1) Small changes in sound level associated with barrier reflections can be meaningful to the public and to barrier effectiveness conclusions, and 2) the benefit of simply implementing absorptive barrier treatments opposite residential areas outweighs the benefit of researching the issue or conducting detailed analyses to justify the use of absorption.

McNerney M. T., Landsberger B. J., Turen T. and Pandelides A. (2000): "Comparative Field Measurements of Tire-pavement Noise of Selected Texas Pavements", Texas Univ. at Austin. Center for Transportation Research, Federal Highway Administration, RR-2957-2, April 2000, p. 56

The effects of traffic noise are a serious concern in the United State and in the rest of the world. One significant component of traffic noise is tire-pavement interaction. Protecting individual receivers by reducing pavement noise at the source rather than by using traffic noise barriers may result in substantial cost reductions and improved community acceptance of highway projects. This research consisted in field-testing fifteen different pavement types found in Texas, in coordination with six pavement types in South Africa. A test procedure was developed using standard test microphones to simultaneously record noise levels at roadside and onboard the test vehicle within a few centimeters of the tire of a towed trailer. The data were analyzed to determine the tire-pavement interaction noise for the different pavements. The test procedure was designed to develop comparisons of pavements while keeping other variables constant. The results, measured on the standard A-weighted scale, indicated a range of 7 dBA of roadside noise levels on the fifteen test pavements in Texas and a roadside noise level on one specially constructed pavement in South Africa to reduce noise that was measured as 3 dBA quieter than that of any Texas pavement measured in the study.

Mun ,S., Seung C. and Muk C., "Influence Of Pavement Surface Noise: The Korea Highway Corporation Test Road", Canadian Journal of Civil Engineering

Because of a significant increase in the number of vehicles using national highway networks that link major urban centers, road traffic noise - with its harmful impact on the environment—has become a major pavement system issue. Therefore, it is necessary to assess the characteristics of different types of pavement and their influence on road traffic noise. The Korea Highway Corporation test road, with eight different pavement surfaces, was used to test and analyze noise from tire–pavement interaction and from vehicle power trains. Noise was measured in a novel test approach using a surface microphone. The results show that traffic noise levels vary widely according to pavement surface type, vehicle type, and vehicle speed. The findings of this investigation can be used to determine appropriate pavement surfaces that will satisfy specific environmental impact assessments for given traffic conditions and requirements.

Nelson, J. T., Kohler E., Öngel A. and Rymer, B., located in the following website: http://trb.metapress.com/content/ugp1208762p15232/

Acoustical absorption coefficients of more than 140 pavement cores were obtained by the impedance tube method with two microphones and cross-spectral analyses. The effectiveness of the impedance tube in predicting noise reduction for different mixes was evaluated by comparing the correlations between onboard sound intensity levels and absorption. Theoretical predictions of acoustical absorption due to friction between air and porous matrix and thermal relaxation were compared with measured results for an idealized porous structure. The model was used to infer porosity, tortuosity, and pore size from measured acoustical absorption spectra for manufactured porous asphalt and extrapolate test results to non-normal angles of incidence, assuming isotropy of the porous structure. This model will help improve mix designs to increase the absorption of pavement surfaces and can be used to estimate porous pavement properties.

Nielsen C., Bendtsen, H., Andersen, B. and Larsen H. (2005): "Noise Reducing Pavements in Japan", Published by Road Directorate, Danish Road Institute.

Porous pavements are widely used in Japan both on highways and in urban areas. Today the total area of porous pavements is 50 million m^2 and it is still increasing. On toll roads more than 50% of the pavement is porous. The structural durability of porous pavements in Japan is generally the same as the durability of dense graded asphalt mixes. In the warm regions the structural durability of porous pavements is 10 years or more, and in the cold regions 7-10 years. Structural damage of porous asphalt is a serious problem in cold regions. Snow removal operations by snow ploughs causes severe damage in the porous asphalt and rutting and raveling occurs after a few years. This has led to use of high viscous SBS modified binders in the cold regions and to the development of a 'hybrid' pavement with a dense structure and an open surface texture. Most pavements are single layer pavements with 13 mm maximum aggregate size, 20% built-in air voids and high viscosity 8 % SBS modified bitumen. In cold regions pavements with 17 % built-in air voids are constructed. Porous pavements are used in urban areas even at intersections and bus stops, and on highways in the countryside. At some intersections a special epoxy based surface treatment is applied in order to improve durability. Tests with two layer porous pavements started in 1998 and are mainly used on urban roads. The driving speed is in general low (below 50 – 60 kmph in urban areas and 100 kmph on highways).

Ongel, A., Harvey, J. T., Kohler, E. R, Lu, Q., Steven, B. and Monismith, C. L. (2008): "Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphalt Pavement Surface Types: First- and Second-Year Results" February 2008. http://pubs.its.ucdavis.edu/publication_detail.php?id=1288

This report summarizes a detailed report presenting the first and second year of field and laboratory measurements and statistical analyses and performance estimates for tire-pavement noise, permeability, ride quality, distress development, and friction properties of four types of asphalt pavement surface types used by the California Department of Transportation: open-graded asphalt concrete (OGAC), rubberized open-graded asphalt concrete (RAC-O), rubberized gap-graded asphalt concrete (RAC-G) and dense-graded asphalt concrete (DGAC). Tire-pavement noise was measured using the on-board sound intensity method (OBSI). A factorial experiment was developed and executed that considered these surface types, rainfall, traffic and age, with sections selected in the following age groups: less than one year old, one to four years old, and four to eight years old. A partial factorial was included for another type of open-graded mix, called F-mix. In addition, special sections placed by various Caltrans pilot and research projects were also included in the plan for field monitoring and laboratory testing. The report summarizes the measured performance and presents summary statistics for the results. Statistical analyses were performed, including single-variant regression to identify significant variables, multivariate regression, survival analysis, and principal components regression, depending on the type of data, in order to estimate performance. The performance models were used to estimate the life of the various surface types for the conditions in the experiment. The median noise reduction across the population included in the experiment is approximately 2 dBA for OGAC and approximately 3 dBA for RAC-O mixes compared to the DGAC mixes for the Standard Reference Test Tire (SRTT), with values converted from the Aquatred tire measurements used in the project. The Aquatred results are slightly different prior to conversion to the SRTT values, indicating slightly less noise benefit from open-graded mixes and less difference between OGAC and RAC-O.

Ongel1, A., Kohler, E. and Harvey, J., "Principal Components Regression of Onboard Sound Intensity Levels" Journal of Transportation Engineering-ASCE Volume: 134 Issue: 11 Pages: 459-466

Roadways paved with open graded asphalt mixes typically generate lower traffic noise levels as compared to other types of pavements. A program was initiated in 2005 in California to evaluate the effectiveness of noise reducing surfaces over time and the pavement characteristics affecting those noise levels. In this study, tire-pavement noise was measured using the onboard sound intensity method. Data were collected on four different types of mixes: conventional open graded asphalt concrete, rubberized asphalt concrete that are open graded, rubberized asphalt concrete that are gap graded, and dense graded asphalt concrete mixes. A total of 72 field pavement sections that were at that time less than 8 years old were included in the study. Various pavement characteristics were measured and their effects on noise levels were evaluated using principal components regression, in addition to ordinary least-squares regression. This research confirmed that open graded pavements exhibit reduced tire noise compared to dense and gap graded mixes and quantified this reduction for typical mixes in California.

Phillips, S.M., Dollamthodi, S. and Morgan, P.A. (2001): "Classification of Low Noise Road Surfacing." The 2001 International Congress and Exhibition on Noise Control Engineering. The Hague, the Netherlands, 2001 August 27-30

An increasingly important aspect of the development of low noise road surfaces is the definition and certification of their acoustic properties. In the UK, a number of complementary methods are being developed for such assessments. One of the most important of these is the noise test attached to the HAPAS (Highway Authorities Product Approval Scheme) type approval system. This test method is based upon the ISO standard Statistical Pass-by (SPB) method and results in a classification rating related to a standard surfacing. To supplement this test and to allow the acoustic properties of road surfaces to be determined at any location, a system based upon the close-proximity (CPX) measurement procedure has been developed. This is carried out using the TRITON vehicle measurement system developed by TRL. This system is used for measuring the rolling noise of specified test tyres at suitable speeds. Combining the results of several tyres allows a representative noise classification measure to be determined. These systems are being used to routinely survey the high-speed road network and could underpin future noise maps. This paper describes these tests and the development and validation of a close-proximity noise test vehicle.

Rasmussen, R. O. (2009): "Tire-pavement and Environmental Traffic Noise Research Study. Final Report: 2009", Colorado Dept. of Transportation, Denver. CDOT-2008-2, Jul 2008

This research study on tire-pavement noise is being conducted in response to CDOT's interest in traffic noise in general, and the tire-pavement interaction in particular. Following a rigid set of testing protocols, data is being collected on highway traffic noise characteristics along with safety and durability aspects of the associated pavements. The overall goal of this research project is to develop and execute a comprehensive, long-term study to determine if a particular pavement surface type and/or texture can be successfully used in Colorado to help satisfy FHWA noise mitigation requirements. The study is needed to accomplish the following: (1) Determine the noise generation/reduction characteristics of pavements as functions of pavement type, pavement texture, age, time, traffic loading, and distance away from the pavement; (2) Determine a correlation between source measurements including close-proximity (CPX) and on-board sound intensity (OBSI), and statistical pass-by (SPB) and time-averaged wayside measurements; and (3) Accumulate information that can be used for validation and verification of the accuracy of the FHWA Traffic Noise Model (TNM) to use on future Colorado highway projects. The information included in this report represents the first in a series of four measurements to be collected over a five-year period. While some of this information can be used immediately for decisions related to pavement design and specification, it is recommended that caution be exercised as the results from future testing will help assess the long-term acoustical durability of these pavement surfaces.

Rasmussen, R. O., Donavan, P. R., Ruiz-Huerta, J. M. and Whirledge, P. R. (2009): "Improving Functional Performance of Highways in the USA using Quieter Pavement Techniques", PIARC International Seminar on Maintenance Techniques to Improve Pavement Performance 24-25 August 2009

Under sponsorship of the Federal Highway Administration of the US Department of Transportation and various State Highway Agencies, a number of recent activities have led to proven alternatives for quieter pavements for pavement maintenance and restoration. Thin-lift porous asphalt overlays, for example, have proven to reduce noise levels while maintaining desirable friction and durability requirements. Diamond grinding has also clearly emerged as one the best techniques available for restoring the functional performance of pavements, with noise reduction as a key indicator. Some details of the key activities in the USA are highlighted herein, with particular emphasis on those techniques that could be applied with relative ease outside the USA.

Rawool1, S. and Stubstad, R., "Effect of Diamond Grinding on Noise Characteristics of Concrete Pavements in California" at http://pdfcast.org/cache/effect-of-diamond-grinding-on-noise-characteristics-of-concrete-pavements-in-california

The construction of sound walls along highways has been the primary noise mitigation strategy in California and in many other western States. Sound walls cost approximately $1.5 million per mile and are effective only in close proximity to the highway, on the "far" side of the sound wall, so to speak. In its efforts to explore other noise mitigation strategies, the California Department of Transportation (Caltrans) recently conducted a study to determine the effect of diamond grinding on the noise characteristics of existing concrete pavements. Since the noise generated at the tire–pavement interface is the greatest contributor to highway noise, quieter pavement surfaces can reduce overall noise levels for both road users and neighborhoods—whether sound walls are used or not. On-board sound intensity (OBSI) measurements were conducted on six routes in California, for a total of 42 evaluation sections; each evaluation section was 440 ft. (136.8 m) long. OBSI measurements before and after diamond grinding were recorded. Following are the overall conclusions that were reached after the pre- and post-grinding OBSI levels were measured: There is a significant and readily audible reduction in OBSI levels (and hence in tire-pavement noise) after grinding. An average 2.7 dBA reduction in OBSI levels was observed for all test sites. Among the six routes, the highest average reduction of 4.4 dBA was observed on I-5 near Richards Boulevard in Sacramento County, and the lowest reduction of 1.2 dBA was observed on State Route 60 (on a single test section) in San Bernardino County. The highest reductions in sound intensity levels on a 1/3-octave band basis occurred in the 1600 Hz band, while the lowest reductions occurred in the 1000 Hz bandwidth.

Reiter, D., Bowlby, W., Herman, L. and Boyer, J. (2004): "Traffic Noise in Montana: Community Awareness and Recommendations for a Rural State", National Technical Information Service, Springfield, Virginia

This research focuses on current policies, practices and procedures for non-traditional noise abatement solutions, solutions that are alternative to noise barrier walls or berms built by a state department of transportation (DOT). Reviews of the literature and the practice have been conducted on pavement related noise, noise-compatible land use planning, sound insulation, and traffic management techniques. Type II (retrofit) noise barrier programs have also been examined. Also, a detailed examination of land use planning and development processes and procedures within the State of Montana has been completed, including discussions with a number of local agency planners. This work reveals that because of concerns over growth, many mechanisms are in places that are conducive to the implementation of a noise-compatible planning and development program. Additionally, two surveys were developed and administered: one for citizens living near busy roads in four Montana urban areas and one for local Montana planners. The surveys deal with people's perceptions of noise and noise mitigation, and interest in noise-compatible planning and development. The analyses of the survey data, the literature and the practice have resulted in a number of recommendations to the MDT regarding implementation of noise-compatible planning and development in Montana.

Rymer, B., Donavan, P., and Kohler, E. (2010): "Tire-Pavement Noise Levels Related to Roadway Friction Improvement", TRB 2010 Annual Meeting

In the United States, much has been learned about pavement acoustics in the past eight years with the development of the new On-Board-Sound-Intensity (OBSI) measurement method. OBSI allows researchers to quickly measure and compare pavement acoustics in great detail. A field demonstration provided a unique and controlled opportunity to examine how tire-pavement noise levels could be influenced with increases in friction on flexible and rigid pavements. The OBSI spectral measurements provided additional insight on how a shot peening process altered the noise generating mechanisms of the pavement surfaces. Spectral shifts in low and high frequencies were observed and the magnitude of the shifts varied between the two flexible and two rigid pavements. Generally, at frequencies below 1000 Hz, the texturing tended to increase the one third octave band levels. The process removed fine surface material and exposed larger aggregates which increased macro-texture depth and improved friction, but generated more low frequency noise. Frequencies from 1600 to 5000 Hz decreased after shot peening. The increase in low frequency noise was counter balanced by a reduction in high frequency noise. Overall OBSI A-weighted noise levels (re SRTT at 60 mph) of the flexible and rigid pavements were not significantly changed by the shot peening (Skidabrader®) process. Rigid pavement became slightly quieter and flexible pavement did not change or became slightly louder.

Rymer, B. and Donavan, P. (2010): "Determining the End Limits of Quieter Pavement Projects"

Ongoing work in the area of tire pavement acoustics has definitively determined that there can be a significant variation of noise levels between the loudest and quietest pavements. Using the On-Board-Sound-Intensity (OBSI) measurement procedure, it has also been determined that tire-pavement noise is highly correlated to the overall traffic noise levels especially when traffic is flowing at freeway speeds. This presents road agencies with a potential new tool for lowering traffic noise levels by using quieter pavements. Changing from a 'loud', or old and raveled pavement to a newer, smoother, lower noise pavement can yield acoustic benefits to roadside communities or 'receivers'. The decrease in noise level depends on the difference between OBSI levels of the existing pavement and the selected quieter pavement and the magnitude of this decrease may also be influenced by vehicle mix. After the decision to use a quieter pavement has been made, the end limits for the pavement must be determined. The problem is somewhat similar to deciding where to terminate a sound wall relative to the location of the roadside receivers. This analysis determined that the quiet pavement end limits are less sensitive to variation in typical roadway cross sections, somewhat sensitive to the distance between the receiver and the roadway and where the quiet pavement terminates, and very sensitive to the absolute differences between the noisier and quieter pavements.

Sachakamol, P. and Dai, L. (2007): "Road and Tire Noise Emission Assessment with Closed Proximity Method on an Asphalt Rubber Concrete Pavement", in Proceedings of the Cost-Effective Assessment/Rehabilitation of the Condition of Materials for the Transportation Association of Canada Fall 2007 meeting, Saskatoon, Saskatchewan

A road/tire noise emission assessment has been performed in Saskatchewan with the Close Proximity Method (CPX), a method based on test tire rolling on a road with microphones located close to the tire surface. In CPX road tests, the average A-weighted sound pressure levels emitted by one specified reference tire are measured with the vehicle speed over a specified road distance. The data are collected by microphones located close to the tires. In order to understand the acoustic characteristics of the newly paved Asphalt Rubber Concrete (ARC) pavement, a special test vehicle was built. Two uniquely different reference tires have been selected in order to represent the tire/road characteristics studied. The road/tire emission noise analysis was performed on 12 different surface types of a highway in Saskatchewan, Canada using the CPX test. This research aims to determine the noise characteristics of the road surface at selected sites, predict the road/tire emission noise and acoustic properties of different road surface materials, evaluate compliance with noise specifications of the specific surface materials, and estimate the state of maintenance, damage or clogging and the effect of cleaning on porous surfaces.

Saemann, E.U. (2008): "Development of Low Noise Tyres in EC Project SILENCE". Euronoise, Acoustics '08 Paris

In this paper the results from the development of low noise tires in the EC project SILENCE are reported. Starting with the state of the art knowledge of a leading tire manufacturer the existing ideas for further lowering the tire/road noise on surfaces used in urban areas were collected by literature research, benchmarking results and evaluation of internal experiments. As all published ideas were tested at Continental in the past and as there was no real new idea to build a low noise tire, some of the existing ideas for lowering the noise were chosen in the project. To find construction with significant less sound radiation 22 experimental tires were constructed. In order to find the noise reduction potential of the constructions tests on a dyno drum were made. The tires of the last loop were further evaluated at the BASt on the PFF. These tires which are optimized for the surfaces defined in another subproject were at the end of the project tested in Copenhagen. The main finding that a low noise tire must have a soft. tread compound and a heavy and soft belt construction was proved on all surfaces.

Salomons M., Zhou, H. and Lohman J. A. (2010): "Efficient Numerical Modeling of Traffic Noise" Acoustical Society of America 127, February 2010, pp796-803

An optimized method is presented for the numerical evaluation of the sound field generated by an incoherent line source, which is commonly used to model road and rail traffic noise. Two different solutions for the numerical integration over the line source are distinguished, a point source solution and a line source solution. With proper segmentation of the line source, both solutions yield accurate results. Special attention is paid to receiver positions close to the (infinite) line through (finite) line source. At these positions, controversial methods give numerical errors, which occur frequently in calculation of large- scale noise maps of cities, employing automatically geographical input data. The problems are avoided by using the optimized method presented here. The method is based on a combination of angular segmentation and linear segmentation of the line source and can be used to minimize the number of point-to-point calculations for noise mapping.

Sandberg, U. (2001): "Noise Emissions of Road Vehicles Effect Of Regulations Final Report 01-1". I-Ince Working Party on Noise Emissions of Road Vehicles (WP-NERV)

This report presents a study with the principal objective of obtaining a global view of the effect of the vehicle noise regulations on road traffic noise. The study has included assessments of the development of vehicle noise emission limits over the past 30 year, the most important noise reduction measures on vehicles, changes in vehicle noise emissions over the past 30 years for various categories of road vehicles and for various driving conditions, expect effectiveness of planned changes in vehicle related noise emission limits, and the reasons why the effectiveness of the regulations have not matched the intended effects. Based on the findings, recommendations for consideration in future noise emission regulations are given.

Sandberg, U. (1987): "Road Traffic Noise- The Influence of the Road Surface and Its Characterization". Applied Acoustics Volume 21, Issue 2, 1987, pp97-118

Unacceptable errors in the prediction of traffic noise occur in some cases when the road surface is largely different from that on which the prediction model is based. The reason is that tyre/road noise has appeared to be the dominating component of the noise from free-flowing traffic and that this noise is to a substantial extent dependent on the road surface. The mechanisms for tyre/road noise generation and its relation to road characteristics are described. Relevant road surface characterization methods are suggested. The major method is the measurement of the road texture profile and subsequent spectral analysis of the profile curve. Supplementary methods concern the measurement of acoustical and mechanical impedances. It is concluded that the road surface effect on traffic noise is extremely complicated and that it is very difficult to generalize any simple relations. For free-flowing traffic it is shown that the tested road surface types and conditions may influence the traffic noise by up to 11 dBA. This calls for a correction term for the road surface in the prediction models. Despite the complicated relations, it appears feasible - within stringent limitations - to use a table where the correction term is a variable of vehicle type, vehicle speed as well as road surface type and condition.

Sandberg, U. and Ejsmont A., "Tire/ Road Noise- Generation, Measurement, and Abatement" From the Handbook of Noise and Vibration Control by Malcolm J. Crocker page 1054-1071

The term tire/road noise denotes the noise emitted from a rolling tire as a result of the interaction between the tire and the road surface. In this chapter, only noise emitted outside the vehicle is considered: that is; exterior tire/road noise. In principle, not only the tire may radiate this type of noise; most notably the structure borne sound may spread to the rim and parts of the vehicle body and radiate from there, possibly also from part of the road surface, but radiation from the tire itself dominates.

<u>Sandberg, U. and Ejsomnt, A. (1993): "The Art of Measuring Noise from Vehicle Tires" Located at the SAE website: http://www.sae.org/technical/papers/931275. Document number: 931275.</u>

During the latest decades tire/road noise has been recognized as one of the most significant parts of road traffic noise. It has therefore become necessary to employ suitable noise reduction measures on tires as well as road surfaces which do not impose safety problems. Since many of these measures rely on appropriate measuring methods, several activities in order to standardize such methods for tire/road noise have started. The paper begins with a systematic analysis of the rather complicated tire/road noise problem and suggests ways to solve it. Then a review is presented of the major measuring methods considered for standardization with regard to classification of tires: the coast-by method; the trailer method; the laboratory drum method; and the trailer coast-by method. The advantages and disadvantages as well as which applications are the most suitable for each one are discussed. Particular attention is paid to the extremely important question of test track surface selection. Especially, the surface recently standardized by ISO for vehicle noise tests is compared to a surface more representative of actual road conditions. Other parameters considered include temperature, speed and microphone positions. Standardized measurement methods are necessary not only for classification of tires but also for classification of road surfaces. Therefore, the paper includes a status review of work going on in an ISO group which aims at standardizing a method for classification of the noise properties of road surfaces. Finally, it is emphasized that due to the many parties involved and the risk of working out too many and separate methods, it is absolutely necessary to co-ordinate the efforts internationally.

<u>Sas, P. and Dehandschutter, W. (1999): "The reduction of Structure borne road noise by active noise and vibration control" The Journal of the Acoustical Society of America; February 1999, Vol. 105 Issue: Number 2, pp1243-1243</u>

In this work, the feasibility of active structural and acoustic control of structure-borne rolling noise in a passenger car is demonstrated. A full vibroacoustical analysis of the demonstrator vehicle was carried out, in order to characterize fully the on-road behavior (coherence analysis, operational force analysis, and transfer path analysis), as well as to derive the necessary input/output models. The results of these analyses have been used as input for the actuator design and the control configuration determination (reference signals, actuator number and location, feedback signal determination). Different control configurations have been investigated and tested by means of numerical simulations and laboratory tests. Two control configurations, each using a different kind of control source, have been retained: a structural acoustic control system which works with six inertial shakers positioned at the main vibration transmission paths of the car suspension, and an anti-noise system with four loudspeakers inside the cabin. A new inertial actuator based on the moving coil work principle has been designed and realized. A broadband control system based on an adaptive feed forward control system using six reference signals, 6/4 actuators (ASAC/ANC), and four error signals has been implemented and tested in the demonstrator car.

Scofield, L., (2010): “Evaluation of Acoustic Longevity of Diamond Ground Surfaces” TRB 2010 Annual Meeting

This paper discusses two approaches to establishing acoustic longevity of pavements. The PMS Approach tests a large number of pavements over a short period of time while the Test Section Approach uses a small number of sites tested over a long period of time. Both approaches can provide good results when properly applied. The advantage of the PMS approach is that tire and equipment effects can be minimized and a reasonable estimate of the acoustic longevity established in a very short period of time. The Test Section Approach allows greater experimental control but requires testing over a significantly long period of time to accurately assess acoustic longevity. A third approach can be developed by combining the PMS and Test Section approaches. Evaluations of diamond ground surfaces in Kansas are presented to demonstrate how these approaches can be used. The two major studies discussed in this paper arrived at significantly different results for the acoustic longevity of diamond ground surfaces. These differences are discussed with possible explanations for the seemingly contradictory results. The OBSI results from the Kansas and California testing presented in this study indicate that diamond ground concrete pavements exhibit little to no increase in noise level over the first five to ten years after grinding.

Thomsen, S., Bendtsen, H. and Andersen, B. (2006): “Noise Reducing Thin Pavements”. Danish Road Institute Report 149 (2006), Road Directorate, Ministry of Transport and Energy

Around 28 % of the homes in Denmark are exposed to road traffic noise that exceeds the recommended national guidelines of 55 dBA (as LAeq, 24h). In the Danish national strategy for a sustainable development from June 2002 it can be read, that noise from road traffic is a widespread local problem for the environment and the healthiness. Many people are living in areas where the noise from road traffic exceeds limits, which can be seen as acceptable for the health. In the strategy the long time goal is that the transport noise shall be reduced to a level which ensures that nobody will be exposed to traffic noise that can give considerably negative effects on the health. In all the European countries road traffic noise causes annoyance among many residents. The noise problems are to some extent concentrated in the urban areas where the speed on most of the roads is around 40-60 kmph, but there are also serious noise problems along highways. There is a great need to develop effective noise reducing tools that are durable, safe, and cost-effective. The noise can be reduced either at the source, under propagation, or at the receiver. An effective way to reduce noise and avoid annoyance is to reduce the emission at the source. The rolling noise is generated when the tires are rolling on the pavements. The type and structure of the road pavement is very important for the level of the noise emitted. In August 2002 the European SILVIA project was started. The title of the project is Sustainable Road Surfaces for Traffic Noise Control. One of the objectives of SILVIA is to evaluate and specify road construction and maintenance techniques that would achieve satisfactory durability of acoustical performance of noise reducing road surfaces while complying with other requirements of sustainability i.e. safety, air pollution, fuel consumption, structural durability, and costs. The SILVIA project is partly financed by EU and partly by national sources. 14 partners from research institutes, universities, public institutions, and private companies from 10 European countries are working together in this comprehensive three year project. The Danish Transport Research Institute is the Danish partner in SILVIA. The Institute has subcontracted the Danish part of the work to the Road Directorate/ Danish Road Institute (DRI).

U.S. Department of Transportation, Federal Highway Administration, (2000): "Highway Traffic Noise in the United States: Problem and Response"

Noise, defined as unwanted or excessive sound, is an undesirable by-product of our modern way of life. It can be annoying, can interfere with sleep, work, or recreation, and in extremes may cause physical and psychological damage. While noise emanates from many different sources, transportation noise is perhaps the most pervasive and difficult source to avoid in society today. Highway traffic noise is a major contributor to overall transportation noise. A broad-based effort is needed to control transportation noise. This effort must achieve the goals of personal privacy and environmental quality while continuing the flow of needed transportation services for a quality society. This report has been developed to provide information about the problem of highway traffic noise and the United States' response to that problem. This report summarizes 1) the general nature of the problem, 2) the response of the Federal Highway Administration to the problem, and 3) highway noise barriers constructed or planned. Before discussing these items, however, a general discussion of the Federal-aid highway program is included to assist the reader.

http://www.vejdirektoratet.dk/publikationer/VIrap153/html/chapter01.htm

There is a great need for durable noise reducing pavements for highways. The concept for noise reduction is to create a pavement texture, with big cavities at the pavement surface in order to reduce the noise generated from air pumping, and ensuring a smooth surface so noise generated by vibration of the tyres will not be increased. Open textured pavements are open only at the upper part and are not expected to need special winter maintenance. European experiences with thin layers have been further developed. Four different pavement concepts are used: Open graded asphalt concrete (DAC-open), Stone Mastics Asphalt (SMA), a thin layer constructed as an UTLAC (Ultra-Thin Layer Asphalt Concrete), and semi porous pavement (PAC). In 2006, ten optimized thin layers were laid on a Danish highway near

Herning. Maximum aggregate sizes were in the range of 6 to 8 mm. Dense Asphalt Concrete with 11 mm maximum aggregate size is a reference pavement.

Volpe, J. (1997): "Interrupted Flow Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model", U.S. Department of Transportation, Federal Highway Administration

During the period November 1994 through January 1996, the U.S. Department of Transportation, Research and Special Programs Administration, John A. Volpe National Transportation Systems Center (Volpe Center), Acoustics Facility, in support of the Federal Highway Administration (FHWA) and 25 sponsoring State transportation agencies, conducted the National Pooled Fund Study (NPFS), SP&R 0002-136, titled "Highway Noise Model Data Base Development." This report presents the results of one portion of that study – the measurement, data reduction, and analysis of individual sound level and speed data for interrupted flow traffic (accelerating from stop signs, toll booths, and on-highway ramps). Also presented is the development of regression equations for the resulting Reference Energy Mean Emission Levels (REMELs) as a function of vehicle speed and vehicle type. These REMELs are part of the data base that is the foundation around which the acoustical algorithms in the FHWA's Traffic Noise Model, Version 1.0 (FHWA-TNM) are being structured.

Vos, E., "Basic Knowledge Development on Tyre/Road Noise in the Netherlands", Innovation Noise Reducing Program for road traffic (IPG), Delft., Netherlands

In the Netherlands the Ministry of Transport, Public Works, Water Management, and the ministry of Environmental Affairs have initiated a sizeable research and development program to reduce road traffic. The focus is on source-oriented measures. The Innovation Program will address the following topics: Investigation of the possible noise reductions by road surfaces, tyres and vehicles and enhanced noise barriers, Scientific research into the knowledge needed to realize the reduction effects, Development of the technologies and products to a level of generally application in the national main road and vehicle population.

The program must result in a significant reduction of the noise production (including advanced shielding effects) of the main road network system. In case of combinations of measures after 4 years of IPG for every location the technology and products for 8 dBA noise reductions will be feasible. This paper focuses to the scientific research on tyre/road noise in the IPG-program. For the IPG-program basic knowledge of the physical processes of rolling noise is of a great importance. Till now this knowledge is rather fragmentary. Much research has been focused on rolling noise processes of personal car tyres on non-porous surfaces. Little research so far has been done on porous surfaces and/or with truck tyres. The same is true for the validation of the different existing models.

The aim and the necessity of basic knowledge on tyre/road noise for the IPG-program is the following: Knowledge of the different mechanisms and their relative magnitude can help by searching to solutions to realize the required noise reductions and thus minimizes a more trial and error approach in the IPG-silent roads cluster, Knowledge of the different mechanisms is of help by the development of quality assurance approach of the construction of noise reducing road surfaces. Based on more quantitative knowledge of the mechanisms adequate specifications and according measuring methods can be developed.

Washington State Department of Transportation, (2006): "Traffic Noise Analysis and Abatement Policy and Procedures", March 17, 2006

This chapter provides criteria for conduction traffic sound level analysis, impact and mitigation consistent with federal highway traffic noise standards 23 CFR 772, "Procedures for Abatement of Highway Traffic Noise and Construction Noise". A traffic noise analysis is required by law for federally funded projects and required by state policy and procedures for other funded projects that: Involve construction of a new highway, significantly change the horizontal or vertical alignment, or Increase the number of through traffic lanes on an existing highway. Roadway projects that incorporate any of the three elements listed above will be considered "Type I" noise projects for the purposes of discussion in this document. Federal guidance and state policy and procedures also require the review and possible consideration of noise abatement on projects that substantially alter the ground contours surrounding roadways (e.g., removes or alters natural or previously constructed berms). The purpose of this document is to provide a means by which the Washington State Department of Transportation (referred to hereafter as the department) and project sponsors associated with the department, in conjunction with other programs, can fairly and uniformly treat citizens seeking relief from the traffic noise of highways. The Federal Highway Administration considers this document an extension and refinement of the requirements set out in 23 CFR 772 for roadway related traffic noise. Fulfillment of the procedures set out in the document assures that the federal noise standard for roadway traffic noise is met. The department will evaluate placing abatement for traffic noise from highways under two project types, Type I (new construction as described above in section 1) and Type II (Retrofit). The development and implementation of Type II projects are not mandatory requirements of U.S.C. 23 109 (i) or 23 CFR 772. However, WSDOT maintains a prioritized retrofit list in order to provide greater traffic noise abatement as funding allows. Retrofit projects are prioritized in an order reflecting traffic noise reductions. Qualifying neighborhoods must have been constructed prior to May 14, 1976 and meet noise impact criteria to qualify for an evaluation and be considered for placement on the retrofit list. Specific retrofit requirements are outlined in department Directive D22-22. Sound level abatement for Type II projects are normally constructed in order of their priority but may be constructed out of priority as part of a Type I project, part of some other project, or as a result of legislative direction.

Woldemariam, W., Olek, J., and McDaniel, R. (2010): “European HNA Mixture Design Practices for Tire- Pavement Noise Reduction”

Porous asphalt (PA) and thin, gap-graded (TG) mixtures are widely used in Europe to reduce tire-pavement noise (TPN). European material specifications for PA and TG mixtures and their component aggregates, binders and additives recommend certain requirements in order to provide improved TPN performance and acoustic characteristics. Mixture design parameters such as air void content (AVC), aggregate gradation, maximum aggregate size (MAS), and binder and fiber contents are also specified in order to improve the acoustic performance of PA and TG mixtures. This paper outlines the requirements for PA and TG mixes used in Europe and elsewhere. Specific topics covered include aggregate properties and gradations, binder grades, types and content of additives and required mixture properties to achieve noise reduction. The use of reclaimed asphalt pavement in these types of mixtures is also discussed. Techniques to control binder drain down are also presented. Lastly, the paper describes the noise reduction levels achieved using the European practices, as well as methods to ensure acoustic durability.

Wulf, T. Dare and Bernhard R. (2008): The Effect of Grinding and Grooving on the Noise Generation of Portland Cement Concrete Pavement. Euronoise (www.acoustics08-paris.org). June 29 - July 4, 2008

In this investigation, studies were done to understand the effects of various grinding and grooving parameters to investigate their effect on noise generation at the tire- pavement interface. Grinding uses diamond- infused blades that re closely spaces such that the fins between the blade tracks break off exposing an entirely new surface. For grooving, the blades are more widely spaced such that the fins do not break off and the surface texture remains largely unchanged except for grooves that are used for water drainage control. Both procedures used independently or in combination, have an effect on the noise produced by the tire- pavement interaction. Variation of grinding parameters was shown to have as much as a 3 dBA effect on noise generation. Variation in the grooving parameters has a secondary effect, which allows grooves to be added to texture without overall effect on overall noise. In this paper the effect on noise of the different parameters, such as grinding depth, blade width, and blade spacing, for grinding and grooving will be illustrated.

9.2 Procedures of Operating PULSE® Program for OBSI Tire-Pavement Noise Measurement

9.2.1 General Guide to Creating a PULSE® Template for OBSI Measurements:

1. Create a PULSE® Template for your specific equipment. To do this open a PULSE® file and set correct front end input module and type of microphones. In the Configure Organizer add each microphone into the transducer list. Each microphone should have their correct nominal sensitivity and individual sensitivities added from factor calibration. List the microphones by serial number so they do not get mixed up during testing.
2. If using two microphone sound intensity probes, group the correct microphones together under configuration properties.
3. In the Measurement Organizer under Frontend each microphone should be listed as a separate signal and there should be a group for each sound intensity probe.
4. In the Measurement Organizer under Setup add Time Capture Analyzer, Recorder, and CPB Analyzer. Each of these should have both sound intensity probes listed under it and be setup to be activated by Manual Trigger or other automated triggering device.
5. Under Measurement Organizer Setup Properties, input the Nominal Spacing for your sound intensity probes, the distance between each microphone's centers.
6. Add the max number of recorded measurements according to what will be tested.
7. Next the Function Organizer needs to be setup correctly. Create a Function Group for data export. This Function Group should include the following for each sound intensity probe: Calculate Intensity Spectrum, Calculate PI Index Spectrum, and Coherence. It is important to have the correct reference microphone set for each of these functions so that the measurements are positive instead of negative.
8. Save Template and perform Sound Intensity and nominal noise calibrations before field use.

9.2.2 General Guide to Using Your PULSE® Template for OBSI Measurements:

1. After correctly setting up hardware and having front end acquire IP address from computer open template and save file as test site and test date.
2. Under Setup Properties add current Ambient Pressure (hPa) and the current Temperature (Celsius). Then Activate Template.
3. Perform pretesting calibration for each microphone using Activate Calibration (Alt+F3).
4. Activate Template again.

5. The software should be ready to perform OBSI measurements now. If set up for manual triggering Start Recording (F5) at designated test site.
6. If recording is at correct location and does not have any negative sound intensities Save Measurement (F7), Rename Measurement as test site.
7. Repeat process for each site as many times as necessary. Start Measurement, Save Measurement, Rename. Safe the file regularly also to prevent data loss.
8. Once testing is completed the data needs to be checked to fulfill valid OBSI measurement standards. Check to see if the deviation between runs is within 0.6 dBA. Check to see if PI index is less than 5dBA in each 1/3 octave band. Check that the coherence of sound pressure between the two microphones of the sound intensity probe shall be equal to or greater than 0.8 for each 1/3 octave band between 400-5000Hz.

9.3 Site Map and Test Site Locations

Figure 9.1 Site Map and Test Site Locations

9.4 Summary of Site Information

Table 9.1 Summary of Pavements Tested for OBSI

Pavement Types	Test Date	County	Highway	Testing Speed
S9.5B	June 23, 2010	Pitt	NC 118 EB	60 mph
S9.5B	June 23, 2010	Pitt	NC 118 WB	60 mph
S9.5B	June 24, 2010	Lenoir	NC 58 NB	60 mph
S9.5B	June 24, 2010	Lenoir	NC 58 SB	60 mph
S9.5B	July 1, 2010	Nash	NC 43 SB	60 mph
S9.5B	July 1, 2010	Nash	NC 43 NB	60 mph
S9.5B	July 1, 2010	Nash	NC 43 NB	60-55-50-45-40-35-30-25 mph
S9.5B	July 29, 2010	Tyrrell	NC 94 SB	60 mph
S9.5C	June 23, 2010	Pitt	NC 118 WB (out of town)	60 mph
S9.5C	June 23, 2010	Pitt	NC 118 EB (to town)	60 mph
S9.5C	June 23, 2010	Pitt	NC 11 SB	60 mph
S9.5C	June 23, 2010	Pitt	NC 11 NB	60 mph
S9.5 C	June 23, 2010	Pitt	NC 11 SB	60-55-50-45-40-35 mph
JPCP longitudinal diamond ground	June 29, 2010	Wake	US 1 SB	60 mph
OGFC	June 29, 2010	Sampson	I-40 EB	60 mph
Concrete	Sept. 15, 2010	Yadkin	I-77	60 mph
Concrete	Oct. 15, 2010	Greensboro	I-73	60 mph
Concrete	Oct. 15, 2010	Greensboro	I-85	60 mph
S12.5D	November 12, 2010	Wilson	I-90	60 mph
S12.5D	November 12, 2010	Wilson	I-90	60 mph

Table 9.2 Summary of Pavements Tested for OBSI (Continued)

Pavement Types	Test Date	County	Highway	Testing Speed
S9.5A	February 9, 2011	Edgecombe	SR 1105 (Close to Mill Road)	60 mph
S9.5A	February 9, 2011	Edgecombe	SR 1523 S. Shiloh Farm Road	60 mph
S9.5B	February 9, 2011	Edgecombe	US 64	60 mph
OGFC	February 11, 2011	Johnston	I-40 EW	60 mph
S9.5A	February 11, 2011	Johnston	SR 1525	60 mph
S9.5A	February 11, 2011	Johnston	SR 1168	60 mph
S9.5A	February 11, 2011	Johnston	SR 1162	60 mph
S9.5B	February 11, 2011	Johnston	SR 1182	60 mph
S9.5A	February 16, 2011	Martin	SR 1501 (at Big Mill Road)	60 mph
S9.5A	February 16, 2011	Martin	SR 1420 (at McCaskey Road)	60 mph
S9.5A	February 16, 2011	Martin	SR 1002 (at Hassell Road)	60 mph
S9.5B	February 18, 2011	Craven	NC 101	60 mph
S9.5B	February 18, 2011	Craven	NC 118	60 mph
S9.5B	February 18, 2011	Craven	NC 306	60 mph

Table 9.3 Summary of Pavements Tested for OBSI (Continued)

Pavement Types	Test Date	County	Highway	Testing Speed
S9.5B	February 18, 2011	Craven	NC 306	60 mph
S9.5A	February 18, 2011	Pamlico	NC 55	60 mph
S9.5A	February 23, 2011	Nash	SR 1945	60 mph
S9.5A	February 23, 2011	Nash	SR 1733	60 mph
S9.5A	February 23, 2011	Nash	SR 1134 (near 4707 SR 1143)	60 mph
S9.5A	February 23, 2011	Nash	SR 1124 (near 7175 SR 1124)	60 mph
S9.5A	February 23, 2011	Nash	SR 1105 (SR 1535 Peele Road) On Old Middlesex Rd	60 mph
S9.5A	March 18th, 2011	Washington	SR 1125 (near SR 1506)	60 mph
S9.5A	March 18th, 2011	Washington	SR 1180	60 mph
S9.5	March 18th, 2011	Washington	SR 1127 N. Slope and Railroad Bed Road	60 mph (not on the NCDOT list, additional test site)
S9.5C	March 25th, 2011	Duplin	NC 24	60 mph
S9.5C	March 25th, 2011	Duplin	US 421	60 mph
S9.5B	April 6th, 2011	Green	NC 58	60 mph
S9.5B	April 6th, 2011	Lenoir	NC 58	60 mph

Table 9.4 Summary of Pavements Tested for OBSI (Continued)

Pavement Types	Test Date	County	Highway	Testing Speed
S9.5C	April 6th, 2011	Lenoir County	NC 118	60 mph
S9.5A	April 15, 2011	Franklin County	SR 1425	60 mph
S9.5A	April 15, 2011	Franklin County	SR 1456	60 mph
S9.5A	April 15, 2011	Franklin County	SR 1001	60 mph
S9.5A	April 15, 2011	Franklin County	SR 1611	60 mph
S9.5A	April 15, 2011	Warren County	SR 1300	60 mph
S9.5A	April 15, 2011	Warren County	SR 1335	60 mph
S9.5A	April 15, 2011	Warren County	SR 1634	60 mph
S9.5A	April 15, 2011	Warren County	SR 1620	60 mph
S9.5A	April 15, 2011	Vance County	SR1518	60 mph
S9. A	April 26, 2011	Hyde County	SR 1104	60 mph
S9. A	April 26, 2011	Hyde County	SR 1114	60 mph
S9. A	April 26, 2011	Hyde County	SR 1304	60 mph
S9. A	April 26, 2011	Hyde County	SR 1305	60 mph
S9.5D	May 26, 2011	Orange County	I-40	60 mph
S9.5D	May 26, 2011	Alamance Co.	I-40	60 mph
S9.5D	May 26, 2011	Guilford Co.	I-40 Exit 135 to 132	60 mph
OGFC	May 27, 2011	Forsyth Co.	40 Bus.	60 mph
OGFC	May 27, 2011	McDowell Co.	I-40	60 mph

Table 9.5 Summary of Pavements Tested for OBSI (Continued)

Pavement Types	Test Date	County	Highway	Testing Speed
OGFC	May 27, 2011	Burke Co.	I-40	60 mph
OGFC	May 28, 2011	Haywood Co.	I-40 TN/NC Border	60 mph
OGFC	May 28, 2011	Polk 2005	I-26	60 mph
OGFC	May 28, 2011	Polk 2010	I-26	60 mph
OGFC	May 28, 2011	Henderson 2005	I-26	60 mph
OGFC	May 28, 2011	Henderson 2008	I-26	60 mph
S12.5D	June 23, 2011	Robeson Co.	I-95 NC/SC Border	60 mph
UBWC	June 23, 2011	Cumberland Co.	I-95 County Line	60 mph
UBWC	June 23, 2011	Harnett Co.	I-95 County Line	60 mph
OGFC	July 22, 2011	Wilson County	US 264	60 mph

Table 9.6 OBSI Site Information and OBSI Data

Test Date	Pavement Types	County	Road Identification	Avg. Noise Level (dBA)
6/23/2010	S9.5C	Pitt	NC 118	100.2
6/23/2010	S9.5C	Pitt	NC 11	98.6
6/24/2010	S9.5B	Lenoir	NC 58	98.8
6/29/2010	JPCP longitudinal diamond ground	Wake	US 1	100.8
6/29/2010	OGFC	Sampson	I-40	102.9
7/1/2010	S9.5B	Nash	NC 43	98.2
7/29/2010	S9.5B	Tyrrell	NC 94	97.7
10/15/2010	Concrete	Greensboro	I-73	104.5
10/15/2010	Concrete	Greensboro	I-85	103.4
11/12/2010	OGFC*	Wilson	I-95	101.8
2/9/2011	SF9.5A	Edgecombe	SR 1523	98.5
2/9/2011	OGFC*	Edgecombe	US 64	102.9
2/9/2011	SF9.5A	Edgecombe	SR 1105	98.6
2/11/2011	OGFC	Sampson	I-40	102.3
2/11/2011	S9.5A	Johnston	SR 1162	99.2
2/11/2011	S9.5A	Johnston	SR 1525	98.6
2/11/2011	S9.5A	Johnston	SR 1168	99.7
2/11/2011	S9.5B	Johnston	SR 1182	100.5
2/16/2011	SF9.5A	Martin	SR1501	99.5
2/16/2011	SF9.5A	Martin	SR 1420	99.2
2/16/2011	SF9.5A	Martin	SR 1002	98.8
2/18/2011	S9.5B	Craven	NC 101 at SR 1735	99.1

Table 9.7 OBSI Site Information and OBSI Data (Continued)

Test Date	Pavement Types	County	Road Identification	Avg. Noise Level (dBA)
2/18/2011	S9.5B	Craven	NC 306-1	98.4
2/18/2011	S9.5C	Pamlico	NC 55	98.7
2/18/2011	S9.5B	Craven	NC 306-2	98.0
2/18/2011	S9.5B	Craven	NC 118	99.5
2/23/2011	SF9.5A	Nash	SR 1945	99.6
2/23/2011	SF9.5A	Nash	SR 1733	98.9
2/23/2011	SF9.5A	Nash	SR 1105	98.7
2/23/2011	SF9.5A	Nash	SR 1124	99.2
2/23/2011	SF9.5A	Nash	SR 1134	99.0
3/18/2011	SF9.5A	Washington	SR 1180	100.5
3/18/2011	SF9.5A	Washington	SR 1125	100.1
3/18/2011	SF9.5A	Washington	SR 1127	98.2
3/25/2011	S9.5C	Duplin	NC 24	99.6
3/25/2011	S9.5C	Duplin/Sampson	US 421	99.3
4/6/2011	S9.5B	Lenoir	NC 118	98.4
4/6/2011	S9.5B	Lenior	NC58	98.3
4/6/2011	S9.5B	Greene	Greene County Line NC 58	97.9
4/15/2011	SF9.5A	Warren	SR 1335	99.4
4/15/2011	SF9.5A	Franklin	SR 1611	98.8
4/15/2011	SF9.5A	Franklin	SR 1001	98.4
4/15/2011	SF9.5A	Warren	SR 1300	99.6
4/15/2011	SF9.5A	Franklin	SR 1425	98.9
4/15/2011	SF9.5A	Franklin	SR 1456	98.7

Table 9.8 OBSI Site Information and OBSI Data (Continued)

Test Date	Pavement Types	County	Road Identification	Avg. Noise Level (dBA)
4/15/2011	SF9.5A	Vance	SR 1518	98.9
4/15/2011	SF9.5A	Warren	SR 1620	98.7
4/15/2011	SF9.5A	Warren	SR 1634	99.3
4/26/2011	SF9.5A	Hyde	SR 1104	99.0
4/26/2011	SF9.5A	Hyde	SR 1114	99.4
4/26/2011	SF9.5A	Hyde	SR 1304	99.4
4/26/2011	SF9.5A	Hyde	SR 1305	99.6
5/26/2011	S9.5D	Orange	I-40	99.2
5/26/2011	S9.5D	Alamance	I-40	99.3
5/26/2011	S9.5D	Guilford	I-40 (from Exit 135 to 132)	99.9
5/27/2011	OGFC	Forsyth	I-40 Bus.	104.1
5/27/2011	OGFC	McDowell	I-40	105.3
5/27/2011	OGFC	Burke	I-40	105.1
5/28/2011	OGFC	Haywood	I-40 TN/NC Border	102.3
5/28/2011	OGFC	Polk[21]	I-26	102.6
5/28/2011	OGFC	Polk[22]	I-26	102.3
5/28/2011	OGFC	Henderson[23]	I-26	102.9
5/28/2011	OGFC	Henderson[24]	I-26	102.6
6/23/2011	S12.5D	Robeson	I-95 NC/SC Border	99.7
6/23/2011	UBWC	Cumberland	I-95 County Line	102.5
6/23/2011	UBWC	Harnett	I-95 County Line	101.2
7/22/2011	OGFC	Wilson	US 264	102

[21] Constructed in 2005.
[22] Constructed in 2010.
[23] Constructed in 2005.
[24] Constructed in 2008.

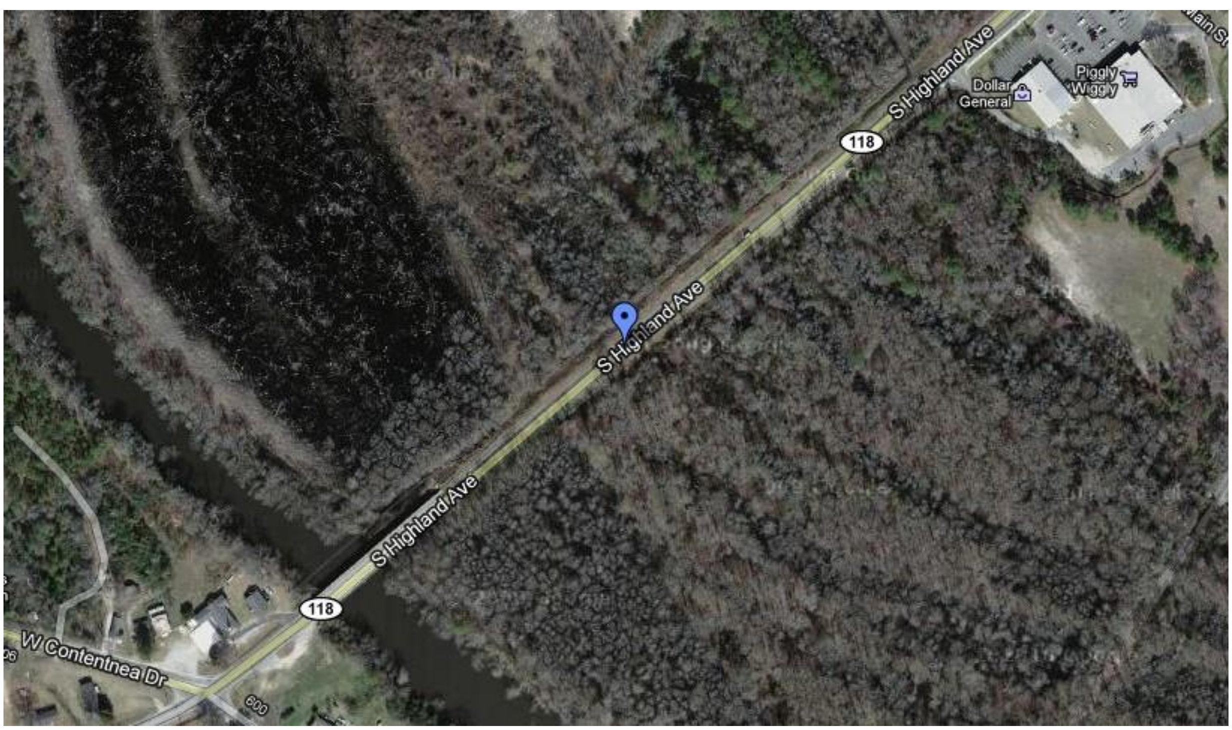
9.5 Site Information and OBSI Data

Site 1: NC 118

Test Date: 6/23/2010
Location: Pitt Co.
Construction Year: 2009
Approx Latitude (N) / Longitude (W): 35.371371 / - 77.443948
Nominal Surface: S9.5C
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
NC 118 EB	100.4	100.1			**100.3**
NC 118 WB	100.1	99.8	100.2		**100.1**
	Overall Average				**100.2**



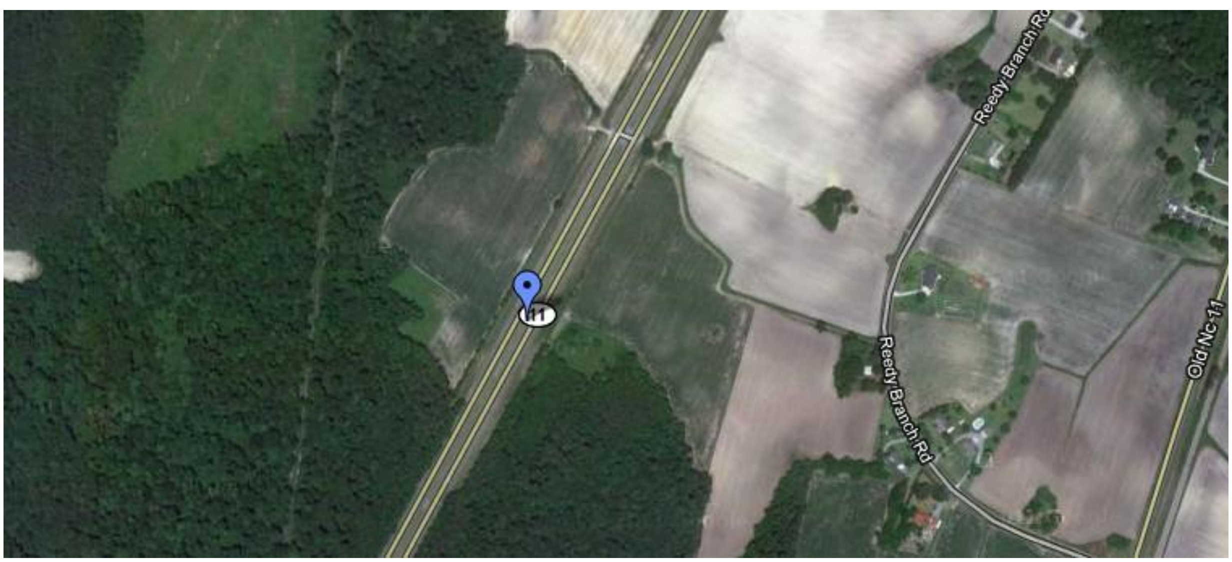


Site 2: NC 11

Test Date: 6/23/2010
Location: Pitt Co.
Construction Year: 2008
Approx Latitude (N) / Longitude (W): 35.503339 / - 77.421473
Nominal Surface: S9.5C
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
NC 11 NB	98.7	98.8			**98.8**
NC 11 SB	98.1	98.9	98.6		**98.5**
	Overall Average				**98.6**



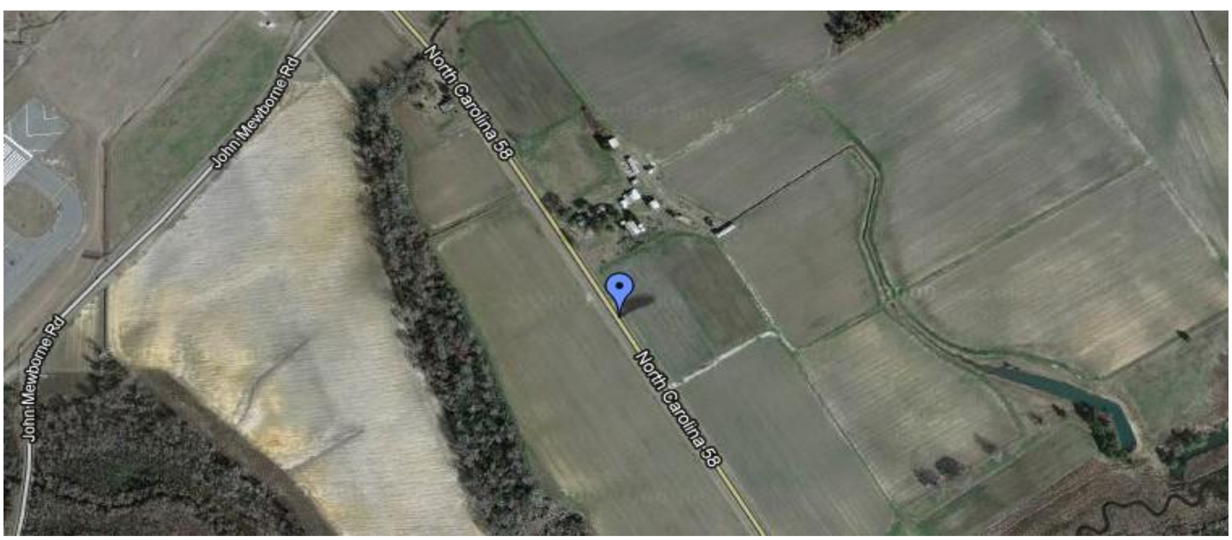


Site 3: NC 58

Test Date: 6/24/2010
Location: Lenoir Co
Construction Year: 2009
Approx Latitude (N) / Longitude (W): 35.341262 / - 77.588285
Nominal Surface: S9.5B
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
NC 58 SB	98.7	98.9			**98.8**
NC 58 NB	98.5	99.0			**98.8**
	Overall Average				**98.8**

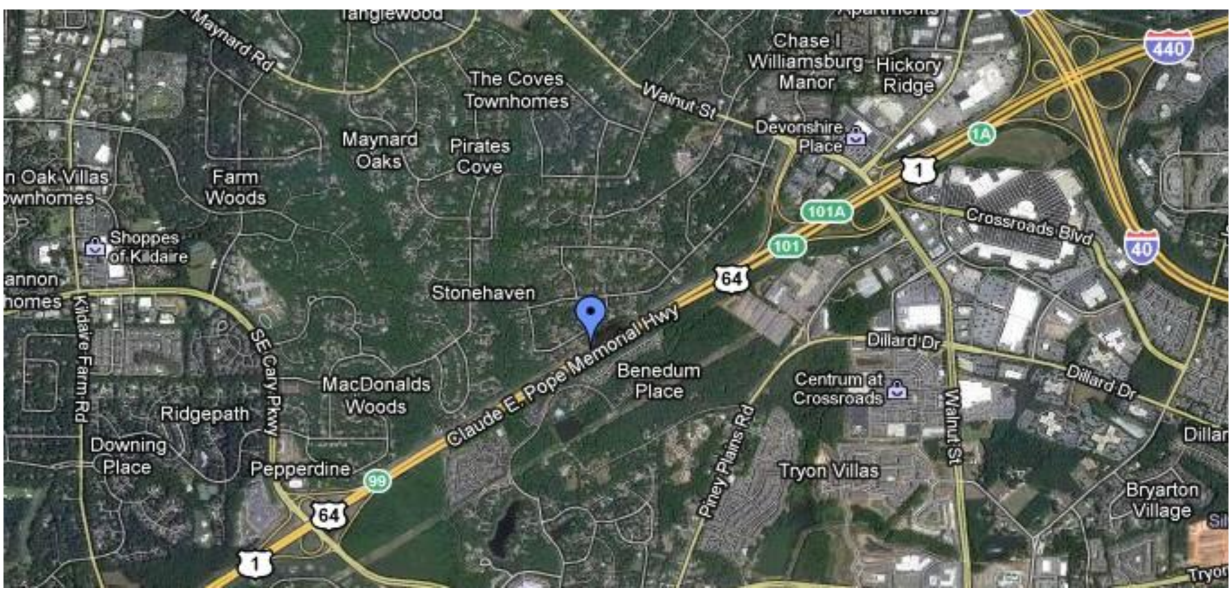


Site 4: US 1

Test Date: 6/29/2010
Location: Wake Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 35.755498 / - 78.758683
Nominal Surface: Concrete
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
US 1 SB	100.8	100.9			**100.8**
	Overall Average				**100.8**



Site 5: US 40

Test Date: 6/29/2010
Location: Sampson Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 35.206426 / - 78.310339
Nominal Surface: OGFC
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
US 40	102.8	**103.0**			**102.9**
	Overall Average				**102.9**

Site 6: NC 43

Test Date: 7/1/2010
Location: Nash Co.
Construction Year: 05/20/08
Approx. Latitude (N) / Longitude (W): 36.022238 / - 77.880633
Nominal Surface: S9.5B
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
NC 43 NB	98.4	98.4			**98.4**
NC 43 SB	97.9	98.0			**98.0**
	Overall Average				**98.2**

Site 7: NC 94

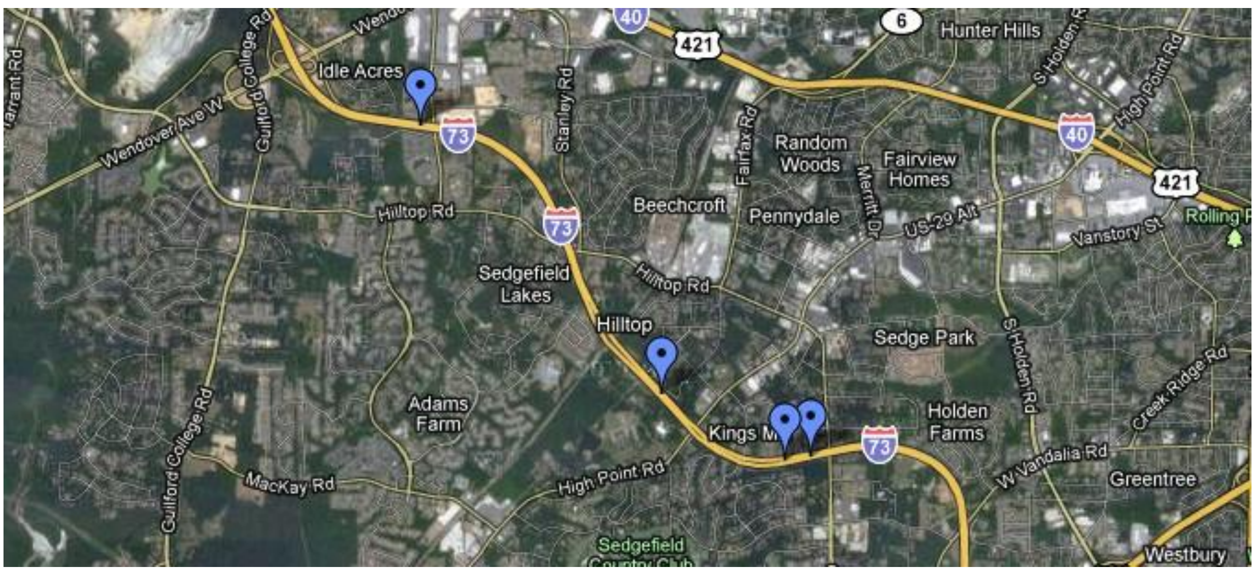
Test Date: 7/29/2010
Location: Tyrrell Co.
Construction Year: 2009
Approx. Latitude (N) / Longitude (W): 35.786627 / -76.188869
Nominal Surface: S9.5B
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
NC 94 SB	97.3	97.7			**97.5**
NC 94 NB	97.9				**97.9**
	Overall Average				**97.7**

Site 8: I-73

Test Date: 10/15/2010
Location: Guilford Co.
Construction Year: Not Verified
Approx. Latitude (N) / Longitude (W): 36.022412 / - 79.877951
Nominal Surface: Concrete
Test method: OBSI

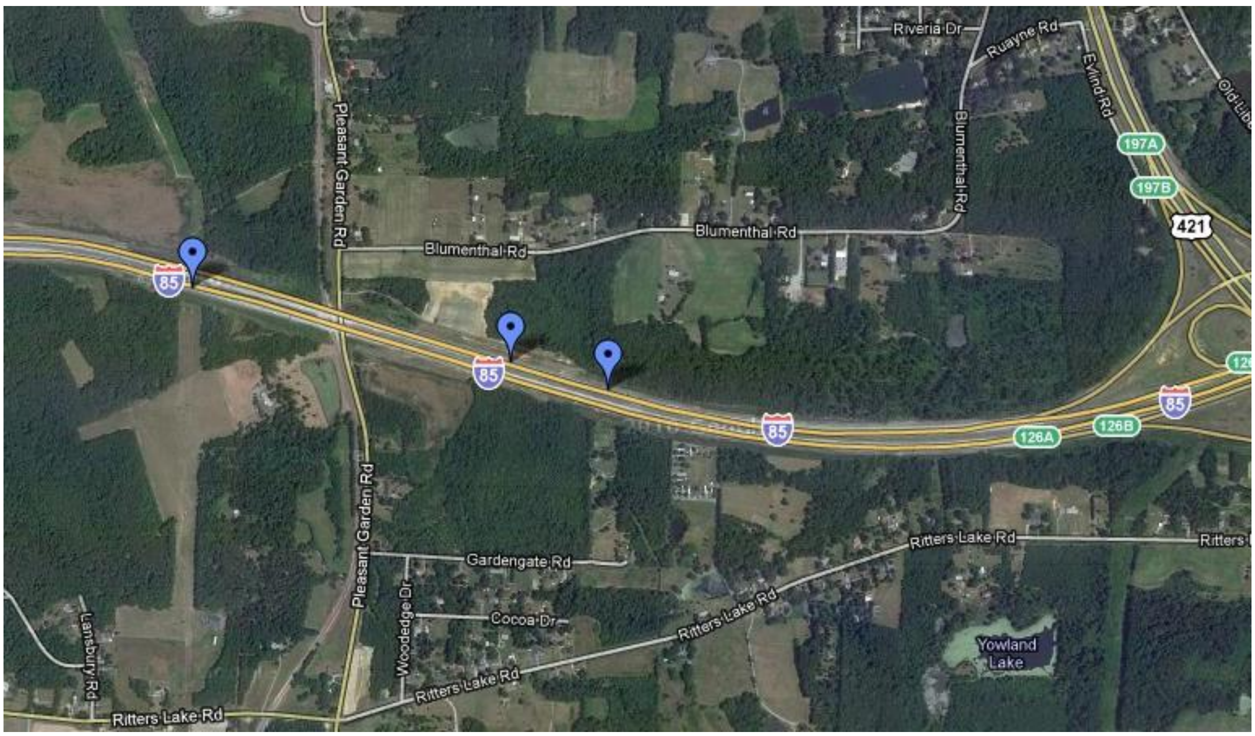
Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Average**	**No Outliers**
I-73 NB-1	100.6	100.9	100.8	100.8	**100.8**
I-73 NB-2	*99.9*	102.7	102.2	101.6	**102.4**
I-73 NB-3	102.9	*105.5*	102.5	103.6	**102.7**
I-73 NB-4	102.9	103.0	102.8	102.9	**102.9**
I-73 SB-1	104.7	104.8	104.5	104.7	**104.7**
I-73 SB-2	104.2	104.2	104.2	104.2	**104.2**
I-73 SB-3	105.5	106.2	105.4	105.7	**105.7**
I-73 SB-4	104.1	103.9	*106.3*	104.8	**104.0**
	Overall Average				**103.4**



Site 9: I-85

Test Date: 10/15/2010
Location: Guilford Co.
Construction Year: Not Verified
Approx. Latitude (N) / Longitude (W): 35.998771 / - 79.774997
Nominal Surface: Concrete
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
I-85 1	104.4	104.8			**104.6**
I-85 2	105.3	105.4			**105.4**
I-85 3	104.5	105.0			**104.7**
	Overall Average				**104.9**



Site 10: I-95

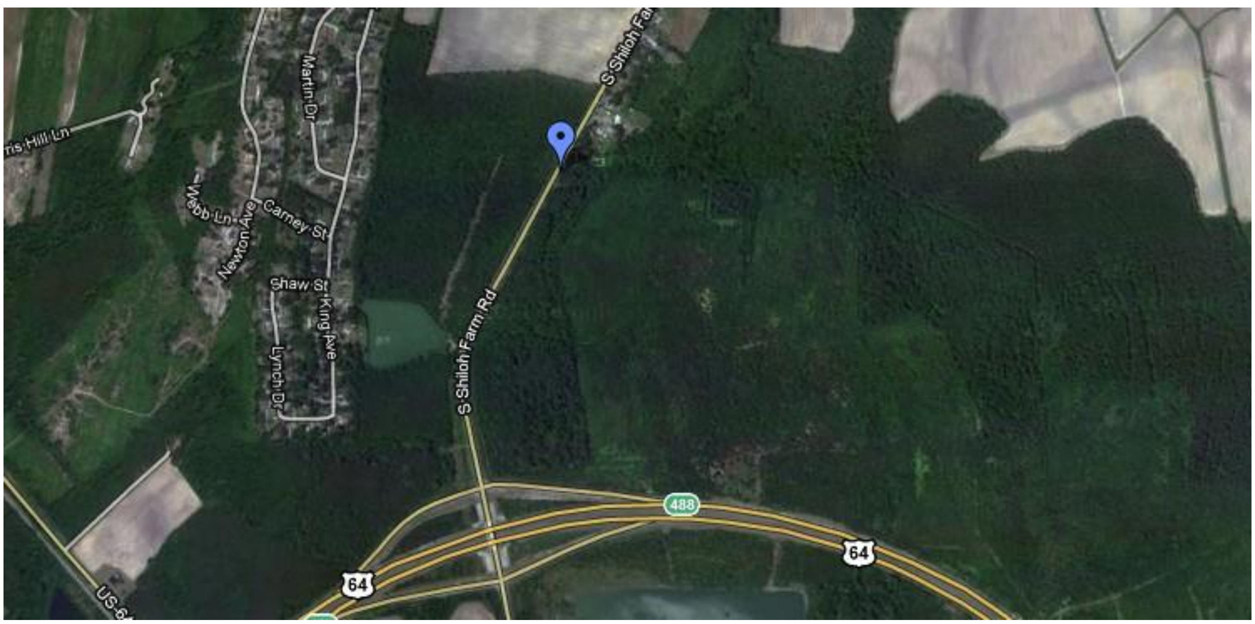
Test Date: 7/29/2010
Location: Wilson Co.
Construction Year: Not Verified
Approx Latitude (N) / Longitude (W): 35.634802 /- 78.10632
Nominal Surface: OGFC
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
I-95-1	102.3	102.0	100.7		**101.7**
I-95-2	102.2	102.5	101.1		**101.9**
I-95-3	101.9	101.8	101.1		**101.6**
I-95-4	102.1	101.3	102.5		**102.0**
	Overall Average				**101.8**

Site 11: SR 1523

Test Date: 2/9/11
Location: Edgecombe Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 35.705018 / - 77.680643
Nominal Surface: SF9.5A
Test method: OBSI

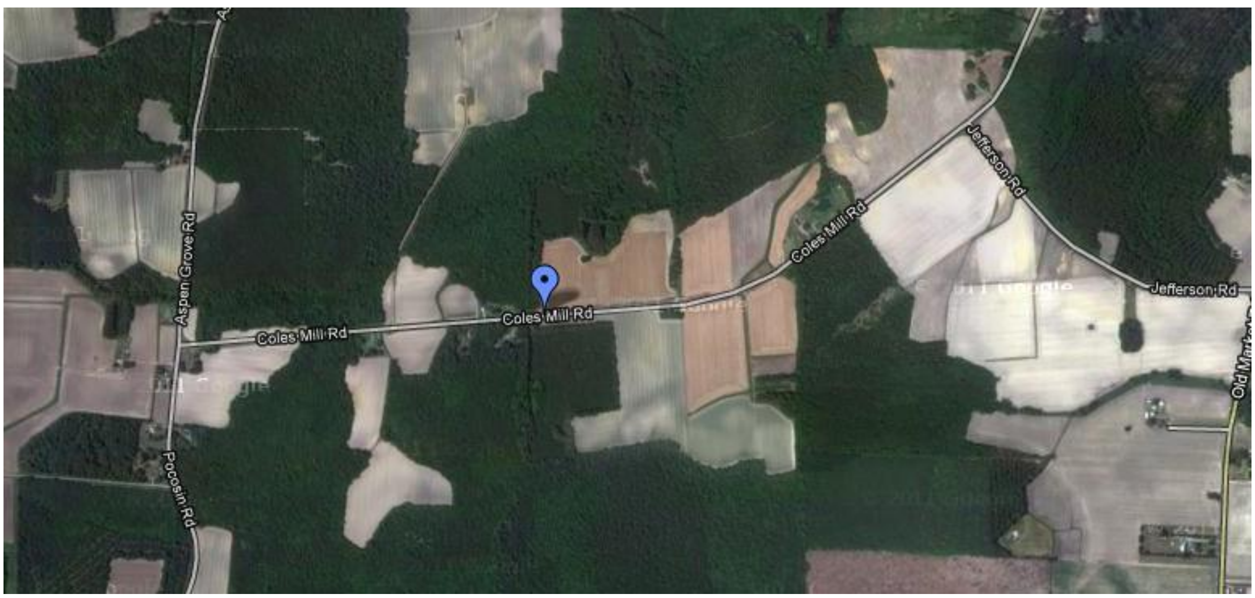
Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1523 SB	98.3	98.5	98.8		98.5
SR 1523 NB	98.4	98.6	98.2		98.4
	Overall Average				**98.5**



Site 12: SR 1105

Test Date: 2/9/2011
Location: Edgecombe Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 35.877124 / - 77.500269
Nominal Surface: SF9.5A
Test method: OBSI

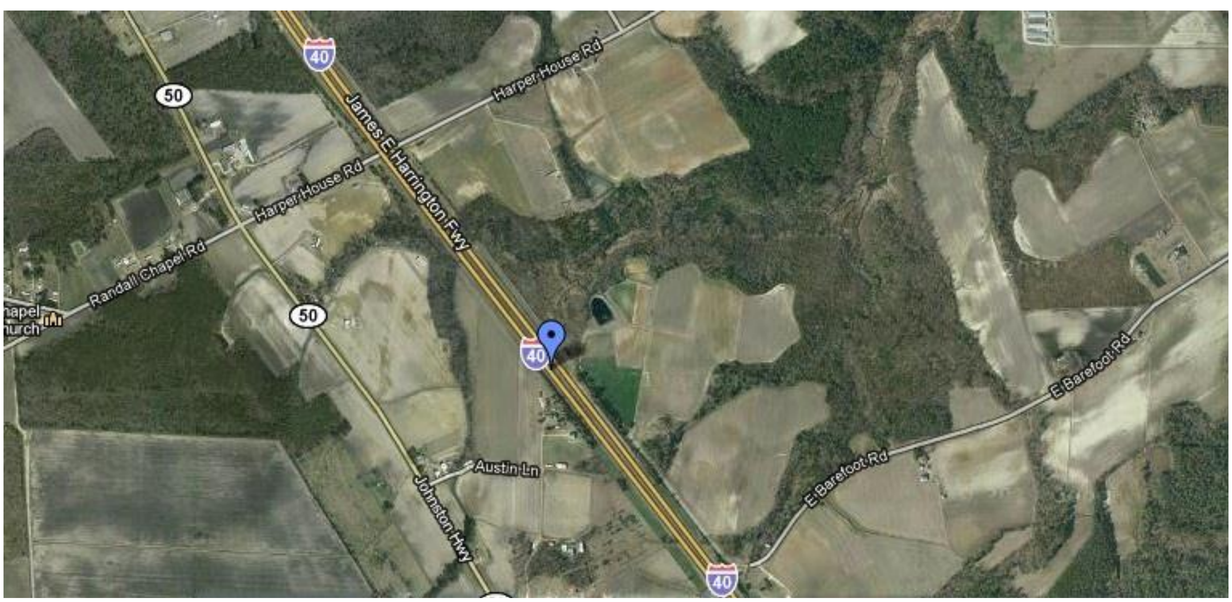
Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1105 EB	98.8	98.6	98.9	98.7	**98.8**
SR 1105 WB	98.6	98.3	98.5		**98.4**
	Overall Average				**98.6**



Site 13: I-40

Test Date: 2/11/11
Location: Sampson Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 35.264578 / - 78.387415
Nominal Surface: OGFC
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
I-40 EB	102.4	102.9	102.5		**102.6**
I-40 WB	101.9	101.9	102.2		**102.0**
	Overall Average				**102.3**

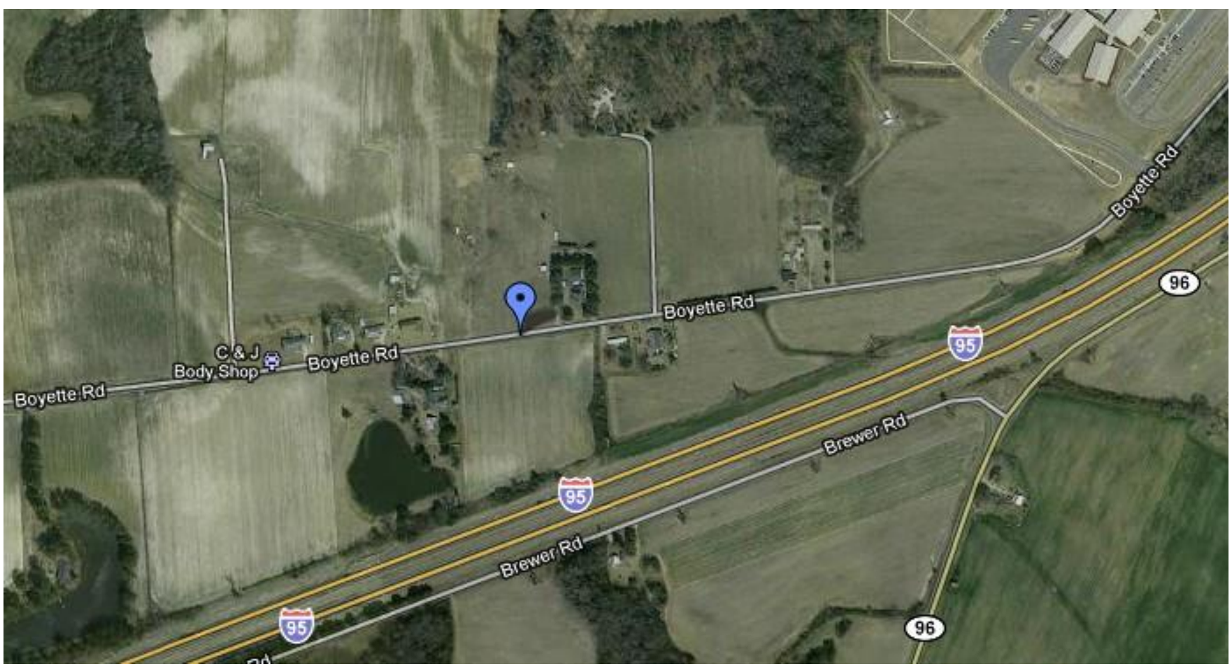


Site 14: SR 1182

Test Date: 2/11/2010
Location: Johnston Co.
Construction Year: 2009
Approx Latitude (N) / Longitude (W): 35.44493 - 78.410702
Nominal Surface: S9.5B
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1182 EB	100.2	100.5	100.6		**100.4**
SR 1182 WB	100.6	100.5	100.4		**100.5**
	Overall Average				**100.5**



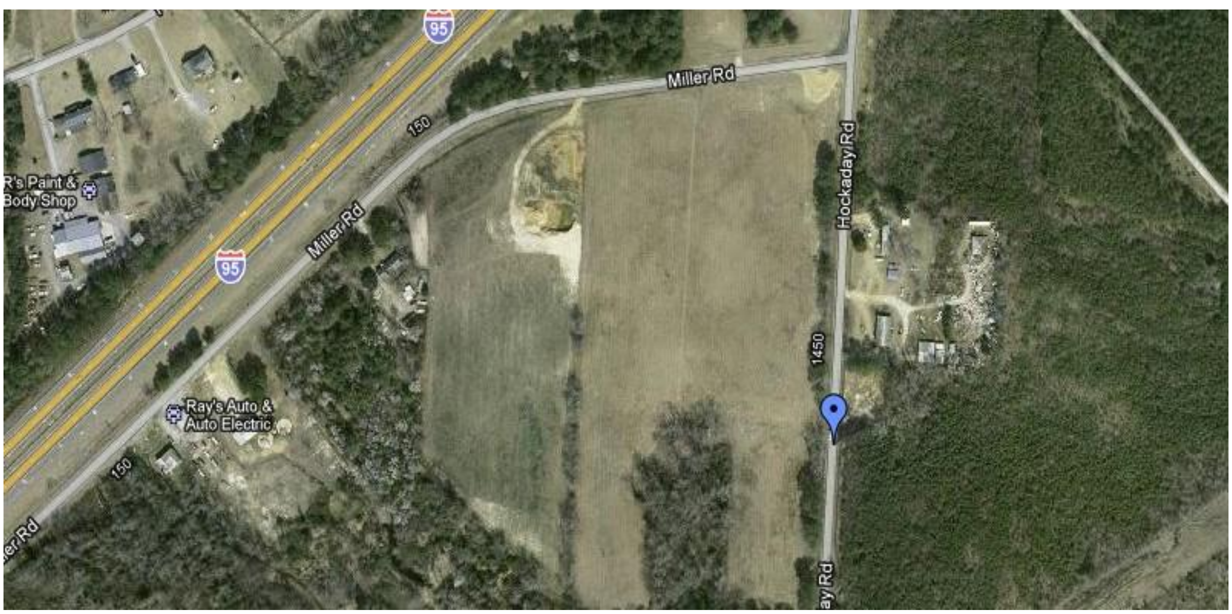


Site 15: SR 1162

Test Date: 2/11/11
Location: Johnston Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 35.431119 / - 78.426399
Nominal Surface: S9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1162 SB	99.0	99.4	99.0		**99.1**
SR 1162 NB	99.3	99.2	99.2		**99.2**
	Overall Average				**99.2**



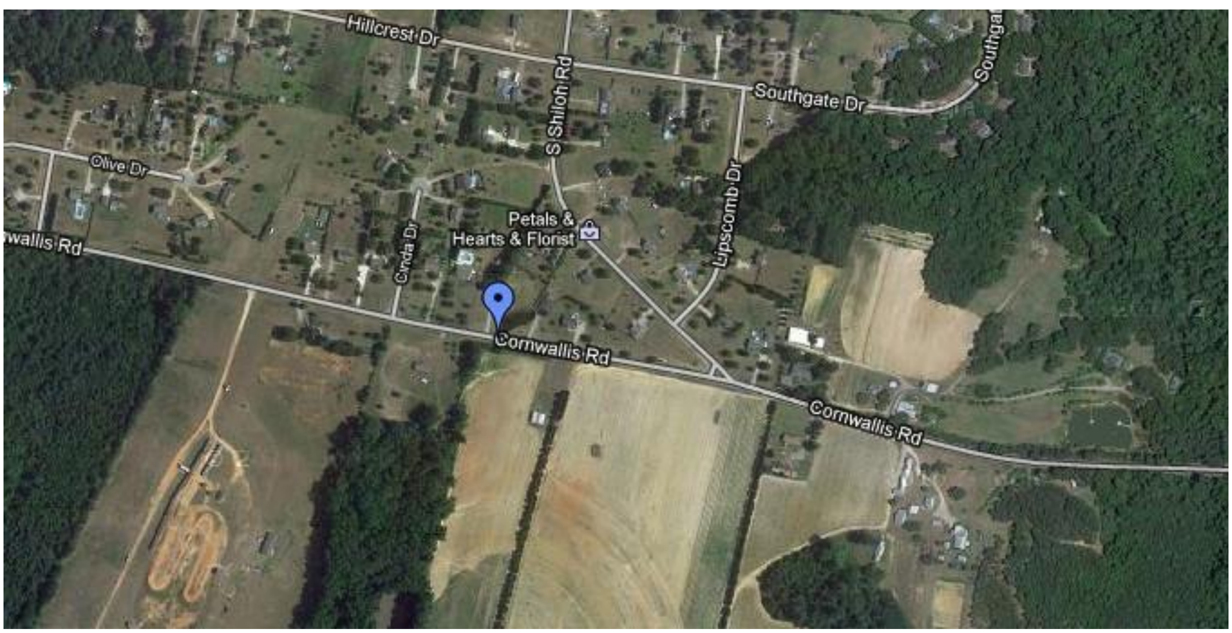


Site 16: SR 1525

Test Date: 2/11/11
Location: Johnston Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 35.57292 / - 78.562721
Nominal Surface: S9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1525 WB	98.5	98.4	*98.4*		**98.4**
SR 1525 EB	98.8	98.7	98.7		**98.8**
	Overall Average				**98.6**



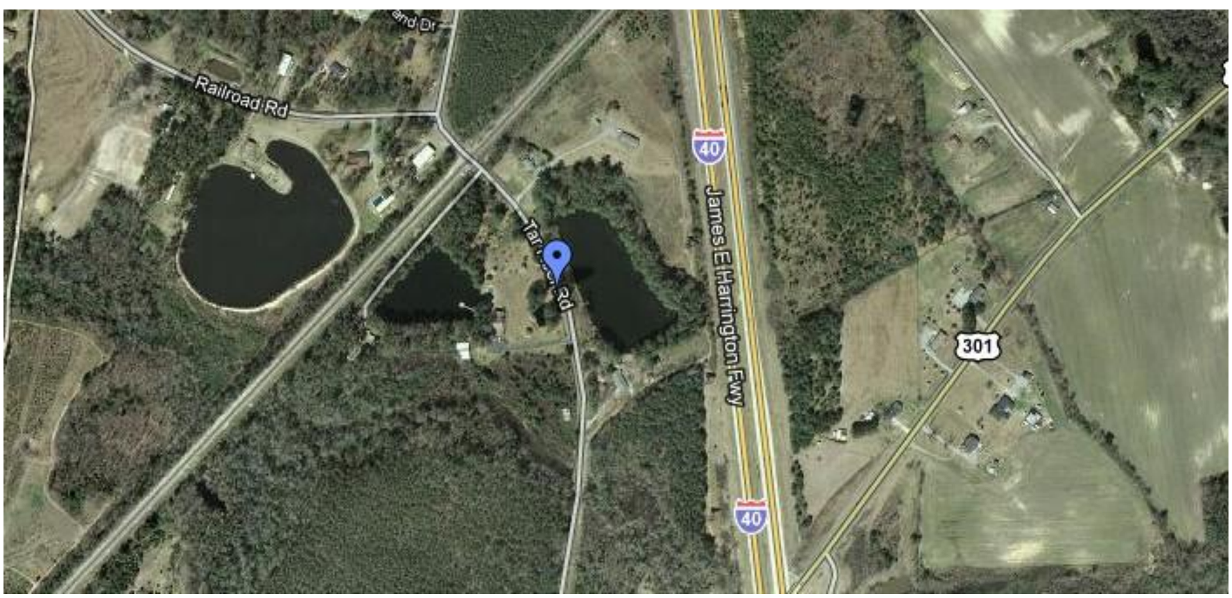


Site 17: SR 1168

Test Date: 2/11/11
Location: Johnston Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 35.401487 / - 78.52532
Nominal Surface: S9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1168 EB	99.95893	99.67432	100.1265		**99.9**
SR 1168 WB	99.32774	99.44125	99.61015		**99.5**
	Overall Average				**99.7**





Site 18: SR 1501

Test Date: 2/16/2011
Location: Martin Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): Not recorded
Nominal Surface: SF9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1501	99.6	99.4	99.6		**99.5**

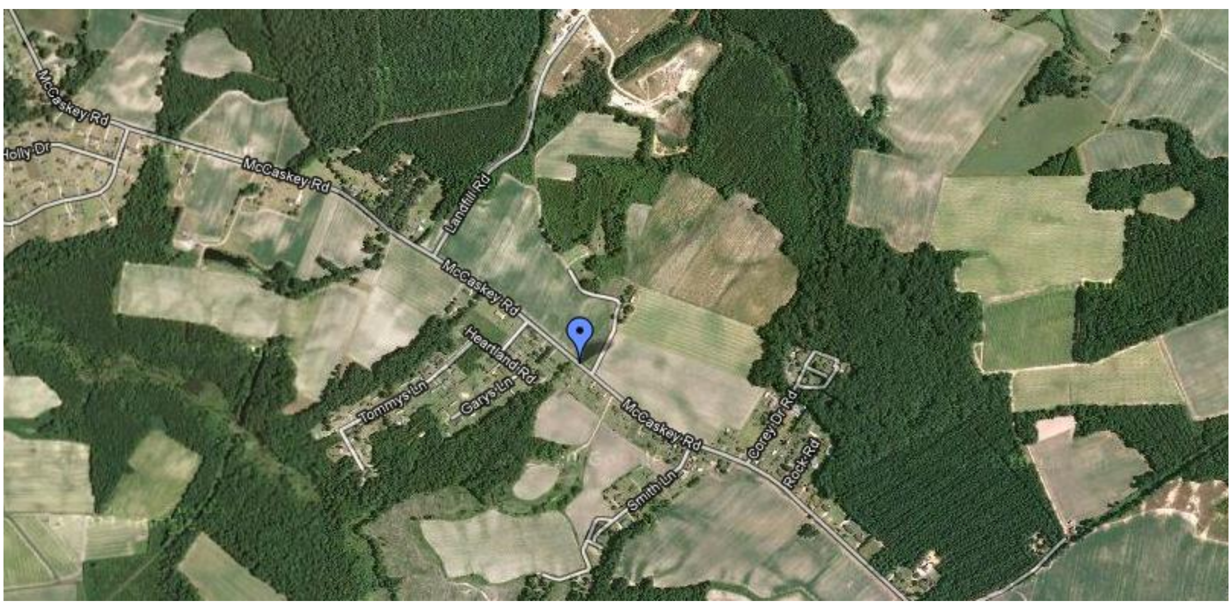
Uncertain Geographical Location on SR 1501 in Martin County.

Site 19: SR 1420 and SR 1501

Test Date: 2/16/11
Location: Martin Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 35.856918 / - 77.094841
Nominal Surface: SF9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1501	99.6	99.4	99.6		**99.5**
SR 1420 NW	99.5	99.0	99.2		**99.2**
SR 1420 SE	99.4	99.2	99.1		**99.2**
	Overall Average				**99.3**



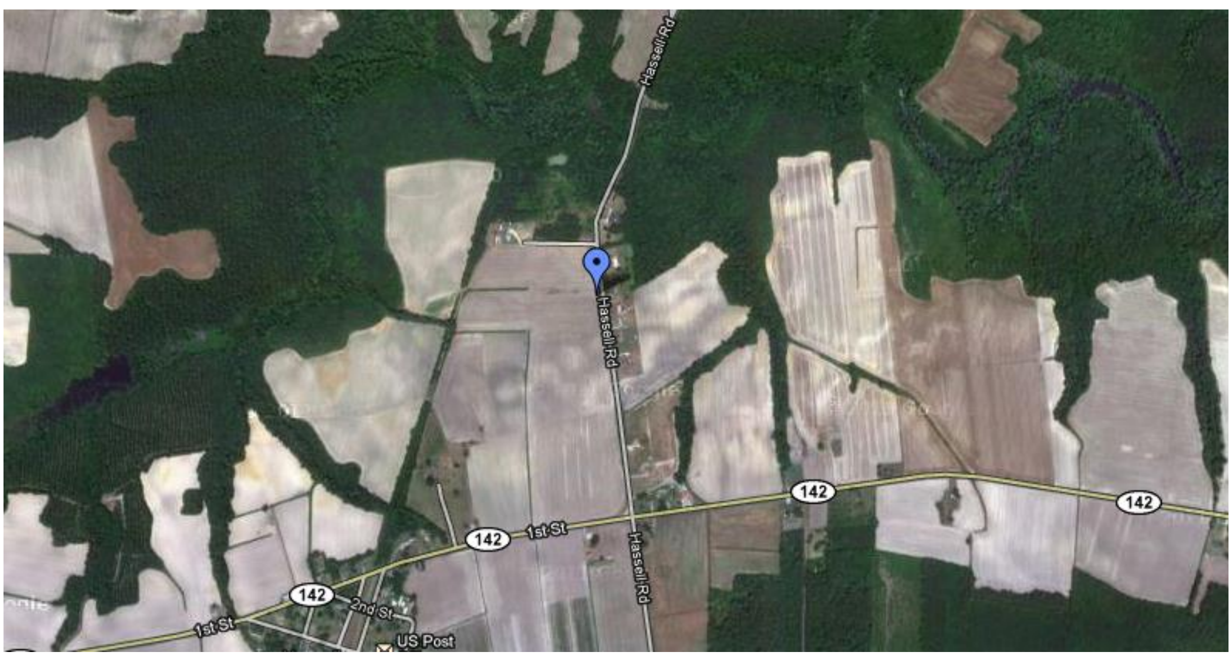


Site 20: SR 1002

Test Date: 2/16/11
Location: Martin Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 35.915921 / - 77.271402
Nominal Surface: SF9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1002 SB	99.0	98.9	98.8		**98.9**
SR 1002 NB	98.6	98.8	98.9		**98.8**
	Overall Average				**98.8**

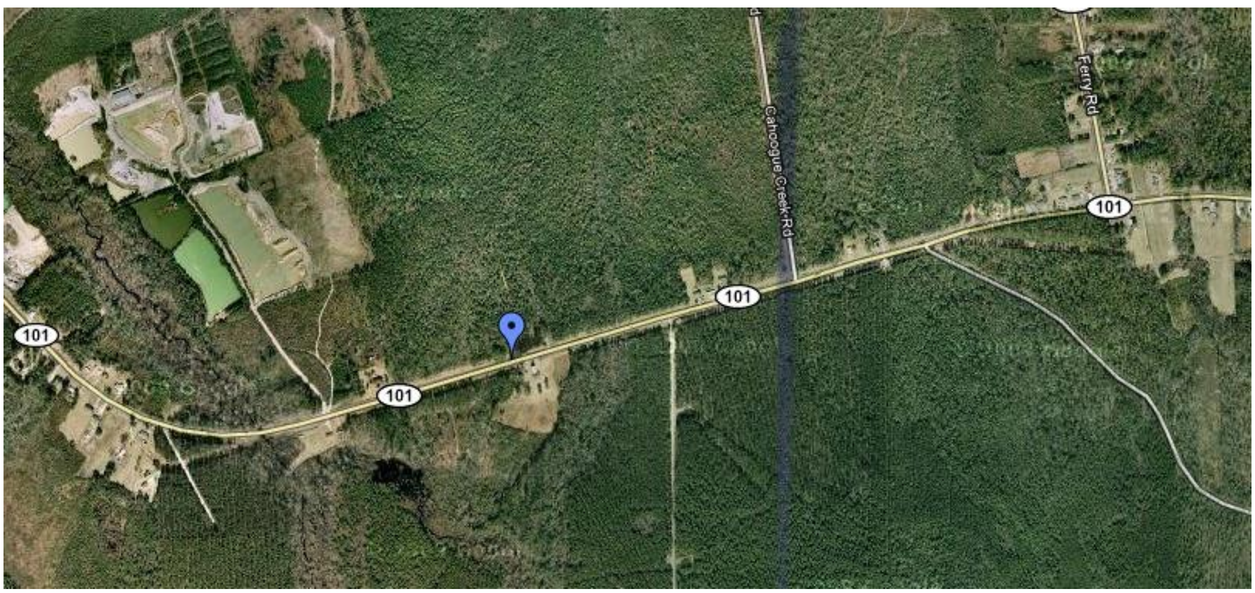




Site 21: NC 101

Test Date: 2/18/11
Location: Craven Co.
Construction Year: 2009
Approx. Latitude (N) / Longitude (W): 34.870722 / - 76.840982
Nominal Surface: S9.5B
Test method: OBSI

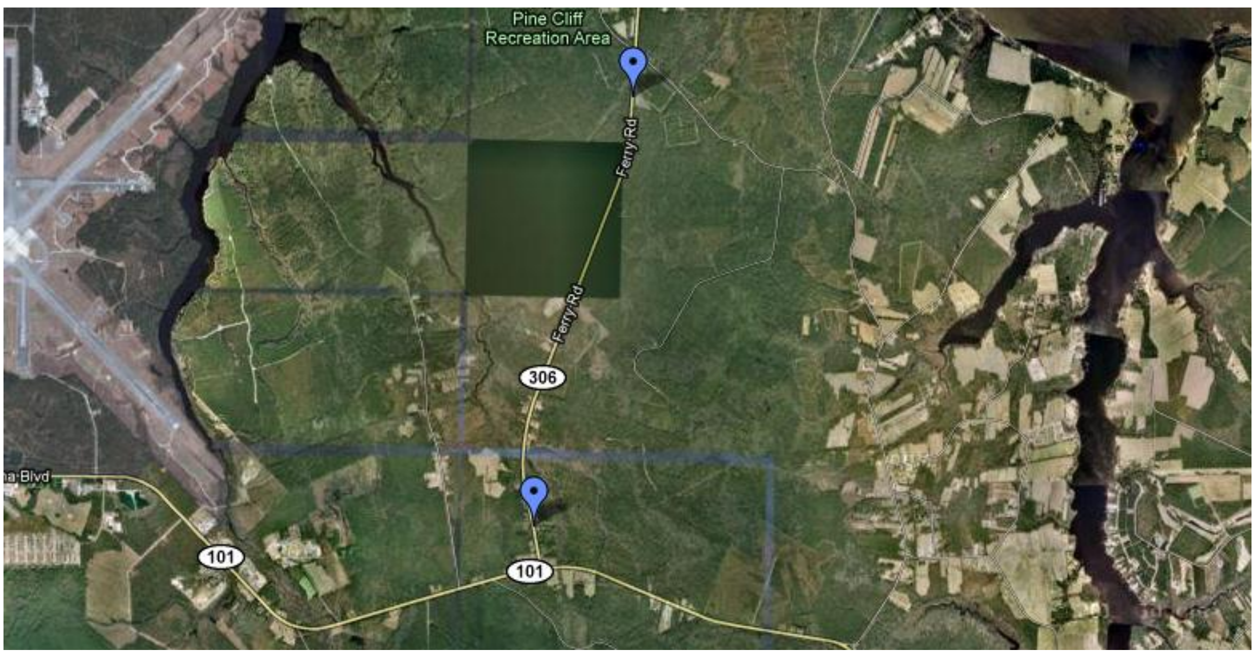
Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
NC 101 WB	99.2	99.1	99.1		**99.1**
NC 101 EB	98.8	99.0	99.1		**99.0**
	Overall Average				**99.1**



Site 22: NC 306

Test Date: 2/18/11
Location: Craven Co.
Construction Year: 2009
Approx. Latitude (N) / Longitude (W): 34.902686 / - 76.818323
Nominal Surface: S9.5B
Test method: OBSI

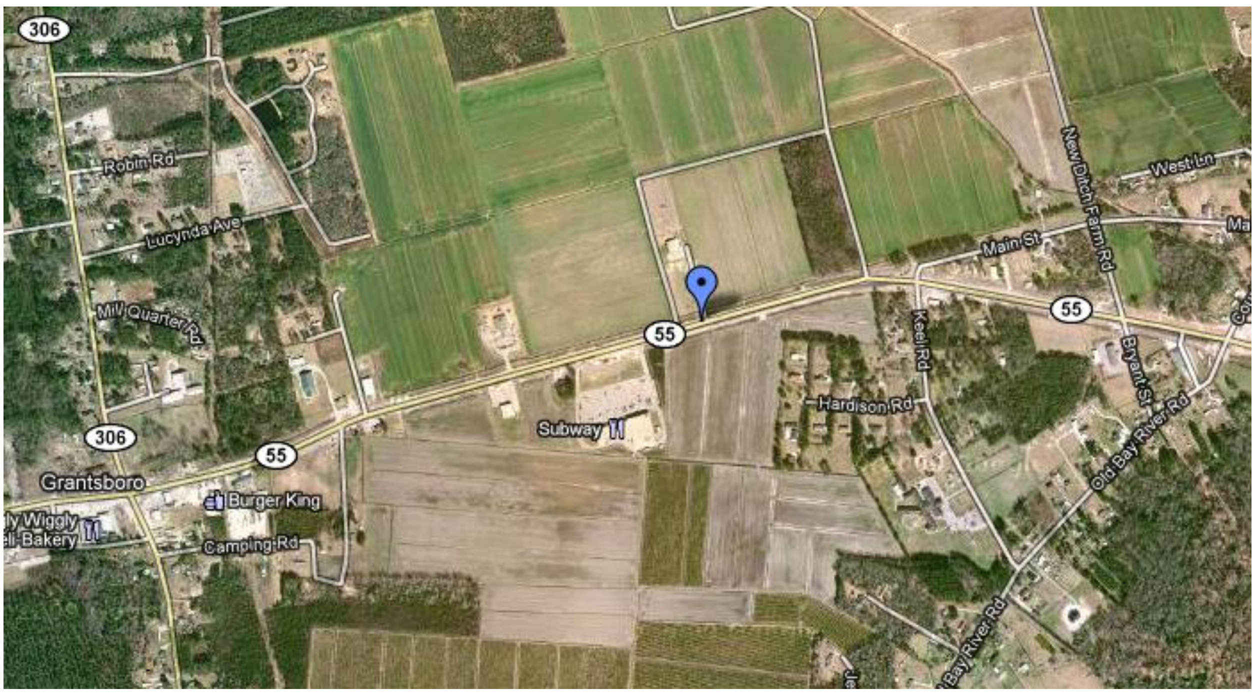
Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
NC 306 SB-1	98.4	98.4	98.3		**98.4**
NC 306 SB-2	98.5	98.3	98.1	98.3	**98.3**
NC 306 NB-1	98.4	98.5	98.4		**98.4**
NC 306 NB-2	97.5	97.9	97.7	98.0	**97.8**
	Overall Average				**98.2**



Site 23: NC 55

Test Date: 2/18/11
Location: Pamlico Co.
Construction Year: 2009
Approx. Latitude (N) / Longitude (W): 35.143915 / - 76.828508
Nominal Surface: S9.5C
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
NC 55 EB	98.7	98.5	98.9		**98.7**
NC 55 WB	98.8	98.8	98.8		**98.8**
	Overall Average				**98.7**

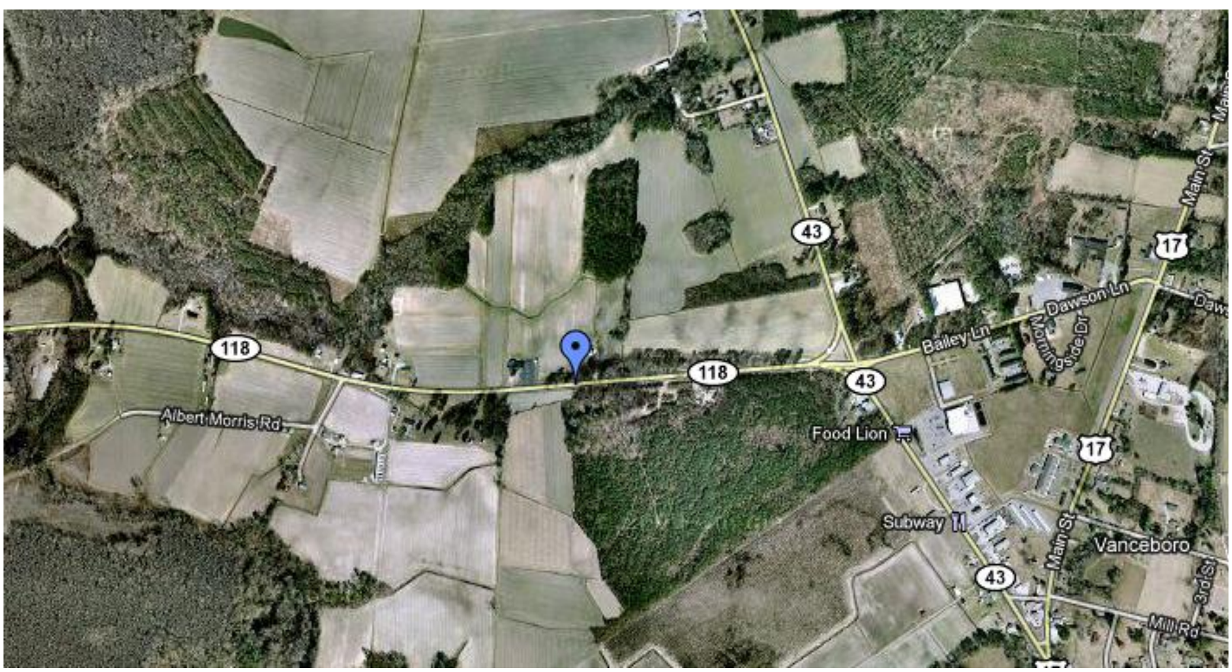


Site 24: NC 118

Test Date: 2/18/11
Location: Craven Co.
Construction Year: 2009
Approx. Latitude (N) / Longitude (W): 35.311973 / - 77.168276
Nominal Surface: S9.5B
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
NC 118 EB	99.2	99.4	99.5		**99.3**
NC 118 WB	99.6	99.7	99.4		**99.6**
	Overall Average				**99.5**

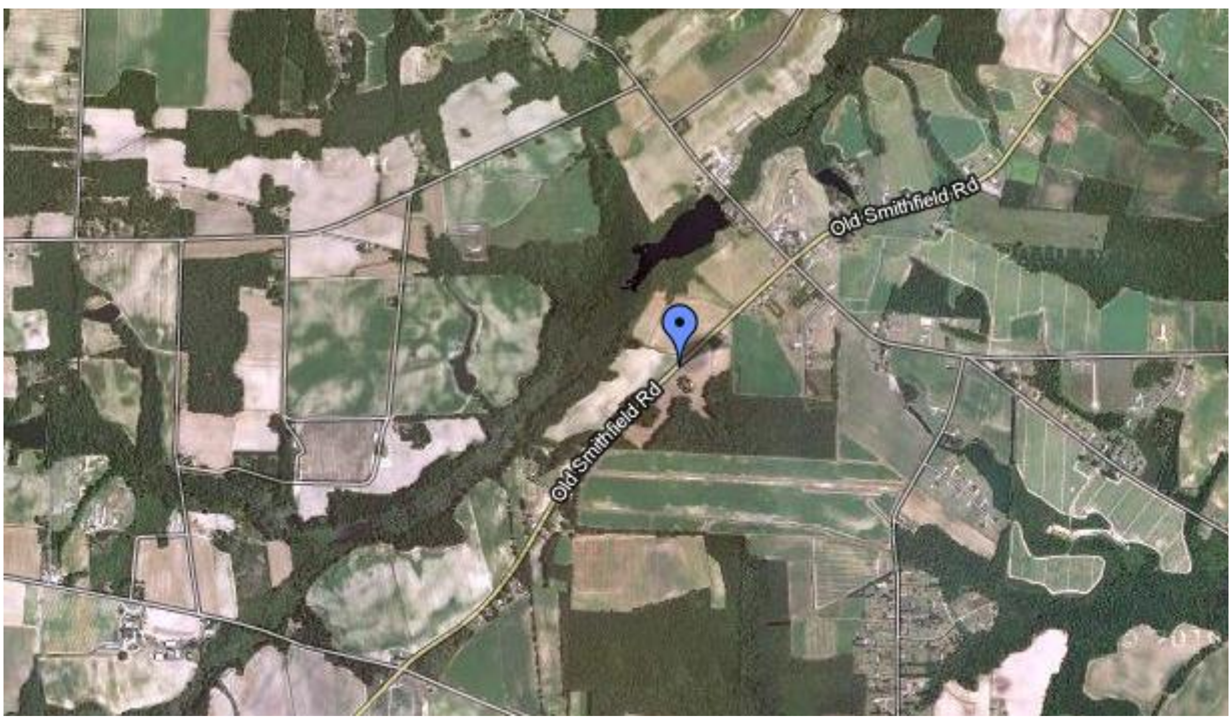




Site 25: SR 1945

Test Date: 2/23/2011
Location: Nash Co.
Construction Year: 2009
Approx Latitude (N) / Longitude (W): 35.803544 / - 78.050408
Nominal Surface: SF9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1945 SW	99.3	99.3	99.5		**99.4**
SR 1945 NE	99.7	99.8	99.8		**99.7**
	Overall Average				**99.6**



Site 26: SR 1733

Test Date: 2/23/11
Location: Nash Co.
Construction Year: 2009
Approx. Latitude (N) / Longitude (W): 35.888024 / - 77.853202
Nominal Surface: SF9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1733 EB	98.9	98.9	98.9		**98.9**
SR 1733 WB	98.6	98.9	99.1		**98.9**
	Overall Average				**98.9**

Site 27: SR 1105

Test Date: 2/23/11
Location: Nash Co.
Construction Year: 2009
Approx. Latitude (N) / Longitude (W): 35.775364 / - 78.134726
Nominal Surface: SF9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1105 NE	98.6	98.9	98.6		**98.7**
SR 1105 SW	98.5	98.6	98.7		**98.6**
	Overall Average				**98.7**



Site 28: SR 1124

Test Date: 2/23/11
Location: Nash Co.
Construction Year: 2009
Approx. Latitude (N) / Longitude (W): 35.796792 / - 78.227166
Nominal Surface: SF9.5A
Test method: OBSI

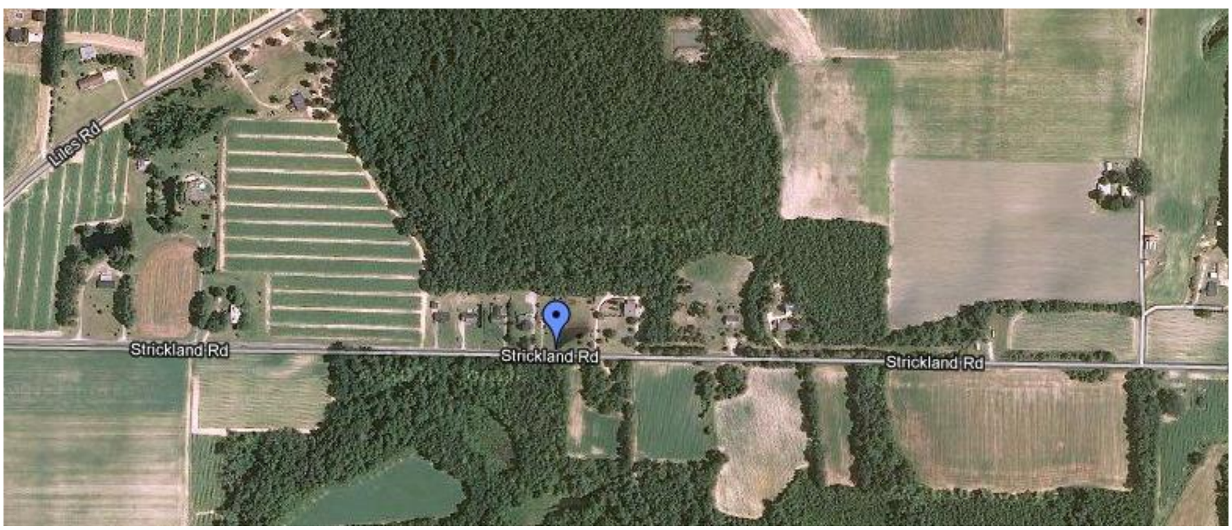
Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1124 NW	99.2	99.2	99.4		**99.3**
SR 1124 SE	98.9	99.1	99.1		**99.0**
	Overall Average				**99.2**

Site 29: SR 1134

Test Date: 2/23/11
Location: Nash Co.
Construction Year: 2009
Approx. Latitude (N) / Longitude (W): 35.826095 / - 78.084708
Nominal Surface: SF9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1134 EB	99.5	98.7	99.6		**99.3**
SR 1134 WB	98.7	98.9	98.8		**98.8**
	Overall Average				**99.0**

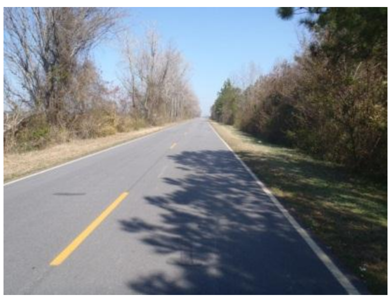


Site 30: SR 1180

Test Date: 3/18/11
Location: Washington Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 35.813515 / - 76.571106
Nominal Surface: SF9.5A
Test method: OBSI

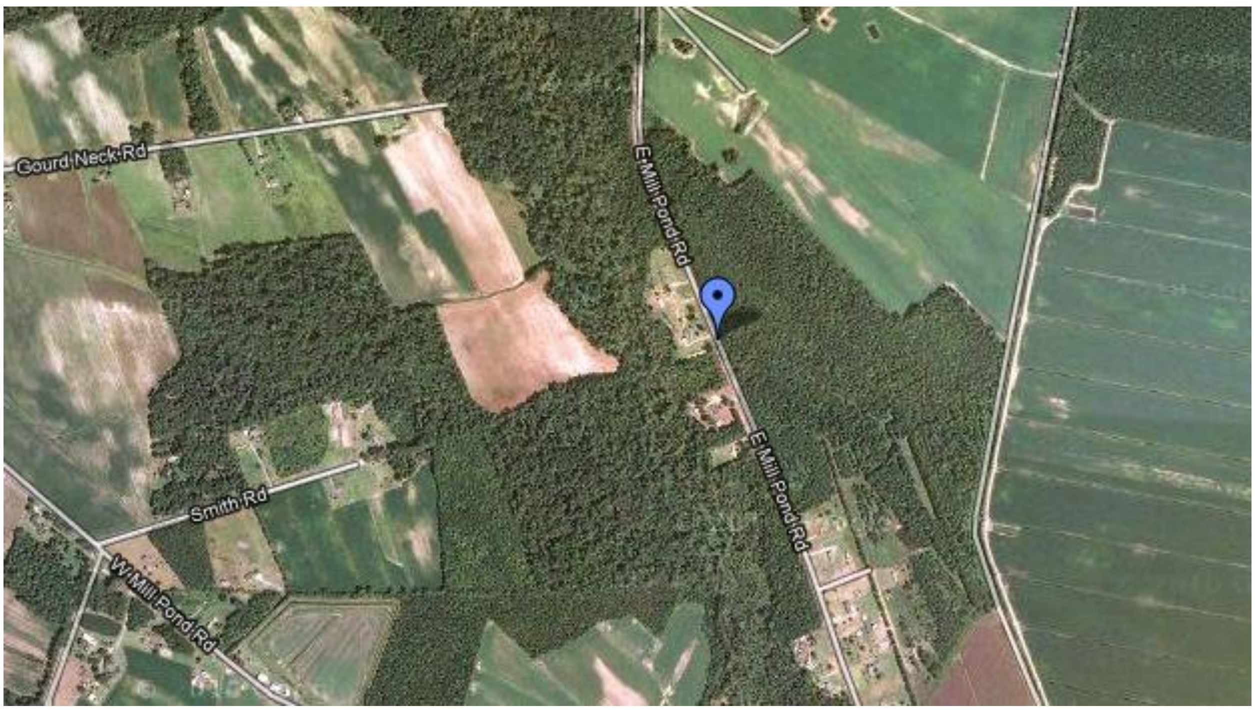
Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1180 A	100.4	100.3	100.6		**100.4**
SR 1180 B	100.4	100.6	100.5		**100.5**
	Overall Average				**100.5**



Site 31: SR 1125

Test Date: 3/18/11
Location: Washington Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 35.852466 / - 76.603682
Nominal Surface: SF9.5A
Test method: OBSI

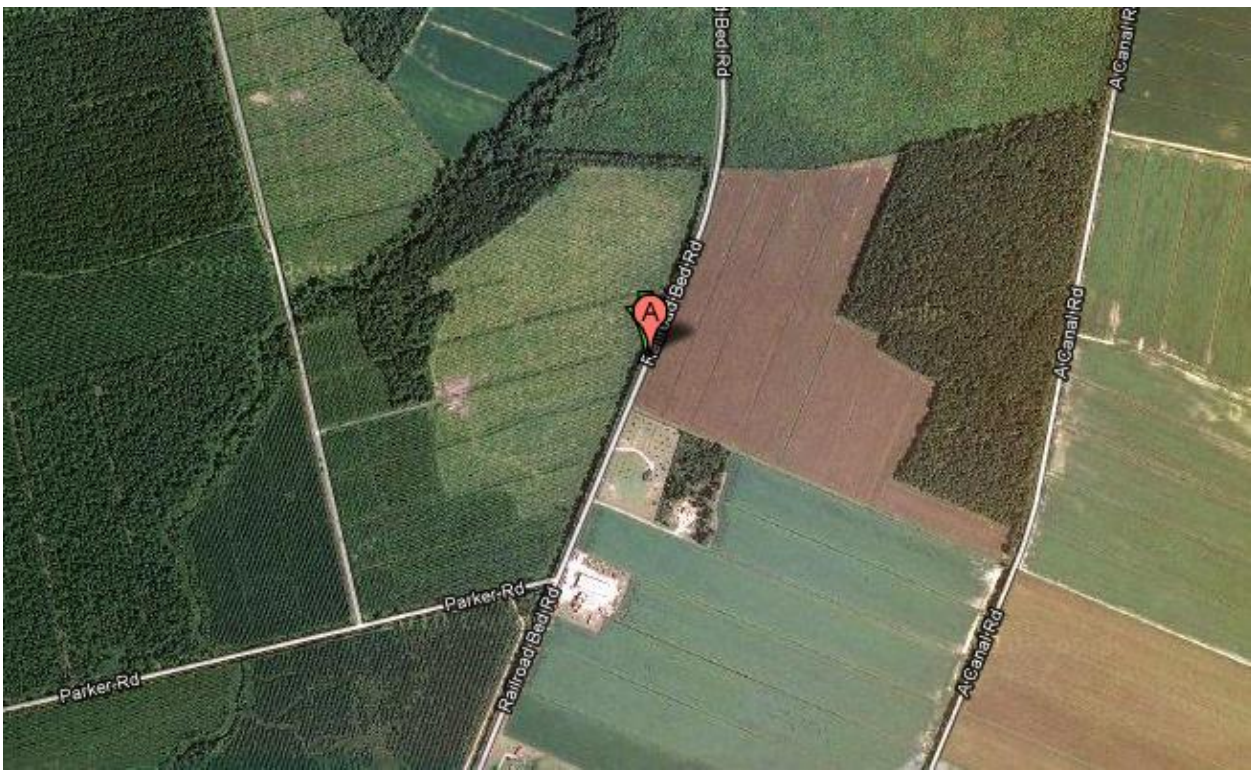
Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1125 SB	99.9	100.1	100.0		**100.0**
SR 1125 NB	100.4	100.3	100.0		**100.2**
	Overall Average				**100.1**



Site 32: SR 1127

Test Date: 3/18/11
Location: Washington Co.
Construction Year: Not Verified
Approx. Latitude (N) / Longitude (W): 35.824808 / - 76.594927
Nominal Surface: Not Verified
Test method: OBSI

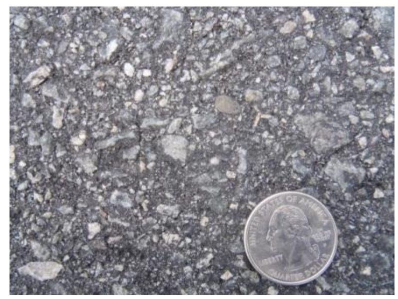
Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1127	98.2	98.5	98.1		**98.3**
SR 1127	98.5	98.5	97.7		**98.2**
	Overall Average				**98.2**

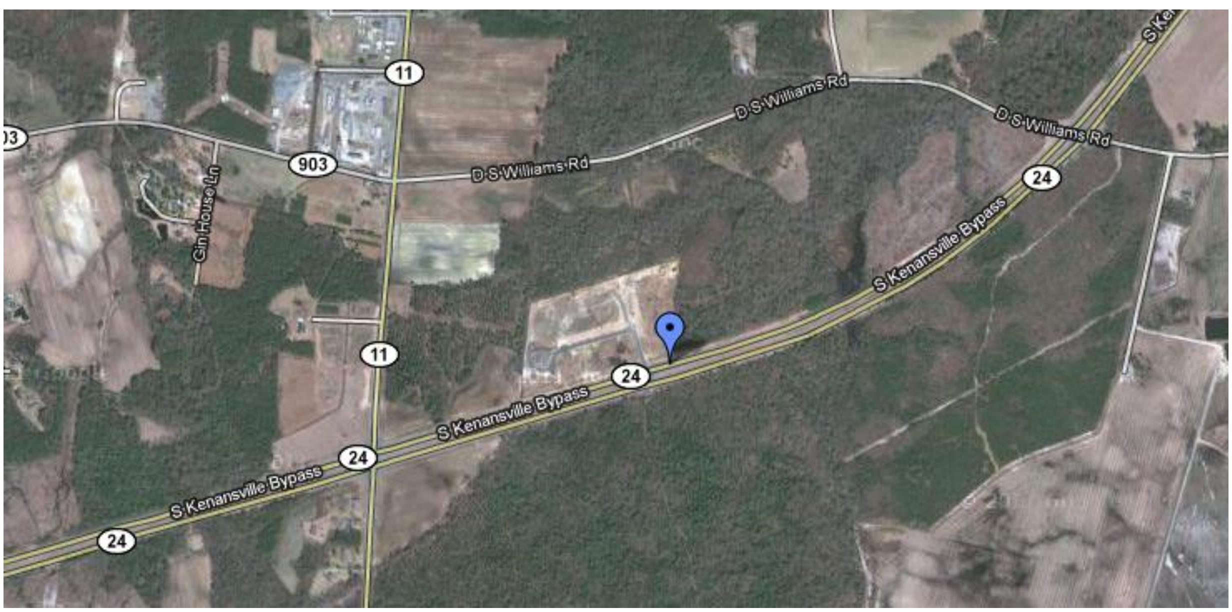


Site 33: NC 24

Test Date: 3/25/11
Location: Duplin Co.
Construction Year: 2009
Approx. Latitude (N) / Longitude (W): 34.936889 / - 77.973025
Nominal Surface: S9.5C
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
NC 24 SB	99.9	99.7	99.8	100.1	**99.9**
NC 24 NB	99.2	99.4	99.5	99.4	**99.4**
	Overall Average				**99.6**



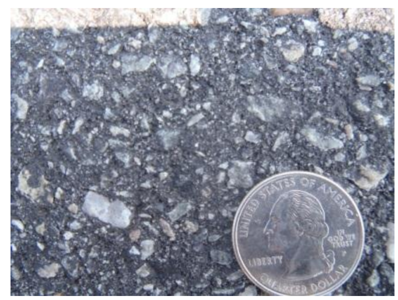


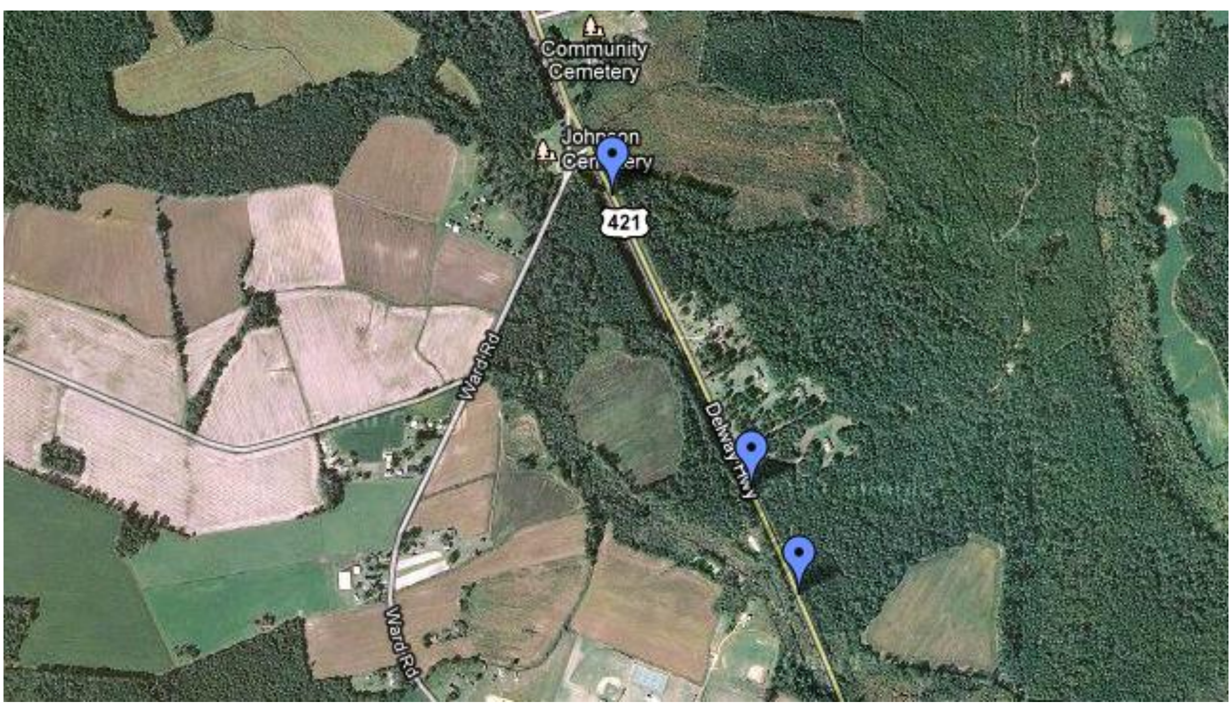
Site 34: US 421

Test Date: 3/25/11
Location: Duplin/Sampson Co.
Construction Year: 2009
Approx. Latitude (N) / Longitude (W): 34.733783 / - 78.196485
Nominal Surface: S9.5C
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
US 421Samp SB-1	99.8	99.7	99.7	99.4	**99.7**
US 421Samp SB-2	99.1	99.2	98.6	98.7	**98.9**
US 421 Duplin SB	99.9	100.2	99.6	99.8	**99.9**
US 421 Duplin NB	99.0	98.6	99.3		**98.9**
US 421Samp NB-1	99.8	99.6	99.9		**99.8**
US 421Samp NB-2	98.8	98.1	98.8		**98.6**







Site 35: NC 118

Test Date: 4/6/11
Location: Lenoir Co.
Construction Year: 2009
Approx. Latitude (N) / Longitude (W): 35.370549 / - 77.452789
Nominal Surface: S9.5B
Test method: OBSI

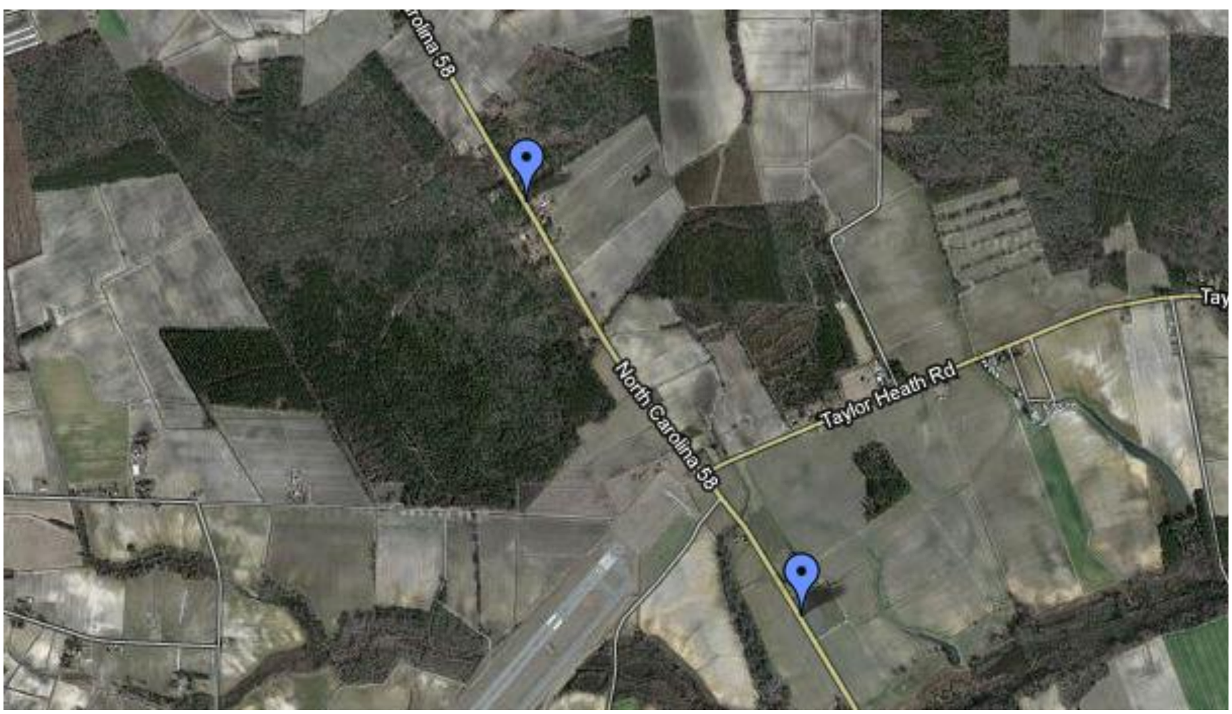
Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
NC 118 EB	98.4	98.7	98.6		**98.6**
NC 118 WB	98.3	98.2	98.3		**98.3**
	Overall Average				**98.4**

Site 36: NC 58

Test Date: 4/6/11
Location: Lenoir/Greene Co.
Construction Year: 2009
Approx. Latitude (N) / Longitude (W): 35.355526 / - 77.599883
Nominal Surface: S9.5B
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
NC 58-Greene NB	97.8	98.0	98.0		**97.9**
NC 58-Greene SB	98.0	97.6	98.2		**97.9**
NC 58-Lenoir NB	97.8	98.2	98.0	98.3	**98.1**
NC 58-Lenoir SB	98.1	98.9	98.6	98.5	**98.5**

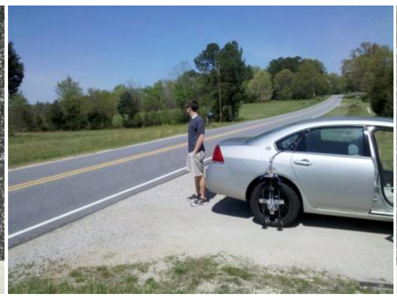


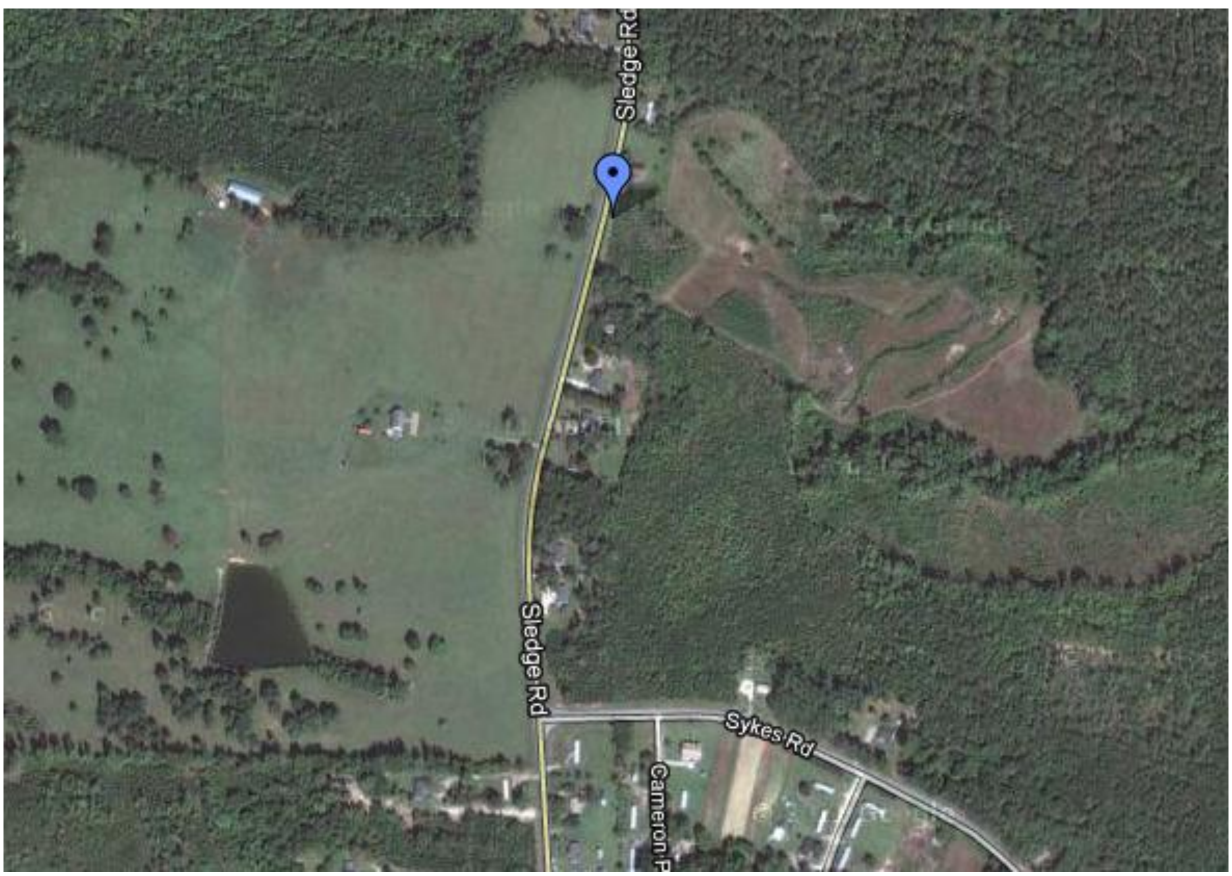



Site 37: SR 1611

Test Date: 4/15/11
Location: Franklin Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 36.003129 / - 78.219506
Nominal Surface: SF9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1611 NB	98.8	98.8	99.2	98.9	**98.9**
SR 1611 SB	98.9	98.4	98.6		**98.6**
	Overall Average				**98.8**

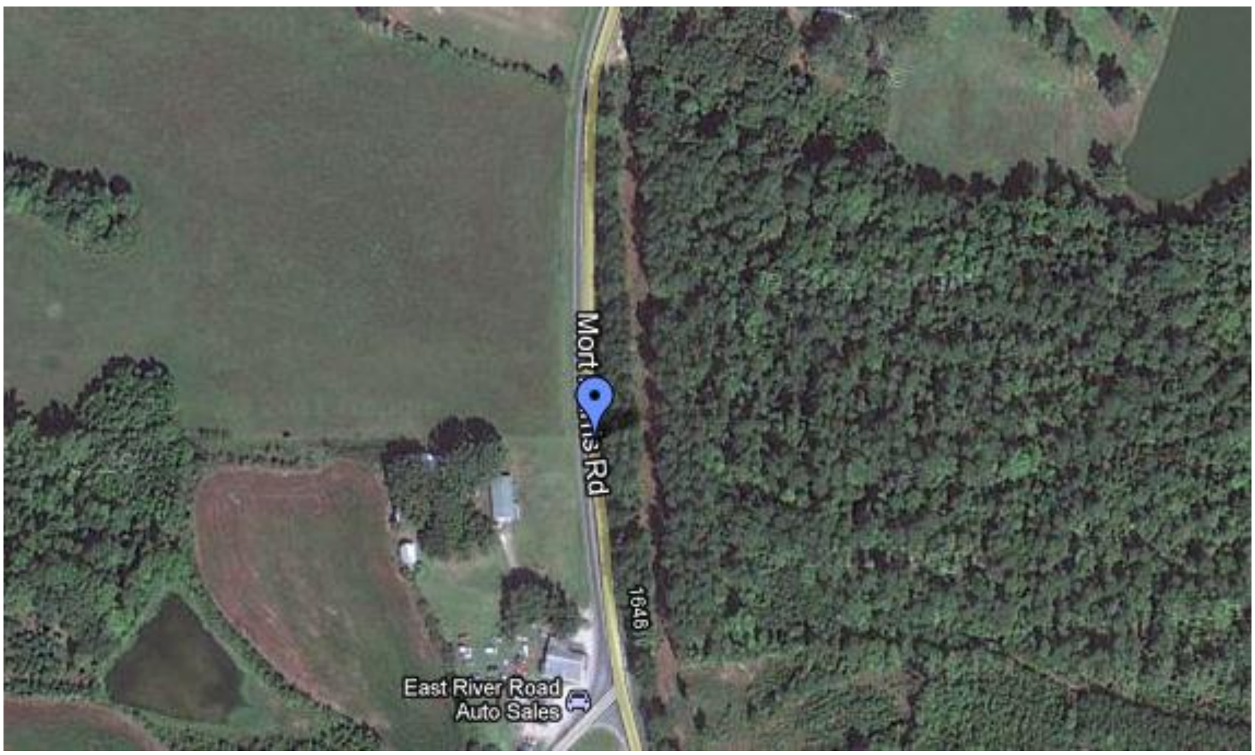





Site 38: SR 1001

Test Date: 4/15/11
Location: Franklin Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 36.025822 / - 78.225941
Nominal Surface: SF9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1001 NB	98.4	98.7	98.2		**98.4**
SR 1001 SB	98.2	98.2	98.6		**98.3**
	Overall Average				**98.4**



Site 39: SR 1335

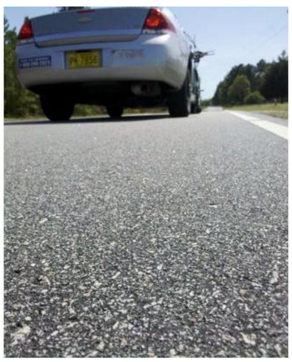
Test Date: 4/15/11
Location: Warren Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 36.472564 / - 78.051406
Nominal Surface: SF9.5A
Test method: OBSI

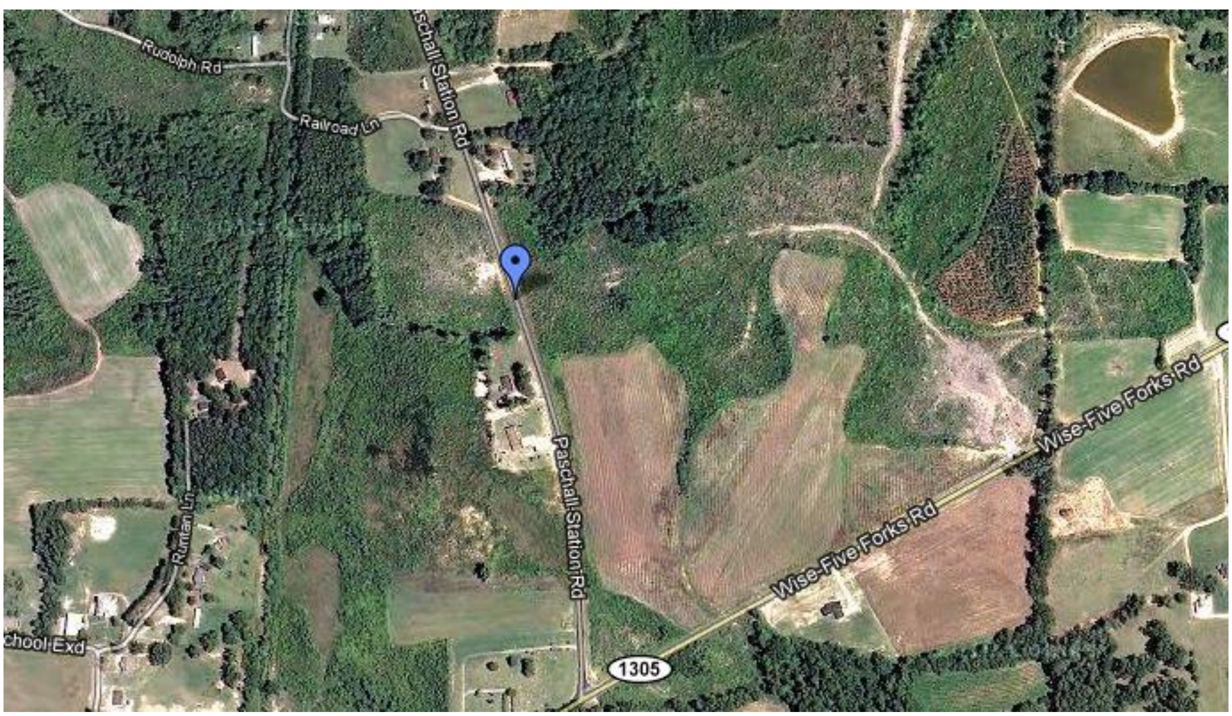
Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1335 NB	99.4	99.6	99.3		**99.5**
SR 1335 SB	99.3	99.5	99.4		**99.4**
	Overall Average				**99.4**

Site 40: SR 1300

Test Date: 4/15/11
Location: Warren Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 36.49946 / - 78.166097
Nominal Surface: SF9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1300 NB	99.6	99.6	99.3	99.5	**99.5**
SR 1300 SB	100.1	99.3	99.8		**99.7**
	Overall Average				**99.6**

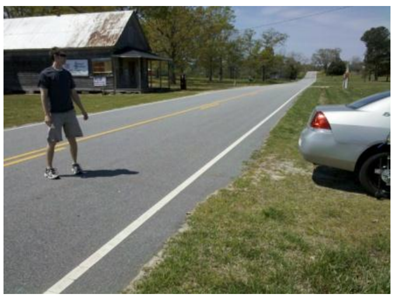


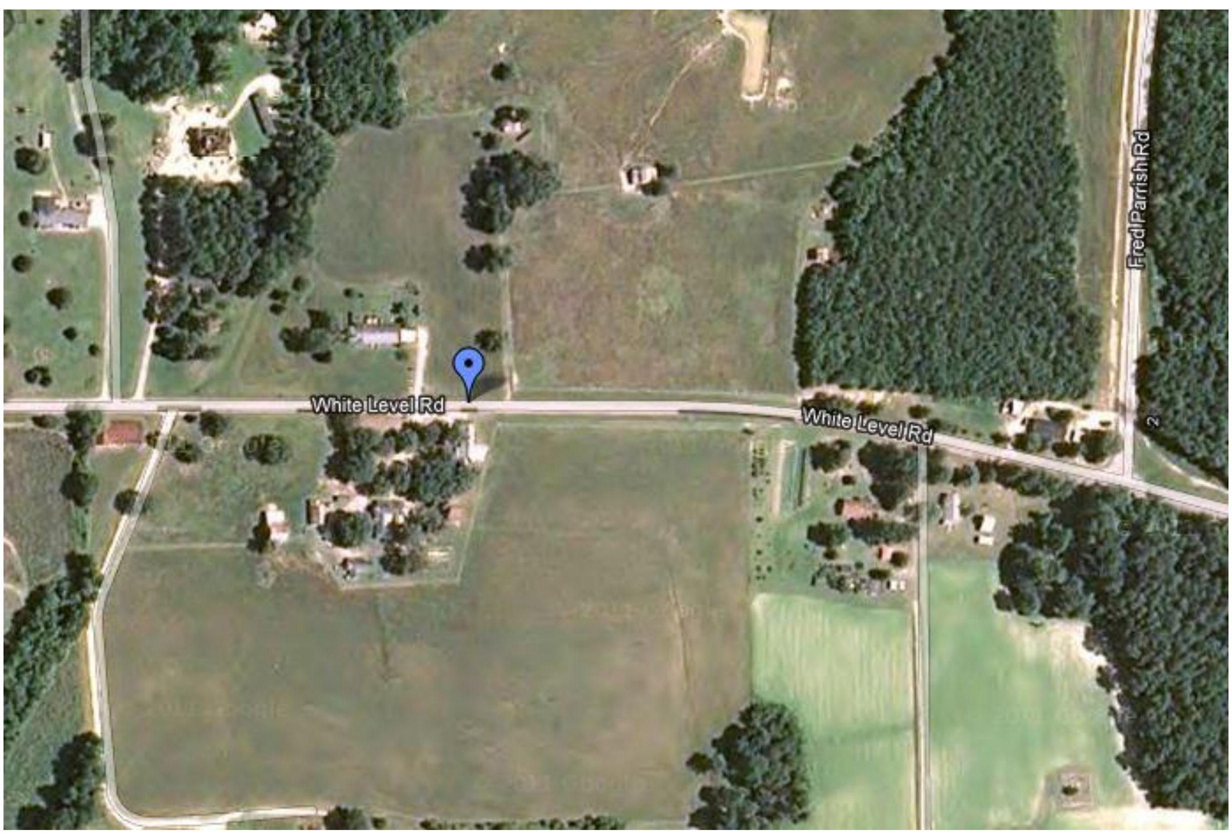


Site 41: SR 1425

Test Date: 4/15/11
Location: Franklin Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 36.13284 / - 78.123406
Nominal Surface: SF9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1425 EB	99.0	99.0	98.8		**98.9**
SR 1425 WB	98.9	98.8	98.6		**98.8**
	Overall Average				**98.9**

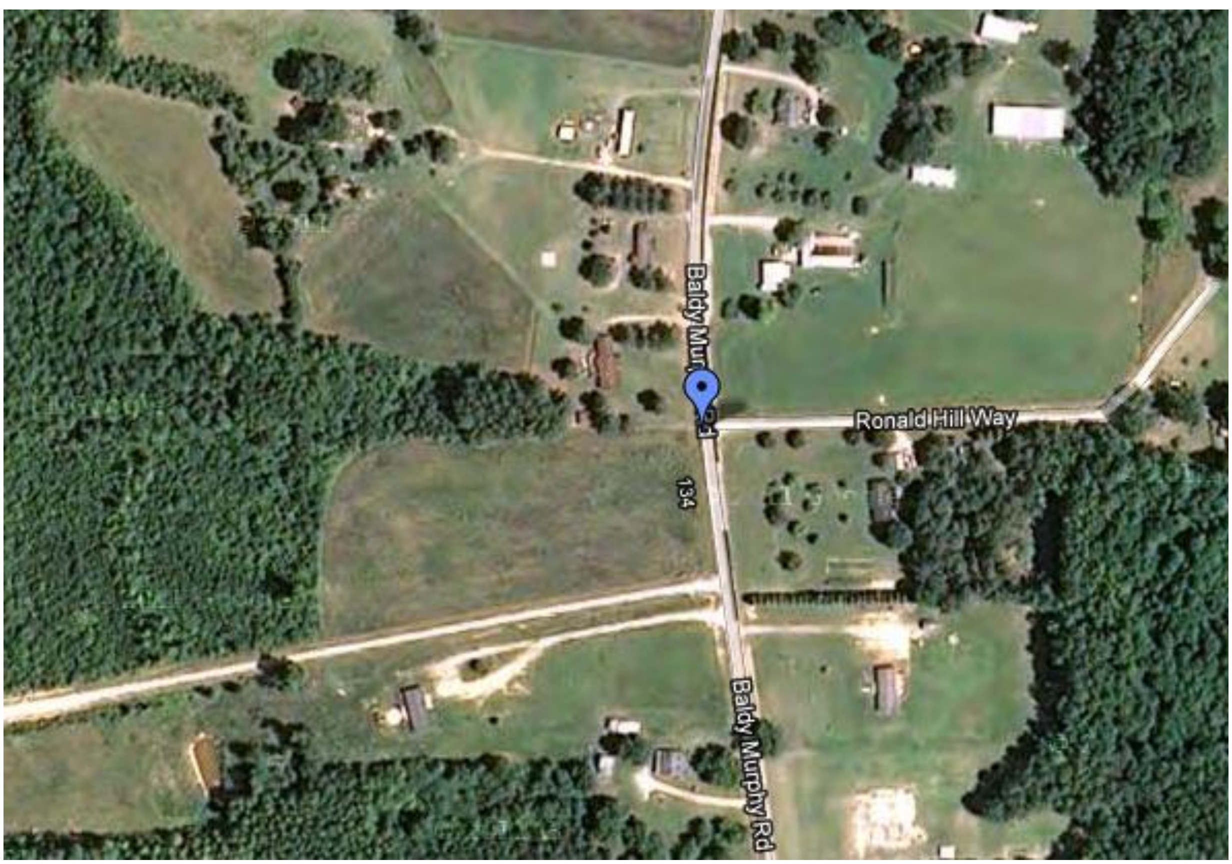




Site 42: SR 1456

Test Date: 4/15/11
Location: Franklin Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 36.137675 / - 78.153253
Nominal Surface: SF9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1456 SB	98.9	98.8	98.4		**98.7**
SR 1456 NB	98.9	98.8	98.8		**98.8**
	Overall Average				**98.7**



Site 43: SR 1620

Test Date: 4/15/11
Location: Warren Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 36.259804 / - 78.15689
Nominal Surface: SF9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1620 EB	98.8	99.2	99.4		**99.2**
SR 1620 WB	98.2	98.4	98.2		**98.3**
	Overall Average				**98.7**



Site 44: SR 1518

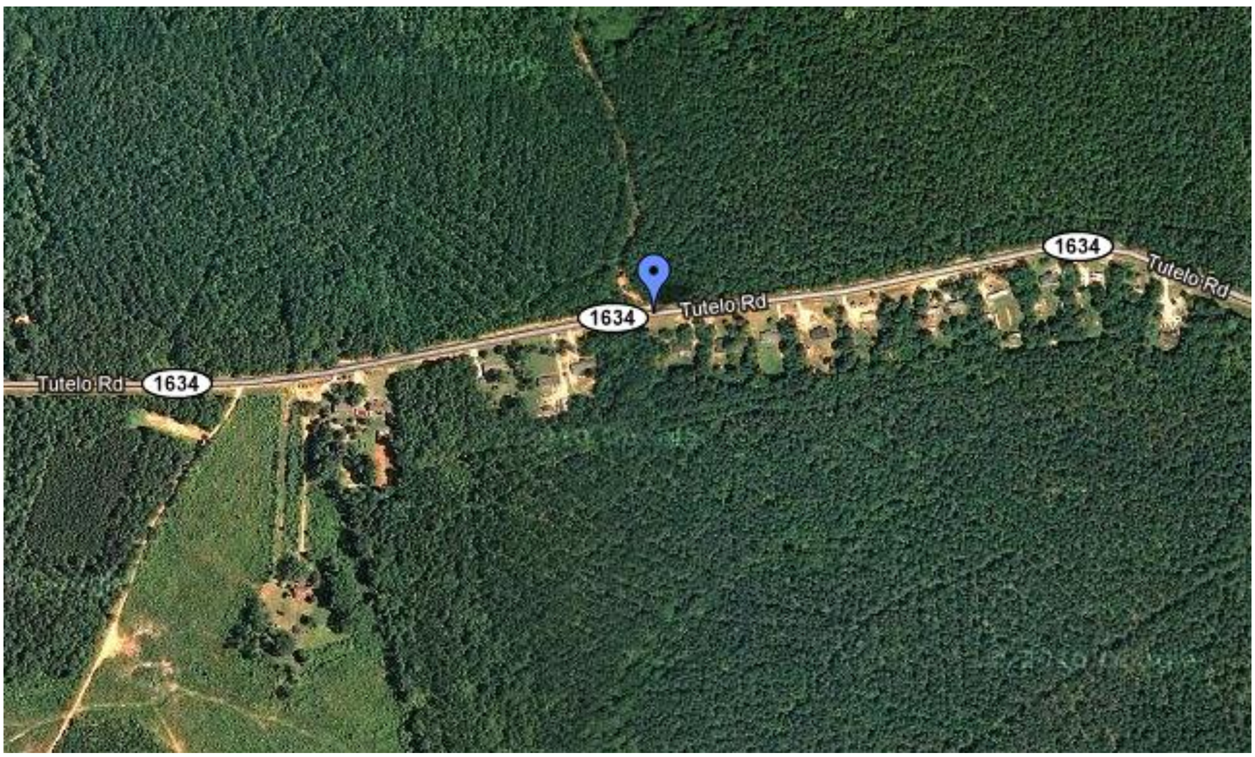
Test Date: 4/15/11
Location: Vance Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 36.328109 / - 78.308725
Nominal Surface: SF9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1518 EB	98.8	98.5	98.5		**98.6**
SR 1518 WB	99.3	99.1	99.6		**99.3**
	Overall Average				**98.9**

Site 45: SR 1634

Test Date: 4/15/11
Location: Warren Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 36.28993 / - 77.99862
Nominal Surface: SF9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1634	99.1	98.9	99.7		**99.2**
SR 1634	99.5	99.3	99.0		**99.3**
	Overall Average				**99.3**

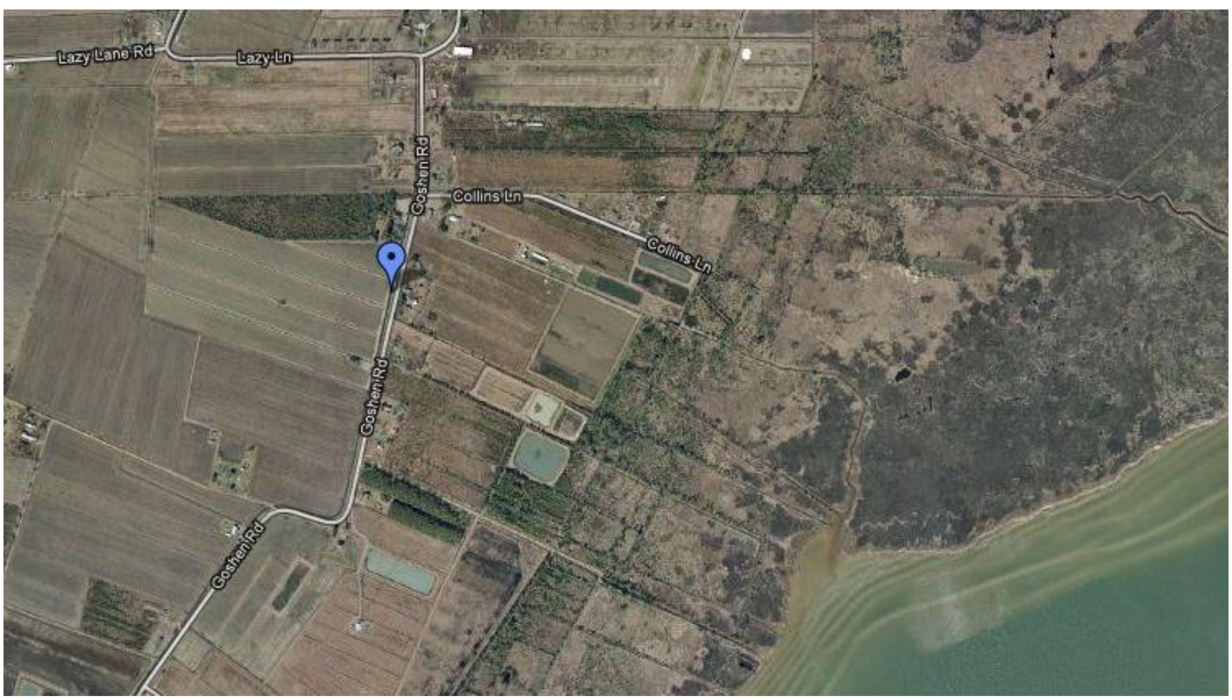


Site 46: SR 1104

Test Date: 4/26/11
Location: Hyde Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 35.492298 / -75.99952
Nominal Surface: SF9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1104 SB	98.7	98.8	98.4		**98.7**
SR 1104 NB	99.0	99.1	99.9		**99.3**
	Overall Average				**99.0**



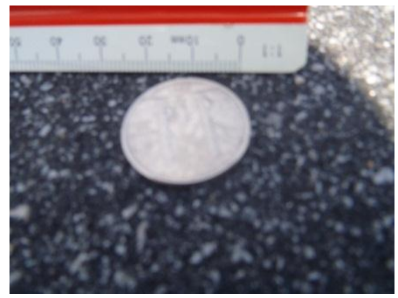


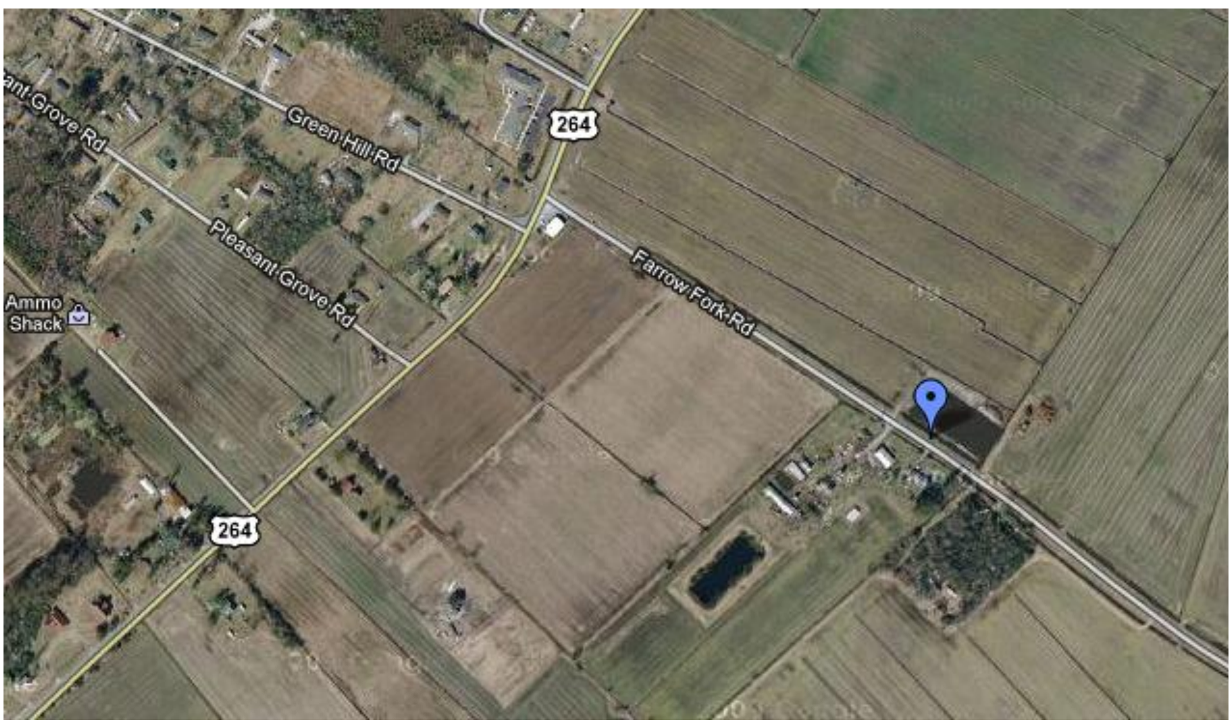
Site 47: SR 1114

Test Date: 4/26/11
Location: Hyde Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 35.490272 / - 76.029428
Nominal Surface: SF9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1114 SB	99.5	99.4	99.2		**99.4**
SR 1114 NB	100.1	100.2	100.4		**100.2**
	Overall Average				**99.8**



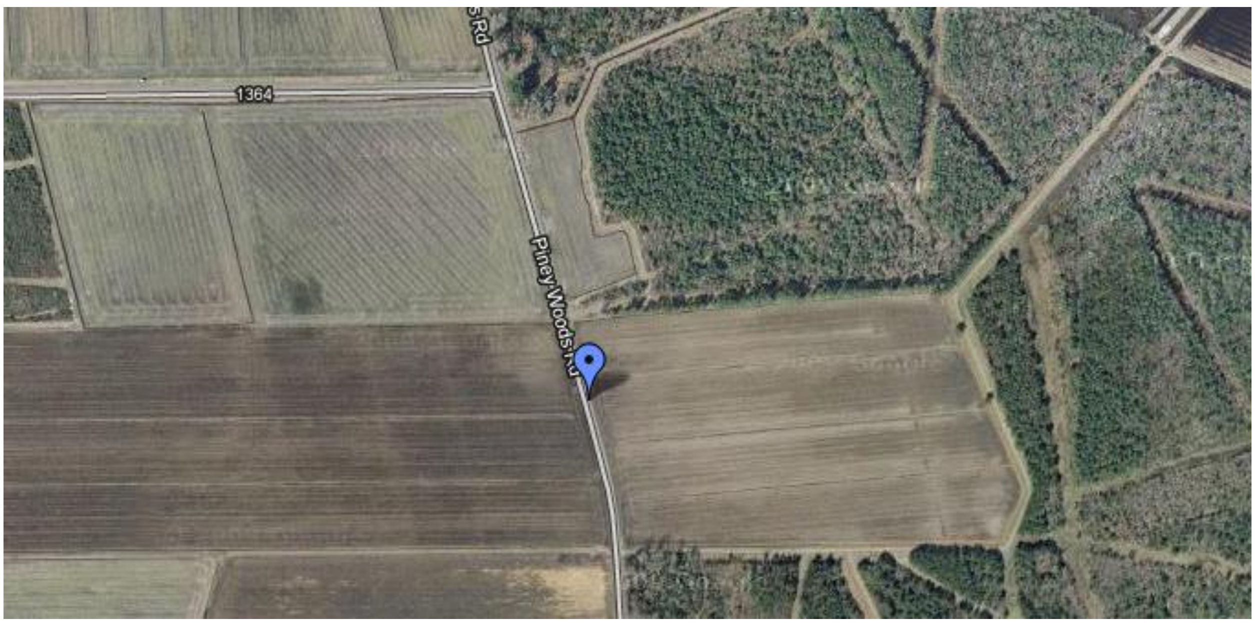




Site 48: SR 1305

Test Date: 4/26/11
Location: Hyde Co.
Construction Year: 2008
Approx Latitude (N) / Longitude (W): 35.489503 / - 76.321875
Nominal Surface: SF9.5A
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1305 NB	99.7	99.5	99.2		**99.5**
SR 1305 SB	99.7	99.9	99.8		**99.8**
	Overall Average				**99.6**



Site 49: SR 1304

Test Date: 4/26/11
Location: Hyde Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 35.475035 / 76.341959
Nominal Surface: SF9.5A
Test method: OBSI

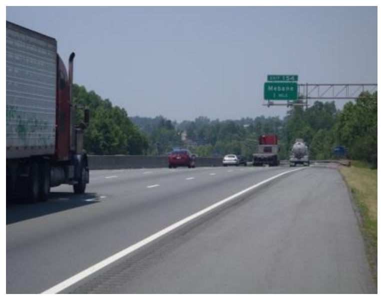
Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
SR 1304 EB	99.3	99.4	99.4		**99.4**
SR 1304 WB	99.4	99.5	99.4		**99.4**
	Overall Average				**99.4**

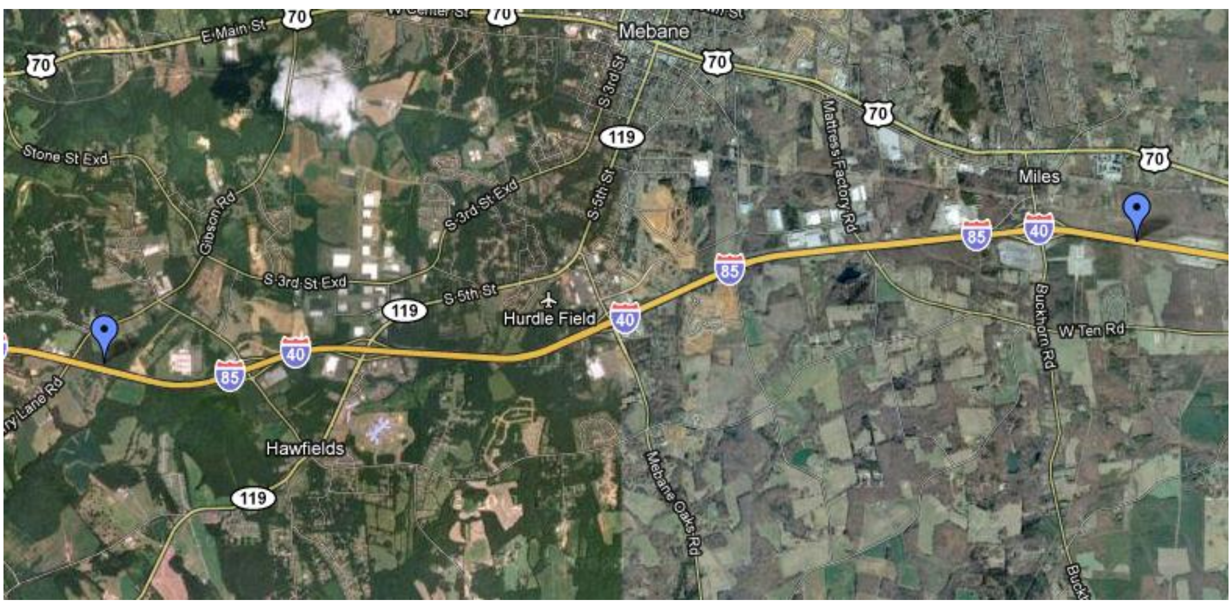


Site 50: I-40

Test Date: 5/26/11
Location: Orange/Alamance Co.
Construction Year: 2008
Approx. Latitude (N) / Longitude (W): 36.067972 / - 79.289045
Nominal Surface: S9.5D
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
I-40 Ala EB	99.0	99.2	99.0		**99.1**
I-40 Ala WB	99.6	99.5	99.6		**99.6**
I-40 Orange EB	99.5	99.1	99.1		**99.2**
I-40 Orange WB	99.2	99.3	99.0		**99.2**

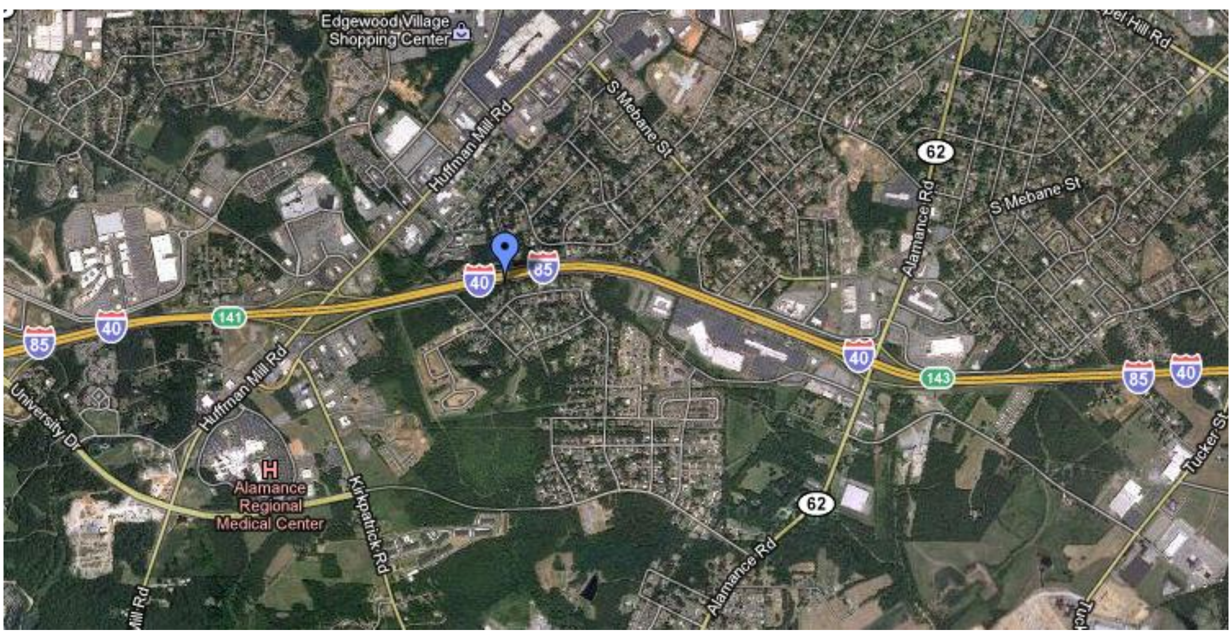




Site 51: I-40

Test Date: 05/26/11
Location: Guilford Co.
Construction Year: 2009
Approx. Latitude (N) / Longitude (W): 36.068805 / -79.487643
Nominal Surface: S9.5D
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
I-40 Guilford WB	99.7	99.9	100.1		**99.9**
I-40 Guilford EB	100.0	100.2	99.6		**99.9**
	Overall Average				**99.9**



Site 52: I-40

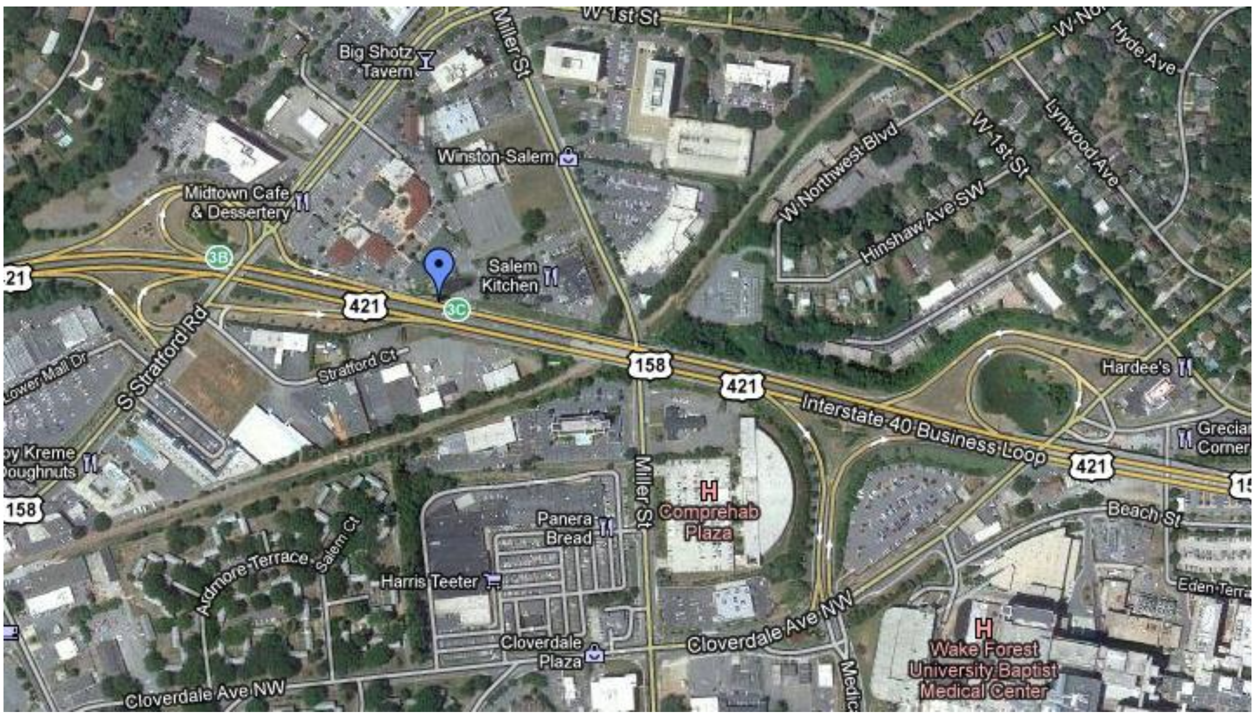
Test Date: 05/27/11
Location: McDowell/Burke Co.
Construction Year: 2001
Approx. Latitude (N) / Longitude (W): 35.695208 / - 81.871494
Nominal Surface: OGFC
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
I-40 Burke EB	104.5	105.1	105.3		**105.0**
I-40 Burke WB	105.3		105.3		**105.3**
I-40 McDowell WB	105.4	105.0	105.8		**105.4**
I-40 McDowell EB	105.5	104.9			**105.2**

Site 53: I-40 Business

Test Date: 05/27/11
Location: Forsyth Co.
Construction Year: 2003
Approx. Latitude (N) / Longitude (W): 36.093655 / - 80.276695
Nominal Surface: OGFC
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
I-40 Business 1	105.1	104.9	105.1		**105.0**
I-40 Business 2	103.8	103.7	103.8		**103.8**
I-40 Business 3	103.2	103.4	103.5		**103.4**



Site 54: I-40

Test Date: 05/28/11
Location: Haywood Co.
Construction Year: 2009
Approx. Latitude (N) / Longitude (W): 35.762533 / - 83.075795
Nominal Surface: OGFC
Test method: OBSI

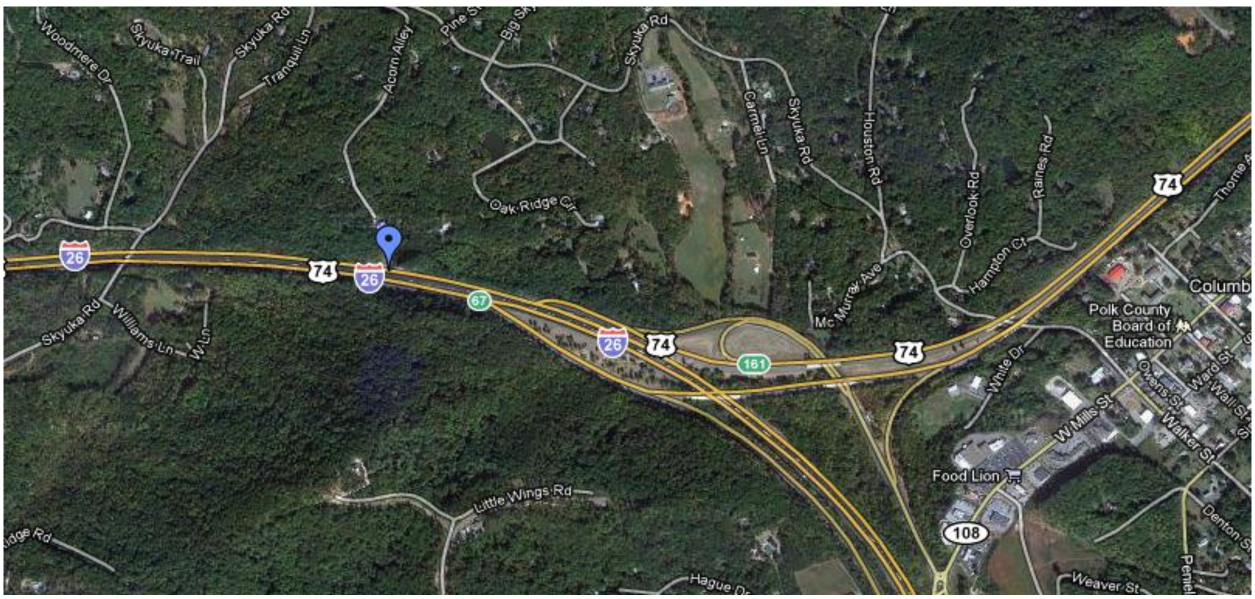
Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
I-40 Haywood EB-1	102.4	102.2	102.3		**102.3**
I-40 Haywood EB-2	103.0	102.9			**102.9**
I-40 Haywood WB-1	101.7	101.8			**101.7**
I-40 Haywood WB-2	102.4	101.9			**102.2**




Site 55: I-26

Test Date: 05/28/11
Location: Polk Co.
Construction Year: 2010
Approx. Latitude (N) / Longitude (W): 35.253855 / - 82.220185
Nominal Surface: OGFC
Test method: OBSI

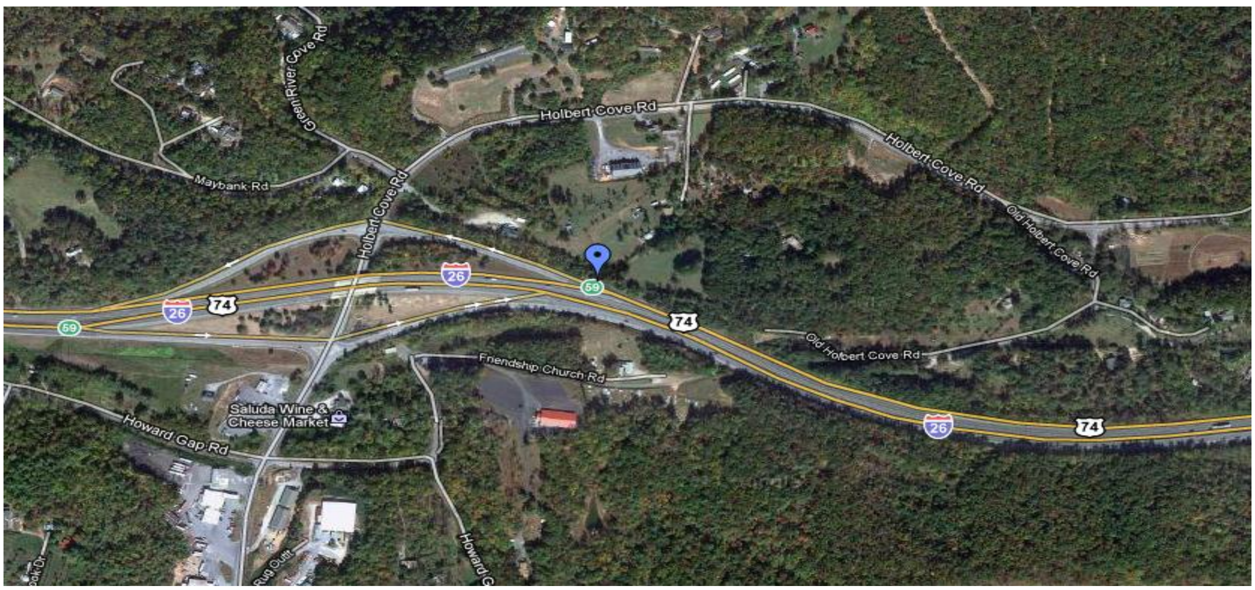
Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
I-26 Polk WB 10	101.7	102.0	102.0		**101.9**
I-26 Polk EB 10	102.6	102.4	102.7		**102.6**
	Overall Average				**102.3**



Site 56: I-26

Test Date: 05/28/11
Location: Polk Co.
Construction Year: 2005
Approx. Latitude (N) / Longitude (W): 35.248528 / - 82.32453
Nominal Surface: OGFC
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
I-26 Polk WB	102.9	102.9	102.8		**102.9**
I-26 Polk EB	102.0	103.0	102.2		**102.4**
	Overall Average				**102.6**



Site 57: I-26

Test Date: 05/28/11
Location: Henderson Co.
Construction Year: 2005
Approx. Latitude (N) / Longitude (W): 35.272059 / - 82.370363
Nominal Surface: OGFC
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
I-26 Henderson WB	102.1	102.8	102.8		**102.6**
I-26 Henderson EB	103.3	102.9	103.6		**103.3**
	Overall Average				**102.9**

Site 58: I-26

Test Date: 05/28/11
Location: Henderson Co.
Construction Year: 2008
Approx. Latitude (N)/ Longitude (W): 35.293078 / 82.403687
Nominal Surface: OGFC
Test method: OBSI

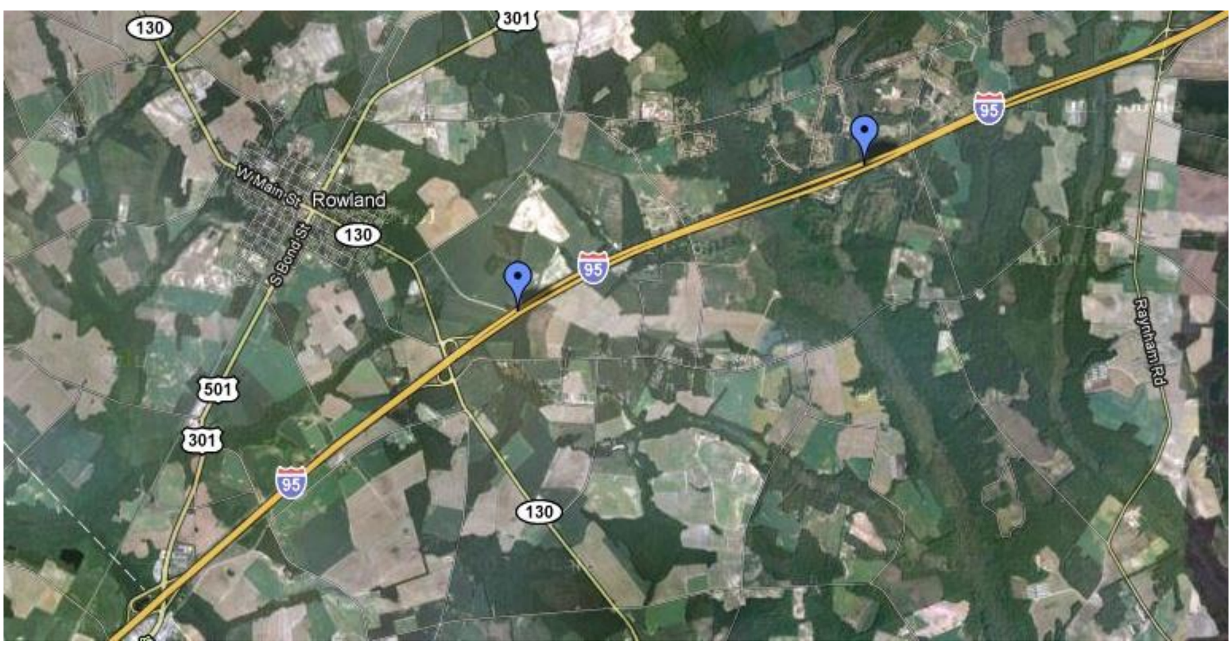
Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
I-26 Henderson WB	101.2	100.5	100.0		**100.6**
I-26 Henderson EB	102.6	103.2	102.0		**102.6**
	Overall Average				**101.6**

Site 59: I-95

Test Date: 06/23/11
Location: Robeson Co.
Construction Year: 2009
Approx. Latitude (N) / Longitude (W): 34.540217 / -79.233427
Nominal Surface: S12.5D
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
I-95 Robeson SB-1	99.6	99.1	98.9		**99.2**
I-95 Robeson SB-2	99.5	99.5	99.7		**99.6**
I-95 Robeson NB-1	100.3	100.0	100.2		**100.2**
I-95 Robeson NB-2	99.3	99.4	99.6		**99.4**
I-95 Robeson NB-3	99.6	100.2	100.0		**99.9**
	Overall Average				**99.7**



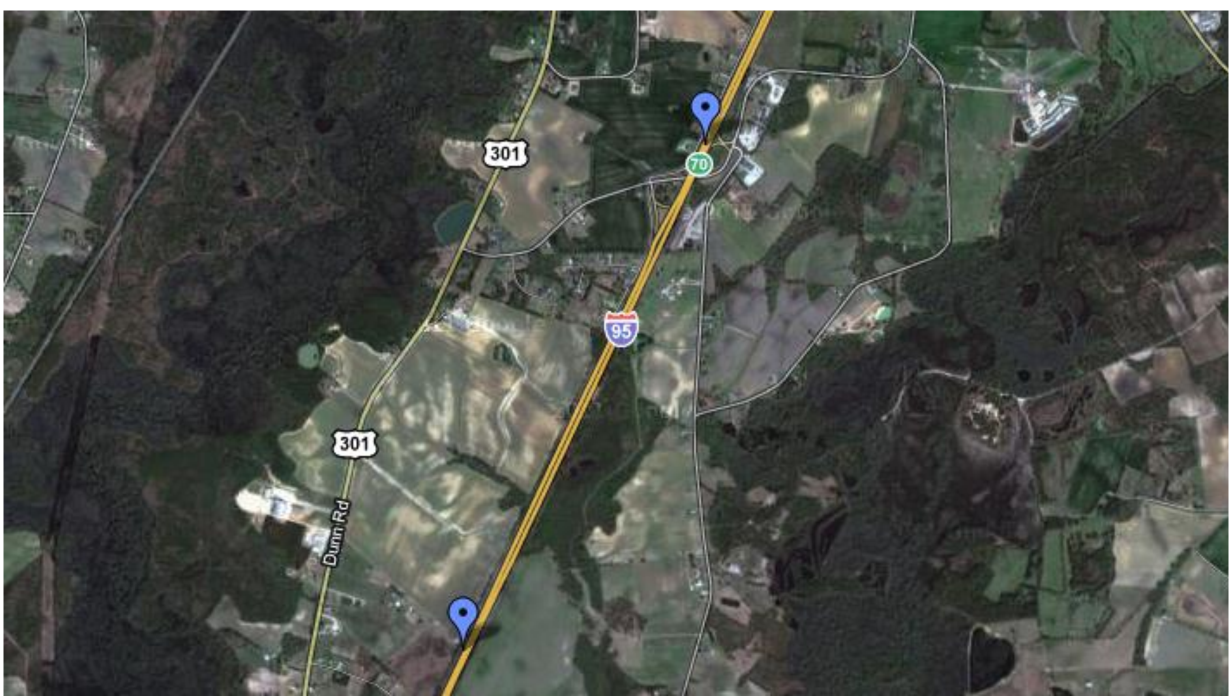


Site 60: I-95

Test Date: 06/23/11
Location: Cumberland/Harnett Co.
Construction Year: 2009
Approx. Latitude (N) / Longitude (W): 35.253399 / - 78.626761
Nominal Surface: UTBWC
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
I-95 Harnet SB	101.0	101.3	101.1		**101.1**
I-95 Harnet NB	101.5	101.2	101.2		**101.3**
I-95 Cumber SB	102.9	102.7	102.7		**102.8**
I-95 Cumber NB	102.5	102.2	101.7		**102.1**



Site 61: US 264

Test Date: 7/22/2011
Location: Henderson Co.
Construction Year: 2010
Approx Latitude (N) / Longitude (W): 35.675984 / - 77.937355
Nominal Surface: OGFC
Test method: OBSI

Road Surface Data					
Site	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Average**
US 264 EB-1	101.8	101.7	101.6		**101.7**
US 264 EB-2	101.8	102.1	102.0		**102.0**
US 264 WB-1	101.2	102.1	102.2		**101.8**
US 264 WB-2	102.8	102.8	102.0		**102.5**
	Overall Average				**102.0**