Technical Report Documentation Page

| 1. Report No. FHWA/TX-07/0-5185-2 | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| 4. Title and Subtitle Preliminary Findings from Noise Testing on PFC Pavements in Texas | | 5. Report Date January 2007; Revised April 2007 |
| | | 6. Performing Organization Code |
| 7. Author(s) Manuel Trevino-Frias, Terry Dossey | | 8. Performing Organization Report No. 0-5185-2 |
| 9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, TX 78705-2650 | | 10. Work Unit No. (TRAIS) |
| | | 11. Contract or Grant No. 0-5185 |
| 12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, TX 78763-5080 | | 13. Type of Report and Period Covered Technical Report July 2006–January 2007 |
| | | 14. Sponsoring Agency Code |

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

16. Abstract

This report documents noise testing performed on Texas pavements in the summer and fall of 2006. Test methods include roadside noise measurement with SPL meters and on-vehicle sound intensity measurement of noise at the pavement tire interface. Comparisons are made between the levels of vehicular noise at the roadside and directly on the source vehicle. The FHWA Traffic Noise Model (TNM) computer program was then used to predict the noise levels at roadside based on the observed traffic and geometry of the roadway, and subsequently compared to the noise as actually measured with precision test equipment. The pavements tested were primarily of the New Generation Open Graded Friction Course type, a permeable asphalt design with air voids in the area of 17 percent, also known as Permeable Friction Course (PFC) in Texas. Preliminary findings indicate that roadside noise levels experienced along PFC pavements are significantly lower than predicted by TNM using either the "Average" or "Open Graded" pavement models included in the program. This suggests that further study is warranted to determine whether these pavements retain their acoustic properties over time and wear and, thus, can be reliably used for noise impact avoidance and abatement.

| 17. Key Words | 18. Distribution Statement |
|---|---|
| Noise, Permeable Friction Course, PFC, Open Graded Asphalt Pavement, OBSI, Sound Intensity, Pass-By, TNM, Quiet Pavement. | No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161; www.ntis.gov. |

| 19. Security Classif. (of report) | 20. Security Classif. (of this page) | 21. No. of pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 122 | |

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

# Preliminary Findings from Noise Testing on PFC Pavements in Texas

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| CTR Technical Report: | 0-5185-2 |
| Report Date: | January 2007; Revised April 2007 |
| Project: | 0-5185 |
| Project Title: | Noise Level Adjustments for Highway Pavements in TxDOT |
| Sponsoring Agency: | Texas Department of Transportation |
| Performing Agency: | Center for Transportation Research at The University of Texas at Austin |

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

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Printed in the United States of America

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# Acknowledgments

The authors wish to express their deep appreciation to the Project Director, Gary Graham, and the Project Management Committee members German Claros and Mike Shearer for their vision, insight, and guidance since the beginning of the study. Very special thanks are due to John Wirth of TxDOT CST Division, who has worked with us every step of the way to facilitate and coordinate gear, training, and testing with TxDOT operations. The continuous collaboration and sharing of all data collected by Mr. Wirth's group and the researchers has created a valuable synergy beneficial to both agencies. Additional thanks are expressed to Jeff Seiders of TxDOT for conceiving and creating the coordination process. We would also be remiss if we did not express our appreciation to the many TxDOT field offices in Dallas, Ft. Worth, Austin, San Antonio, Corpus Christi, and Waco, who have helped us locate sections and keep our test vehicle fueled and operational.

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# 1. Introduction

This report is the second developed under Research Project 0-5185, “Noise Level Adjustments for Highway Pavements in Texas,” a 5-year study funded by the Texas Department of Transportation (TxDOT), currently in its fourth year and scheduled to terminate on August 31, 2008. This is an interim report produced to document all findings to date from field-testing of pavement noise at the tire-pavement interface and at the roadside, as well as all analyses, conclusions, and recommendations derived from the data to date.

## 1.1 Background

Traffic noise near densely populated areas has become an increasing concern worldwide in recent years. Accordingly, many national and international departments of transportation (DOTs) and other agencies have committed significant funding to investigating methods to reduce roadside noise. Although noise barriers erected between the source (roadways) and the *receivers* (people and buildings near the roadway) remain the primary solution to excessive roadside noise, “quiet” pavements are increasingly being studied as an alternative.

In Texas, a new type of pavement called “Permeable Friction Course,” or PFC, has been developed and deployed in many areas to reduce splash and spray during wet weather, with the hope of reducing the incidence of accidents caused by hydroplaning or poor visibility during these conditions. This type of pavement, which is open-graded asphalt with typically 18 percent or more air void content, allows water to drain very rapidly through the pavement. It is in use by a number of states and is more formally termed “New Generation Open-Graded Friction Course,” nationally and internationally.

Because of their relatively high air void content and sometimes the inclusion of crumb rubber in the mix, PFC pavements also exhibit the fortuitous side effect of reducing noise, both inside the vehicle and at the roadside. In Texas, these pavements have become quite popular with the driving public who have noticed and appreciated the quiet ride they provide. Not surprisingly, their use in Texas and several other states is increasing rapidly. Some states with more severe winter conditions than Texas do not currently use them or have discontinued their use due to icing problems and difficulties in winter maintenance [Yildirim 2006].

Currently, the Federal Highway Administration (FHWA) does not allow the use of quiet pavement design for the purpose of noise impact avoidance or abatement on federally funded projects. This is due to two concerns: (1) a need to quantify how much of the noise generated by traffic comes from the tire/pavement interaction (and thus can be reduced by quieter pavement), and (2) how long and under what conditions “quiet” pavements remain quiet. At this time, the FHWA’s Traffic Noise Model (TNM), which predicts roadside noise based on traffic and roadway geometry, includes an option for open-graded pavement but may not be used by practitioners determining the need for noise barriers. Instead, an “average pavement” option must be used for all pavements, which essentially implies that all pavement types are acoustically equivalent—an assumption that everyone, including the FHWA, knows to be incorrect. It is, in reality, an effort to be conservative in predicting the noise impact from traffic and is reasonable until the two concerns about quiet pavements have been sufficiently addressed.

Accordingly, several states, most notably California, Arizona, and now Texas are making a strong effort to address these concerns. TxDOT has funded this study and equipped two test vehicles, one operated by the research team and one by TxDOT, to measure pavement noise levels over time using the On-Board Sound Intensity (OBSI) methodology developed by CalTrans and their consultant, Illingworth & Rodkin. Because one of the issues is pavement remaining quiet over time, pavements of various ages will need to be tested over a period of years. It is also anticipated that OBSI noise testing of the Texas pavement network will become a permanent function of TxDOT.

Report 1 of research project 0-5185 [Trevino 2006] evaluated various equipment for pavement noise testing and other states' experience in the area, recommending a protocol and experimental factorial for noise testing in Texas. That protocol has now been finalized for the remainder of the study and is presented in this report along with preliminary findings to date.

## 1.2 Objectives of the Study

The objectives of this study were presented in the first report and remain substantially the same:

***FHWA Restrictions*:** Present sufficient evidence to the FHWA to persuade them to lift the existing restrictions against using pavement design for noise avoidance and abatement. This would allow the use of the "open graded" pavement option in the TNM program, which is used to determine the need for noise barriers.

***Long-Term Noise Monitoring:*** Measure the effects of aging on the acoustic properties of pavements, particularly open graded pavements.

***Develop Noise Models:*** Correlate pavement design elements for porous pavements to their acoustic properties to assist designers in predicting the noise levels generated by various mix designs.

***Assist TxDOT in Developing an In-House Noise Program:*** Provide protocols, equipment recommendations, and training to TxDOT to assist it in creating its own network-level noise-monitoring program.

## 1.3 Organization of the Report

The report is organized as follows:

- Chapter 1 explains the background and objectives of the study, and gives the organization of the report.
- Chapter 2 updates the literature review given in 0-5185-1, adding new information on developments and publications in the field of pavement noise research since the last report was prepared.
- Chapter 3 details the final protocol for pavement noise testing under the study, as well as explains the nature and purpose of all equipment used in the testing, as used by the researchers and as recommended to TxDOT.
- Chapter 4 presents in detail all results from OBSI testing of Texas pavements available to date.
- Chapter 5 summarizes the data obtained from roadside/pass-by noise measurements and compares the observed data to the noise levels predicted by the TNM program
- Chapter 6 explains the calibration, validation, and comparison methodology used to insure that all data collected by the researchers and by TxDOT are comparable and stay accurate over time.
- Chapter 7 provides conclusions and recommendations based on the data and experience presented in the report.

# 2. Update to State of the Practice and Literature Review

## 2.1 Introduction

This chapter presents some of the new developments in the area of tire/pavement noise measurements, along with literature updates and project updates from the Transportation Research Board meeting in Washington, D.C.

Up until a few years ago, even though tire/pavement noise has increasingly become a concern for highway agencies and the general public, there has not been a standard single procedure that has been widely utilized for the measurement of tire/pavement noise under in-service conditions.

Sound intensity, measured on-board a test vehicle, was developed as an alternative technique to wayside, pass-by, or trailer methods. Initially Caltrans developed this technique for application in the State of California for in-situ highway evaluation. With the dissemination of their research and results, the On-Board Sound Intensity (OBSI) method has been adopted by several other states, including Texas, and it seems to be gaining wide acceptance with time. As the method develops into a new standard procedure, with the contributions of the tire/pavement noise community, most of the changes and advancements in the area have some relationship with OBSI. The innovations taking place now will have a historical significance in the tire/pavement noise area as they lead to the establishment of a standard method.

## 2.2 Standard Reference Test Tire

An important recent development in the OBSI is the establishment of a standard tire to conduct the test in passenger cars. The characteristics of the tire used for the sound tests have a definite influence on the results obtained. In the past, many agencies utilized the Goodyear Aquatred 3 tire, which was the most widespread tire used for noise-testing purposes. However, this tire is no longer available on the market. The new standard tire is referred to as SRTT (Standard Reference Test Tire) and it resembles the Uniroyal Tiger Paw AWP model but has a slightly different tread pattern, and it has "SRTT" markings on the sidewall. The size is P225/60R16, and is now available through Michelin (Figure 2.1). This tire is said to be available on the market for at least 10 years, which bodes well for the continuity and repeatability of the testing procedure. This SRTT is also under study by ISO Working Group 33 as a possible new standard test tire for the ISO CPX method.

*Figure 2.1: SRTT Uniroyal Tiger Paw (Source: Dr. Donavan)*

## 2.3 Tire/Pavement Noise Research Consortium

During the FHWA Tire/Pavement Noise Strategic Planning Workshop held in Indianapolis in April 2006, a pooled fund for tire/pavement noise studies was established, with the participation of several states. The participant states are Kansas, Montana, North Carolina, Ohio, Washington, and Texas, with the Washington State Department of Transportation being the lead agency, and of course, FHWA.

The objectives of this research consortium are as follows:

- Provide a forum for states to discuss tire/pavement noise issues and develop a proposed research plan.
- Pool resources and efforts of multiple state agencies and industries to perform tire/pavement noise research in a similar manner, sharing data and avoiding duplication.

The anticipated scope of the group would consist of the following tasks:

1. Provide a forum for states to discuss noise issues, utilize the same techniques to build a larger database, and share data. The ultimate goal is to incorporate pavement type into the FHWA Traffic Noise Model.
2. Perform a synthesis of global practices in regards to utilizing pavement technology for decreasing tire/pavement noise;
3. Perform a synthesis on the cost/benefits of using low-noise pavements;
4. Produce a document for general public information regarding noise reduction;

5. Provide a baseline for quieter pavement discussion (e.g., definitions, list of acronyms, etc.);
6. Provide a guideline for best practices in measuring and evaluating noise benefits and decreases over the wearing life of the roadway surface.

## 2.4 Pavement-Related Traffic Noise Clearinghouse

An additional outcome of the April 2006 FHWA Tire/Pavement Noise Strategic Planning Workshop was a new website, created by FHWA and the Volpe Center, to act as a clearinghouse website for tire/pavement noise, and thus to help facilitate sharing of information in the tire/pavement noise community. The website has not been released to the public; its access is password-protected. The site allows United States federal, state, and local governments, researchers, and industry to access information related to tire/pavement interaction noise.

## 2.5 Expert Task Group and OBSI Standard

In September of 2004, FHWA held a Tire/Pavement Noise Strategic Planning Workshop, hosted by Purdue University in West Lafayette, Indiana. Its purpose was to help build a roadmap to quieter highways. Workshop participants determined that an expert task group needed to be established to help guide tire/pavement noise measurements in the U.S. The primary purpose of the measurement guidance is to identify goal-based measurement methodologies and encourage consistency of the application of each type of methodology throughout the U.S. Following the September 2004 workshop, a working group was formed.

The Expert Task Group (ETG) meets periodically and has other discussions via e-mail and conference calls regarding the tasks outlined during the FHWA 2004 workshop. Group members reach out to others in the noise and pavement communities to gather input for the various tasks. The ETG is overseen by the FHWA.

The 2004 FHWA Roadmap to Quieter Highways identified the following tasks for the ETG:

1. Develop provisional standards for consideration by the American Association of State Highway and Transportation Officials (AASHTO) for measurement of tire/pavement noise.
2. Coordinate with international groups and various practitioners in the U.S. to advance measurement methods.
3. Coordinate with international groups and various practitioners in the U.S. to establish the correlation between various types of measurements.
4. Contribute data to the FHWA clearinghouse.
5. Promote implementation of provisional standards by practitioners.
6. Evaluate and refine the provisional standards to facilitate adoption as full standards.

The ETG identified the following items as priorities:

1. Write a provisional standard, adapt an existing standard, or adopt an existing standard for tire/pavement noise source measurement methodologies. This may include on-board sound intensity and the close proximity methodology.

2. Write a provisional standard, adapt an existing standard, or adopt an existing standard for tire/pavement noise wayside measurement methodologies. This may include a time-averaged methodology and the statistical pass-by methodology.
3. Write a provisional standard, adapt an existing standard, or adopt an existing standard for pavement noise absorption measurement methodologies. This may include impedance tube testing, the impulse response measurement–extended surface methodology, and the ground impedance using effective flow resistivity methodology.

Mike Shearer of TxDOT and researchers from the Center for Transportation Research (CTR) at The University of Texas at Austin have contributed to the ETG during conference calls and meetings.

During a meeting on March 3, 2005, the writing of a tire/pavement noise source measurement methodology, specifically on-board sound intensity (OBSI), as an AASHTO provisional standard was discussed. It was also established that other measurement methodologies would be addressed in future meetings.

The ETG reviewed the components (section topics such as methodology, instrumentation, measurement sites, data collection, data analysis, etc.) for a provisional OBSI standard. For each component, the group discussed key elements, concerns, and who or what organization or reference to access to obtain more information.

Dr. Roger Wayson, with the University of Central Florida, agreed to write the initial version of a draft provisional standard for OBSI. It was determined that once the first draft is written, the ETG will review it; in addition, the ETG gets input from organizations such as the Transportation Research Board (TRB) Committee on Transportation-Related Noise and Vibration (ADC40).

The first version of a draft AASHTO provisional standard for the OBSI methodology was initially received on April 6, 2005. It has since gone through several revisions based on input from ETG members, TRB ADC40 members, and others. The standard is currently divided into two parts: equipment specification and standard practice, to make it easier to understand. It was designated a provisional standard because provisional standards apply when technology is rapidly changing on the matter of interest, such as the case of OBSI; thus, standards of this type have a limited lifespan of 7 years. If after that period of time the provisional standard has not become a definite standard, it will be dropped.

During the ETG Meeting held in Washington, DC on January 25, 2006, following the Transportation Research Board Meeting, the expert group worked on finalizing the OBSI AASHTO Standards for both the equipment and the test procedure. However, after a day's worth of work, the standards could not be finished, but a good deal of progress was made. As a result of this meeting, the group is a step closer to the conclusion of this work, which will be of great importance in establishing the consistency and homogeny of the testing procedure. The outcome of this meeting, the updated version of the standard, is presented in Appendix A.

It is expected that the documents will be finished by August 2007, and that by the beginning of 2008 the standard will be valid, i.e., become official and be released. Once the OBSI procedure is standardized, its use will facilitate the exchange of information among agencies by allowing various pavements and textures to be directly compared.

## 2.6 Additions to Literature Review and TRB

Report 0-5185-1, written in July 2006, included a synthesis of the literature on pavement noise testing at the time; since then, much has happened. The sections below document some important developments in pavement noise measurement that have taken place since the last literature review.

### 2.6.1 NCHRP 01-44: Measuring Tire-Pavement Noise at the Source

This NCHRP project has Illingworth & Rodkin, Inc. as the research agency, and Dr. Paul Donavan as its principal investigator. This project is expected to provide key elements for the development and establishment of OBSI as a widespread technique in the measurement of tire/pavement noise, even though its scope is to evaluate other methods as well. The objectives of this research are to (1) develop rational procedures for measuring tire-pavement noise and (2) demonstrate applicability of the procedures through testing of in-service pavements.

The project is divided in two phases. The main tasks established in each phase are as follows:

**Phase I:** (1) Collect, review, and synthesize information relative to methods of measuring tire-pavement noise in close proximity to the tire. This information may be obtained from domestic and foreign literature, contacts with highway agencies and industry organizations, and other sources. Identify potential tire-pavement noise-measurement methods applicable to flexible, rigid, and composite pavements for evaluation in Task 2. (2) Evaluate the potential tire-pavement noise-measurement methods applicable to both light and heavy vehicles identified in Task 1. Based on this evaluation, recommend rational method(s) for testing in-service pavements at highway speeds for further evaluation in Phase II. If available methods are considered deficient, modify existing methods or develop new methods. (3) Prepare an updated, detailed work plan for Phase II that includes tests of in-service pavements to demonstrate applicability of the recommended measurement method(s) for different pavement types, vehicles, and noise levels. (4) Prepare an interim report that documents the research performed in Phase I and includes an updated work plan for Phase II. Following review of the interim report by the NCHRP, the research team will be required to make a presentation to the project panel. Work on Phase II of the project will not begin until the interim report is approved and the Phase II work plan is authorized by the NCHRP.

**Phase II:** (5) Execute the Phase II work plan as approved in Task 4. Based on the results of this work, evaluate applicability of the recommended measurement method(s) and refine these methods, if necessary. Prepare the recommended method(s) in a format suitable for consideration and adoption by AASHTO. (6) Submit a final report that documents the entire research effort. The report will include an implementation plan for moving the results of this research into practice.

The literature search reviewed the available methods for measuring tire/pavement noise, and after the first assessment concluded that only OBSI and Close Proximity (CPX) were going to be evaluated further because other methods were too expensive or too complex, or they failed to provide correlation to far field or pass-by microphones. The testing with CPX and OBSI has been conducted at the NCAT test track facility in Opelika, Alabama, which has various types of AC pavements. Additional tests were run on a jointed PCC pavement nearby. Preliminary findings indicate that the OBSI results correlate slightly better to pass-by than CPX and that the enclosure surrounding the test tire on the CPX trailer causes some spectral distortion in the lower frequencies.

### 2.6.2 NITE Study

The Noise Intensity Testing in Europe (NITE) study [Donavan 2004], funded by Caltrans, intended to provide the first definitive data base comparing European pavement noise to that in the U.S. and to establish the benchmark for "quiet pavement" in regards to the U.S. versus Europe, complementing the AASHTO/FHWA Scan Tour of 2004. The study's objectives were:

1. To measure the quietest pavement of all types
2. To measure the range of pavements in use
3. To relate Caltrans OBSI and European CPX measurements

The project used 97 km/h (60 mph) as the primary test speed, at which sixty-two pavements were tested and 56 km/h (35 mph) as a secondary speed, at which thirty-three pavements were evaluated, utilizing the Goodyear Aquatred 3 tire and the Uniroyal Tiger Paw AWP as test tires. The pavements analyzed were classified into three categories to correlate them with surfaces in the U.S.: dense-graded AC, porous AC, and PCC. Figure 2.2 shows what a good correlation was found between OBSI and pass-by, driving an Opel Vectra.

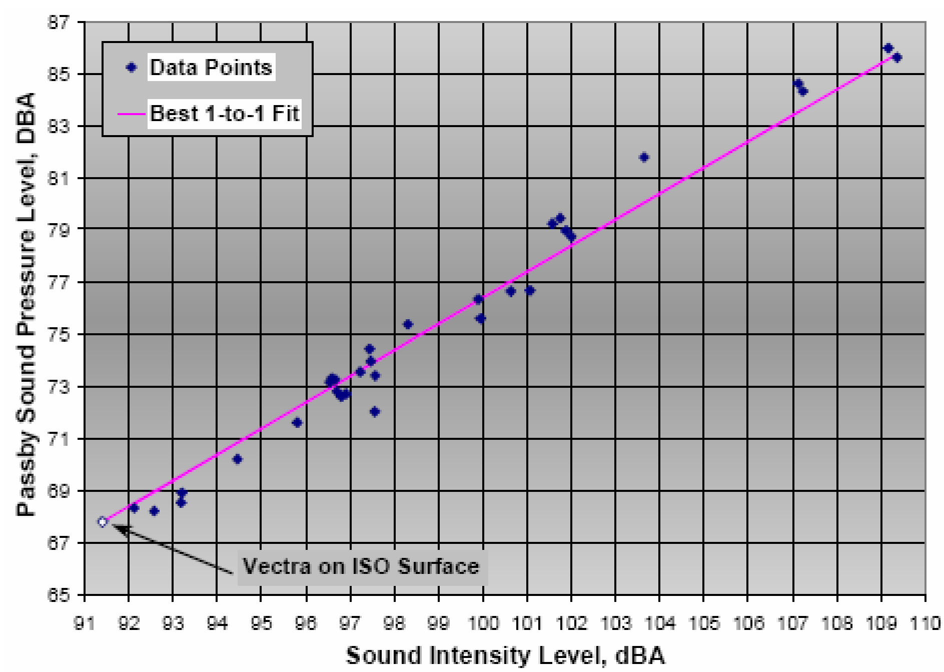


*Figure 2.2: Correlation of SI data to pass-by, NITE study (Source: Dr. Donavan)*

Figures 2.3, 2.4, and 2.5 show the comparisons for the three pavement categories between European surfaces and the Caltrans pavement database.

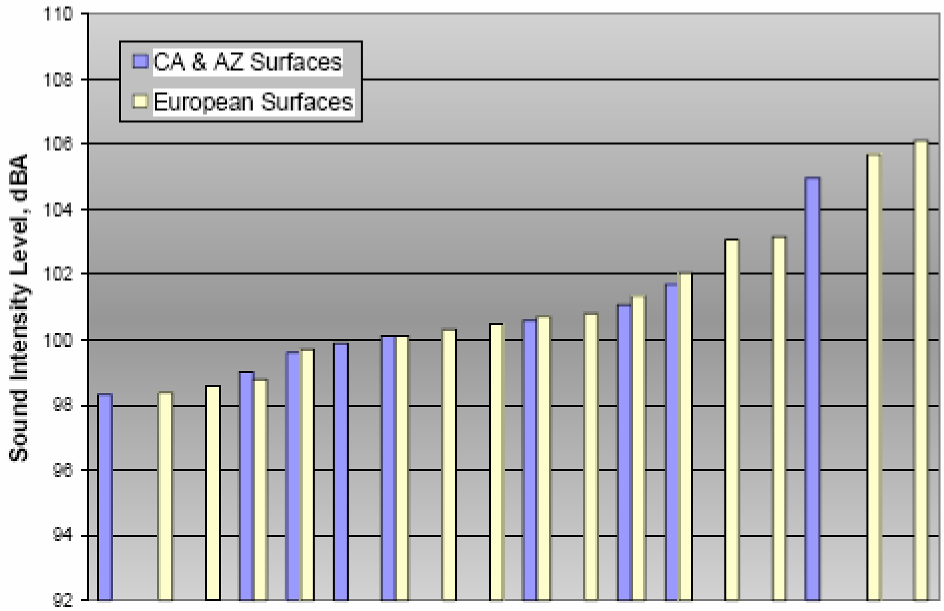


*Figure 2.3: Comparison of dense-graded AC pavements from Europe vs. California and Arizona (Source: Dr. Donavan)*

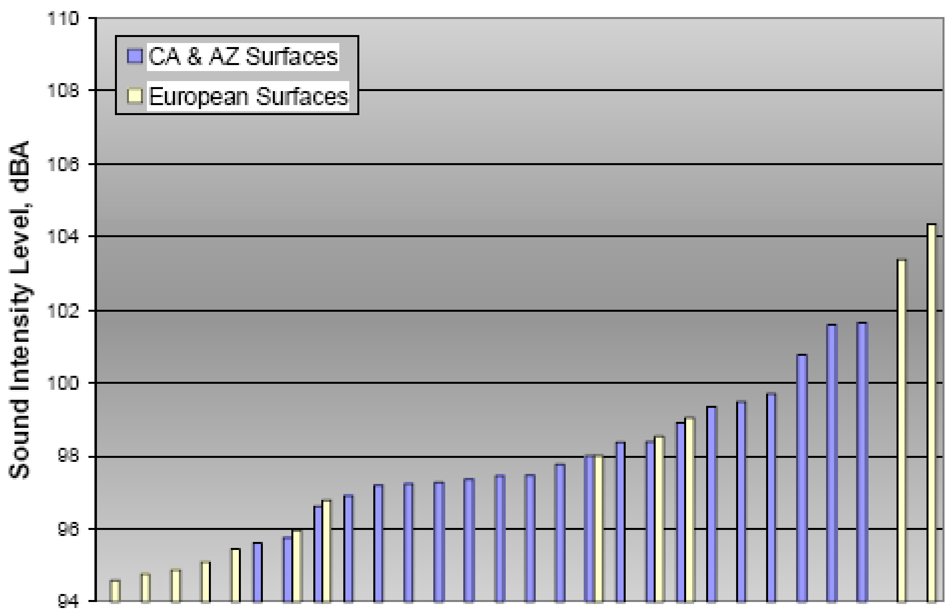


*Figure 2.4: Comparison of porous AC pavements from Europe vs. California and Arizona (Source: Dr. Donavan)*

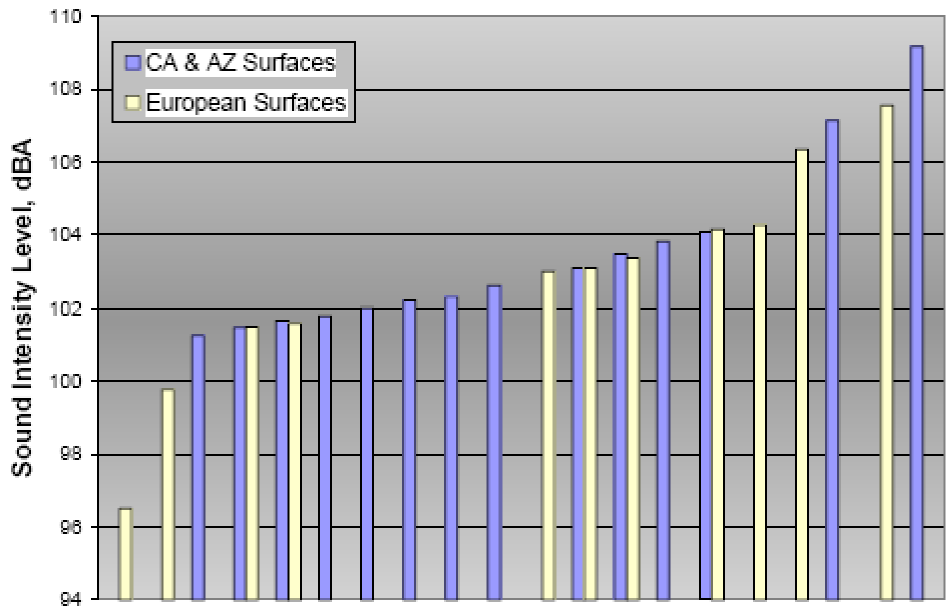

*Figure 2.5: Comparison of PCCs from Europe vs. California and Arizona (Source: Dr. Donavan)*

The conclusion of this project is that pavement can reduce tire/pavement noise up to 8 to10 dBA depending on existing and final conditions. There was a significant range in performance in each major pavement category, but as a group, open-graded ACPs showed the best noise performance in California and Arizona. Other conclusions are:

1. Apparent surface roughness/texture has more influence in the lower frequencies
2. Highly porous, 2-layer AC construction can provide slightly better performance
3. Porous PCC can produce noise performance comparable to other quiet pavements
4. Exposed aggregate PCCs were not found to be “quieter”
5. SMA surfaces provide similar ranges of performance to dense-graded AC
6. Constructions of the same specification can produce variations of up to 2 dBA

### 2.6.3 Caltrans—UC Davis Study

This research project, developed by the University of California (UC) Davis for Caltrans [Ongel 2007], intends to correlate noise level, measured with the OBSI method, with other pavement characteristics such as air-void content, permeability, texture, friction, roughness, traffic, and overall condition.

Twenty-three test sections with different AC surfaces have been analyzed in six Caltrans pavement test sites. The pavement types evaluated include rubberized and non-rubberized open-graded, gap graded, and dense-graded mixes. Pavement sections were ranked by the different pavement parameters.

Pavement characteristics were categorized by mix type. Additionally, measured pavement surface characteristics were correlated with the sound intensity levels. Although the size of the sample data is still relatively small in terms of number of pavement sections, the following conclusions could be drawn from the analysis of the sections included in this part of the investigation:

1. Sound intensity measurements indicate that open-graded mixes may reduce the tire/pavement noise up to 4.5 dBA, compared with other AC mixes. Open-graded mixes typically have higher air-void contents, permeability, and surface macrotexture (MPD, mean profile depth) than gap or dense-graded mixes.
2. The sections with the same materials and under the same traffic and weather conditions but with thicker layers seem to have lower noise levels. A moderate correlation was found between noise level and the product of surface layer thickness and air-void content. Increasing either the thickness or the air-void content may reduce the tire/pavement noise, but further investigation is needed.
3. Rubberized mixes provide less friction than non-rubberized mixes.
4. Open-graded mixes seem to be prone to raveling. Reflection cracking is more likely to occur when an open-graded mix is placed directly on top of PCC.
5. Air-void content is positively correlated with permeability.

## 2.7 Summary

The field of pavement noise measurement is developing at a rapid pace, both nationally and internationally. Though many methodologies for measuring noise at the tire/pavement interface are still in use by various agencies, the development of the AASHTO OBSI specification provides a standardized protocol through which researchers and other practitioners in the field can compare results meaningfully. Efforts such as the NITE project, the FHWA's Volpe Center website, and others are now in place and will assist noise researchers in correlating and comparing noise data from all sources.

Additionally, findings from other agencies continue to indicate that porous pavements can reduce roadside noise significantly.

# 3. Final Test Protocols for OBSI and Roadside

## 3.1 Introduction

One of the goals of this study is to document acoustic changes in "quiet" pavement over time, to determine if aging, traffic exposure, and environmental effects alter the acoustic characteristics of the pavement and thus change the character and intensity of roadside noise. In order to accurately monitor the statewide experimental test sections over a period of years, it is very important that all other sources of test variability be identified and eliminated so that any measured differences can be attributed solely to pavement aging and other variables that are time dependent. This requires that a set of protocols be established for the testing that can be repeated with good precision during the initial and subsequent noise tests.

The following sections present a detailed, finalized protocol, used to gather the data that is presented in this report and will be used for all future noise testing.

## 3.2 Selection of Test Sections

Noise test sections are selected via a two-step process: first, the experimental factorial developed earlier in the study is examined to determine what characteristics a desired test pavement would have, such as age, pavement type, and climate factors. A database of candidate pavements statewide and a determination of where each fits into the experimental factorial has been prepared and was reported on in Technical Report 0-5185-1 [Trevino 2006].

The second step is to choose test sections within the projects selected in step one. At least three test sections for each direction of travel within the selected roadway are needed to give a measure of variability within the project. In keeping with the revised AASHTO standard for OBSI noise testing, the sections must meet the following criteria:

1. Allow for at least a 5-second data collection pass, which at the standard 60 mph would imply a section length of 400 feet or longer,
2. Be relatively straight and level so as not to add noise due to turning movement of the tires,
3. Be reasonably free of nearby barriers so as to minimize reflected noise (though the OBSI system is designed to reduce reflected noise),
4. Be of one continuous pavement type, free of any significant localized damage such as punch outs, patches, potholes, etc.

It is highly desirable, but not required, that the sections be fairly close together and near convenient exits/turnaround spots so that the multiple passes over each section on both sides of the highway can be accomplished in a circular repetitive manner as quickly and safely as possible. It should be noted that if the test sections are chosen carefully, the actual driving and testing phase of the procedure is a fairly quick process, with the choosing, marking, and roadside pass-by testing requiring more time. This is an important consideration when choosing the sections, because several of the more time-consuming tasks need be done only the first time the project is tested.

When selecting test sections, consideration should also be given to choosing at least one in each direction of travel that affords a wide shoulder or at least has no barrier in place, in order to facilitate pass-by testing if that is desired.

## 3.3 Provisions for Precise Section Relocation

Once the test sections within a project have been chosen, it is extremely important to precisely mark them in some way for relocation and future testing. Because there is considerable noise variability within a pavement project, the only way to measure change in pavement acoustics over time is to revisit the exact section tested previously, at least as closely as possible.

To accomplish this, a redundant system has been adopted that allows us to find the beginning of a previously tested section with good accuracy after months or years and also reveals any major changes that have taken place on or near the section since the last visit that may be relevant to the testing. This system consists of three elements: video taping from the vehicle, logging the GPS coordinates of the vehicle while testing, and marking the test sections with paint. Each is described in detail below.

### 3.3.1 Video Taping

The entire test route (which may encompass many test sections) is videotaped from inside the vehicle to record the driver's perspective on the route (Fig 3.1).

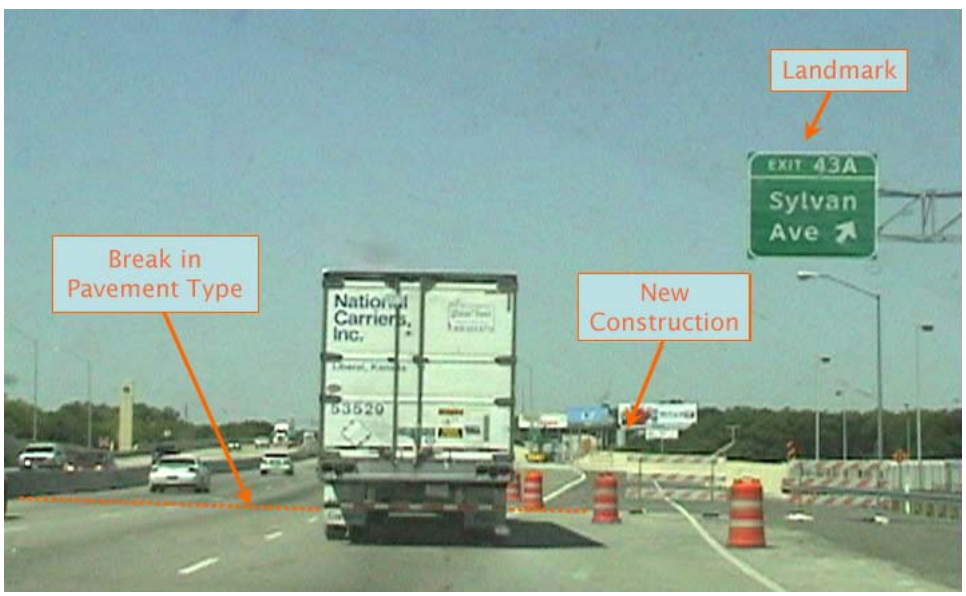


*Figure 3.1: Windshield video capture with annotations of interest, Dallas IH-30*

As annotated in Figure 3.1, videotape also serves to document any construction in progress that may be relevant to follow up testing months or years later. Additionally, if there is any confusion later while analyzing the data, the tapes may be reviewed to determine exactly what took place on the day of the test.

Frequently, useful discussion by the driver and equipment operator pertaining to selecting sections, possible geometric problems, or difficulty maintaining test speed in traffic are also captured on the audio portion of the tape and may be reviewed at a later time. The video record is important because it captures much more information than just the section locations and thus supplements the GPS log of the test runs.

The video tapes are marked and stored after each day of testing. Additionally, the videos are uploaded to a computer as .AVI files and archived to DVD-ROM. This allows quick indexing and referral to any project location, and easy matching to the GPS log.

### 3.3.2 GPS Logging

Two GPS devices are currently in use for logging the location of test sections. The first is a handheld device that is used at the time the section is marked with paint to determine the location of the test section begin point to within 10-ft accuracy. These two coordinates (latitude and longitude in degrees, minutes, and seconds) are written on the log sheet.

The second GPS device connects to a laptop computer in the vehicle and logs the test vehicle's location, speed, and heading every second for the duration of the test (Figure 3.2).

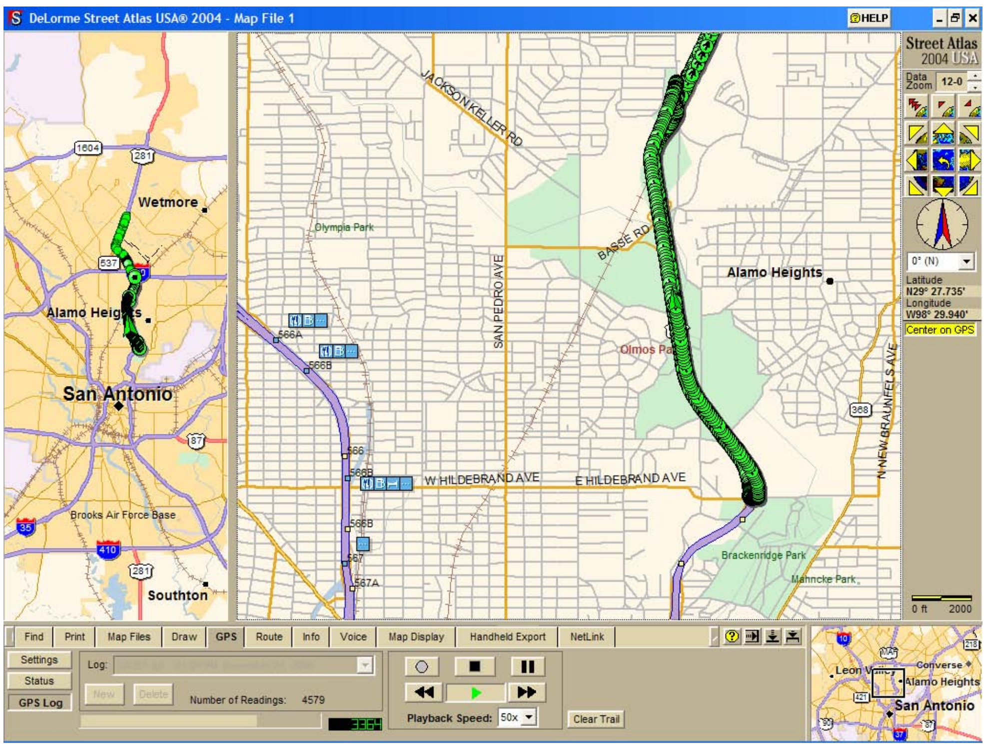


*Figure 3.2: GPS log for US 281, San Antonio*

The coordinates captured by the software are automatically plotted onto a real time mapping system and stored for later retrieval, if desired. This is particularly useful when returning to the test sections at a later date, or if there is a question of where a specific stored noise recording was taken, or if there is a question regarding whether the test vehicle was operating sufficiently near the specified test speed of 60 mph.

In addition to storing the dynamic data of vehicle location, direction, and speed, the software allows electronic marking and labeling of each test section. On a return trip to the test section, the equipment operator can locate the beginning of the section to within 10 feet, even if the paint marker cannot be located.

### 3.3.3 Paint Markers

Marking the test sections with paint is a simple and generally very reliable way of making the sections easy to find at a later date. Moreover, the paint markers are necessary because the test equipment operator must press the RUN button on the analyzer the moment the vehicle crosses into the test section. Accordingly, the marking must be large and bright so that the driver and equipment operator can see the section coming in time to stabilize the speed of the vehicle and operate both the analyzer and the data recorder. The convention adopted for this study is to use bright reflective construction grade paint and to label the sections with a code indicating the District, the project number, direction of travel, and the test section. Figure 3.3 shows a paint marker on an IH-37 PFC section in Corpus Christi.


*Figure 3.3: Paint marker for Project 1, northbound section 1, IH-37, Corpus Christi*

## 3.4 Environmental Measurements

The AASHTO standard specification for OBSI testing requires that air temperature, pavement temperature, relative humidity, and wind speed be recorded during the noise testing period, and it specifies that under some environmental conditions testing may not be conducted (chiefly excess wind speed). In addition, if there is any possibility the pavement may be wet, the testing cannot be carried out. In the case of porous pavements, a primary focus of this study, it is sometimes necessary to check for the presence of hidden water by using a can of compressed air. Any spray from the pavement rules out the testing until a later date. The OBSI specification, updated in January of 2007, can be seen in its entirety in Appendix A.

Accordingly, several devices are carried in the noise test vehicle to measure these environmental variables. The devices and their purpose are described in Table 3.1.

**Table 3.1: Devices Used For Environmental Measurements**

| Measurement | Device | Usage Notes |
|---|---|---|
| Air Temperature | Handheld meter | Logged at start of testing |
| Relative Humidity | Handheld meter | Logged at start of testing |
| Wind Speed | Handheld meter | Avg. and peak wind speed logged at start of testing |
| Pavement Temperature | Thermochron | Left in contact with pavement |
| Moisture* | Compressed air can | Check for spray before testing |

*Detected, not measured

Figure 3.4 shows the devices. They are, from left to right: Thermochron i-buttons, multipurpose meter, handheld GPS, compressed air can with directional nozzle. The i-buttons are lightly coated with silicon heat sink grease and pressed into the pavement to measure and record surface temperature during the test. The button logs temperature every 10 minutes and saves a time and date stamp with the measurement. The GPS unit is used for location recording as described in section 3.2.2.


*Figure 3.4: Devices used to measure environmental variables*

## 3.5 Traffic and Geometry for TNM Model

Comparing the measured roadside noise levels to the levels predicted by the FHWA's Traffic Noise Model (TNM) program is one of the primary objectives of this study. In order to accomplish this task, the following data must be collected at each test site:

- $L_{EQ}$ noise measurement over a timed interval, taken several times at each location, using a precision sound pressure level (SPL) meter with integration capability. $L_{EQ}$ is the average noise level for the location over the time measured.
- An accurate traffic count during the measurement period, including the number of passenger vehicles, light trucks, and heavy trucks, and the lane each was in when it passed.
- The geometry of the test site, including the distance and elevation between the meter and the roadway, the lane widths, locations of barriers, reflective surfaces, etc.

All distances needed are measured with a tape prior to the test, including lane widths and elevations, if traffic allows (otherwise estimations are used). These are logged on a clipboard along with a sketch of the roadway geometry; several photographs are taken as needed for clarification.

Collecting traffic information in real time using a clipboard or other manual device is difficult at best on a busy Interstate highway. Therefore, a protocol used for traffic measurement has been established using a tripod-mounted video camera. The video recording is started simultaneously with the Leq measurement interval on the sound meter, and both are set to run for exactly 10 minutes (or longer until Leq stabilizes) and then paused. Figure 3.5 shows the setup for recording Leq and videotaping the traffic.

*Figure 3.5: Recording traffic and Leq on IH-30, Dallas District*

Back at the office, the video is captured and converted to MPEG format on a PC computer. The researcher can then view the video in slow motion (or even frame by frame) as needed to count and categorize traffic. This traffic data, along with the geometry sketch and measured distance is used to run the TNM model and compare predicted roadside noise to observed levels.

## 3.6 Roadside (Pass-By) Protocol

One or two Class A sound pressure level (SPL) meters are set up on the shoulder or roadside at a distance and elevation specified in the ISO statistical pass-by test (Figure 3.6).


*Figure 3.6: SPL meter at roadside (Austin District)*

The meters are positioned 7.5 meters (25 ft) from the centerline of the outside lane, with the microphone elevated 1.2 meters (4 ft) above the crown of the roadway. This requires a tape to be used to measure from the right lane centerline to the test position. In some circumstances, notably urban Interstate highways, it is not practical or safe to measure on the pavement while it is in use. In these cases, the lane width is assumed to be 12 feet and the distance is taken from the edge of the lane.

The $L_{EQ}$ meter(s) are set to collect $L_{EQ}$, which is an integration of noise over time and the standard method of quantifying environmental noise. $L_{EQ}$ may simply be thought of as the average noise level over the time period the test is taken. Thus, the $L_{EQ}$ will generally stabilize in a few minutes on a heavily trafficked road, provided sufficient trucks have passed by the test location. In practice, the test is run for at least 10 minutes and repeated twice. If 10 minutes is not long enough for the $L_{EQ}$ to stabilize, or if the researchers note that few trucks have passed, the test will be extended for a longer period of time.

The B&K 2250 SPL meters have the additional capability of recording the actual noise onto an internal flash card. This capacity is used in lieu of a separate tape recorder if it is desired to re-analyze the raw data at a later time or to review a particular incident such as a vehicle honking its horn or using air brakes while passing. In practice, the audio track on the test video is sufficient for the latter purpose, and there is a “backspace” button on the 2250 that erases the last 5-second event.

Roadside noise measurements are made after OBSI testing is complete, and generally, one pass of the test vehicle itself is recorded to compare onboard to roadside noise for the test vehicle.

## 3.7 OBSI Measurement Protocol

The primary instrument for measuring road noise in this study is the On-Board Sound Intensity (OBSI) method, which has been used with great success in California, Arizona, and other states. A near-final specification for the OBSI equipment (as of January 2007) has been included in this report as Appendix A. Figure 3.7 shows the standard test vehicle, a front-wheel drive Chevy Malibu, outfitted with a wheel jig allowing very close proximity of the SI test probe to the tire/pavement contact area (Figure 3.8).


*Figure 3.7: TxDOT vehicle with attached OBSI noise probe*

The OBSI protocol and equipment have been evaluated and tested very thoroughly by the research team. OBSI has been shown in research by CTR and others to give the same result as the older close proximity method, but unlike that method is not affected significantly by traffic or nearby barriers. The two-microphone SI probe effectively excludes (or in some cases simply identifies) noise coming from the right of the vehicle (e.g., barrier reflections) fairly reliably. The analyzer used gives a display in real time of both the direction and amplitude of the noise being measured for each frequency band, allowing checks both in the field and back at the office for any reflection problems.

The researchers also considered the issue of engine noise from the test vehicle. Noise trailers avoided this problem by using extended tongues. To check for a potential problem, the operating RPM of the vehicle at 60mph was noted and then the vehicle was parked and run up to that RPM (approximately 2,000 rpm) while measuring the noise. The level was found to be significantly lower than the tire/pavement noise from PFC pavements and therefore was deemed not a problem.

*Figure 3.8: Close up view of assembled SI test probe on vehicle*

The procedure for the test run is straightforward. After multiple test sections on a selected pavement project have been selected and marked with paint, the driver makes a full circuit of the test route three or more times, which includes travel in both directions. If the instrumentation operator indicates no problems, the vehicle is parked in a safe area and the crew repositions the SI probe to the rear contact point of the tire. The process is then repeated. Front and rear contact point measurements give different and unpredictable results, so both must be taken.

The passenger is responsible for all equipment operation during the test. Once the Larson Davis 3000+ analyzer has been set up for automatic SI testing at 5-second intervals (see Appendix B for procedure), all that is required to measure and log the noise from each section is to press START as the paint mark is passed, and STORE afterwards. A note is made on the clipboard to indicate which section corresponds to each file.

## 3.8 Data Archiving

As has been shown in the preceding sections, the amount of data collected from a test project is very substantial, and most of it could be reanalyzed later if desirable. This suggests the need for an archival system to handle the many types and large volumes of data. Currently all the data from each test project is archived to hard disk and backed up to DVD-ROM. This data comprises raw sound files, analyzed noise summaries, video clips, GPS logs, and a scan of the log sheet from the testing including $L_{eq}$ values from the roadside tests.

The primary data from the test is the noise data itself. The noise is analyzed in real time and stored in the Larson Davis analyzer, but the raw data is recorded also, using the Edirol flash card recorder. This raw data can be reanalyzed at any time by playing it back into the analyzer, and it is sometimes very advantageous to do so when the results of the standard analysis appear unreasonable.

Figure 3.6 shows the data from the first run made on IH 37 in Corpus Christi District. In the figure, the calibration tones for the outside and inside microphones appear first and are used to calibrate the recorded noise, normalizing it to the 94 dB 1 kHZ reference tone. Ideally, the reference tone would appear as a straight block; the slight peaks as shown are due to traffic passing on the Interstate during the calibration.

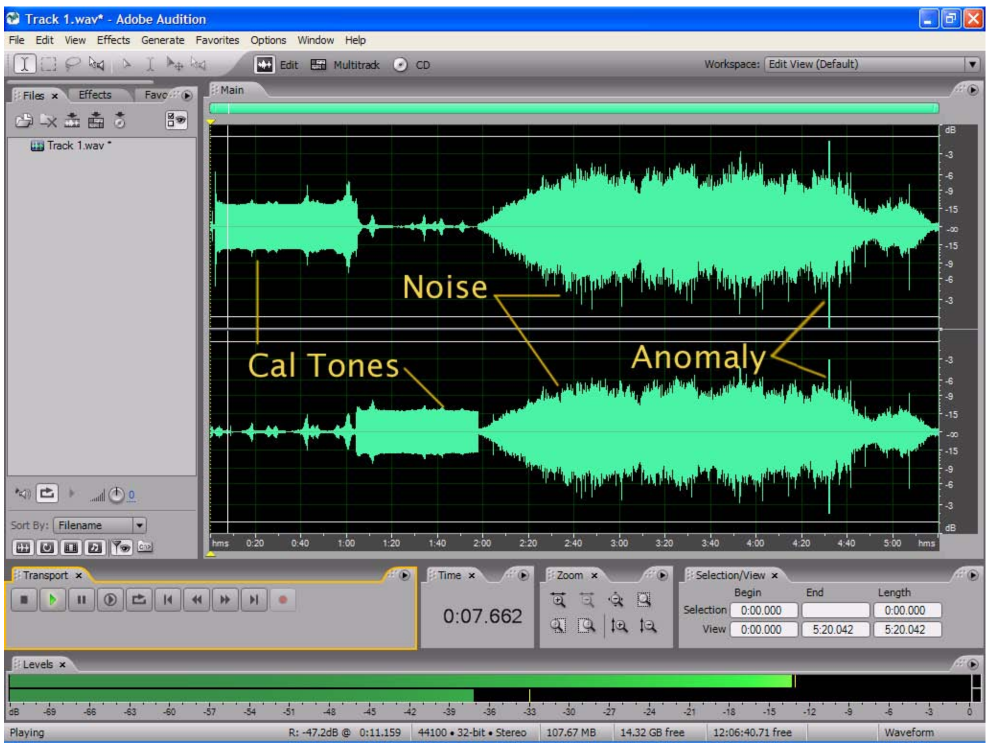


*Figure 3.9: Recorded noise from IH 37, Corpus Christi District*

Figure 3.9 also shows a brief anomalous spike in both channels near the end of the noise recording, revealed to be the recognizable sound of the vehicle passing over a joint in the roadway. In this case, the information is of no concern, because three factors confirm that the joint is outside the test sections and that the vehicle is probably passing over a bridge approach or exit ramp: the GPS data for the same run and the duration of the noise recorded (more than 2 minutes), combined with the fact that the vehicle is slowing down.

Finally, the recording shown in the figure above has had a section between the calibration and the first run (while the researchers were completing preparation of the vehicle) removed so that the relationship between the data and the calibration can be shown on the same graph.

## 3.9 Data Analysis & Reporting

Once the field tests are performed, the noise data stored in the analyzer is downloaded to a computer. The RTA Utility software (Figures 3.10 and 3.11), downloaded from the Larson Davis website, is used to get the data to the computer by means of a serial cable.

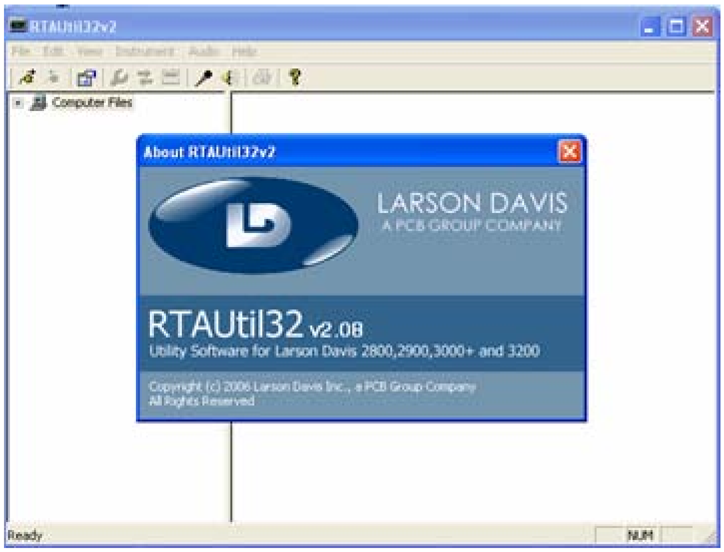


*Figure 3.10: Utility software used to download sound data from analyzer to computer*

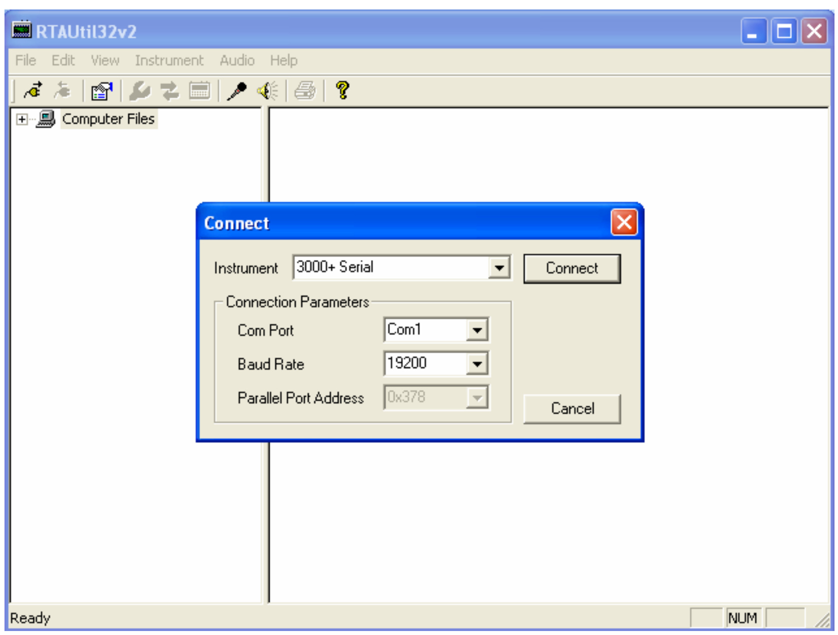


*Figure 3.11: Software connection between analyzer and computer to download sound data*

The data is in text format and can be opened with Excel. Dr. Paul Donavan and his group have developed a spreadsheet to analyze the data and plot the sound levels and sound spectra. Within the spreadsheet, the user must know how to manipulate certain portions of the raw files and assign them to the appropriate worksheets and cells in order to come up with the data analysis. The outcome of the analysis can be seen in the 1/3-octave band frequency spectra and the averaged sound levels by section, examples of which are shown in Figures 3.10 and 3.11.

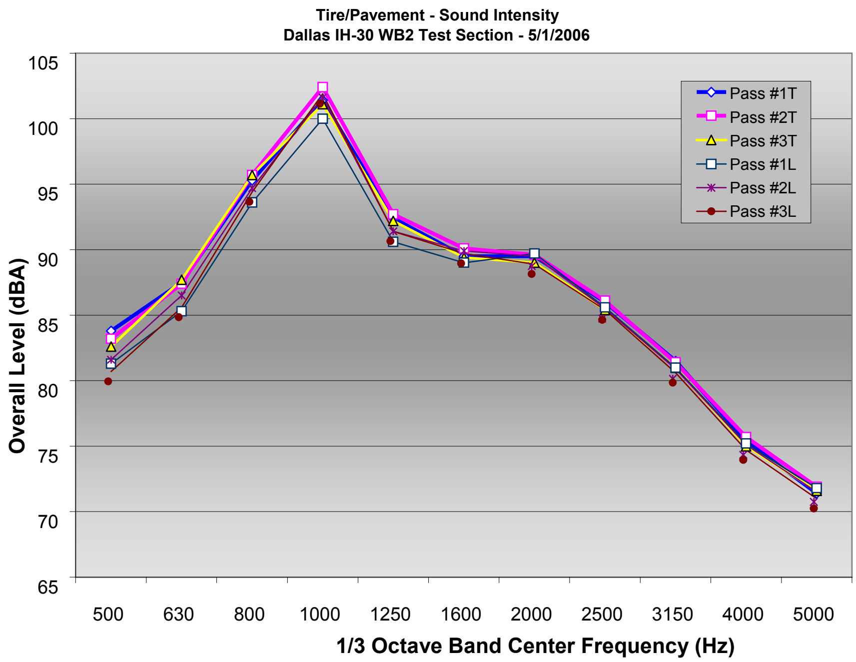


*Figure 3.12: Example of the sound data analysis output (frequency spectra)*

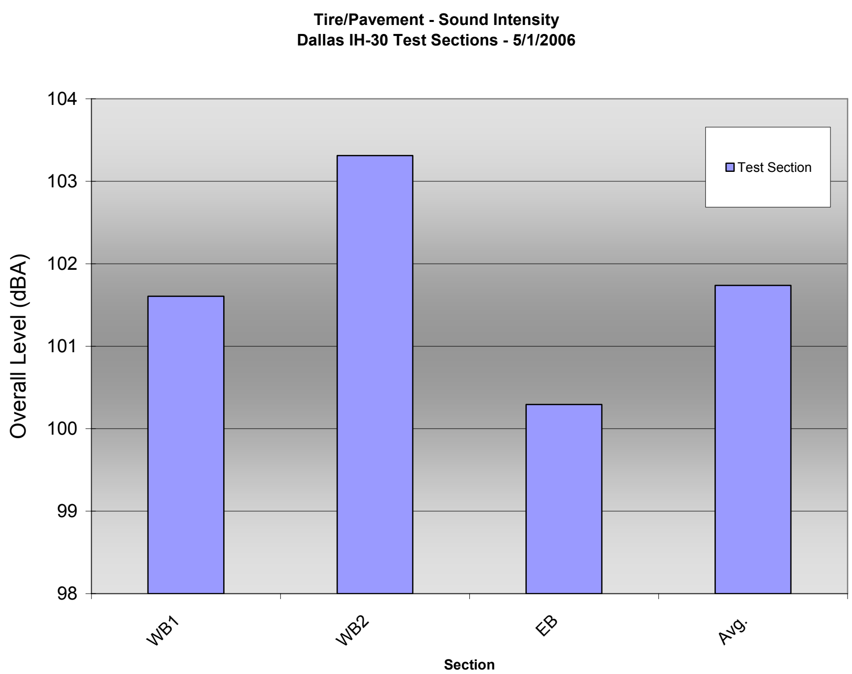


*Figure 3.13: Example of sound data analysis output (summary of overall levels)*

The data can be reported in any way the user needs it: by total project average, by subsection, by showing separate curves for leading edge and trailing edge and/or separate curves for each pass, etc. For consistency, in this report, for each section analyzed, a plot of the overall sound levels and the 1/3-octave band frequency spectra are presented, which are the most summarized plots that can be shown.

## 3.10 Summary

A comprehensive, repeatable protocol has been developed addressing all instruments used and data types collected on a project. This protocol is essential in facilitating comparisons with TxDOT collected data, data-sharing with researchers in other states, and, most importantly for this study, correctly assessing acoustic changes in pavements over time. The protocol is followed very carefully in all noise testing conducted under this project, and any deviations are noted in the log.

Organized storage of all data collected at the test sites including raw sound files, video tape, GPS logs, roadside measurements, and scans of the test logs, allows reanalysis of the data (using the Larson Davis analyzer) at any time. This is important for the following reasons:

- Questionable results can be double checked and possibly explained
- Controversial findings can be verified
- Sharing with other researchers and practitioners is greatly facilitated
- Improved analysis procedures developed in the future can be applied to the existing data without requiring additional field work
- In some cases, errors in the field analysis can be corrected by editing the sound files and reanalyzing them

This protocol will be used for the remainder of the study, and is recommended to TxDOT for their field data collection.

# 4. Results from OBSI Testing

## 4.1 Introduction

This chapter presents the outcome of the on-board sound intensity (OBSI) tests performed up to this date in the project. As mentioned in other sections of this report, the testing in the first stages of the project has been focused on open-graded friction course (OGFC) pavements, also known in Texas as permeable friction courses (PFC), according to the factorial of test sections presented in the first report of this project. Thus, most of the noise testing has occurred on these types of surfaces, which are commonly regarded as quieter.

## 4.2 Procedure

The procedure utilized for these tests complies with the provisional "AASHTO Standard Practice for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method." The equipment being utilized adheres to the "AASHTO Standard Equipment Specification for System to measure Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method." These standards are still being modified; the latest versions of these documents are included in Appendix A. These specifications are mostly finalized and are not expected to be substantially modified, according to the conclusions of a recent meeting in Washington, D.C. attended by one of the authors, a meeting which worked out most of the final details of the documents.

## 4.3 Sections

The sections that have been tested are as follows:

a. IH-30 in Dallas (tests on both CRCP and PFC overlay)
b. US 183 North in Austin (PFC)
c. US 183 North in Austin (CRCP)
d. FM 620 in Austin (PFC)
e. IH-35 in Austin (PFC)
f. IH-35 in Austin (Between Buda and Kyle, PFC)
g. SH 6 in Waco (PFC)
h. IH-35 in Waco (PFC)
i. IH-37 in Corpus Christi (PFC)
j. IH-35 in San Antonio (PFC)
k. US 281 in San Antonio (PFC)

The following paragraphs describe each section and present graphs with the overall sound levels, and the spectra for the frequency range analyzed (500 to 5000 Hertz). A discussion of the OBSI results is presented after the projects' descriptions at the end of this chapter. Some of the tests have been performed by TxDOT's John Wirth and his group, using their vehicle and OBSI equipment, which is analogous to CTR's. The contributions from the TxDOT group to the data collection efforts and their cooperation to the development of this research endeavor are very much appreciated. The sections are presented in chronological order, according to when the tests were conducted, except for the last section, the US 281 PFC in San Antonio, which was visited on three different occasions.

### 4.3.1 Dallas IH-30 CRCP

The first project tested in this phase was the IH-30 CRCP in downtown Dallas. The main drive to conduct noise tests in this project was that the existing CRCP surface was going to be overlaid within a short period of time with a PFC overlay, the main purpose of which was to reduce the high tire/pavement noise levels. Therefore, this project offered a valuable opportunity to compare noise levels before and after the PFC overlay was placed. The segment that was overlaid extends from Sylvan Ave. to Loop 12, just west of downtown Dallas. This is a short stretch, approximately ¾ of a mile. The tests on the CRCP were conducted on May 1, 2006. Figure 4.1 shows the map of the project location: the GPS system kept track of the full loop in which the test vehicle was driven to test both the westbound and eastbound directions.

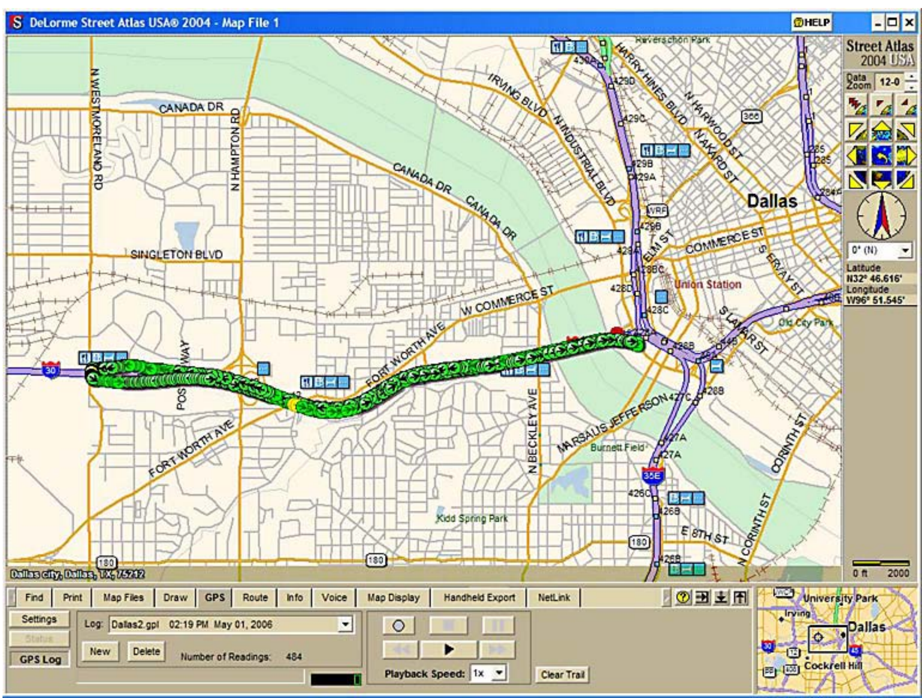

*Figure 4.1: Map of IH-30 in Dallas, showing the loop driven while performing the OBSI tests*

The beginning of the westbound segment, west of Sylvan Ave., at exit 43 A, is presented in Figure 4.2, where the change in pavement type can be seen, from AC to CRCP.

*Figure 4.2: Beginning of IH-30 CRCP westbound section*

On this occasion, three subsections were tested, two in the westbound and one in the eastbound. At that point, it was unclear to the researchers what the westernmost limit of the segment to be overlaid was in the eastbound direction; that is why only one subsection was tested on that side of the roadway. The overall noise levels obtained are illustrated in Figure 4.3.

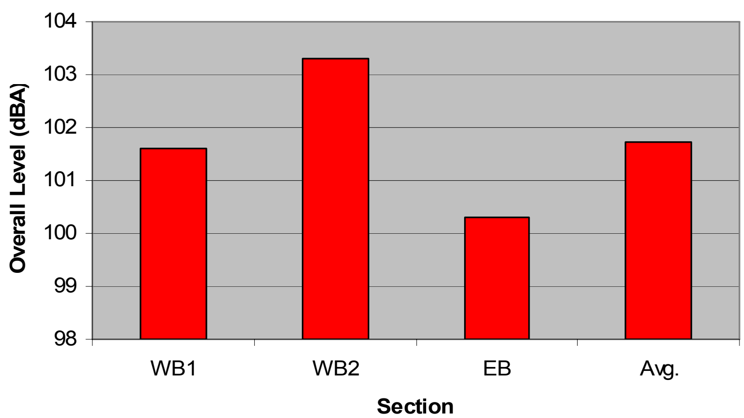


*Figure 4.3: Overall noise levels for IH-30 CRCP Sections in Dallas*

The WB2 subsection had a few distresses, and part of it was below grade, with a tall retaining wall close to the outside line, which might explain the higher overall noise level. However, the results in the OBSI method are not supposed to be affected by walls, given the proximity of the microphones to the tire/pavement interface.

The overall A-weighted sound intensity level over 1/3 octave bands from 500 to 5000 hertz was calculated. The resulting spectra for the IH-30 sections are shown in Figure 4.4.

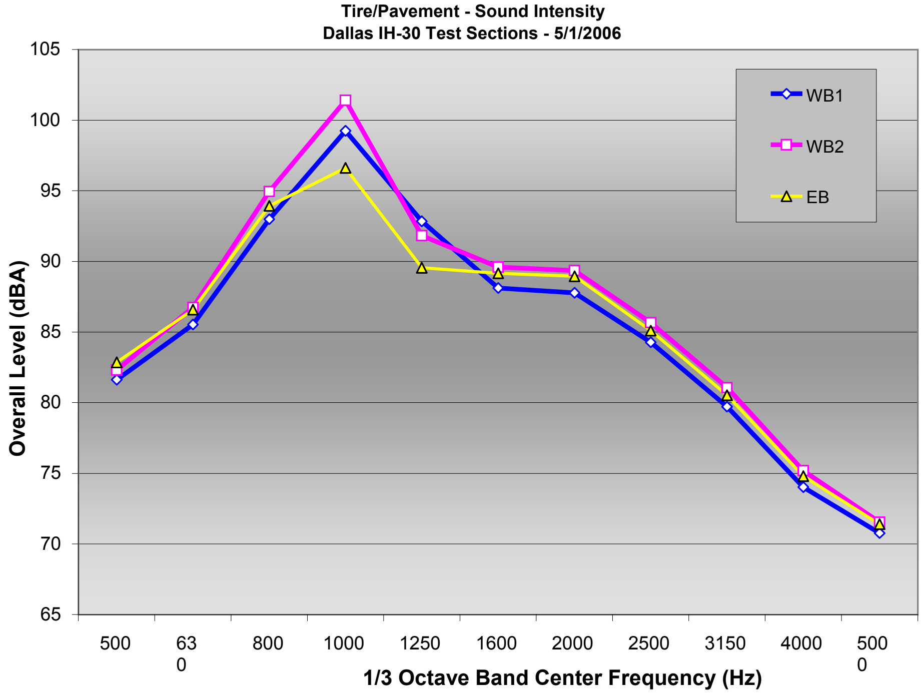


*Figure 4.4: Spectral analysis for the Dallas IH-30 CRCP sections*

The subsequent results of this project after the sections were overlaid with the PFC are presented in section 4.3.7 in this chapter.

### 4.3.2 Austin US 183 North PFC

The section on US Highway 183 was tested on August 23, 2006. This PFC was constructed in 2003. It extends for 2 miles, from the north fork of the San Gabriel River to Seward Junction (SH 29) in Williamson County. Within that stretch, four segments were tested by TxDOT personnel, two on the northbound direction, labeled as 1T and 2T, and two on the southbound direction, tagged as 3T and 4T.

A detailed map of the project showing the four subsections is shown in Figure 4.5.


*Figure 4.5: Detailed location of US 183 N PFC sections*

Some images from the section are captured in Figures 4.6, 4.7, and 4.8.


*Figure 4.6: Section 1T on US 183 N northbound*


*Figure 4.7: Section 3T on US 183 N southbound*


*Figure 4.8: Section 4T on US 183 N southbound*

Figure 4.9 summarizes the overall noise level results for the US 183 PFC.

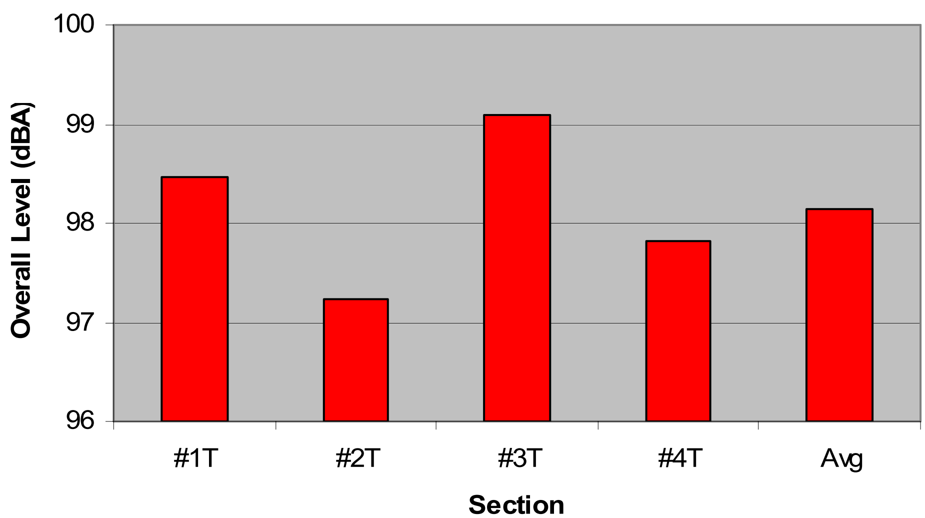


*Figure 4.9: Overall noise levels for US 183 N PFC Sections*

The spectra for the sections are presented in Figure 4.10.

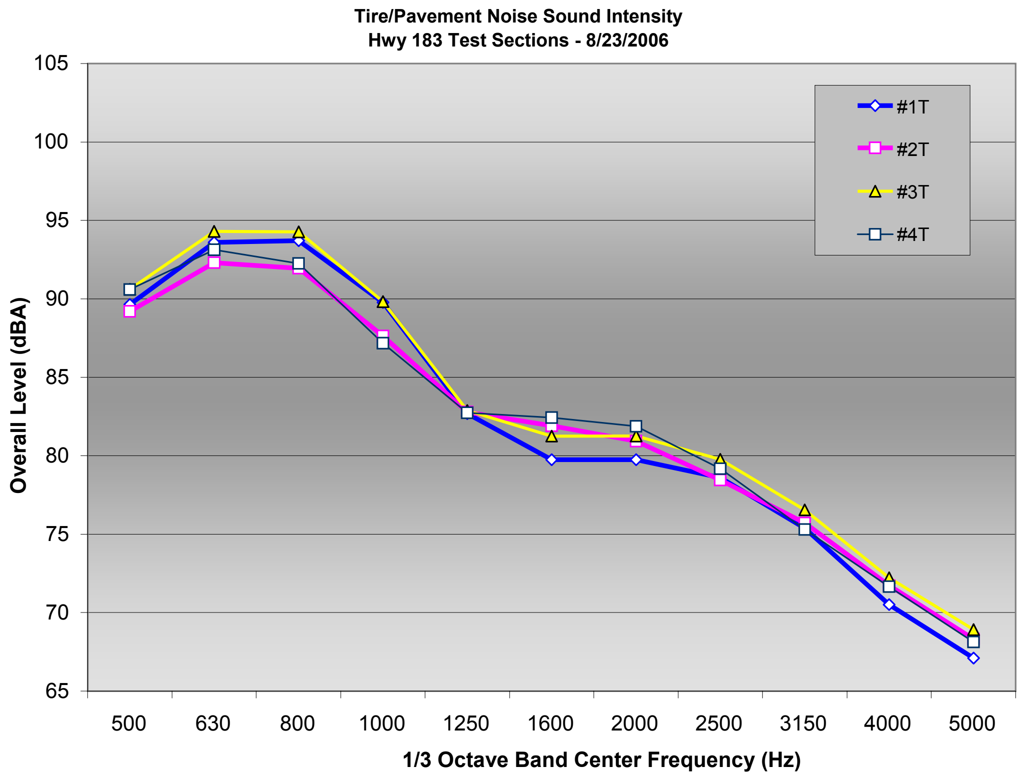


*Figure 4.10: Spectral analysis for the US 183 N sections*

### 4.3.3 Austin US 183 N (CRCP)

On August 24, 2006, a concrete pavement was tested on US 183 N. This pavement offered a good opportunity to compare the results of a CRCP surface with those obtained on the PFC surface, which is just a few miles north of this section. The project is located between McNeil Dr. and Anderson Mill Rd. in Williamson County. This project was tested by TxDOT. Five sections were marked, three on the northbound direction (labeled as 5T, 6T, and 7T, respectively) and two on the southbound direction (8T and 9T). Figure 4.11 shows a map with the subsections' locations.


*Figure 4.11: Detailed location of US 183 N CRCP sections*

The overall noise levels obtained are illustrated in Figure 4.12.

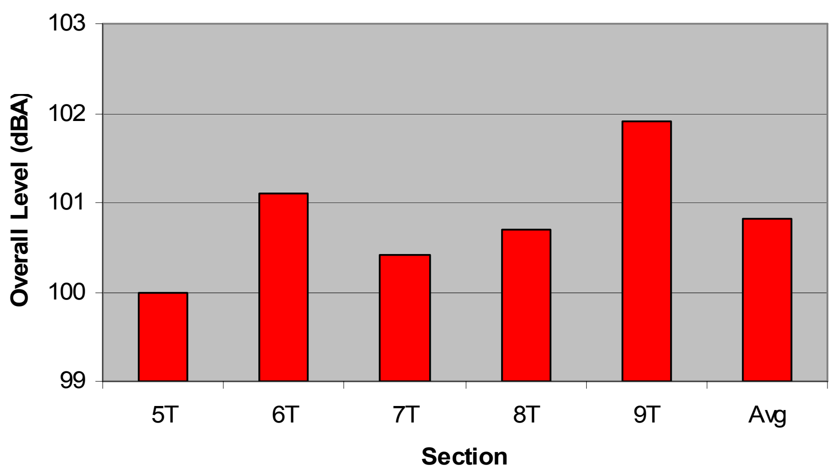


*Figure 4.12: Overall noise levels for US 183 N PFC Sections*

The 1/3 octave band spectra from these sections is shown in Figure 4.13.

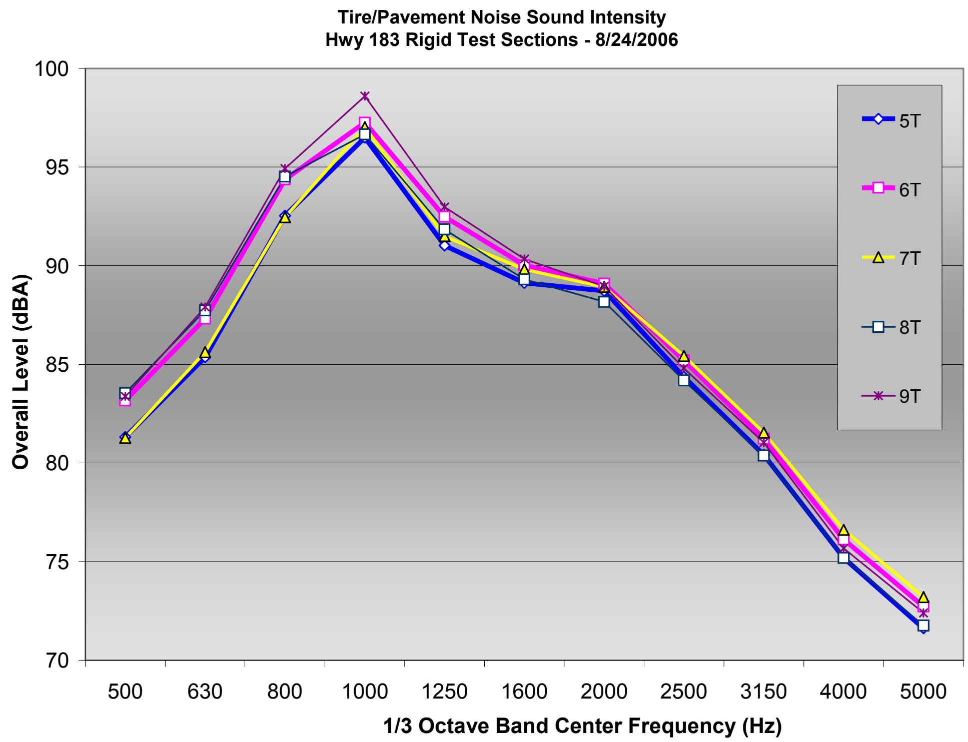


*Figure 4.13: Spectra for the US 183 N CRCP sections*

### 4.3.4 Austin FM 620

The FM 620 PFC section in Austin was tested on September 7, 2006. It is a 3.6-mi stretch, from SH 45 on the west side, to IH-35 on the east side, in Williamson County, constructed in 2004. The section location is presented in Figure 4.14., and Figure 4.15 shows the beginning of the eastbound segment.

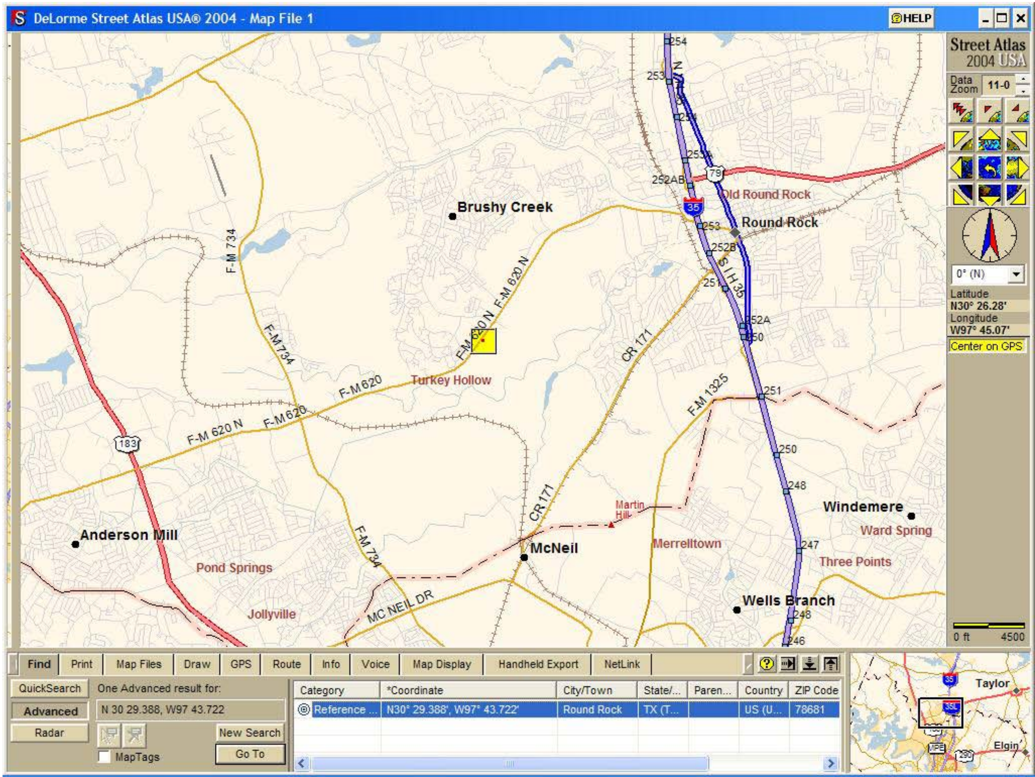


*Figure 4.14: FM 620 PFC section location in Austin*


*Figure 4.15: FM 620 PFC project in Austin*

Only one segment in each direction was measured. Unfortunately, the section is relatively short and there are several traffic lights, thus it was not possible to measure more than one segment in each direction. Additionally, two tests were conducted while the test vehicle was stopped on the side of the road: in one of those, the engine was running, while in the other one, the engine was off. The results of both of these tests show up in the graphs that follow. The overall sound levels for the FM 620 PFC are presented in Figure 4.16.

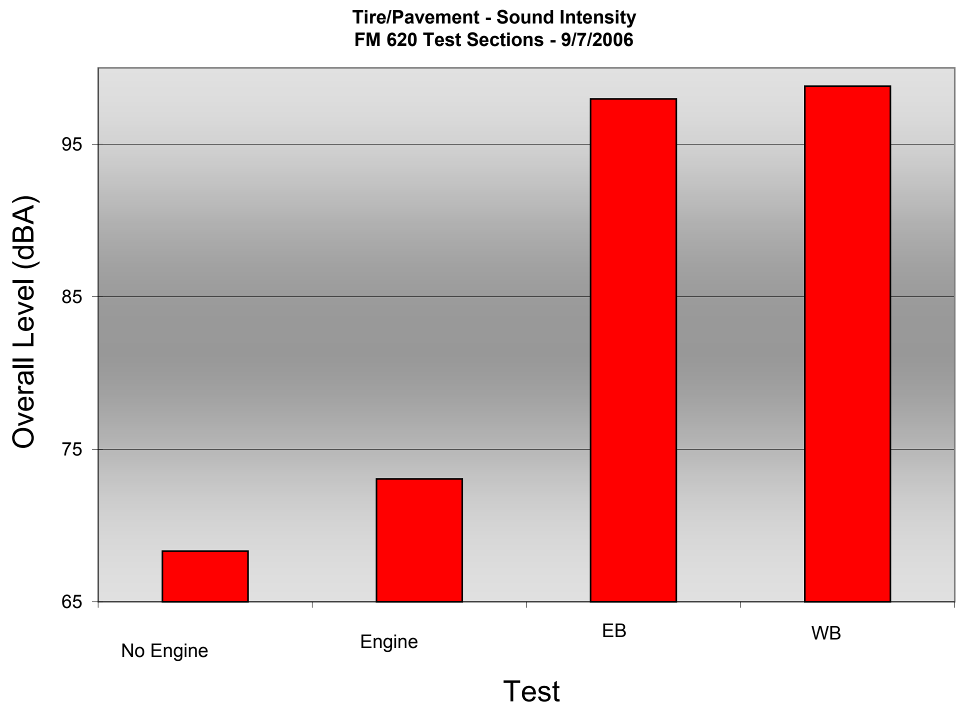


*Figure 4.16: Overall levels for FM 620 PFC*

The 1/3 octave band spectra for the tests is shown in Figure 4.17.

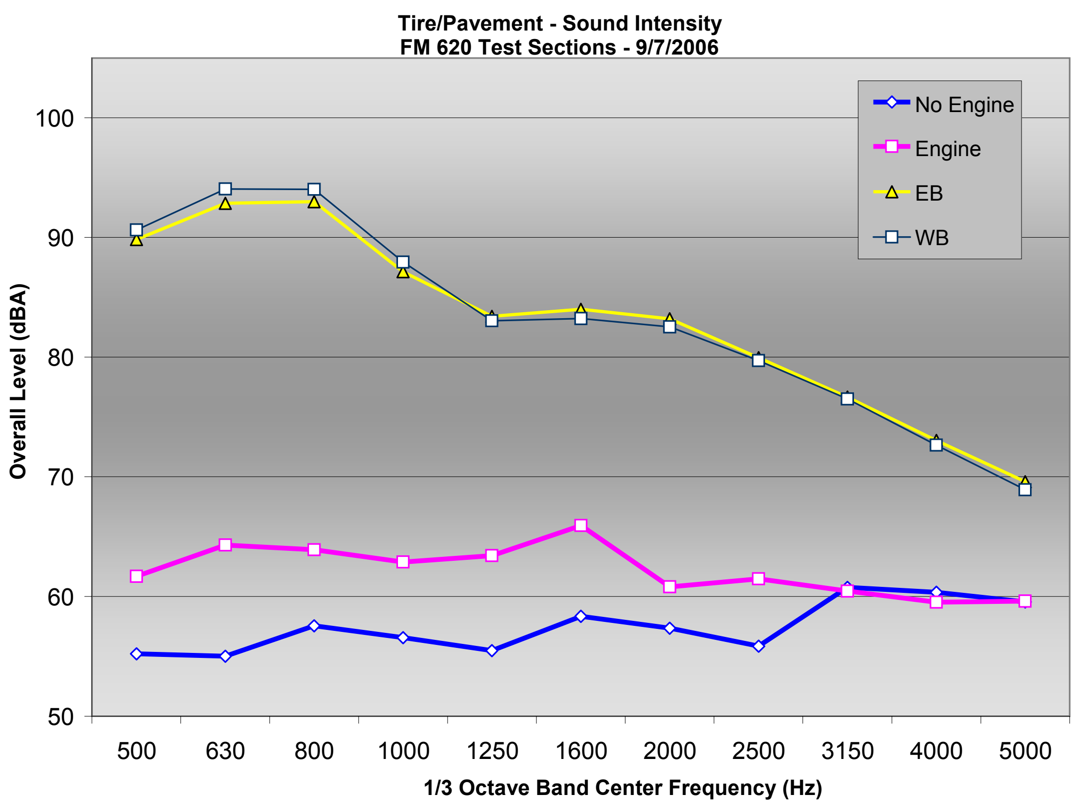


*Figure 4.17: Spectra for the FM 620 PFC project in Austin*

### 4.3.5 Austin IH-35 PFC

The PFC on IH-35 in Austin, from the Colorado River to Ben White, was tested on September 22, 2006. The section in question is a 1.7-mile long stretch, just south of downtown Austin, in Travis County, and was placed in 2006. This test was performed by TxDOT. Six subsections were marked and tested, 1T, 2T, and 3T in the northbound lane, and 4T, 5T, and 6T in the southbound direction.

The overall sound levels for all the subsections are shown in Figure 4.18, and the spectra are presented in Figure 4.19.

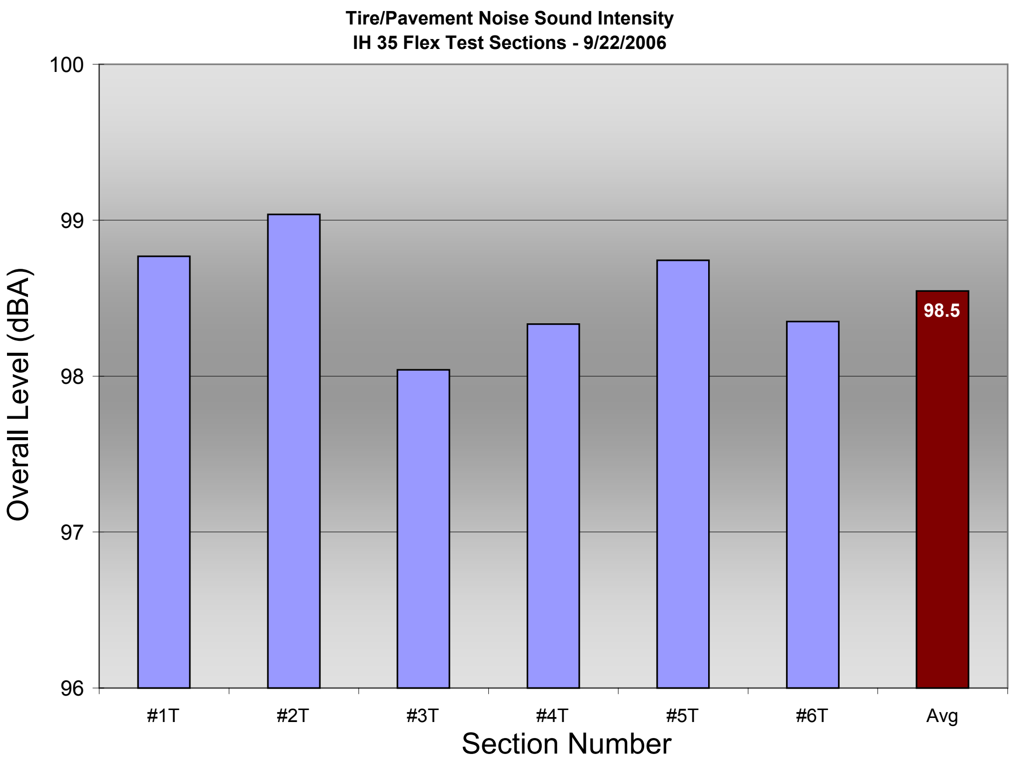


*Figure 4.18: Overall sound levels for the PFC on IH-35 in Austin*

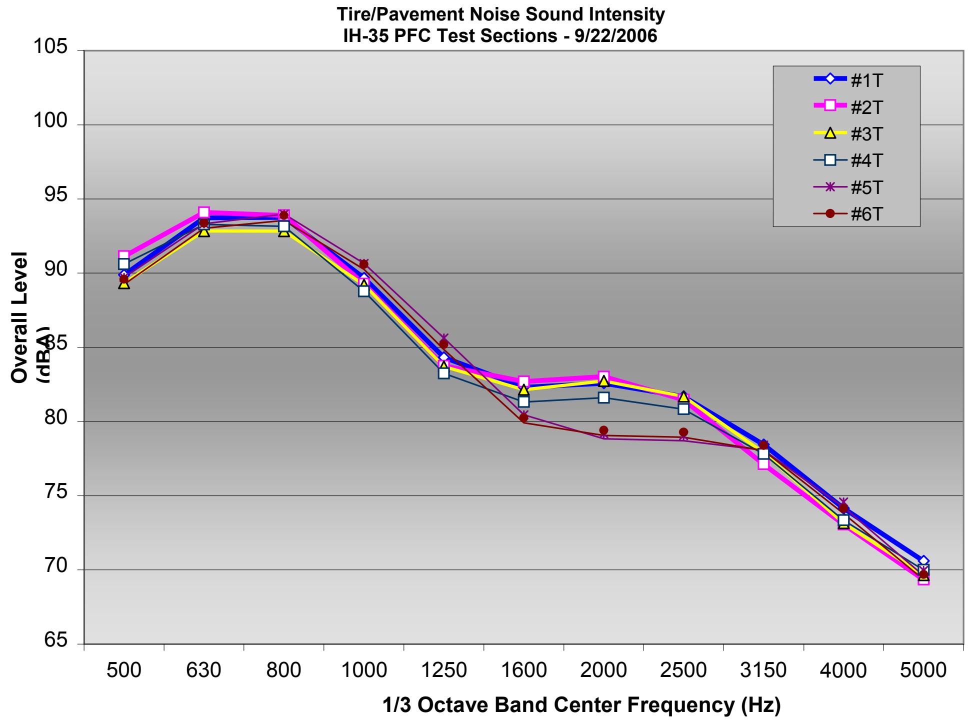


*Figure 4.19: Spectra for the IH-35 PFC sections in Austin*

### 4.3.6 Austin IH-35 PFC, Between Buda and Kyle

The PFC on IH-35 in Austin, from the Loop 4 to Yarrington Road was also tested on September 22, 2006, by TxDOT personnel. This is a 9-mile long PFC section south of Austin, between Buda and Kyle, in Hays County, Austin District, constructed in 2005. It should be noted that the northbound and southbound pavements are different: even though both sides are PFCs, the asphalt binder differs in each direction. Sections 7T, 8T, 9T, and 10T were marked and tested in the southbound lane and 11T, 12T, and 13T in the northbound direction. The overall levels are illustrated in Figure 4.20, and the spectra are presented in Figure 4.21.

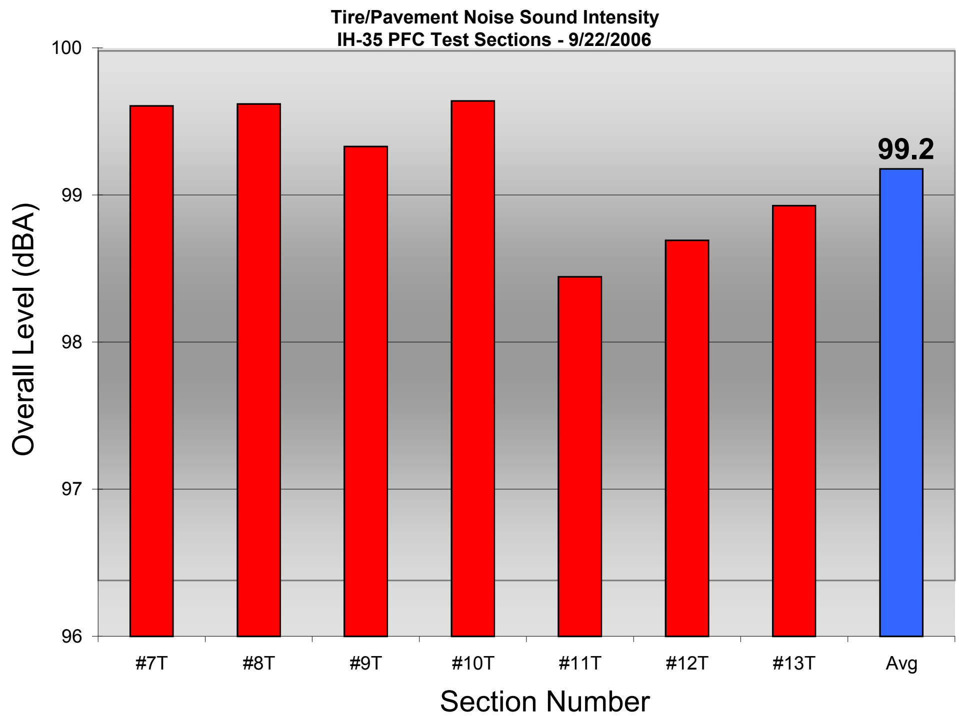


*Figure 4.20: Overall sound levels on IH-35 PFC sections between Buda and Kyle (Austin District)*

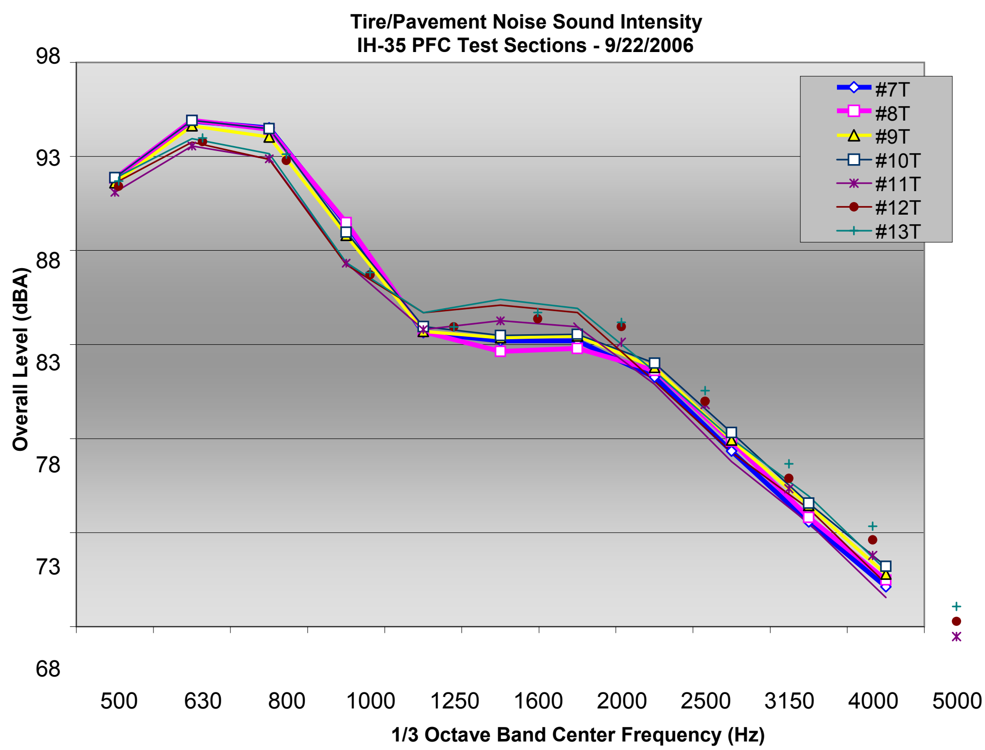


*Figure 4.21: Sound level spectra for IH-35 PFC sections between Buda and Kyle (Austin District)*

### 4.3.7 Dallas IH-30 PFC

The Dallas IH-30 project described in Section 4.3.1 was overlaid on May 11, 2006, shortly after the first round of tests was completed on the CRCP. The research team visited the section again once the PFC overlay was already in place, on September 26, 2006, to conduct the OBSI tests on the new surface (Figures 4.22 and 4.23).

*Figure 4.22: Texture of the new PFC overlay on IH-30 in Dallas*

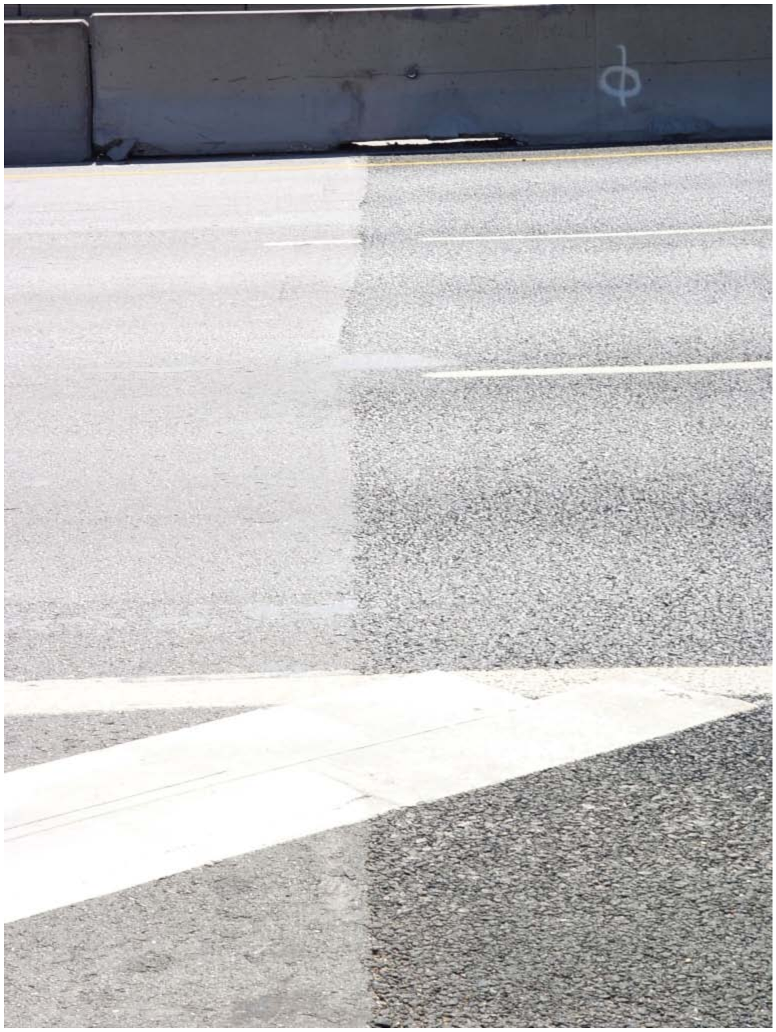

*Figure 4.23: Westbound transition to new PFC overlay on IH-30 in Dallas*

This time, two PFC subsections were tested in each traveling direction, WB1, WB2, EB1, and EB2, plus an additional westbound segment beyond the limits of the new PFC overlay, i.e., a CRCP segment, which was run to have another reference for the original noise levels prior to the overlay rehabilitation. This subsection is identified as WBCRCP in the graphs that follow. The noise levels are shown in Figure 4.24.

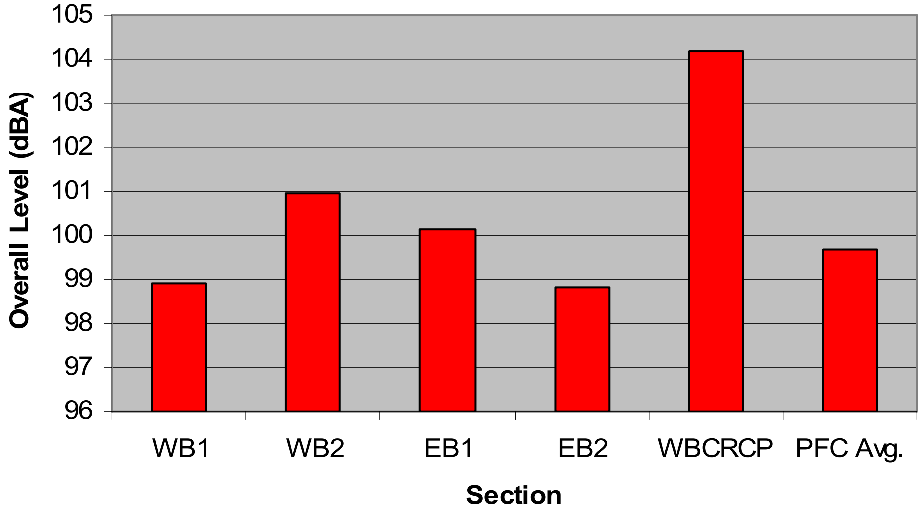


*Figure 4.24: Overall noise levels from IH-30 PFC in Dallas*

The spectra for each subsection are presented in Figure 4.25, where, as expected, the pattern of the PFC spectra are quite different from that of the CRCP, which, as observed throughout this project, has a characteristic peak in the 1000-Hz frequency band.

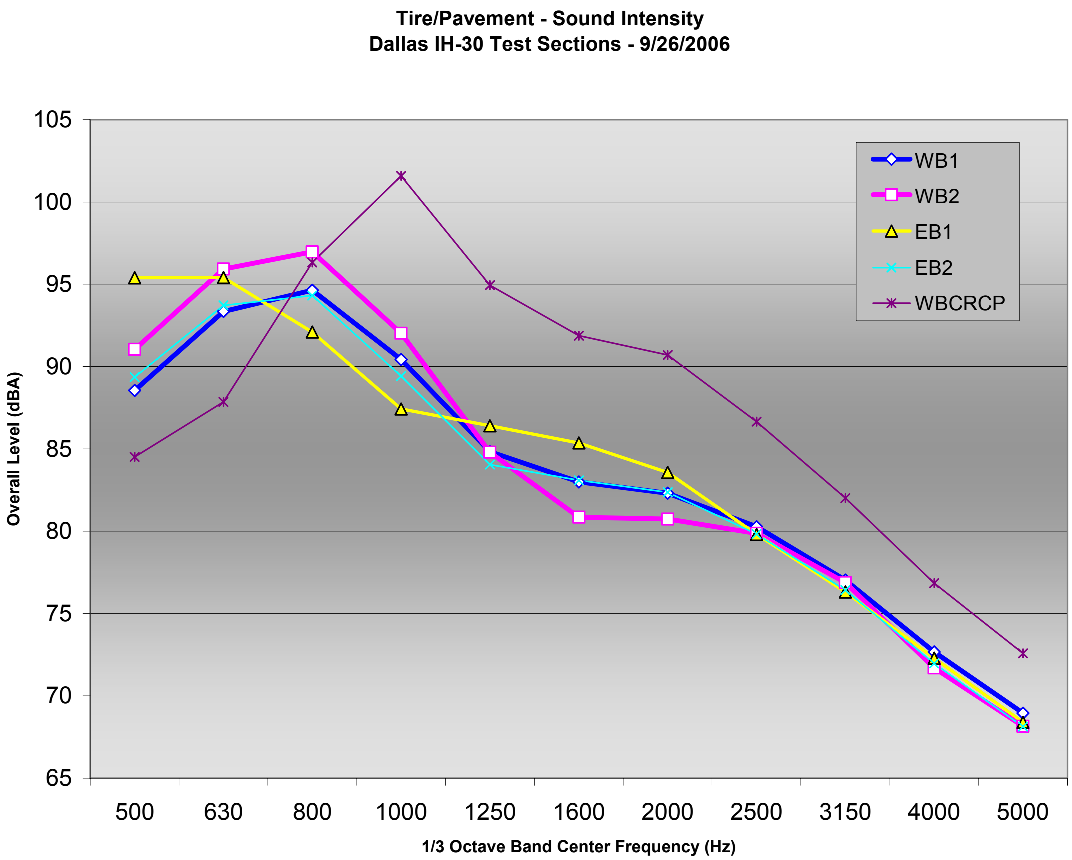


*Figure 4.25: Spectra for the IH-30 Dallas PFC project*

As mentioned before, this project offered the opportunity to compare the test results from both before and after the PFC overlay was placed on the original CRCP. The overall sound level comparison is illustrated in Figure 4.26, in which, evidently, the PFC fulfilled its purpose of making the pavement quieter.

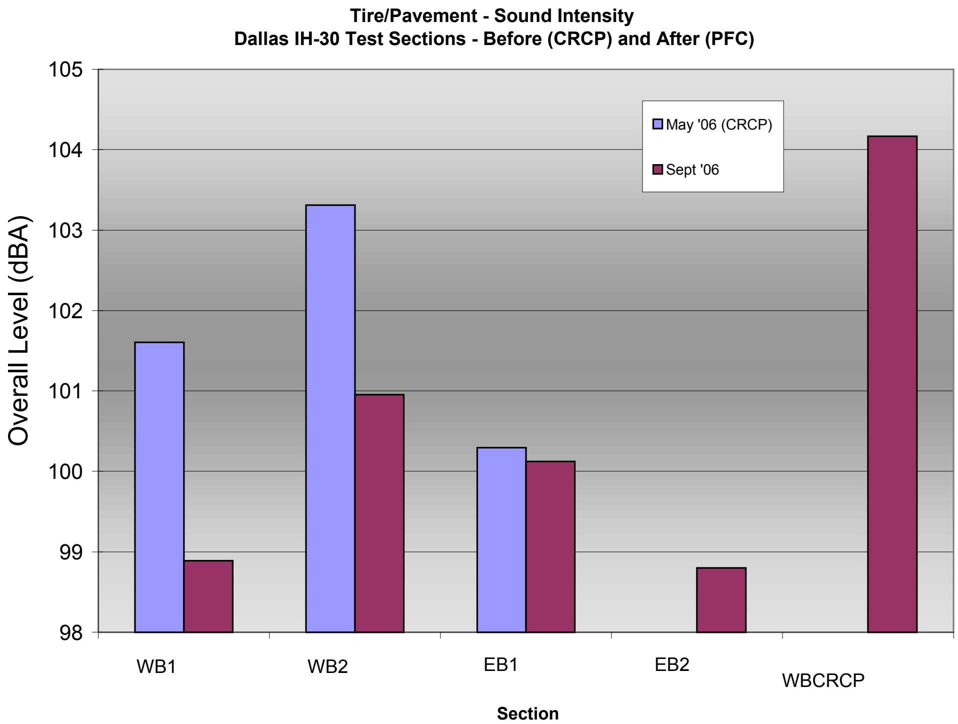


*Figure 4.26: Overall level comparison for the IH-30 Dallas project before and after PFC overlay*

In comparing the 1/3-octave band spectra for the two occasions (Figure 4.27), it can be seen that the CRCP spectra have the characteristic peak in the 1000-Hz band, which is consistent with other CRCP results, whereas PFC spectra do not show any such pronounced peak, and their highest levels tend to occur in a lower frequency range.

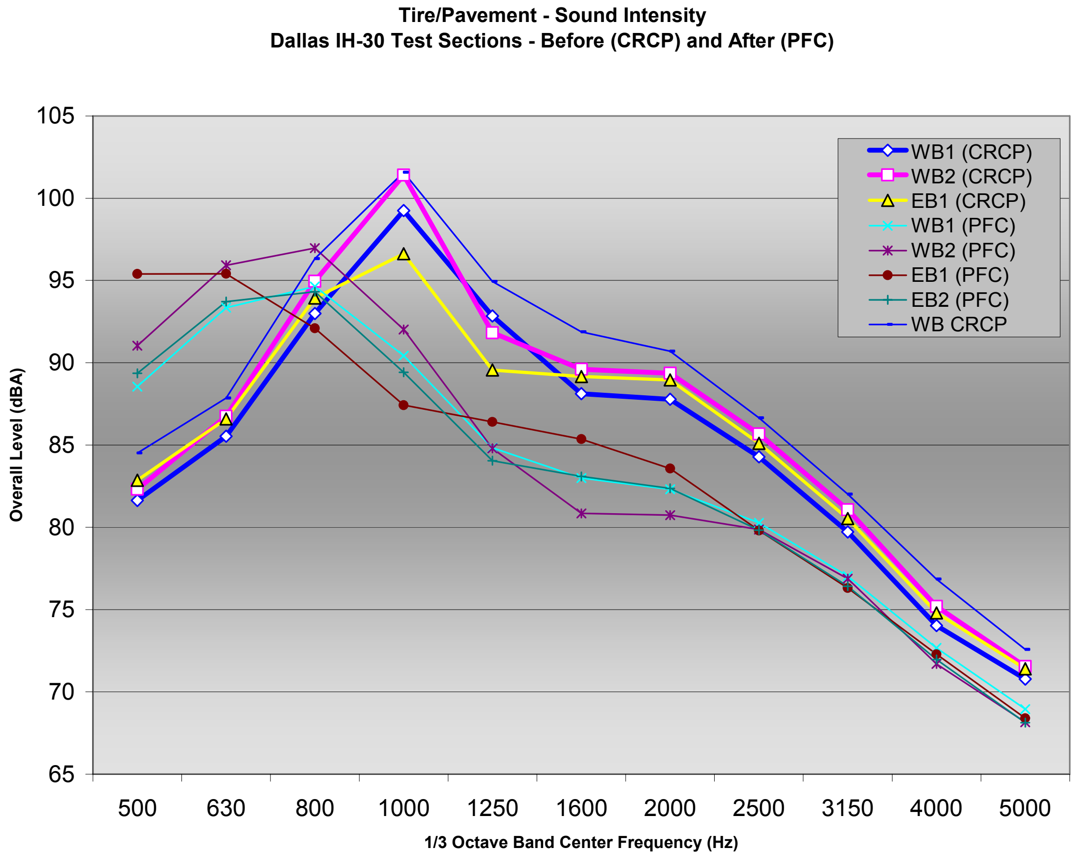


*Figure 4.27: Spectra comparison for the IH-30 Dallas project before and after PFC overlay*

### 4.3.8 Waco SH 6 PFC

The PFC project on SH 6 in Waco was tested on September 29, 2006. This pavement is an 8.7-mi stretch, from BU 77 to SH 164 in McLennan County, constructed in 2005. The section location is shown in a GPS map in Figure 4.28. Various aspects of this section are presented in Figures 4.29 through 4.31.

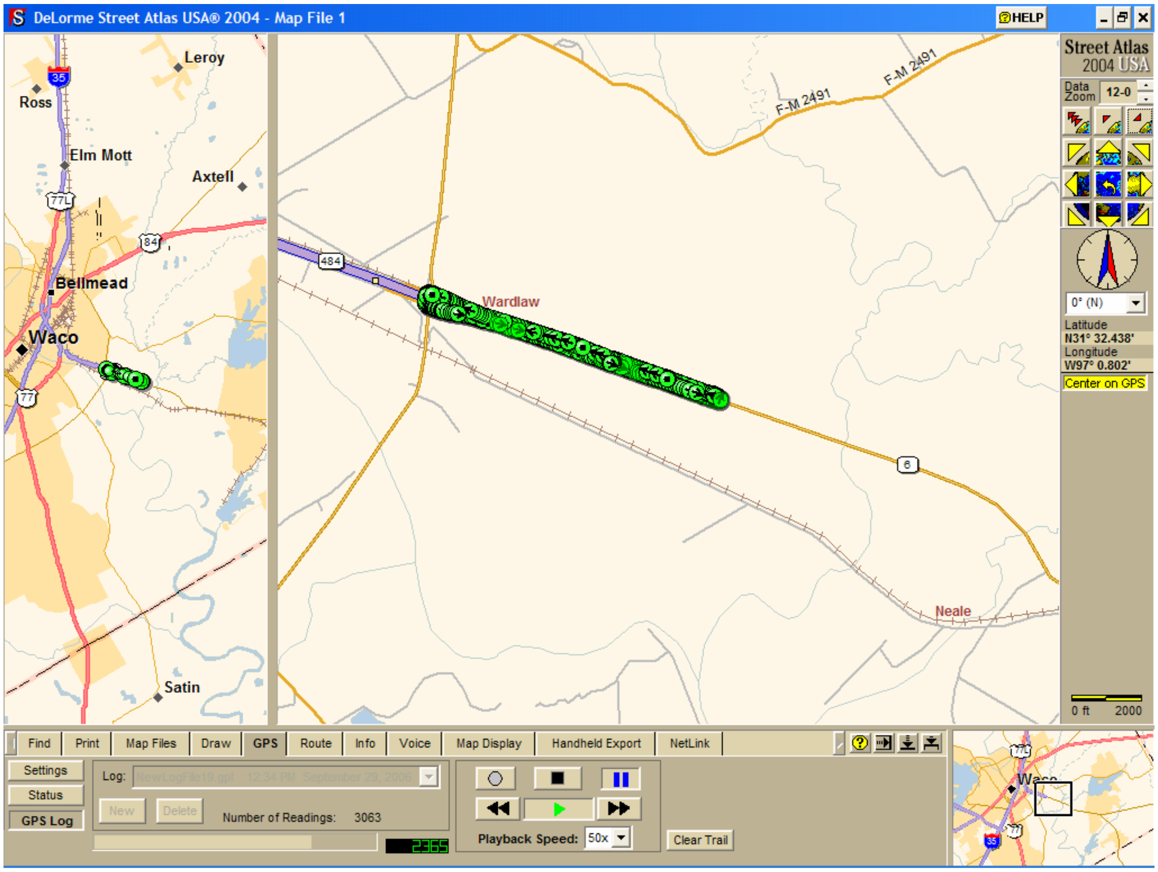


*Figure 4.28: SH 6 PFC section location in Waco*


*Figure 4.29: SH 6 PFC in Waco*

*Figure 4.30: Pavement texture of SH 6 PFC in Waco*


*Figure 4.31: SH 6 PFC westbound section in Waco*

Two subsections in each direction were identified for measurements, EB1 and EB2 for the eastbound direction, and WB1 and WB2 for the westbound lanes. The overall levels and the 1/3 octave band spectra are presented in Figures 4.32 and 4.33, respectively.

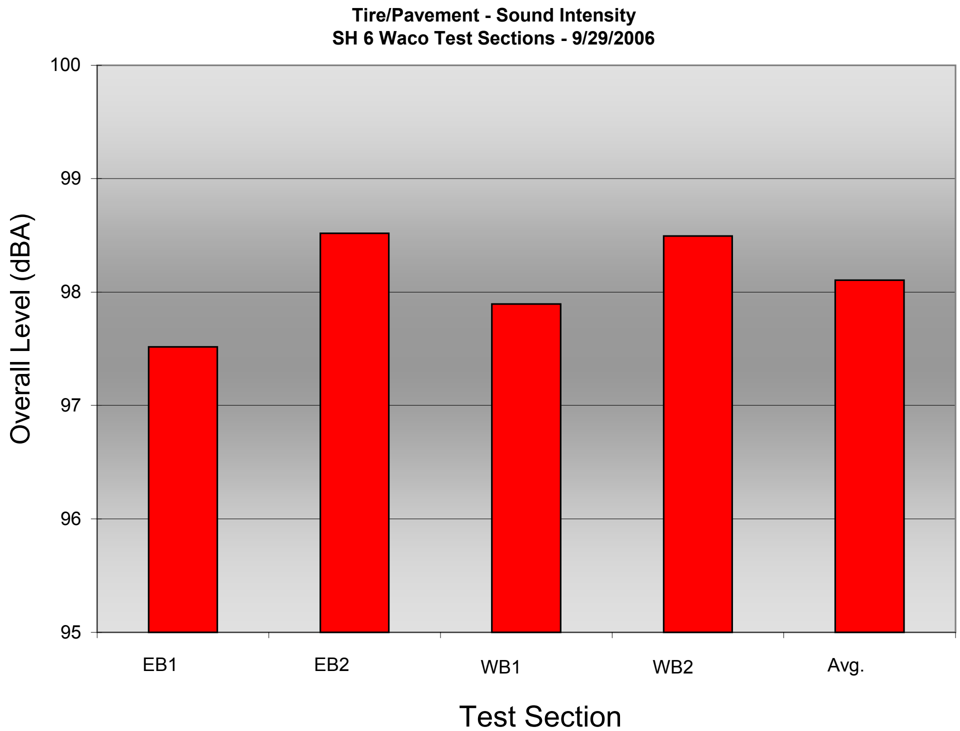


*Figure 4.32: Overall sound levels for SH 6 in Waco*

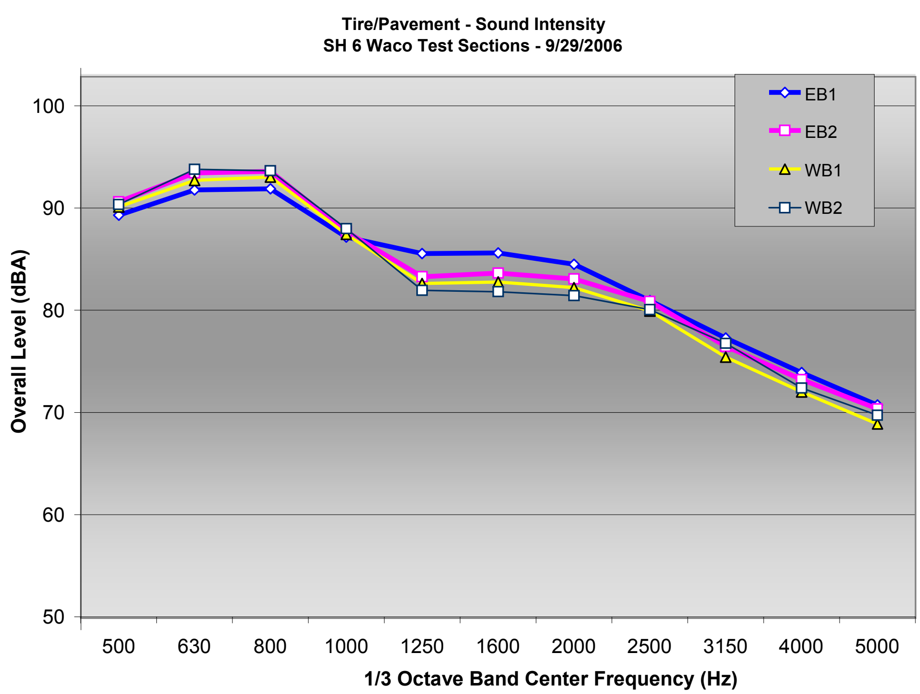


*Figure 4.33: Spectral analysis for the PFC on SH 6 in Waco*

### 4.3.9 Waco IH-35 PFC

The PFC on IH-35 in Waco, at Craven Ave. in McLennan County was tested on September 29, 2006. This is a 2.6-mi section in which two northbound (NB1 and NB2) and two southbound (SB1 and SB2) segments were identified and tested, in addition to a dense-graded AC subsection (NBDGAC), which was run for comparison with the PFC. Figure 4.34 shows the section location, and Figure 4.35 shows the beginning of the northbound segment, where the pavement changes from a conventional AC to a PFC.

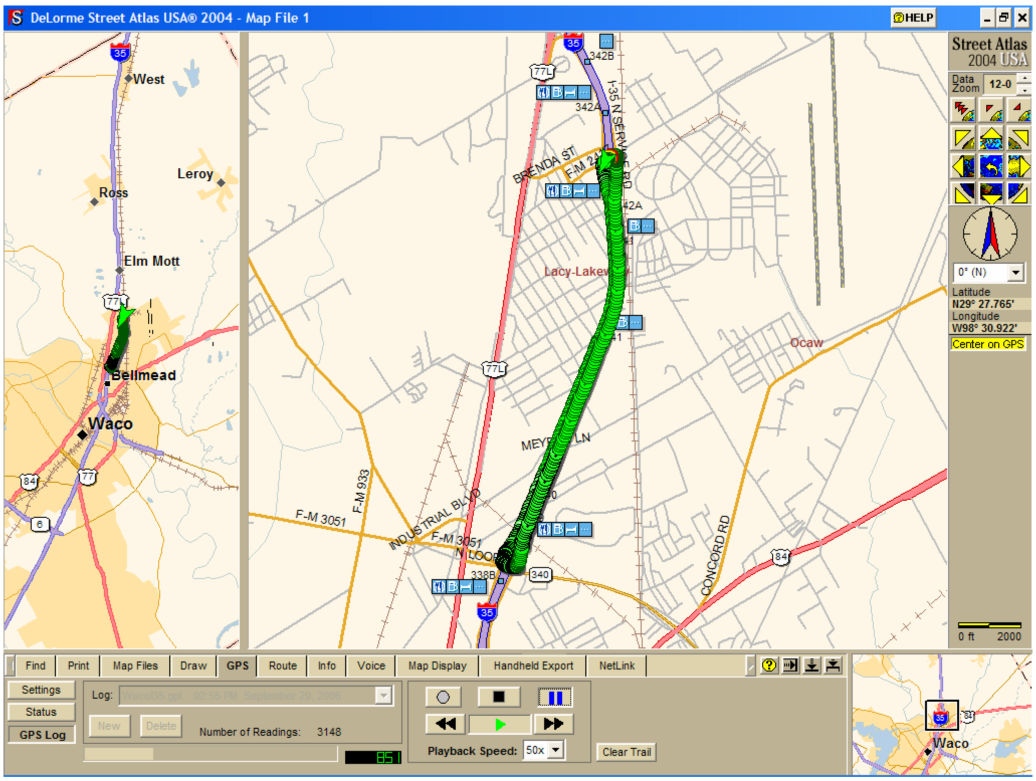


*Figure 4.34: GPS map of IH-35 PFC section in Waco*


*Figure 4.35: Beginning of northbound IH-35 PFC section in Waco*

Figure 4.36 shows the Craven Ave. limit of the PFC section and Figure 4.37 gives a closer look of the open-graded structure of the surface.


*Figure 4.36: IH-35 PFC section limit at Craven Ave. in Waco*

*Figure 4.37: Pavement texture of IH-35 PFC in Waco*

The open-graded pavement is 1 ½ -in. thick and was placed in 2003. Overall noise levels for the PFC were slightly below the noise level for the dense-graded pavement (Figure 4.38).

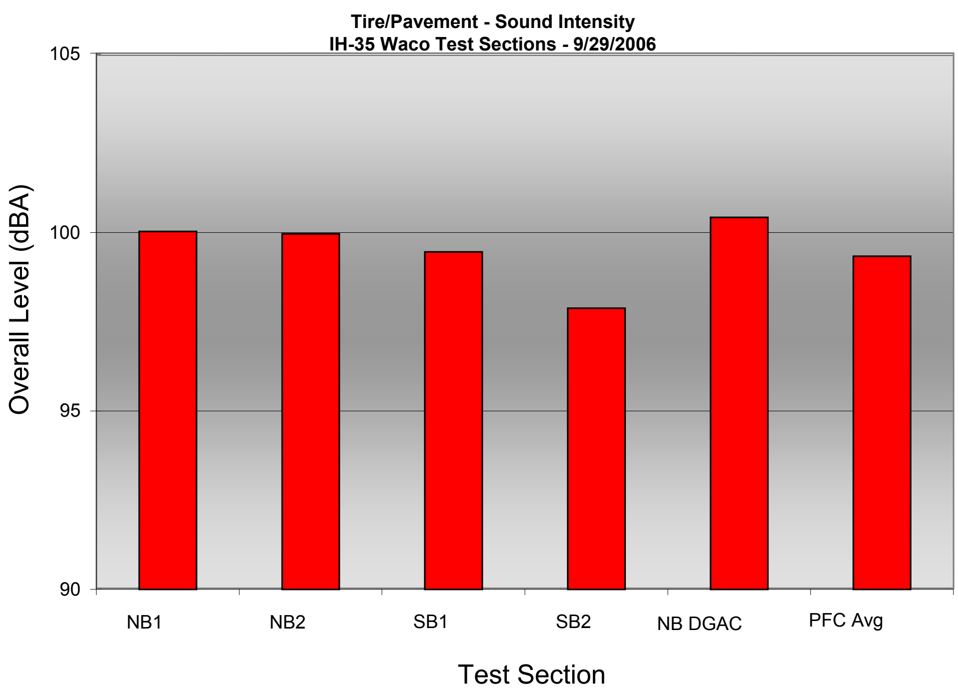


*Figure 4.38: Overall noise levels for the IH-35 PFC in Waco (including a DGAC segment)*

The 1/3 octave band spectra is shown in Figure 4.39.

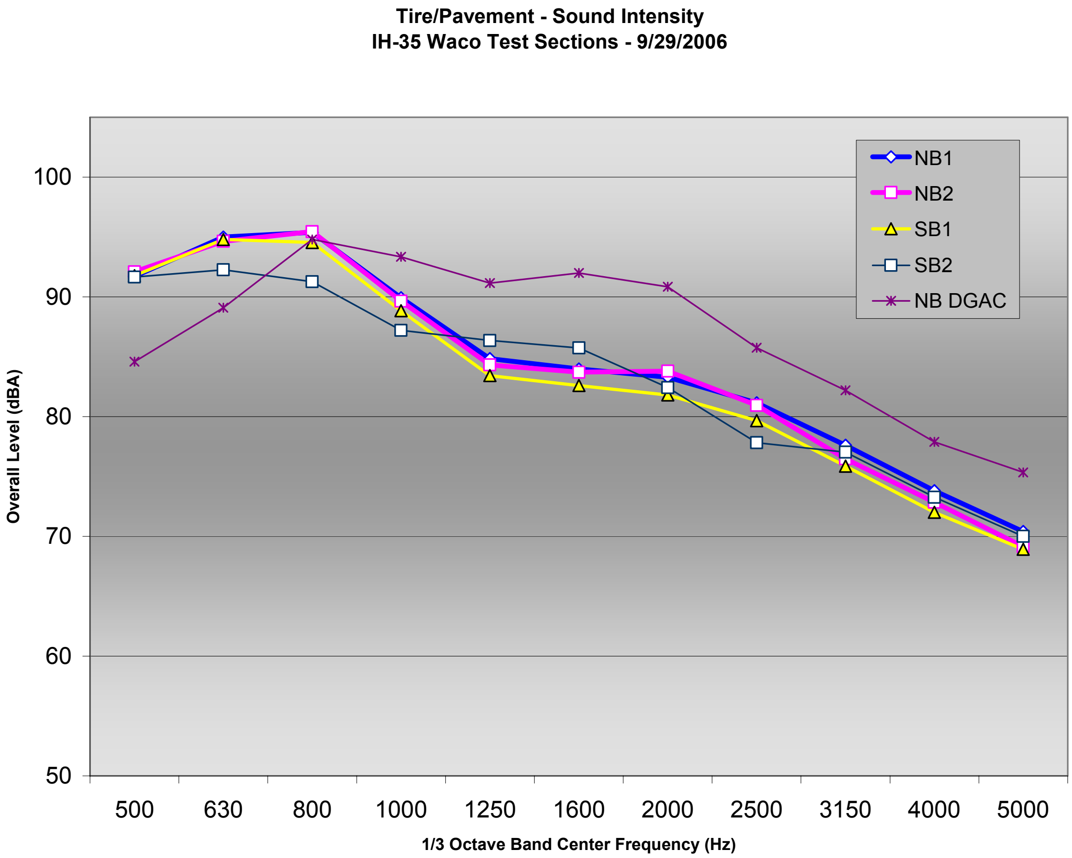


*Figure 4.39: Spectra for the IH-35 PFC in Waco*

### 4.3.10 Corpus Christi IH-37 PFC

Two different sections were tested in Corpus Christi on October 11, 2006; both are PFCs on IH-37 and were labeled as CC1 and CC2, both having northbound and southbound components. The reason for this is that even though both are PFCs, they were constructed with different materials: CC1 is an asphalt rubber mix, with limestone as coarse aggregate, while CC2 has fibers and limestone. CC1 extends from downtown Corpus Christi at US 181 to north of the Nueces River Bridge. The limits of section CC2 are from the Nueces River Bridge to the Atascosa County line. The location of the tested segments is illustrated in Figure 4.40 with a GPS map. Figures 4.41 through 4.43 show various aspects of both subsections, including the pavement texture.

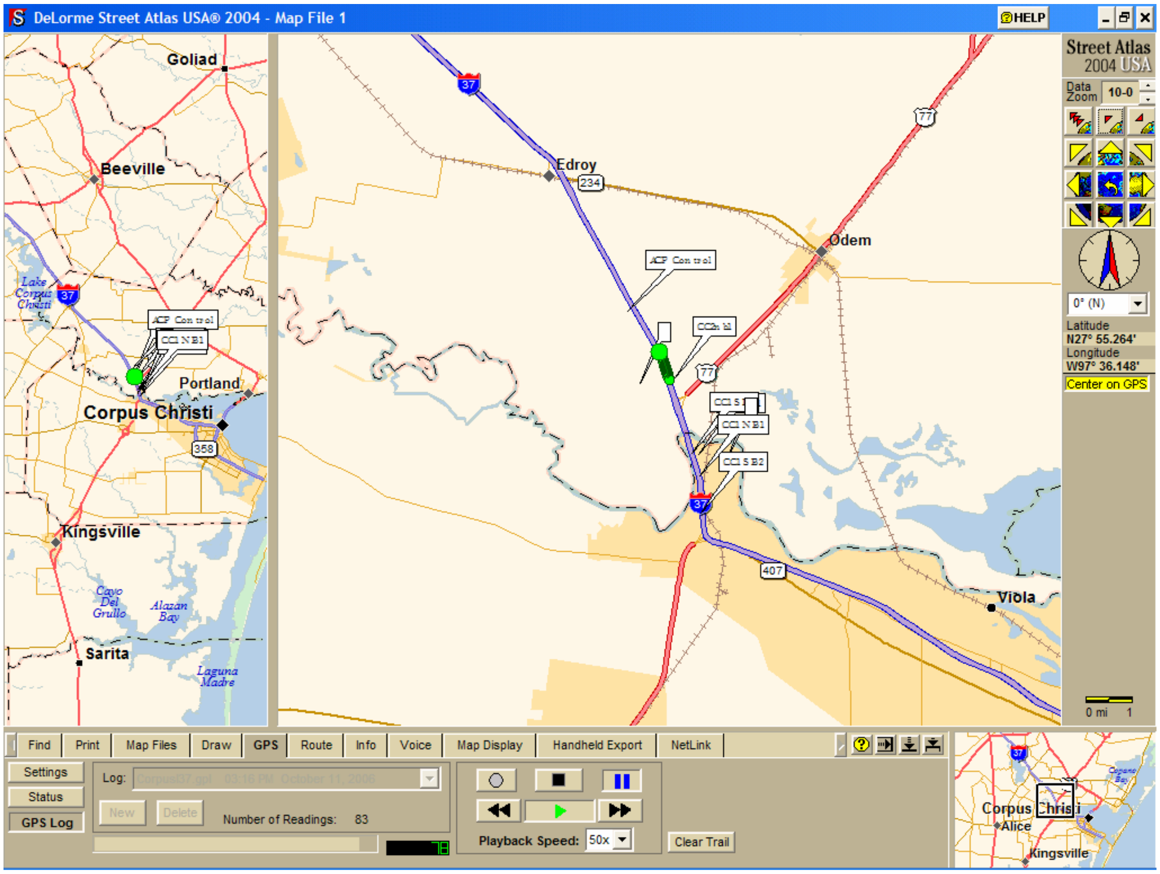


Figure 4.40: IH-37 section location

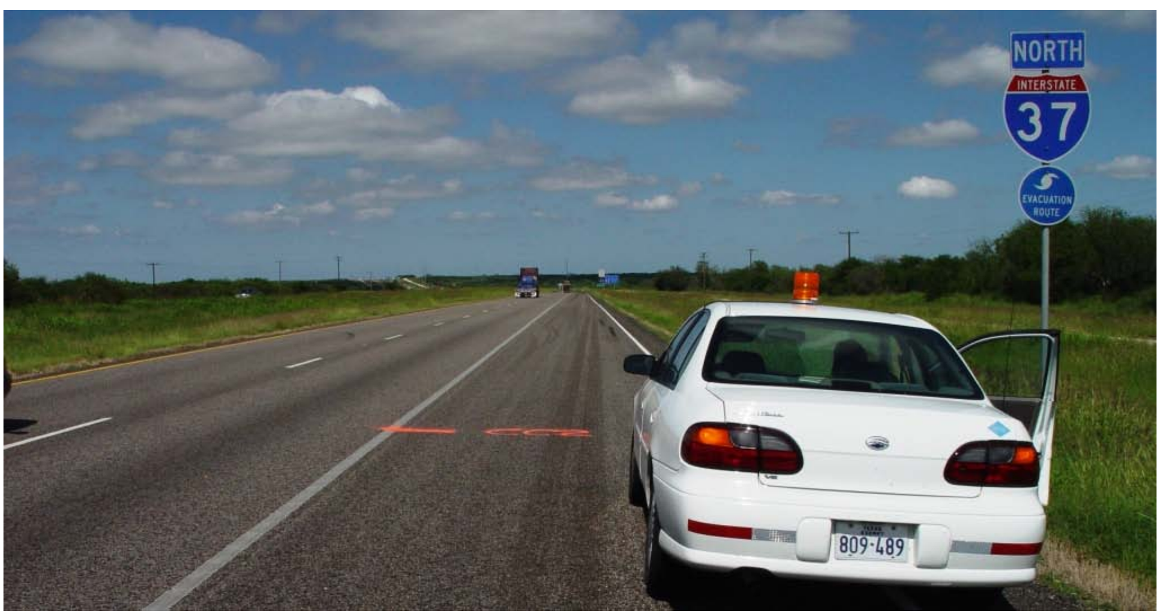


Figure 4.41: Beginning of CC2 PFC section on IH-37 in Corpus Christi

*Figure 4.42: Pavement texture of IH-37 PFC in Corpus Christi*


*Figure 4.43: Beginning of CC1 NB1 section on IH-37 in Corpus Christi*

The OBSI overall sound level results for all the subsections are presented in Figure 4.44, which includes the level obtained from an adjacent dense-graded segment that was tested in the southbound direction for comparison purposes. The comparison indicates that the dense-graded segment sound level was very similar to the PFC with asphalt rubber in it (CC1), especially to the southbound component, and was definitely quieter (almost by 5 dBA) than the PFC section with limestone and fibers (CC2).

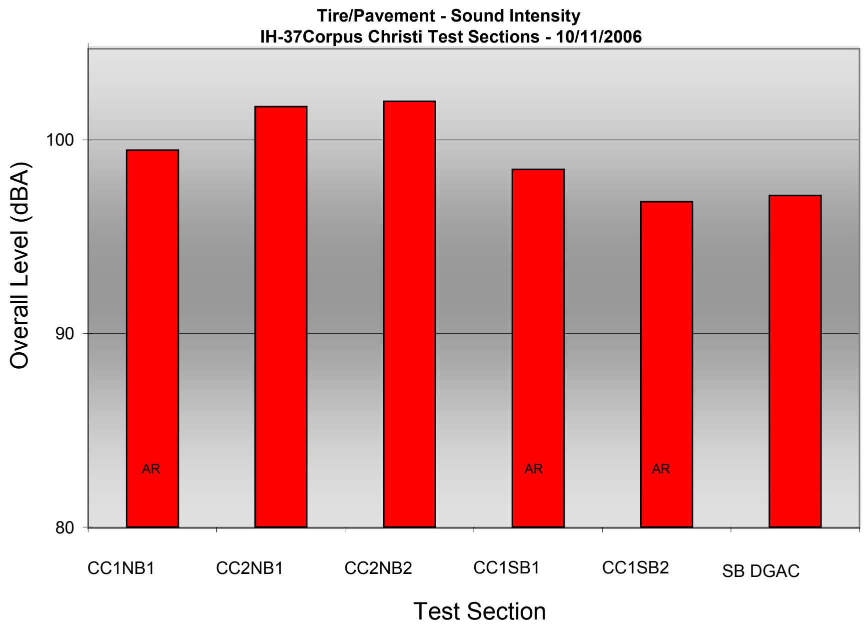


*Figure 4.44: Overall sound levels for the Corpus Christi PFC sections on IH-37*

The 1/3 octave band spectra (Figure 4.45) indicates that both CC2 segments in the northbound direction have almost identical acoustic performance, and their pattern differs from that of the rubberized segments (CC1). The dense-graded spectrum shape is consistent with other observations from conventional AC mixes.

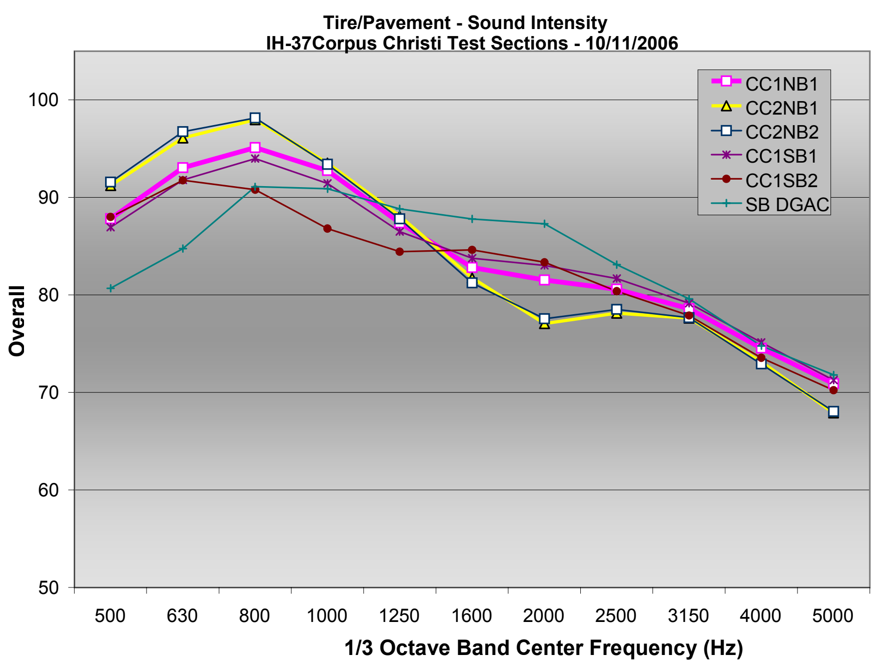


*Figure 4.45: Spectra for the IH-37 Corpus Christi PFC sections*

### 4.3.11 San Antonio IH-35 PFC

Two adjacent PFC projects were tested on IH-35 in San Antonio, between IH-410 and Loop 1604, in Bexar County; one of them extends from Walzem to Weidner Rd., and the second one extends from Weidner Rd. to Loop 1604. The OBSI tests were performed on October 24, 2006. At this point, it is uncertain whether these pavement mixes were different from one another. Two subsections were identified and tested in each direction within the project limits (Figure 4.46).

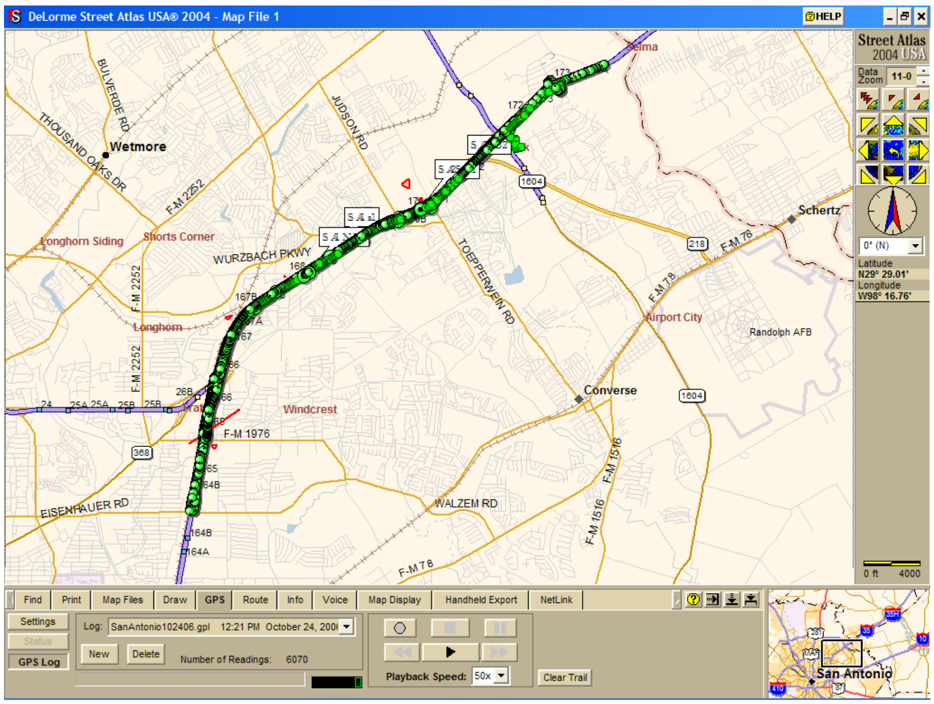


*Figure 4.46: IH-35 PFC in San Antonio section location*


*Figure 4.47: Northbound PFC on IH-35 in San Antonio*

The overall chart indicates that all four subsections had little variation among their respective sound levels (Figure 4.48).

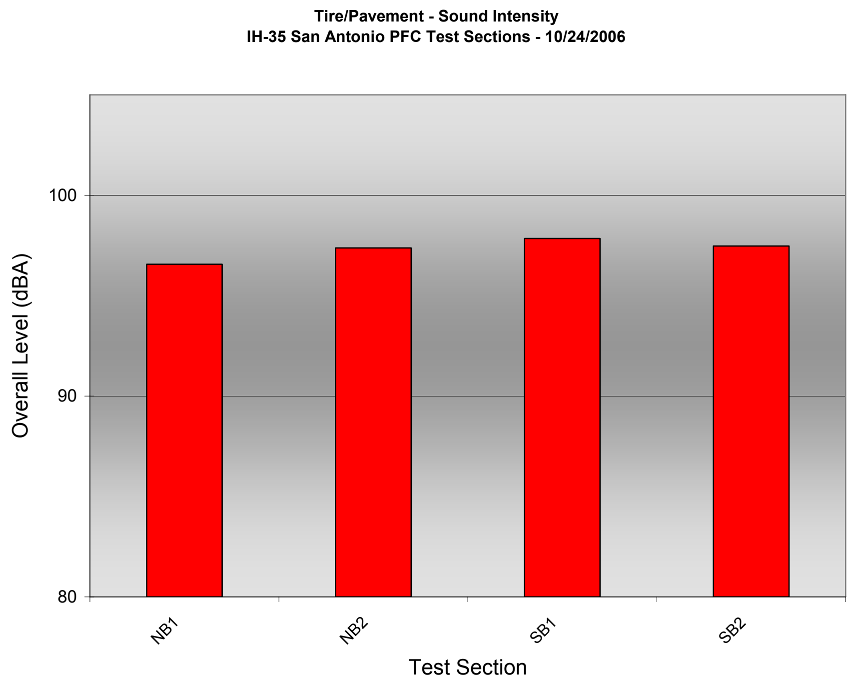


*Figure 4.48: Overall levels for IH-35 PFC sections in San Antonio*

Likewise, the spectra for the IH-35 PFC show a similar pattern for all four subsections (Figure 4.49).

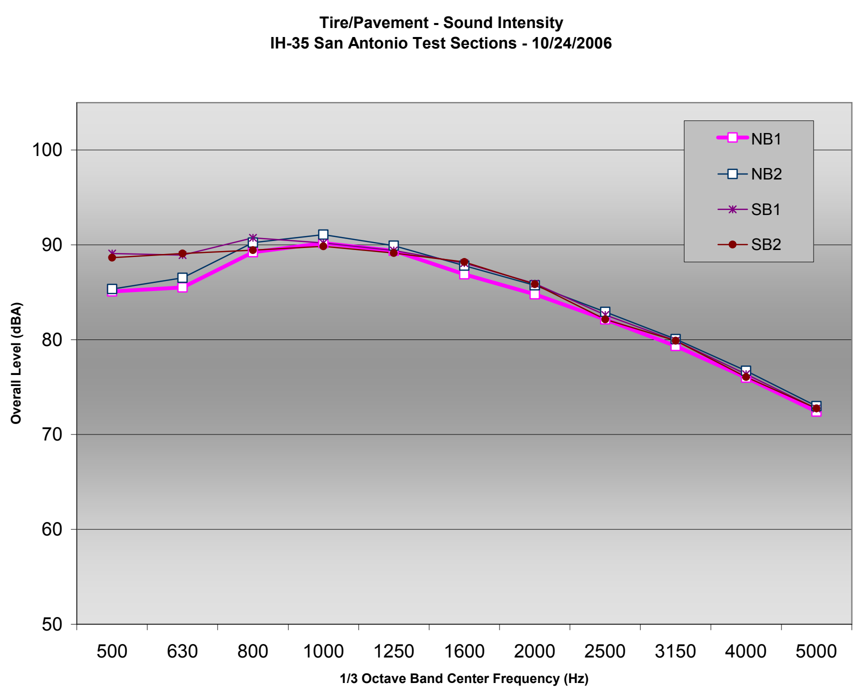


*Figure 4.49: Spectra for IH-35 PFC sections in San Antonio*

### 4.3.12 San Antonio US 281 PFC

The US 281 PFC has been tested on various occasions both by TxDOT and by CTR. It was initially tested by TxDOT on October 9, 2006. Several adjacent sections were identified and tested, including some conventional AC segments. The sections tested on that occasion were a Type C mix and two different PFCs labeled as PFC1 and PFC2, both including rubber in their mixes. The Type C surface is a 1 ½-in thick overlay on concrete pavement, placed in 2000, over 4.6 miles from IH-410 to Basse Rd. The PFC1 section is a 2-in thick overlay on concrete pavement, constructed in 2006, extending almost 2.4 miles from Basse Rd. to 0.4 miles north of Hildebrand, while the PFC2 is also an overlay on concrete pavement, 1 ½ in. thick, placed in 2006 over 2.5 miles, from 0.4 miles north of Hildebrand to Pearl Parkway. All these segments have components in the northbound and southbound directions. A map with the location of the sections is presented in Figure 4.50.

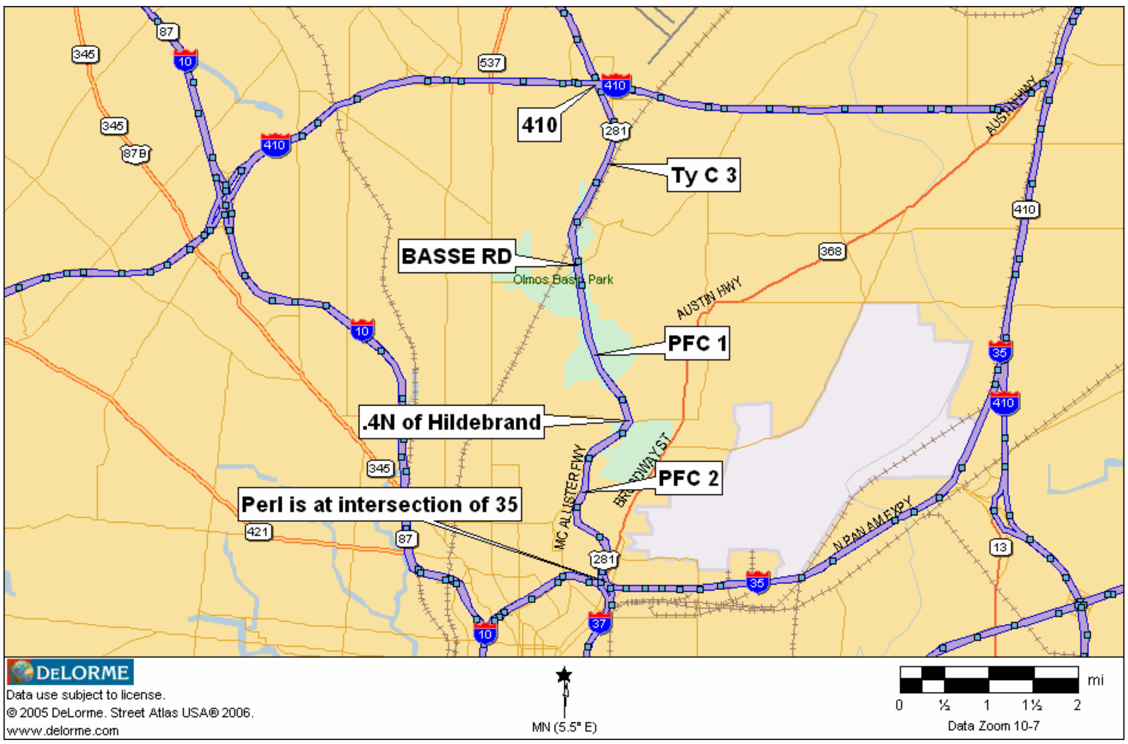


*Figure 4.50: San Antonio test sections on US 281*

The subsections that correspond to the Type C mix AC were labeled as 1T and 2T in the southbound direction and 15T and 16T in the northbound lanes. The PFC1 pavement is comprised of subsections 3T, 4T, and 5T in the southbound direction, and 12T, 13T, and 14T in the northbound direction. The PFC2 pavement was subdivided into sections 6T, 7T, 8T, and 17T, in the southbound direction, and 9T, 10T, and 11T in the northbound direction. A more detailed map, showing the location of all the subsections within the project is presented in Figure 4.51.

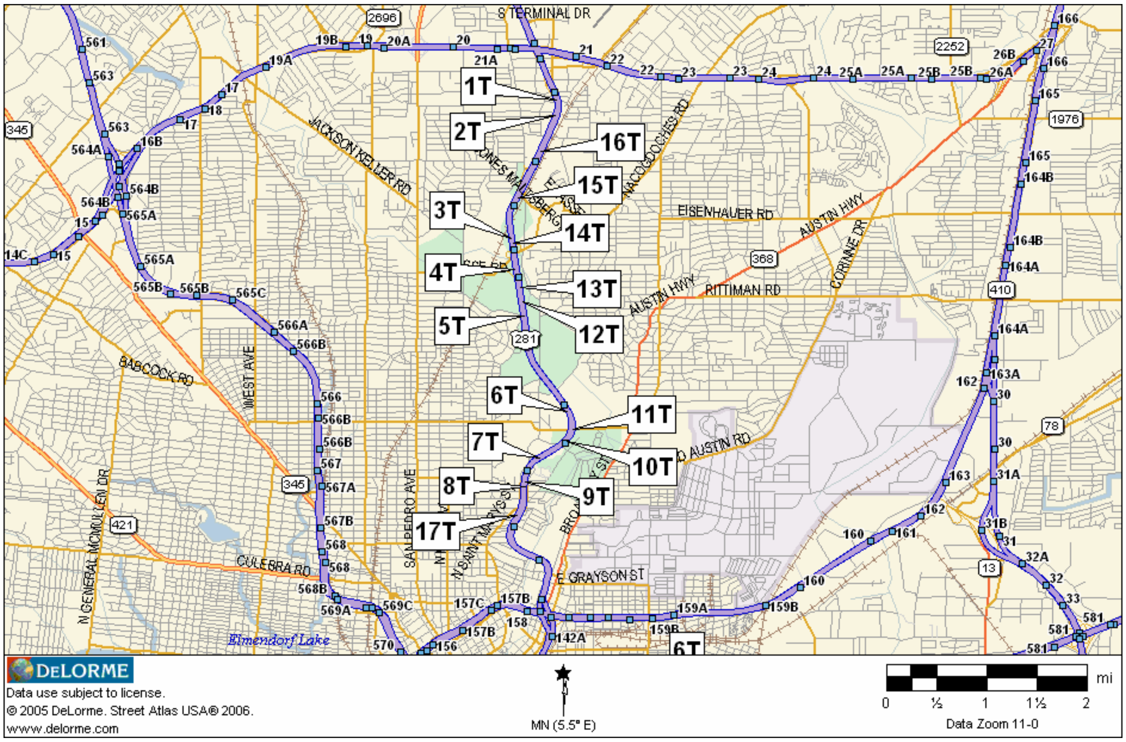


*Figure 4.51: US 281 subsections in San Antonio*

The sound levels for the PFC sections were considerably lower than those for the Type C mix, as expected, but there was also a significant difference between PFC1 and PFC2, as can be seen in Figure 4.52, which summarizes the overall sound levels for these sections. In fact, PFC1 had the lowest sound levels of all the sections tested, with an average level of 94.9 dBA. The variability within the section is small, showing that the quiet level is consistent throughout that segment. This quiet level prompted repeated visits for additional testing to confirm the results, both from TxDOT and CTR, the outcome of which is presented in subsequent paragraphs within this section.

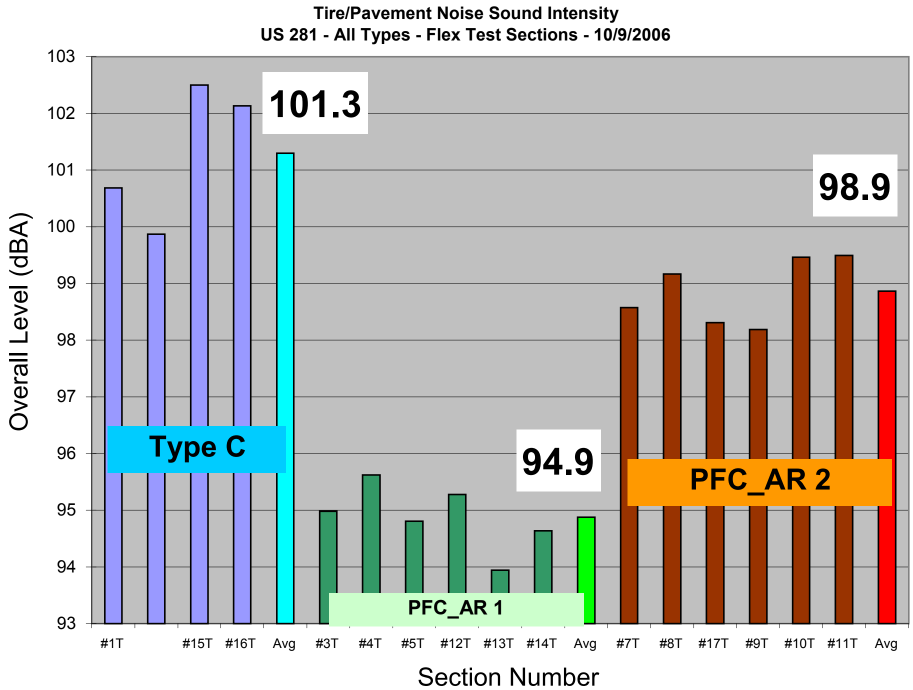


*Figure 4.52: Overall OBSI levels for US 281 sections in San Antonio*

The spectra for the sections, from October 9 (Figure 4.53) shows that the sections within the same type of pavement present similar patterns, which is an encouraging sign of consistency between the tests and the pavements themselves.

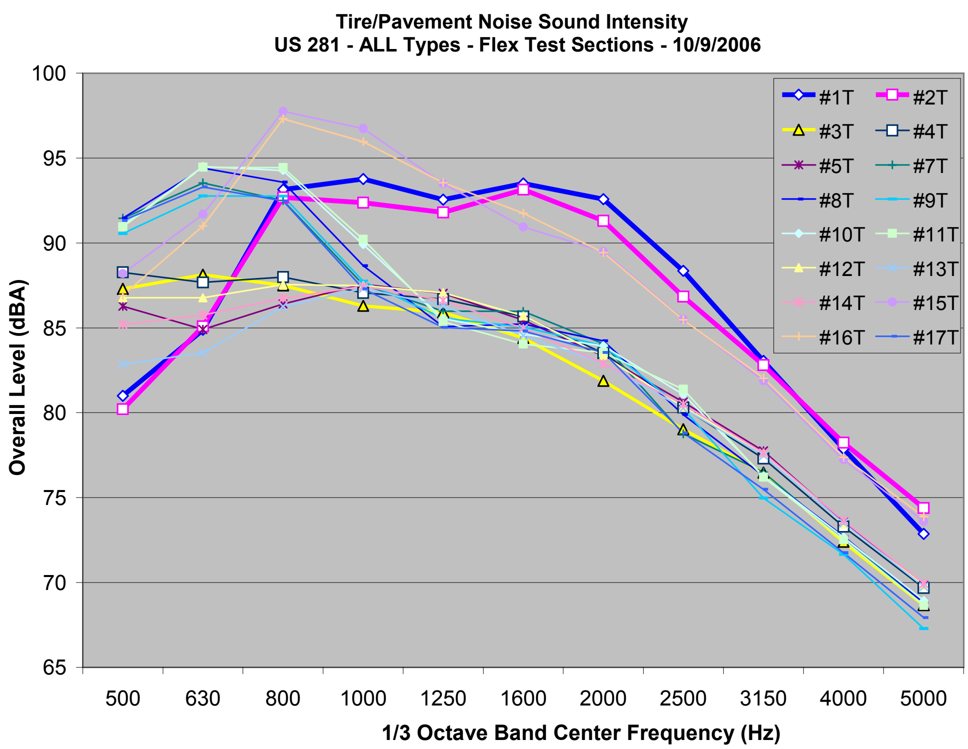


*Figure 4.53: Spectra for US 281 sections in San Antonio*

On November 29, 2006, the CTR researchers visited the US 281 project, and focused on the PFC1 section, which had yielded the quietest results among the US 281 tests and was the quietest of all the tests performed by both TxDOT and CTR up to this stage of the project. The researchers deemed that conducting the tests on this particular segment, either confirming the previous results or refuting them, would offer great insight. Only the PFC1 asphalt rubber section was tested in this round, which was comprised of three northbound segments (NB12, NB13, and NB14) and three southbound segments (SB3, SB4, and SB5). The GPS map of the loop driven while performing the tests and a view of the northbound lanes are shown in Figures 4.54 and 4.55, respectively.

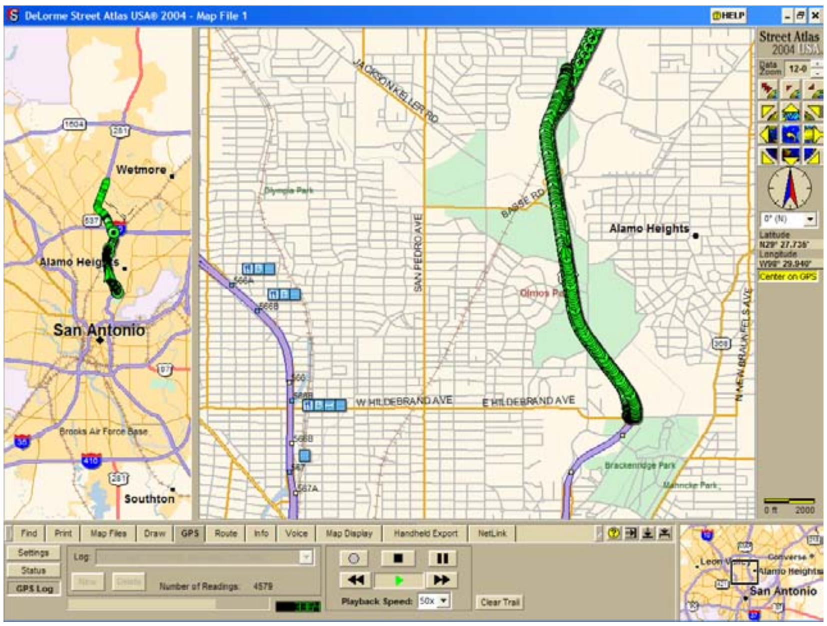

*Figure 4.54: Location of US 281 PFC1 in San Antonio*

*Figure 4.55: Northbound US 281 PFC1 section in San Antonio*

The texture of the asphalt rubber PFC1 section is shown in Figure 4.56.

*Figure 4.56: Texture of asphalt rubber PFC1 section on US 281 in San Antonio*

The overall results of the November 29 tests are displayed in Figure 4.57. The levels indicate it is indeed a quiet pavement, even compared with other PFC sections, but it turned out slightly louder than it was in the previous set of tests, which were conducted almost 2 months before. The comparison chart, showing both sets of tests, is presented in Figure 4.58.

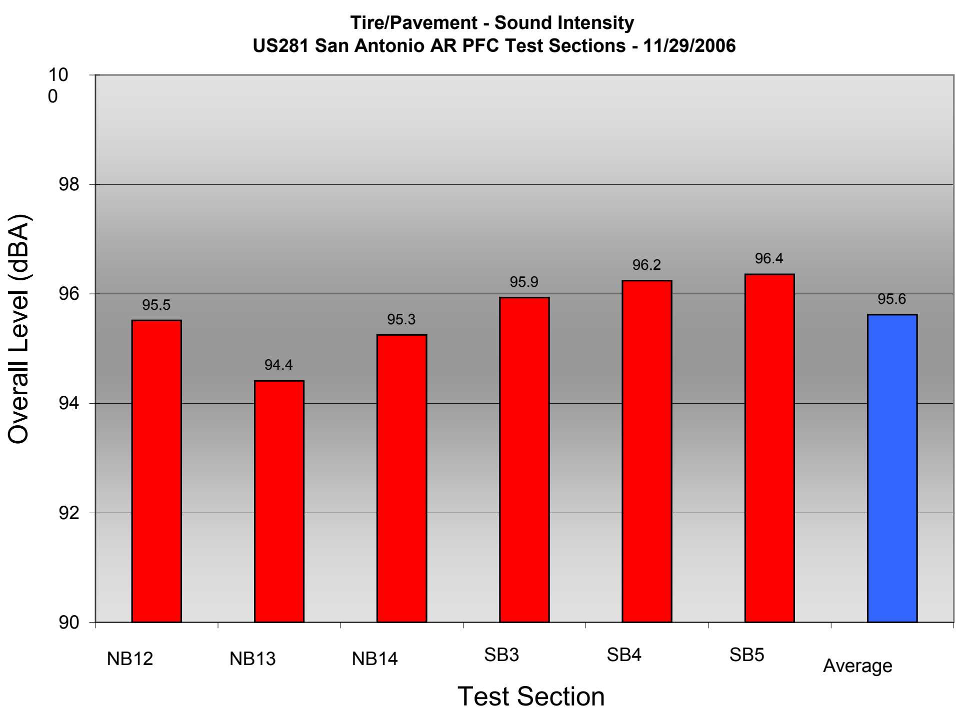


*Figure 4.57: Overall sound levels for the US 281 PFC1 section in San Antonio*

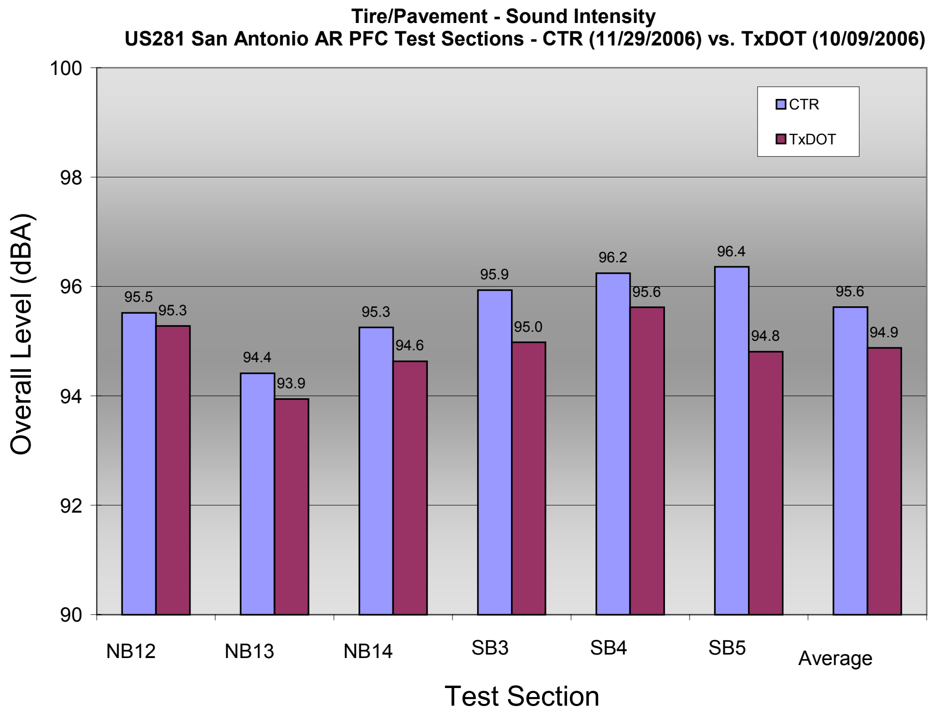


*Figure 4.58: Sound level comparison for both tests on US 281 PFC1 sections in San Antonio*

The 1/3 octave band spectra for the November 29 CTR tests is shown in Figure 4.59.

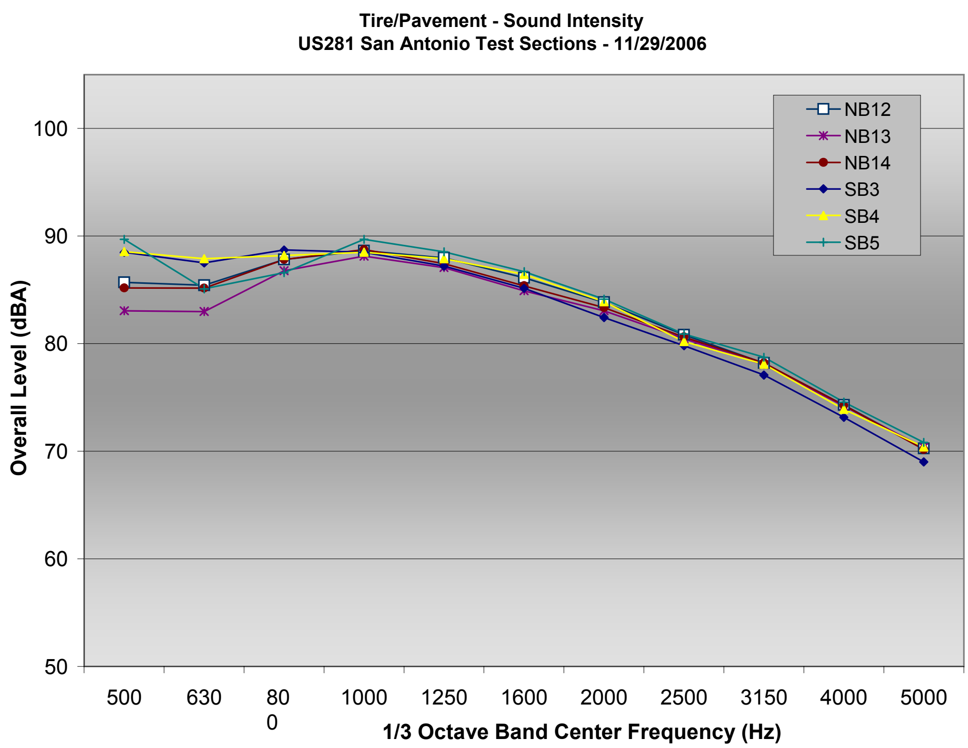


*Figure 4.59: Spectra for the CTR tests on US 281 PFC1 in San Antonio*

These results originated another testing round, which was performed by TxDOT on December 6, 2006. The results obtained then are compared to the previous two sets of tests in Figure 4.60.

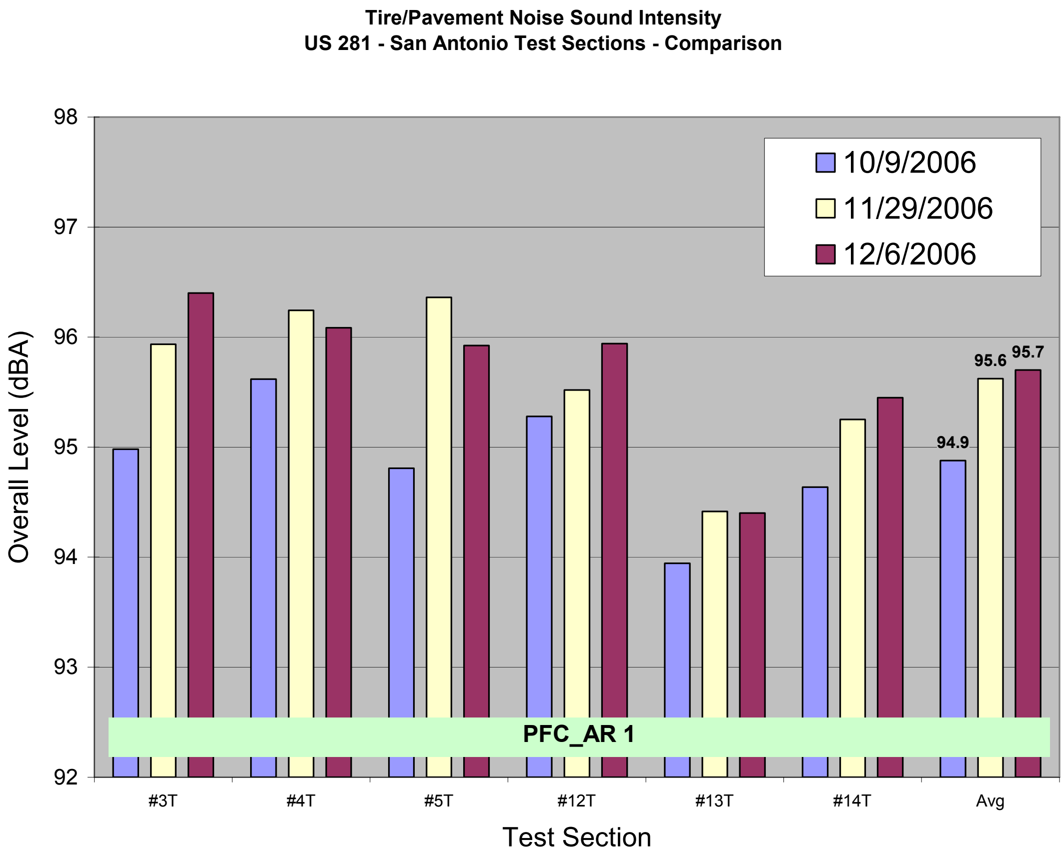


*Figure 4.60: Comparison of tests on PFC1 section on US 281 in San Antonio*

In most of the subsections, the levels are louder in the most recent tests, indicating that the surface might be getting louder with time. However, it seems that the time frame in which the tests occurred might be too short to produce such changes in the acoustic properties of the surface. An element that can influence sound test results is the climatic conditions during the test. Table 4.1 summarizes the weather conditions for the three dates of testing at the site.

**Table 4.1: Weather Conditions During PFC1 OBSI Tests**

| | Wind Speed (mph) | Temperature (°F) | Relative Humidity (%) |
|---|---|---|---|
| October 9, 2006 | 9.0 | 82.4 | 51 |
| November 29, 2006 | 13.8 | 82.0 | 70 |
| December 6, 2006 | 3.0 | 71.6 | 67 |

The temperature, which could be an important factor, is very similar for the first two rounds of testing, whereas the December test, with the lowest temperature, had the loudest sound levels. It is a normal occurrence that higher temperatures are associated with lower noise levels in the tests. The main reason for the noise reduction with higher temperatures is due to a decrease of impact noise, caused by the softened materials in the tire structure when the temperatures rise.

## 4.4 Discussion of Results

The overall average level results for all the sections tested up to date is shown in the bar chart in Figure 4.61, in which only one bar corresponds to each project, except for those that were tested on several occasions. Thus, each bar is the average for the pavement type in question in each project, and the projects are sorted from loudest to quietest.

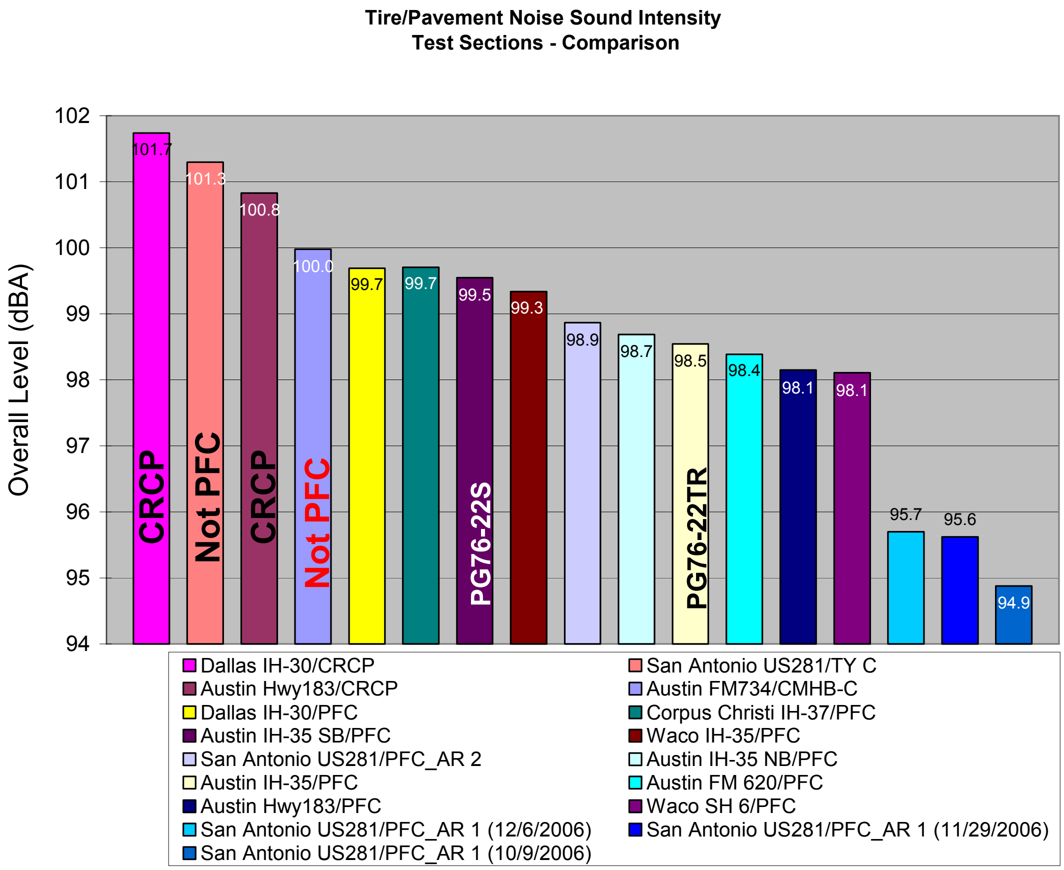


*Figure 4.61: Comparison of overall sound levels among all sections tested*

It should be noted that the previous graph includes data from FM 734 in Austin, which has not been discussed so far. This is a conventional asphalt section, consisting of four subsections that were tested to compare TxDOT's vehicle and OBSI equipment to CTR's vehicle and equipment. Detailed information on those tests is presented in Chapter 6, section 6.2.3.

As expected, the CRCP, with its characteristic transverse tining, and the conventional AC sections were, in general, louder than the more porous AC sections (PFCs). Interestingly, the graph shows that the four loudest pavements tested are either CRCP or dense-graded AC, which are widely considered "typical" pavements in terms of their acoustic properties, and then every other pavement that follows to the right of those four pavements is a PFC, which is considered the "quieter" category. The average level for the "typical" pavements is 101 dBA, whereas the average level for the PFCs is 98.1 dBA.

The comparison chart shows a wide variability, with noise levels spanning almost 7 dBA between the loudest and the quietest sections. However, the pavements' characteristics also represent great variability, which explains the results. The rubberized PFC on US 281 in San Antonio almost seems like an outlier when compared to the rest of the pavements because it is considerably quieter than all of them. That is the reason this section deserved some additional repeated testing from both TxDOT and CTR. The section is a very new pavement, constructed in 2006, and it is in optimal condition, as Figures 4.55 and 4.56 indicate. If this section is disregarded, the variability among the rest of the sections is less than 4 dBA. The loudest PFCs are the new overlay on IH-30 in Dallas, and the IH-37 sections in Corpus Christi (99.7 dBA, on average). The Dallas IH-30 PFC overlay reduced the loudness of that segment, from when the riding surface was CRCP, by an average of 2 dBA.

For comparison, the data from the Caltrans database is shown in Figure 4.62, which shows a wider range on the louder end of the spectrum than the Texas pavements and a narrower range for the quieter pavements. A few pavements from Arizona are included in the data. It should be noted that this database has more pavements than have been measured in the 0-5185 project, and that it has a higher proportion of PCC pavements.

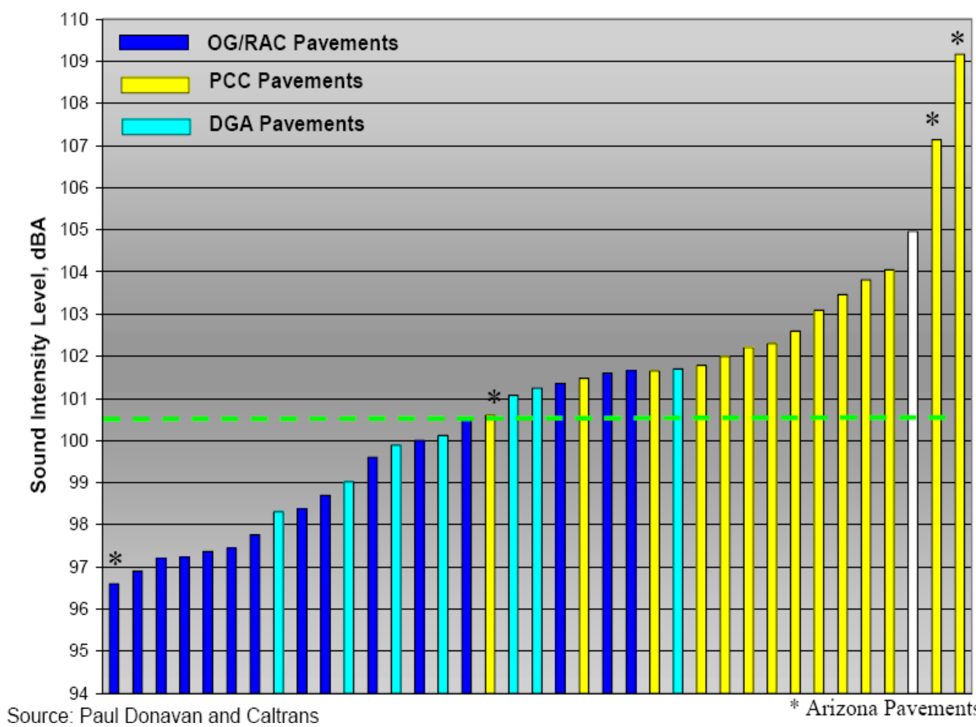


*Figure 4.62: Caltrans statewide database*

The average SI level in this database is about 100.5 dBA, and the average for the Texas pavements tested so far is 98.8 dBA. Another interesting comparison with the Caltrans pavements is observing the range between "typical" and "quieter" (open-graded AC) pavements (Figure 4.63). The Caltrans data had about a 6-dBA range in this regard, whereas the Texas pavements had less than a 3dBA range.

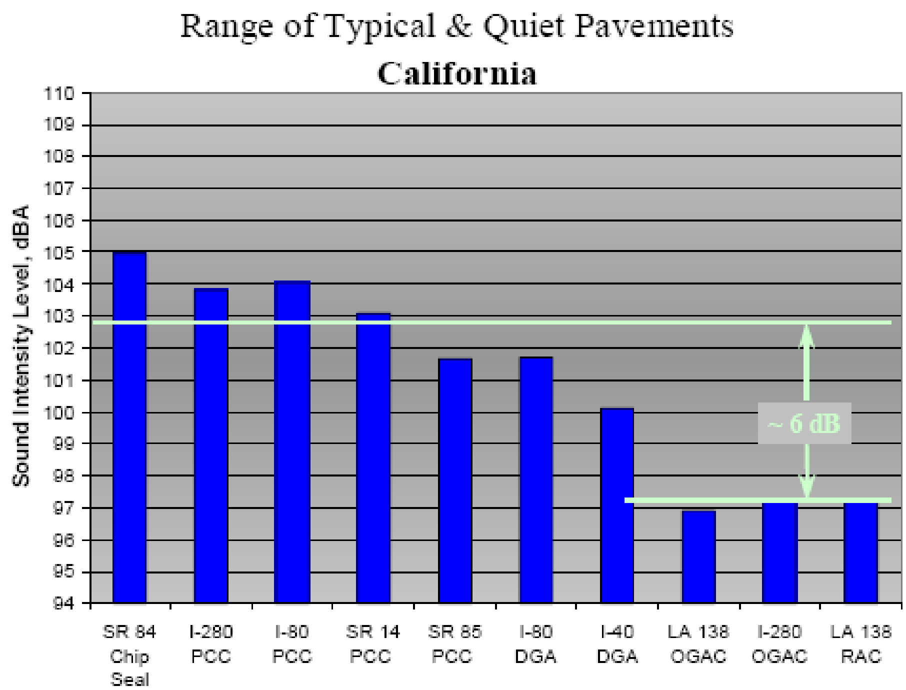


*Figure 4.63: Range of typical and quiet pavements in the Caltrans database (Source: Dr. Donavan)*

In summary, the results obtained are consistent with the expectations and with what other agencies have found in analogous tests on analogous pavements. In general, PFCs are quieter, although there is high variability among the various PFC results.

The results obtained in San Antonio on the US 281 PFC lead to the conclusion that the PFC is extremely quiet, but it is getting slightly louder. The increase in overall level is not very significant, but the fact that the tests were conducted in a relatively short time frame might be an indication that the PFC gets louder at a higher rate when it is fairly recent and in excellent condition to begin with, perhaps because some clogging of the voids occurs.

# 5. Roadside Measurements and TNM Comparisons

## 5.1 Introduction

One of the most important goals of this project is to assess whether some types of pavements can be purposely designed to be quieter. The relevance of this finding could mean the removal of the FHWA restrictions in regards to the use of quieter pavements as noise abatement, as stated in the objectives of this project.

The FHWA allows a state to spend federal-aid highway funds for noise abatement projects along highways. Most states would consider changing pavement types for noise abatement purposes. However, the FHWA stipulates that pavement type or texture cannot be considered a noise abatement measure. Furthermore, the policy states that "while it is true that noise levels do vary with changes in pavements and tires, it is not clear that these variations are substantial when compared to the noise from exhausts and engines," and that additional research is needed to determine to what extent different pavement types contribute to traffic noise. This policy, cited in [FHWA 1995], applies to all federally funded projects. The implication of this policy is the restriction of noise reduction measures for evaluation by highway engineers and planners.

In accordance with the aforementioned policy, the current FHWA approved traffic noise and barrier modeling software, Traffic Noise Model (TNM), is restricted, for the time being, to use only with an "Average Pavement" option, in spite of the fact that the program has other options enabled for modeling the pavement type that would render quieter noise levels, such as the "Open-Graded Asphalt Concrete." This applies to impact avoidance.

Specifically, there are two restrictions derived from the FHWA policy that this research project aims to remove with its findings, which are as follows:

- The exclusive use of "average" as pavement type in TNM. The removal of this restriction would allow the use of other specific pavement types with which the software is equipped, which could in turn result in a better estimation of noise levels.
- The prohibition on the use of "quieter" pavement as noise abatement. The elimination of this restriction would allow the possible consideration of quieter pavements as noise abatement.

The FHWA policies establish that "unless definite knowledge is available on the pavement type and condition and its noise generating characteristics, no adjustments should be made for pavement type in the prediction of highway traffic noise levels." Thus, this project attempts to contribute to the definite knowledge on the matter.

Roadside noise measurements are performed to assess the impact of traffic noise from the standpoint of the receivers, i.e., the homes, businesses, and people experiencing the traffic noise from the nearby road. Such measurements are considered the most appropriate technique to evaluate the impact of traffic noise on receivers adjacent to the facility. The TNM program allows the modeling of the road geometry and conditions, as well as traffic, and calculates the sound levels for receivers at specified distances from the side of the road, results which are analogous to roadside noise measurements. Thus, comparisons between roadside measurements and the corresponding modeling of the road conditions with TNM is a sensible endeavor.

One type of pavement that is commonly considered quieter than conventional asphalt pavement (i.e., dense-graded) and concrete pavement is open-graded asphalt pavement, also known in Texas as permeable friction courses (PFC). Because of their quieter characteristics, it was deemed appropriate that the first stage of roadside measurements of this project be conducted on open-graded surfaces, aiming at gathering data that would make possible challenging the FHWA policies.

This chapter presents the measurements conducted on various open-graded asphalt pavements on the side of the road. The roadside results are also compared to the TNM results. For these comparisons, both the "average pavement" and the "open-graded AC" options in the TNM program have been gauged.

So far, various PFC sections have been measured in the Austin, Dallas, Waco, Corpus Christi, and San Antonio Districts.

## 5.2 Roadside Noise Measurement Procedure

In devising the roadside noise measurement procedure, the researchers have tried to follow and stay as consistent as possible with the methods outlined in the FHWA Sample Data Acquisition Plan, to help ensure FHWA acceptance of the data. The procedure used to measure noise on the side of the road in this project is based upon the use of a calibrated Type I instrument (handheld or tripod-mounted sound pressure level meter), such as the one illustrated in Figure 5.1.


*Figure 5.1: B&K Handheld Recording SPL Meter.*

The distances from the measuring device to the road, as well as the vehicle classification are based upon the methodology for Statistical Pass-By Testing, which is established in an international standard, ISO 11819-1 [ISO 1996].

As specified by the standard, the sound pressure level meter is mounted on a tripod located precisely 7.5 meters (24.6 ft) from the center of the travel lane, with the measurement microphone elevated 1.2 meters (3.9 ft) above the plane of the roadway. Measurement is not possible during windy conditions or when the roadway is wet. The meter and its position relative to the roadway are shown in Figure 5.2.

*Figure 5.2: SPL meter on a tripod during pass-by test*

The standard classifies each vehicle into one of three vehicle categories: "passenger cars," "dual-axle heavy vehicles," and "multi-axle heavy vehicles." Because most of the sections that are surveyed under this project normally have intense traffic, it would be difficult for the researchers to be able to count and classify the traffic mix, on the spot, as the sound measurements are being performed. Therefore, it has been found that recording the traffic by means of a video camera is the best option, because it has the advantage of allowing pauses and slower playback when the heavy traffic conditions would make it difficult to perform an accurate vehicle count and classification.

The standard establishes that free-field conditions should exist for at least 25 m (82 ft) around the microphone. This means that the site should be free of walls, barriers, buildings, and other large objects on the side of the road, such as highway signs, that could cause noise reflection. Another important consideration in the measuring procedure is to select a stretch of road that is fairly flat, to avoid additional noise caused by engine acceleration or braking, and that the road should also be straight. It is also advisable that the roadway at the measurement site be away from entrance and exit ramps, as these will alter the speed of the traffic flow and could potentially represent higher noise levels because of the acceleration and deceleration of the vehicles. Additionally, the air temperature at the time of the measurements should be between 5 and 30° C (41 and 86° F), while the pavement temperature should remain between 5 and 50° C (41 and 122° F), and the wind speed must not exceed 5 m/s (16.4 ft/s).

Regarding the duration of the test, the researchers have found that it is reasonable to conduct the measurements at each location until the noise level stabilizes, so that the elapsed time allows for a measurement that is a good representation of the acoustic characteristics of the site, regardless of the time of the day or the traffic mix that traverses that particular stretch of road. Various experiences conducting this type of measurements have shown that a 10-minute period is sufficient for the noise levels to become stable. At each location, the researchers typically perform pass-by tests in two different 10-minute periods and use both noise levels in the modeling and calculations. Evidently, the time of day has an effect on the noise level that is measured in the test; however, these variations with time of day and amount of traffic are not the subject of interest of these measurements; by relating the noise level to its corresponding traffic count and mix and using it in the computer modeling, the effects of the time of the tests are neglected, and thus, the tests are able to evaluate the acoustic properties of the site only, including what is most important for this study, the pavement's properties.

## 5.3 TNM Modeling

TNM is the FHWA approved traffic noise and barrier modeling software. The TNM program, version 2.5, is used to estimate the noise levels that correspond to the conditions observed in the field. This is done for each of the locations measured, using the roadside procedure described in the preceding section.

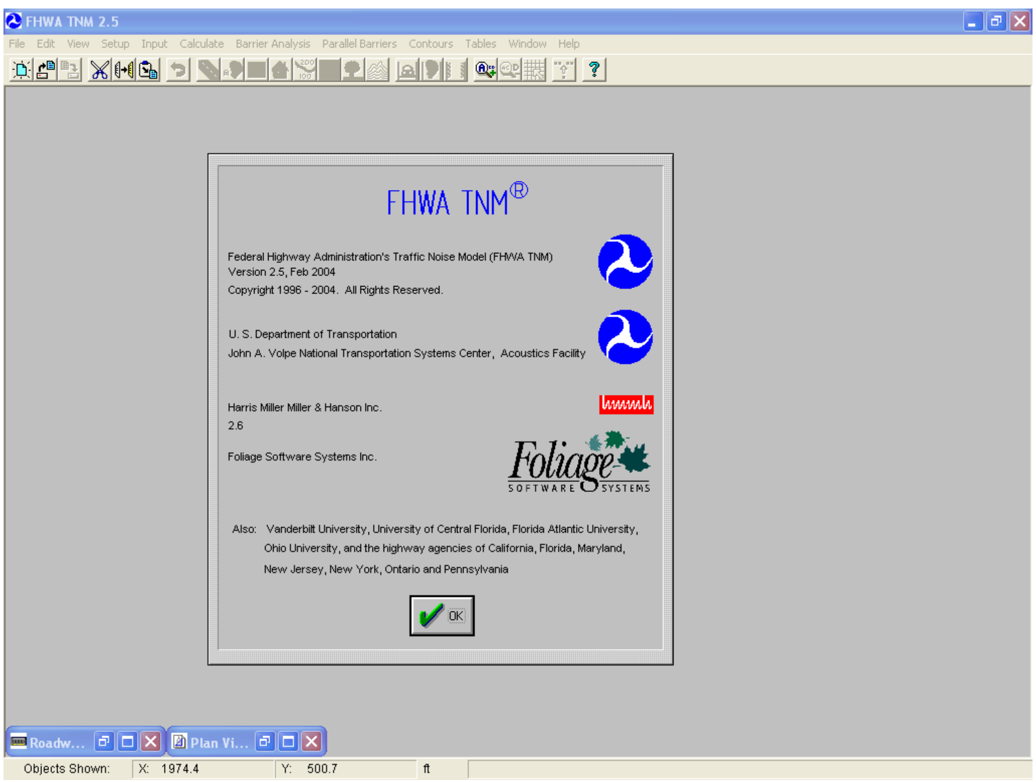


*Figure 5.3: TNM Introductory screen*

The program, for the intended purpose of the comparison to roadside measurements, requires the following inputs in regards to the roadway and its geometry:

1. Number of lanes in each direction
2. Lane and shoulder widths

3. Whether there is a median barrier and its dimensions
4. Median width
5. Pavement type (runs with both "average" and "open-graded" are performed)
6. Location of receivers

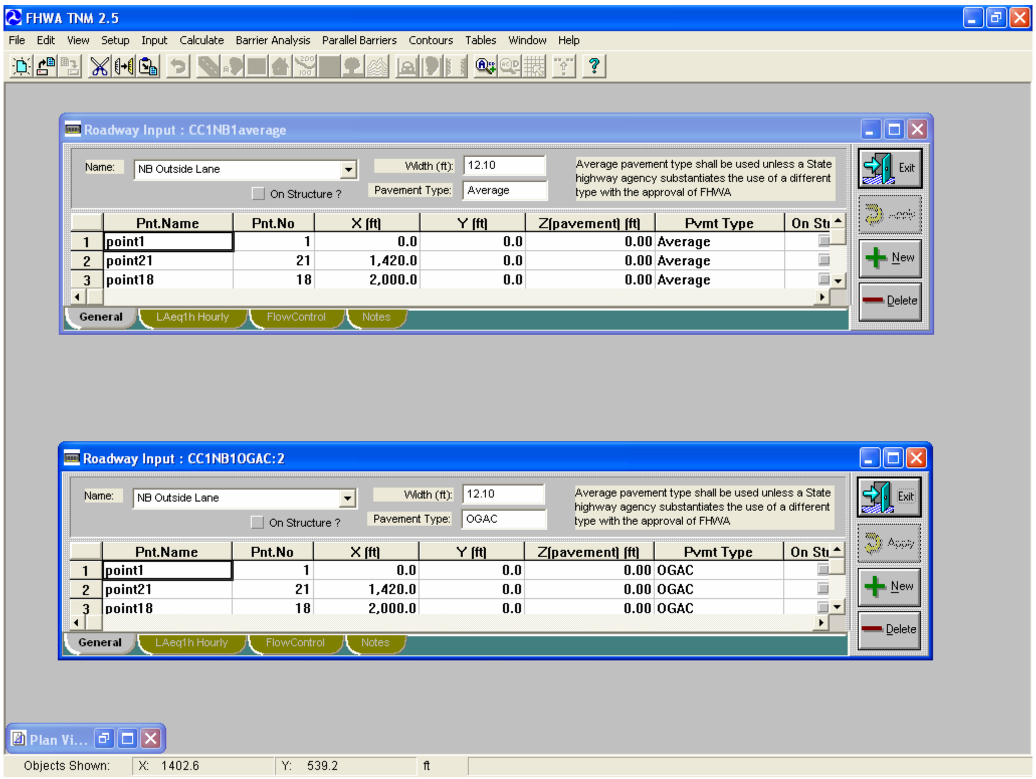


*Figure 5.4: Runs using both "Average" (top window) and "OGAC" (bottom window) pavement type options are performed*

For the purpose of the comparison model with roadside tests, only one receiver is required, which corresponds to the microphone situated at the position specified by the standard.

In addition, the following inputs are necessary regarding the traffic:

1. Posted speed limit
2. Number and type of vehicles passing by the microphone location during the test

The models used in these comparisons are very simplified versions of the roadway and do not make use of all the capabilities that the software has, because for this case, it is not necessary to use them. For instance, the terrain lines describing the vertical profile of the roadway are not used, assuming that the test site has been properly selected according to the standard, i.e., that the site is fairly flat. Also, no curves are modeled in the roadway, assuming that the stretch of road is indeed straight. Similarly, no building rows, tree zones, other barriers, and other receivers are introduced in the model.

The comparison between roadside noise levels and the results obtained with TNM is illustrated in Figure 5.5. The output of TNM yields the noise level estimated for an hour of traffic, and that number is compared to the level obtained with the meter in the field. The actual traffic counts are multiplied by six (because a 10-minute period has been recorded with the meter) when entered into the model to have a consistent result with what was measured in the field.

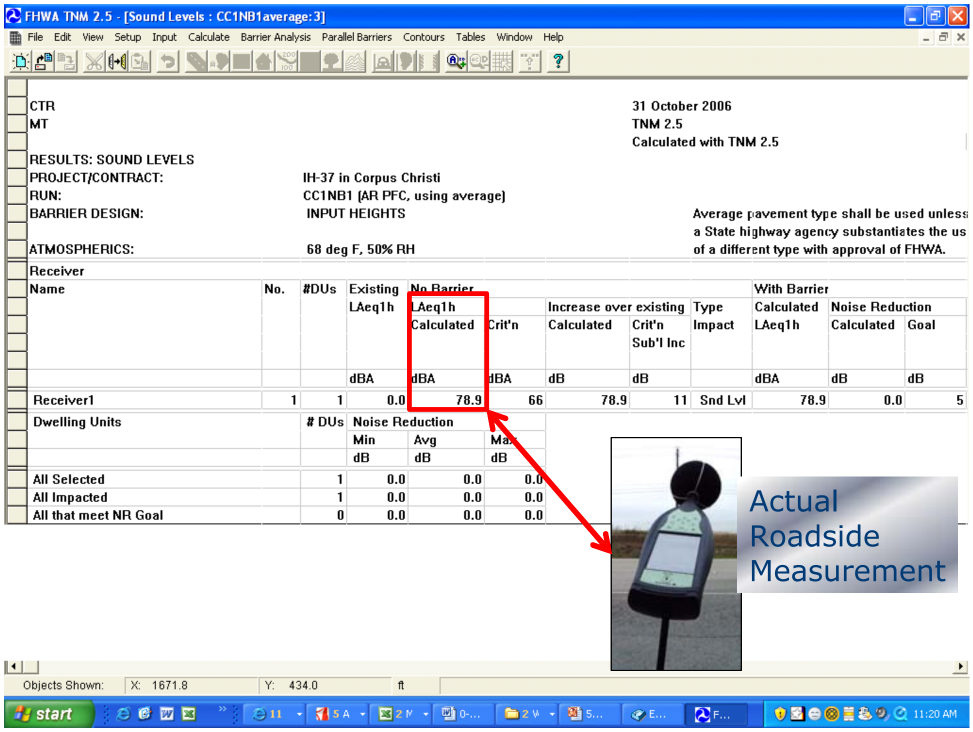


*Figure 5.5: Roadside and TNM comparison from the output screen of TNM*

## 5.4 Roadside Test Results and Discussion

The following PFC sections have been tested for roadside noise levels up to this stage of the project: FM 620 in Austin, IH-30 in Dallas, SH 6 and IH-35 in Waco, IH-37 in Corpus Christi, and IH-35 and US 281 in San Antonio. Table 5.1 presents the results in chronological order, with the last three columns showing the noise levels, first, the measured level, then the TNM calculation using the "Average" pavement option and then the TNM calculation using the "OGAC" pavement option. Several sections were measured on more than one occasion, i.e., more than one 10-minute period, and those are shown under the column labeled as "Meter" in the Table. There are two adjacent sections that were measured on IH-37 in Corpus Christi, which were constructed with different materials. Thus, those two sections are treated as different.

**Table 5.1: Pass-by Tests Results and TNM Comparisons**

| Roadway | District | Section | Test Date | LAeq (dBA) | | |
|---|---|---|---|---|---|---|
| | | | | Meter | TNM ("Average") | TNM ("OGAC") |
| FM 620 | Austin | PFC 29-2 | 9/7/2006 | 70.9<br>69.9 | 75.0 | 73.4 |
| IH-30 | Dallas | WB @ exit 43A | 9/26/2006 | 78.2<br>78.0<br>78.5 | 80.6 | 79.0 |
| SH 6 | Waco | WB1 | 9/29/2006 | 70.9 | 75.5 | 74.0 |
| IH-35 | Waco | NB1 | 9/29/2006 | 77.0 | 81.1 | 79.5 |
| IH-37 | Corpus Christi | CC1NB1 (AR PFC) | 10/11/2006 | 76.0<br>74.7 | 78.9 | 77.2 |
| IH-37 | Corpus Christi | CC2NB1 (Fibers & LS PFC) | 10/11/2006 | 73.4 | 76.2 | 74.5 |
| IH-35 | San Antonio | NB2 | 10/24/2006 | 78.4 | 81.4 | 79.8 |
| US 281 | San Antonio | NB12 | 11/29/2006 | 73.7<br>74.1 | 79.3<br>79.7 | 77.7<br>78.0 |

The table shows that in every case, the actual noise levels measured in the field are lower than those predicted with the program. As expected, the predicted values using the "OGAC" pavement type option are lower than those predicted using the "Average" pavement type option, but are still higher than the real levels recorded with the meter. Figure 5.6 illustrates the pass-by results and the comparison with the TNM predictions. For this graph and the subsequent discussion, in those cases in which more than one pass-by test period is available per section, the results have been averaged to be able to show one noise level value per section.

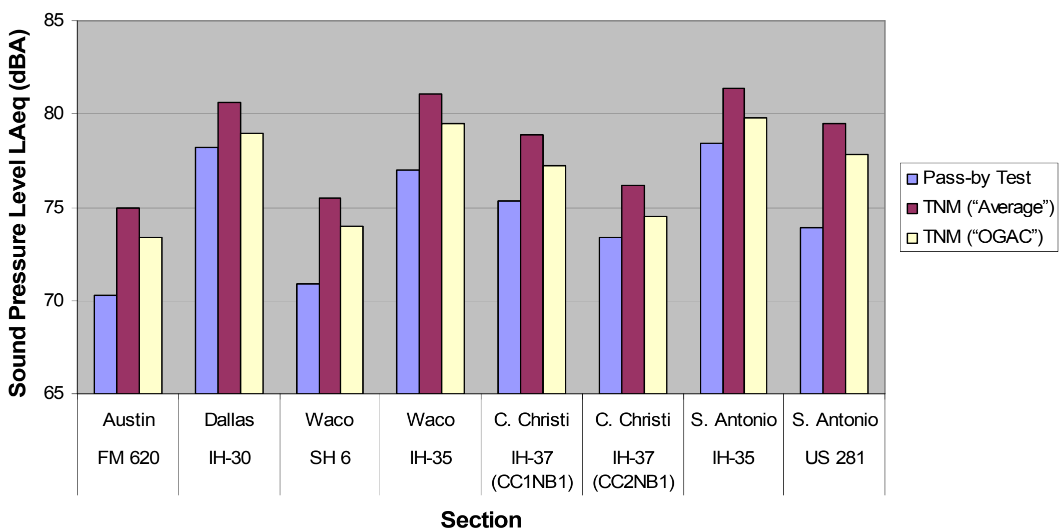


*Figure 5.6: Pass-by results versus TNM predictions*

Table 5.2 shows the differences between the measured levels and the predicted levels. It also presents the percentage by which TNM over-predicts the noise levels with respect to the actual pass-by measured level.

**Table 5.2: Pass-by and TNM Comparison, Showing the Differences (in dBA) Over-Predicted Noise Level with Respect to Pass-by Levels**

| Roadway | District | Pass-by Test (Meter Average) | TNM ("Average") | TNM ("OGAC") | TNM "Average" - Pass-by | TNM "OGAC" - Pass-by |
|---|---|---|---|---|---|---|
| FM 620 | Austin | 70.3 | 75.0 | 73.4 | 4.8 | 3.2 |
| IH-30 | Dallas | 78.2 | 80.6 | 79.0 | 2.4 | 0.8 |
| SH 6 | Waco | 70.9 | 75.5 | 74.0 | 4.6 | 3.1 |
| IH-35 | Waco | 77.0 | 81.1 | 79.5 | 4.1 | 2.5 |
| IH-37 (CC1NB1) | C. Christi | 75.4 | 78.9 | 77.2 | 3.6 | 1.9 |
| IH-37 (CC2NB1) | C. Christi | 73.4 | 76.2 | 74.5 | 2.8 | 1.1 |
| IH-35 | S. Antonio | 78.4 | 81.4 | 79.8 | 3.0 | 1.4 |
| US 281 | S. Antonio | 73.9 | 79.5 | 77.9 | 5.6 | 4.0 |
| Mean | | | | | 3.8 | 2.2 |
| Standard Dev. | | | | | 1.11 | 1.13 |
| C. Variation (%) | | | | | 28.8 | 50.6 |

The means, standard deviations, and coefficients of variation of those differences have been calculated and are shown at the bottom of the table. The "Average" pavement option in TNM over predicts noise levels by almost 4 dBA, while the "OGAC" pavement option over predicts noise levels by about 2 dBA, on average. The consistency found in the outcome of the models leads to the conclusion that in fact, considering that the roadside measurements were performed on PFC sections, which are widely regarded as quieter than conventional AC pavements, the TNM program delivers very reasonable and adequate results for most pavement types. Accordingly, the results of this comparison show that, indeed, PFC pavements are quieter than the "Average" pavement considered in TNM, and that they are also quieter than the "OGAC" pavement considered in TNM.

This is an encouraging result toward attaining one of the main objectives of this project, stated at the beginning of this Chapter: the removal of the two FHWA restrictions regarding a) the exclusive use of "Average" pavement types in TNM, and b) the prohibition to use pavement types as noise abatement. The results show that PFC deviates from what is considered "Average" in the program, and because of its quieter characteristics, a pavement of this type merits its consideration for noise abatement. The researchers plan to continue gathering pass-by results and running the TNM model for comparison to enlarge the database of results that has been presented here and to gather even more conclusive evidence that the restrictions could be lifted.

# 6. Continuous Calibration & Validation

## 6.1 Introduction

One of the most important goals of this project is to assess whether some types of pavements can be purposely designed to be quieter. The relevance of this finding could mean the removal of the FHWA restrictions in regards to the use of quieter pavements as noise abatement, as stated in the objectives of this project.

## 6.2 Variability in Measurements

In order to measure the variability in pavement noise between pavements and over time, it is critical to reduce all other sources of variability to a minimum before each test.

### 6.2.1 Continuous Calibration of Equipment

The first and most critical calibration used in all measurements is calibration of the test microphones, both on the OBSI rig and on the roadside SPL meters. Microphones and preamplifiers drift slightly over time, so it is necessary to establish a relationship between voltage and microphone pressure before all tests. Figure 6.1 shows the use of a 1 kHz 94 dB tone generator in calibrating the OBSI microphones.

*Figure 6.1: Field Calibration of OBSI microphones*

Because the accuracy of the OBSI method depends on the two microphones being precisely matched in terms of both amplitude and phase, periodic comparison testing of the microphones is also required. This test is performed on a monthly basis using a GRAS Sound Intensity Calibrator, Model 51AB (Figure 6.2).

*Figure 6.2: Checking phase and levels between SI microphones*

The calibrator is a small acoustic chamber into which the two matched pair microphones can be inserted face to face. A small speaker is located at a right angle and equally distant from the two microphones. The microphones are first calibrated to 94 dB using the 1 kHz generator as in the field. Next, pink noise, random noise (which has an equal amount of energy per octave band) is fed in from the LD 3000 analyzer as a test signal (Figure 6.3).

*Figure 6.3: Examining the transfer function between microphones (amplitude)*

The analyzer provides a graphical representation of the transfer function between the two microphones. The transfer function is simply the difference between the noise as measured by the two microphones, and should ideally be unity (or 0dB difference) for all frequency bands. Failing this test is unlikely unless the microphones have been damaged.

The second, more critical test shows phase differences between the microphones at various frequencies (Fig 6.4). Figure 6.5 shows the SI error introduced by varying degrees of phase error. In practice, any phase error more than a fraction of a degree within the test region (500 Hz–5 kHz) indicates a need for microphone service or replacement.

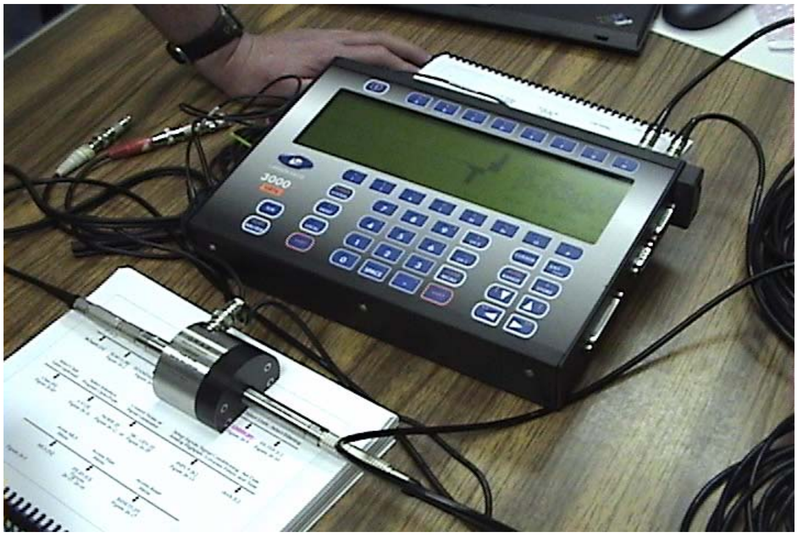

*Figure 6.4: Phase comparisons between the two OBSI microphones*

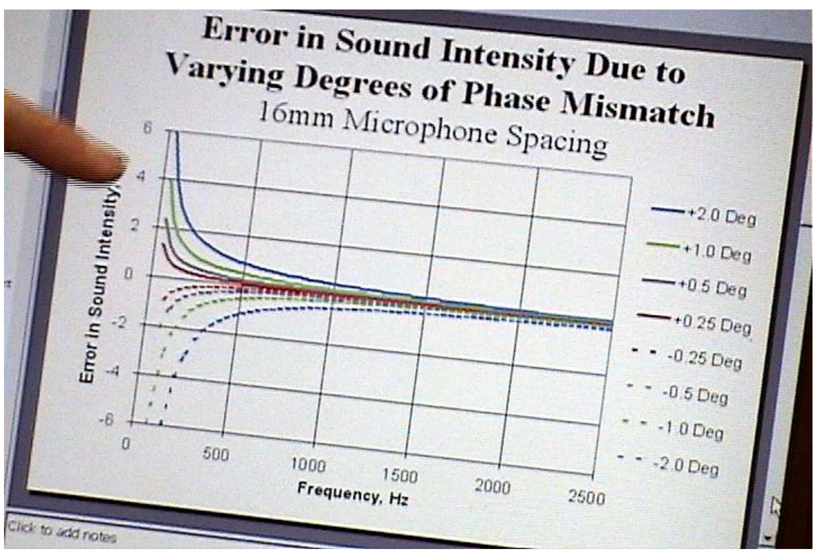


*Figure 6.5: Acceptable phase angle differences by frequency*

Finally, because all equipment accuracy ultimately depends on the microphone calibrator and the preamplifiers within the Larson Davis analyzer, these two items will be sent back to the manufacturers on a yearly basis for calibration to known standards. The short Texas winter season is an ideal time to do this because noise testing cannot be conducted when ambient and pavement temperatures are too low.

### 6.2.2 Variability within Test Projects

Pavements are not designed to be homogenous in their acoustic properties. Accordingly, within any selected paving project it is possible to find a great deal of noise variability. Therefore, it is necessary to select at least three 400-ft test sections (5 seconds at the 60 mph test speed) in each direction of travel for testing. This gives a good measure of variability and a reasonable average noise level for the project. More, of course, is better and time is usually the limiting factor.

The test protocols given in Chapter 3 eliminate many of the common causes for variability within a project. These include, but are not limited to, visible distress in the test wheel path, curves in the road causing additional noise due to turning friction, changes in pavement surface or type due to bridge approaches or exit ramps, elevated sections, nearby sources of significant noise, variance in vehicle speed during the 5-second test run, unusually close structures at the roadside, or unexpectedly loud noises from nearby vehicles. Any of these problems invalidate the run and the data must be discarded and/or the section must be relocated as required.

Only a rough analysis of the test section data is possible in the field, which reveals only extreme problems. This is why it is essential for the equipment operator to monitor the tire noise in real time using appropriately noise-isolated headphones or ear buds. In the event an unusual noise is heard, the log entry for the run is marked as questionable and an additional run is made.

Back at the office, after a detailed analysis has been run and plotted, any significant variability may be investigated by listening to the recorded noise, checking GPS logs, etc. Often a brief noise may be edited out of the file and the noise reanalyzed successfully.

### 6.2.3 Variability between Vehicles and Equipment

In order to verify that the equipment was in good working order and to perform comparisons among CTR's and TxDOT's vehicles and OBSI equipment, several rounds of tests were performed in August 2006, on a section of FM 734, also known as Parmer Lane, in Round Rock, north of Austin. This pavement is a conventional, dense-graded AC, designated as CMHB-C. Four subsections were identified and tested on various occasions, namely 1T, and 2T, in the southbound direction, and 3T and 4T in the northbound lane. The overall results are presented in Figure 6.6.

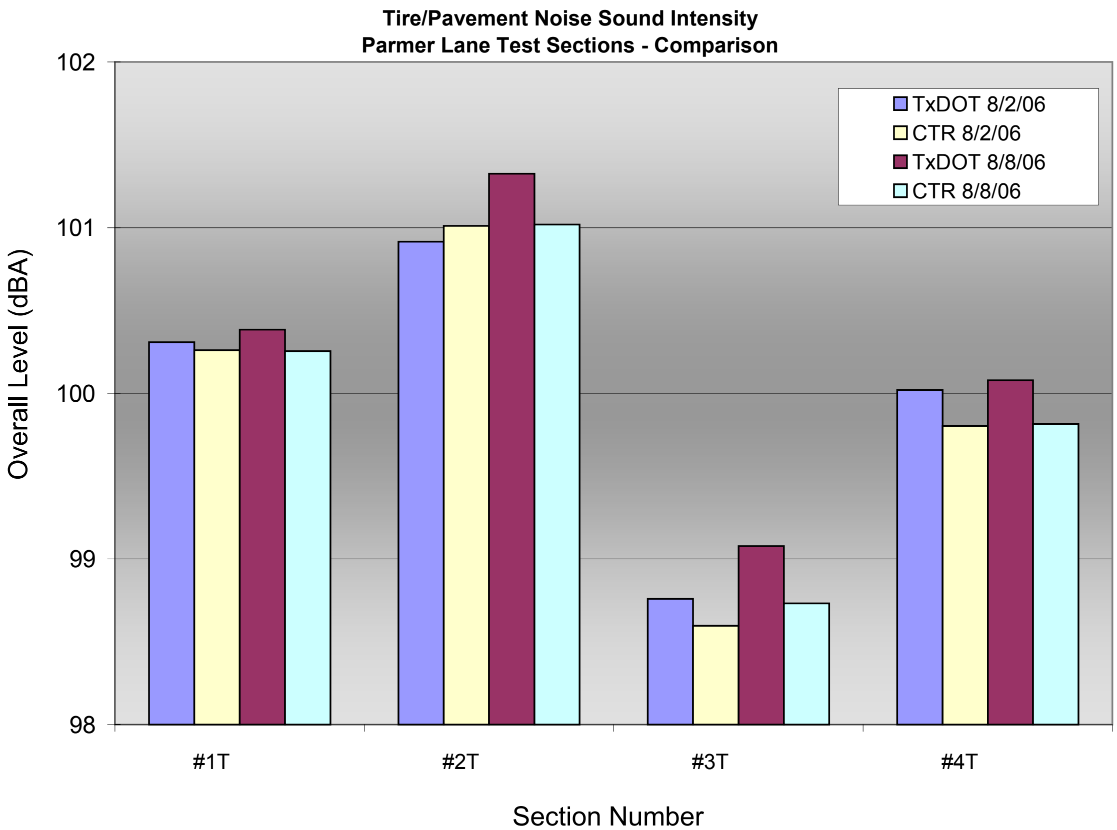


*Figure 6.6: Comparison of equipment and vehicle between CTR and TxDOT on Parmer Ln.*

Even though the TxDOT data from August 8 seem to yield the highest sound levels in all four cases, the differences are relatively small. The rest of the data look very similar as well, the differences are indeed negligible. The spectra (Figure 6.7) also present little variability among the dates and the vehicles, and the patterns of the graphs are the same in every case, which is an encouraging indication that both sets of equipment and vehicles can be considered equivalent for every aspect needed in this research.

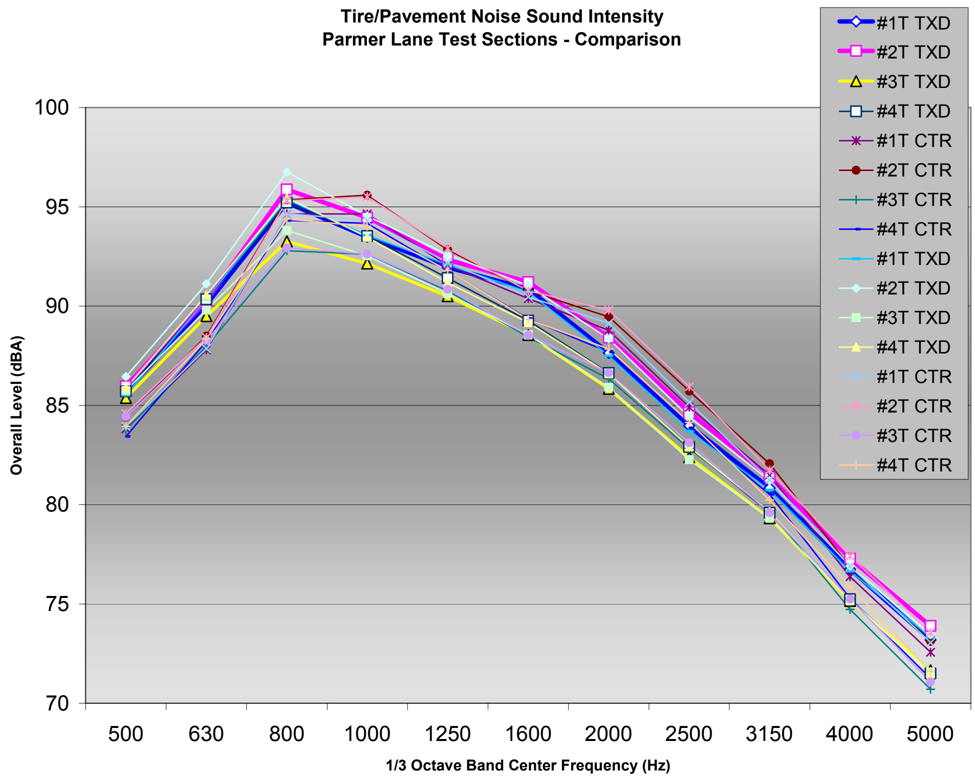


*Figure 6.7: Sound spectra for Parmer Ln. tests comparing TxDOT and CTR equipment*

### 6.2.4 Variability from Other Sources

When all equipment has been properly set up, calibrated, and checked, and procedures are followed precisely, there will still be variability. Hopefully, the remaining variability between runs and between sections within a test project will largely reflect the actual variability due to the pavement. However, several other sources of variability are known from the literature and from practical experience.

One such source is temperature. Ambient temperature (within the specified limits for the OBSI test) is not of great concern, but pavement and tire temperature has been shown to affect pavement noise. Although the mechanism behind this effect is not yet completely understood, several empirical studies indicate that tire / pavement noise increases about 1 dB per *decrease* in temperature of 10° C (50° F) [Sandberg 2002]. Section 6.3.3 details testing done as part of Project 0-5185 that may show this effect.

An attempt to identify the source of any additional unexpected variability will be made whenever it is encountered in data collected under this project.

## 6.3 Validation Sections

As an ongoing effort to assure continuous accuracy of equipment and procedures, several experimental pavement sections have been identified for repeated testing over time, using both the CTR noise test vehicle and the TxDOT vehicle.

### 6.3.1 Selection & Location of Validation Sections

The sections chosen for this purpose were selected using two criteria: proximity and special interest. Proximity allows more frequent cross-vehicle testing, which is desirable as it insures that use of data taken with each car is interchangeable for analysis purposes. Special interest sections are identified as data is collected by CTR and TxDOT and are generally chosen because they are surprisingly quiet (or noisy) or hold other interest either to the research effort or to TxDOT environmental noise considerations.

### 6.3.2 Cross Vehicle Testing in San Antonio

The San Antonio section on US 281, described in detail in Section 4.3.12, can also be used to verify the equivalency of TxDOT's and CTR's test equipment and vehicles because this segment was tested on several occasions. The PFC surface was initially tested by TxDOT on October 9, 2006. The results from those tests revealed that the asphalt rubber section 1 was exceptionally quiet, with an average level of 94.9 dBA for the section. That level is the quietest result obtained up to this date on any of the test sections in this project. In fact, no other PFC or other pavement type section has a level that has been close to it. That result caused CTR to visit the section on November 29, 2006 for additional testing. The result was that the PFC was still very quiet (95.6 dBA, overall average), although the levels went up slightly when compared with the first tests (Figure 6.8)

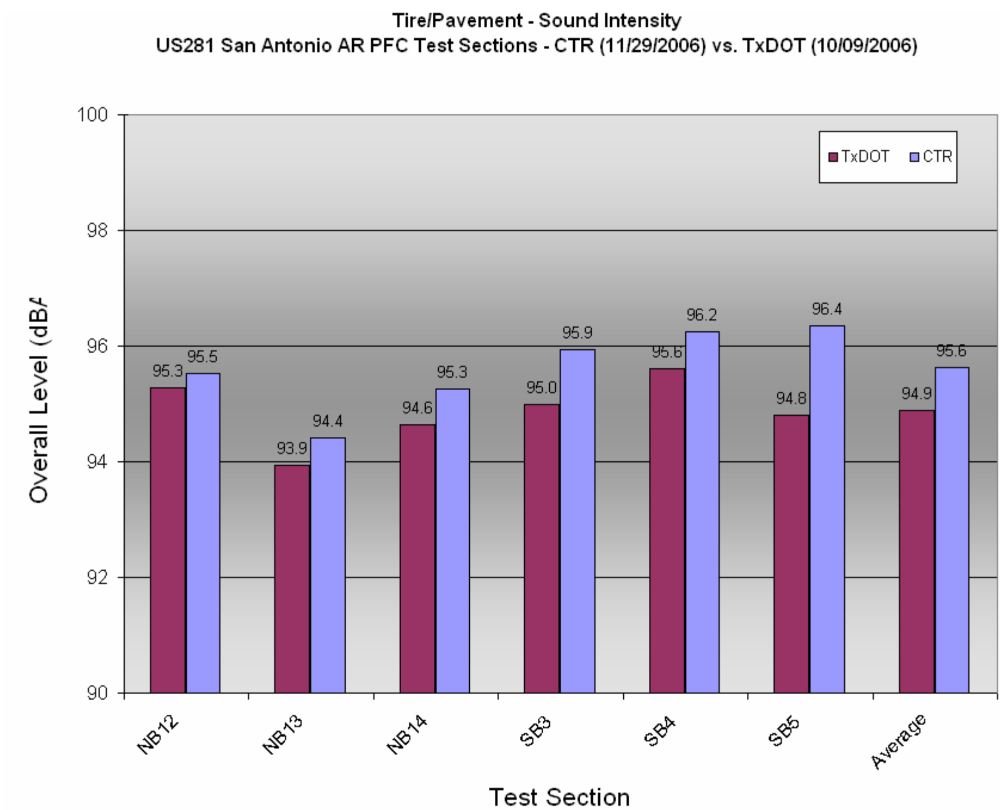


*Figure 6.8: Cross-vehicle comparison on AR PFC1 on US 281 in San Antonio*

Following CTR's tests, TxDOT personnel decided to perform another round of tests using their vehicle and gear on December 6, 2006. The comparison of the three sets of tests is shown in Figure 6.9.

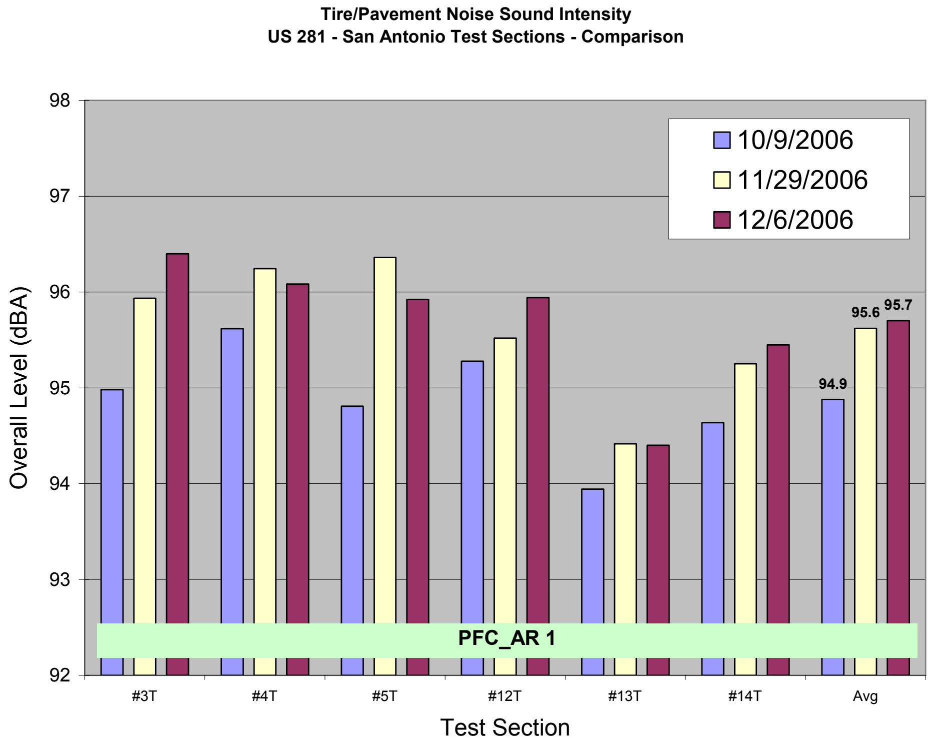


*Figure 6.9: Cross-vehicle comparison on AR PFC1 on US 281 in San Antonio*

The results confirm that the section is indeed the quietest among those tested so far. In the December tests, the overall levels went slightly up (96.7 dBA) once again when compared to the previous tests. The reasons for the quietness of this particular section can be attributed to the excellent condition of the pavement and the fact that it is new, but the tests also showed that both sets of equipment and vehicles are very similar and that the results delivered are consistent. The slight increase in loudness of the section could be attributed to environmental factors during tests, which were discussed in Section 4.3.12, and to the fact that the increase in loudness due to wear and clogging of the voids commonly observed in other PFC sections might occur at a higher rate when the section is very new, as it is the case of this roadway.

### 6.3.3 Cross Vehicle Testing on Austin Test Sections

For reasons of proximity, test sections were selected in Austin on Parmer Lane near RR 620 (Figure 6.10). These sections are used both for cross vehicle testing and routine calibration. The detailed results of the first round of vehicle comparison testing were presented in Section 6.2.3. Those results indicated that the variability between TxDOT's and CTR's equipment and vehicles is minimal and for the purpose of the testing is considered negligible.

Comparison of vehicles will continue using the Austin test sections at regular intervals during the remainder of the project.

### 6.3.4 Noise "Rodeo"

Not all agencies have switched to the OBSI system for pavement noise measurement; some are still using enclosed CPX trailers, some are using OBSI mounted to a trailer instead of the vehicle (presumably to reduce vehicle-related noise), and some will be switching to a double OBSI rig that allows measurement at the leading and trailing edges of the tire simultaneously. The latter procedure will save much time but possibly introduce additional wind noise from the additional microphone assembly, which is currently under study.

Therefore, there has been some talk between agencies about meeting at a central location so that all those participating can test the same pavement sections and compare results. CTR is involved in that effort on the national level and will participate when such a "noise rodeo" is arranged.

## 6.4 Summary

A well-defined system for monitoring and evaluating data variability has been established as presented in this chapter. The system relies on continuous calibration of the test microphones and analyzer. Periodically, the calibrator itself along with the analyzer must be returned to the manufacturer for certified calibration.

Additionally, it is a useful equipment and protocol cross check to run nearby or especially interesting sections using both the CTR test vehicle and the TxDOT vehicle. Any discrepancy in the data returned from the two noise rigs can be investigated and corrected, insuring that all data is interchangeable and likely correct within the precision required.

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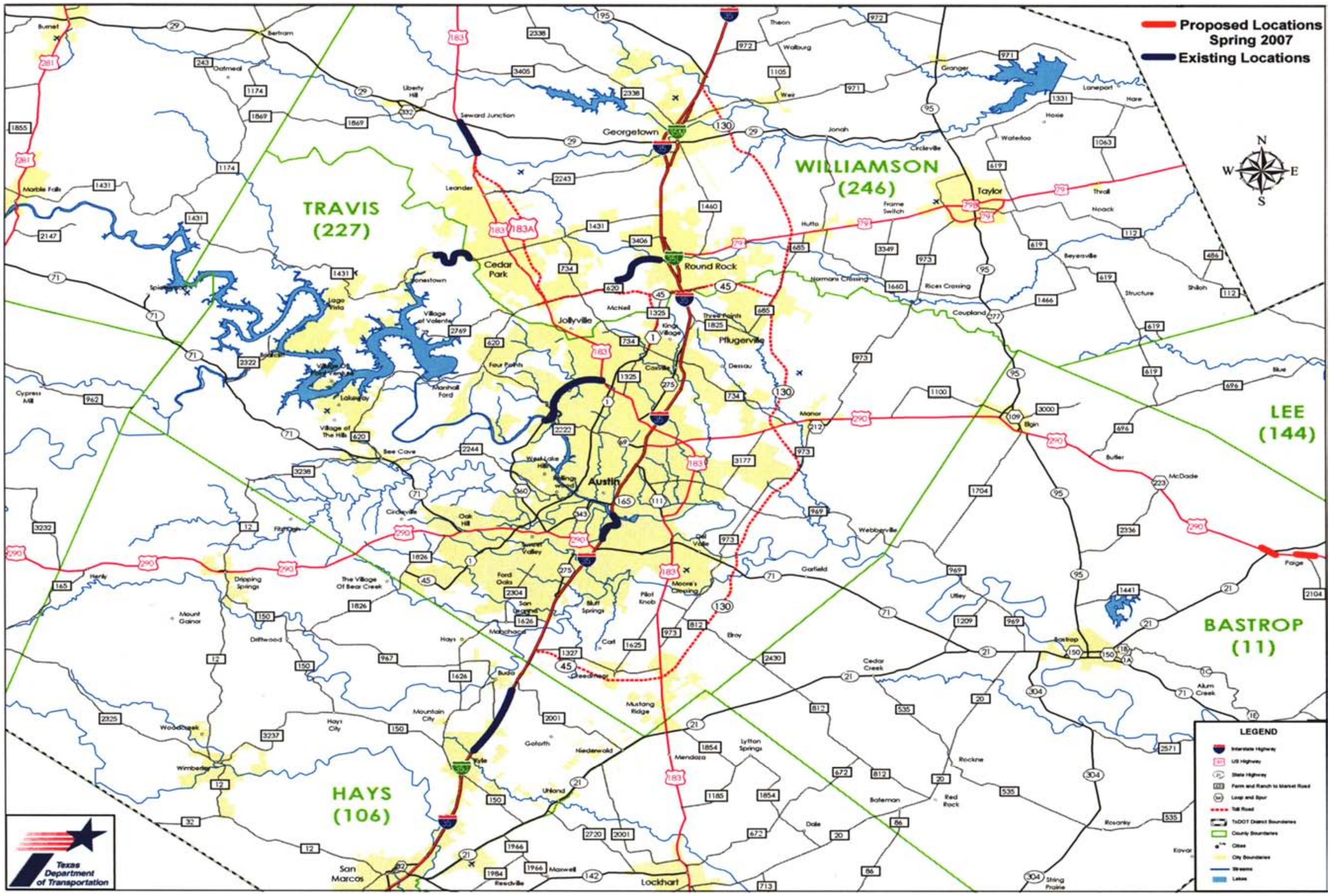


*Figure 6.10: Location of calibration sections in Austin District*

# 7. Conclusions and Recommendations

During the last few years, important steps have been taken toward the advancement of tire/pavement noise research and measurement, especially with the development of the upcoming AASHTO OBSI Standard. The fact that the national tire/pavement noise community, tire industry, researchers from both acoustics and pavements areas, private consultants, and experts have convened on various occasions to discuss the matter has been a key factor in these developments. In each of the last 2 years, the FHWA has put together Strategic Planning Workshops to propel this movement and identify the areas of opportunity, the benefits, the gaps and issues, and methods regarding how to utilize the technology to improve and make the measurements uniform. The most immediate outcome will be the standardization of the procedure to measure tire/pavement noise using the OBSI method, which will enable the exchange of comparable measurements and parameters. Another visible fruit of this work is the recent extensive dissemination of knowledge on the matter, with seminars, studies and publications, websites such as the FHWA clearinghouse, and a pooled fund study with the collaboration of various states.

However, additional data collection (OBSI and roadside) is necessary to obtain FHWA approval for the use of various types of pavements (other than “average”) in traffic noise analyses/TNM.

## 7.1 What Has Been Learned So Far

The results gathered so far in this project by means of pass-by measurements and their respective comparisons with equivalent models in TNM, both using the “average” and the “open-graded” pavement options built in the program, have confirmed that PFC pavements are indeed quieter than the model predicts. The results of the sections measured indicate that the “average” pavement option in TNM over predicts noise levels by almost 4 dBA, while the “open-graded” pavement option over predicts noise levels by about 2 dBA, on average. Although these over predictions seem small, it must be remembered that a 3dB reduction in noise corresponds to a halving of traffic volume, assuming that most of the roadside noise is generated by pavement/tire contact. These results are a very positive indication that the policy could be changed. For that, more evidence will be gathered in this project in hopes of supporting such change.

The OBSI tests performed so far have also confirmed that PFCs are quieter than other pavements, such as CRCP and dense-graded AC. Overall sound levels of PFCs averaged 98.1 dBA, while overall average sound level for other pavements was 101 dBA; this represents a potential reduction of almost 3 dBA, which is significant in terms of equivalent traffic levels, as explained above.

These results are especially encouraging in that the roadside measurements, which do not require the assumption that all traffic noise is generated by tire contact (since other sources such as engine noise, truck stack exhaust, etc. are included in the measurement), agree with, or exceed the OBSI figure. PFC pavements provide a significant reduction in noise that is readily and reliably measurable at the roadside, where receivers such as homes and businesses are located.

## 7.2 Additional Work Required

Much more testing is needed, regarding both wayside tests as well as OBSI. It is expected that future wayside results, along with the results obtained up to this date, will contribute enough evidence to help overturn the aforementioned FHWA policies. It is also expected that such results and those gathered from OBSI will yield a consistent correlation between both test methods, which will enable the prediction of wayside levels from OBSI tests, Given that the OBSI tests are easier and faster to perform, it is desirable that in the future, near-field measurements alone, such as OBSI, might be used for pavement noise evaluations. But until then, wayside tests will continue to be conducted by this project on the same PFC sections on which OBSI tests are run. Furthermore, this project should deliver important contributions from its wayside tests to the noise community in general, regarding the procedure utilized as well as the results, as a new Expert Task Group will be formed in the near future with the purpose of developing a new standard for roadside measurements.

The OBSI equipment only became available at the end of the third year of the study and the OBSI standard test specification is only now being finalized as of January 2007. This situation delayed the beginning of testing significantly but also assured that the data being collected now is much more accurate, repeatable, and exchangeable with other agencies' data. Therefore, the delay was ultimately of great benefit to the research.

Although the PFC sections have been prioritized for first data collection, conventional asphalt sections and some Portland Cement Concrete sections must also be tested. Most importantly, the PFC sections must be followed up with additional testing over time to characterize the change in their acoustic properties with age—a key requirement for FHWA acceptance of pavement design for noise reduction. Figure 7.1 shows the experimental factorial for noise testing.

| Section Location | | Number of Sections | | | |
|---|---|---|---|---|---|
| | | Pavement Age | | Pavement Type | |
| Climate | District | Old | New | Plant Mix Seal | PFC |
| Dry-Freeze | Amarillo | | 1 | | 1 |
| | Wichita Falls | | 8 | | 8 |
| | Austin | 5 | | 5 | |
| | Waco | | 3 | | 3 |
| | Fort Worth | 3 | | 2 | 1 |
| Dry-No Freeze | San Antonio | | 2 | | 2 |
| | Odessa | 2 | 12 | 9 | 5 |
| | Pharr | 3 | | 3 | |
| | Corpus Christi | | 2 | | 2 |
| | El Paso | | 1 | | 1 |
| Wet-Freeze | Lufkin | 2 | | 2 | |
| | Tyler | | 2 | | 2 |
| Wet-No Freeze | Yoakum | 10 | | | 10 |

*Figure 7.1: Experimental Factorial for Test Section Selection*

As the figure indicates, additional test sections will be marked and tested based on the primary variables of pavement type, climate, and pavement age. The numbers in the factorial indicate the number of test pavements that have been located for each combination of variables after contact with the District offices. As has been reported in detail, thus far testing has been conducted in five Districts, leaving a similar number to complete.

An intensive test schedule will be resumed shortly as winter weather recedes and conditions permit.

## 7.3 Cooperation with TxDOT

Synergy between TxDOT's noise test efforts (conducted by CST Division) and CTR's testing has been very productive for both agencies. CTR was able to rapidly respond to TxDOT's emergency request to determine pre-overlay noise levels on a section of IH-30 in the Dallas District. CTR also conducted the follow-up survey after the new PFC overlay had been placed. All data collected by CTR is promptly shared with CST and vice versa.

Conversely, some of the noise data collected by TxDOT has been especially useful to the research study and has been used to prepare some of the analyses in this report. TxDOT has also been very generous with their time and machine shop in making minor modifications to the CTR vehicle.

TxDOT and CTR personnel attended a 2-day joint training seminar by Dr. Paul Donavan, developer of the OBSI device. Consequently, the two crews are interchangeable when more workers are needed on a project or when the two vehicles are being crossed tested, as described in the previous chapter. More importantly, the data is interchangeable because procedures are identical.

Currently, meetings between the CTR researchers and the TxDOT CST crew are held informally on approximately a monthly basis, and more formal coordination meetings are held at TxDOT Cedar Park about once every 3 months. This insures that duplication of effort is avoided, except when desired, as in the vehicle comparison checking.

This cooperation and coordination will continue for the duration of the noise study.

# References


[Donavan 2004] Donavan, P., "Comparative Measurements on Tire/Pavement Noise in Europe and the United States, A Summary of the NITE Study," Illingworth and Rodkin, Inc., prepared for the California Department of Transportation, 2004.

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# Appendix A: AASHTO Draft OBSI Specification

Standard Practice for

# Measurement of Tire/Pavement Noise Using On-Board Sound Intensity Method (OBSI)

AASHTO Designation:

American Association of State Highway and Transportation Officials

444 North Capitol Street N.W., Suite 249

Washington, D.C. 20001

Standard Practice for

# Measurement of Tire/Pavement Noise Using On-Board Sound Intensity Method (OBSI)

## AASHTO Designation:

## SCOPE

**This test method describes the procedure for measuring tire–pavement noise using the on-board sound intensity (OBSI) method and verifying the calibration of the measurement system. This test method will provide an objective measure of the acoustic power per unit area at points near the tire/pavement interface in order to rank pavement surfaces.**

**Data resulting from application of this test method should not be used to replace the pass-by method for determination of impacts on the highway neighbors. Too little is known on the relationship between the sound intensity at the tire and the propagation effects to the nearby receivers to make a direct connection at this time. The on-board intensity measurement described here will permit the tire/pavement sound intensity to be measured directly and allows various pavements and textures to be directly compared.**

**As more information becomes available, this method will be modified to include pertinent results.**

## REFERENCED DOCUMENTS

**ISO10844: "Acoustics - test surface for road vehicle noise measurement”.**

**ISO 11819-1: "Acoustics - METHOD FOR MEASURING THE INFLUENCE OF ROAD SURFACES ON TRAFFIC NOISE - Part 1: The Statistical Pass-By Method"**

**ISO 11819-2: Draft: “Acoustics – MEASUREMENT OF THE INFLUENCE OF ROAD SURFACES ON TRAFFIC NOISE – Part 2: THE CLOSE-PROXIMITY METHOD”, ISO Working Group 33.**

**ISO 13473-1: "Characterization of pavement texture utilizing surface profiles - Part 1: Determination of mean profile depth"., Working Group 39**

**ISO/DIS 13473-5: “Characterization of pavement texture by use of surface profiles - Part 5 – Determination of megatexture”.**

2.6 ANSI S1.9 (complete)

**2.7 ANSI S1.10 / IEC 9162 title to be included**

**2.8 ANSI S1.11 / IEC 1260 title to be included (numbers to be verified)**

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# TERMINOLOGY

## Definitions:

**Average or Equivalent Sound Level (Leq) - The average sound level during a measurement is the sound pressure level recorded by the measuring instrument using the appropriate frequency weighting and averaged on the basis of energy over a certain time or corresponding road distance interval. Unit: dB**

**Sound Intensity - Sound intensity is the acoustic energy flowing through a unit area in a sound field and hence is a vector quantity with an associated direction of propagation. Unit: Watts per square meter.**

**Average Sound Intensity Level - The logarithmic time average of the sound intensity level. Unit: dB with a reference value 1 x $10^{-12}$ watts per square meter used for Sound Intensity Level.**

**On-board Sound Intensity Method (OBSI) – A measurement procedure that evaluates the tire/pavement noise component resulting from the interaction of a test tire on different sections of a pavement surface. The system measures the sound intensity at defined locations near the tire/pavement interface. The system includes one or more intensity probes with amplitude and phase-matched microphones in combination with analyzer(s), recording systems, and other associated equipment. The measurements are made with microphones operating close to the test tire, which is mounted on a test vehicle or prepared trailer. Multiple tests should be conducted over the same road section to evaluate repeatability. Results, obtained using the procedure, are measured at standard speeds according to the category or type of road being considered.**

**Power train (propulsion) unit noise - The noise from the power train, including the vehicle engine, exhaust system, air intake, fans, transmission, differential, and axles is known as the power train unit noise.**

**Baseline Surfaces - The main purpose with this method is to compare road surfaces with respect to tire/pavement noise emission for each one-third octave band. Each State or region should define a reference surface to be used. It is highly desirable that this surface be similar to the national test reference surface described later in this section. Additionally, testing of two systems should occur with a narrow time frame to quantify any differences in the systems since the pavement characteristics will change with time. Results should be thoroughly and continually documented for the system. This surface should be used to verify correct equipment operation and to evaluate test tires being used as described in Section 3.1.7. It is crucial to compare intensity levels measured by each system using the reference surface before any direct comparison is made between the two measurement systems. If data are to be included in a national database, compared to measurements of other states,**

**or if a comparison to national trends is to be done, predefined reference surfaces must be used by each system and the data differences by one-third octave band determined. This is needed for verification of equipment, for continuity of the databases and for ultimate comparisons. The reference surfaces will be defined as measurements occur and reliability is observed. Specifications of this surface are included in Section 10.1. This surface will be tested bi-annually to observe any changes that may occur by a reference system and test tire that will be carefully maintained.**

**Standard Reference Test Tire (SRTT) – ASTM (include number) 16 inch rim SRTT.**

**System - As referred to in this document, system refers to the entire system used to measure the onboard sound intensity. This includes the matched microphone pairs, preamplifiers, cables, sound analyzers, meteorology equipment, probe holders, and associated equipment.**

**Tire/pavement Noise –This is the sound generated by the interaction of the tire as it traverses lengths of pavement. The tire/pavement noise includes sounds of the tire during this activity but does not include other sources attributed to traffic noise (see Traffic Noise).**

**Traffic Noise - Traffic noise is the overall noise emitted by the traffic running over the road under study.**

**Vehicle Noise - Vehicle noise is the total noise from individual vehicle sources. This includes a component of noise generated by the tire-road interaction called tire/pavement noise and components generated by the vehicle engine, exhaust system, air intake, fans, transmission, etc. The noise from these components is known as power train (propulsion) unit noise.**

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## SIGNIFICANCE AND USE

**This test method will provide an objective measure for on-board determination of sound intensity at defined points near the tire/pavement interface. This permits a rank ordering of pavement surfaces. This test method should not be used to replace the pass-by (wayside) method for determination of impacts on the highway neighbors. Too little is known, at this time, about the relationship between the acoustic intensity (specifically OBSI) at the tire and the propagation effects to the nearby receivers to make an accurate prediction.**

**The frequency analysis of the measured sound intensity is performed using one-third octave band resolution. During measurements, the frequency range of 200 -10000 Hz (center frequencies of third-octave bands) should be included in analysis. However, it is recognized that in this range, contamination of the lower frequency ranges is expected. It is estimated that one-third octave**

**band frequencies of 500-5000 Hz. is the range in which the results are accurate. However, different frequency ranges could be reported. The one-third octave band filters should conform to ANSI S1.11 / IEC 1260. This or other standards do not preclude the supplemental reporting of data processed with narrower band filters. Additionally, the reporting of directly measured or derived A-weighted values shall be included in final reporting. The characteristics of any additional filters or other signal post-processing that do not conform to these standards shall be described in the reporting.**

## GENERAL REQUIREMENTS

**The measurement methodology presented measures the sound intensity emitted in close proximity to the reference tire. Reporting of intensity levels in fractional octave frequency bands along with total levels (A-weighted) is the final goal. A single probe containing two (2) microphones (phase and amplitude matched pair) are required. Additional probes may be used but the effect of possible turbulence effects should be evaluated.**

**Measurements shall be conducted using the 16 inch Standard Reference Test Tire (SRTT).**

**One-third octave band measurements shall be measured and reported for standardized speeds depending upon the facility type. A-weighted values should also be reported and presented with the metric descriptor dB(A) or $L_A$. Equipment that is used for these measurements is discussed in the accompanying specifications and a general measurement procedure that could be followed is presented in Annex C. Each individual test of a section of pavement together with its vehicle speed must be recorded. Although not required, additional speeds may also be tested on the same surface and if done should follow the same reporting procedure as for the standard reference speeds. In these cases it is desirable to perform a regression analysis of sound intensity using the OBSI method versus the logarithm of speed. This can be done for both A-weighted and one-third octave bands.**

## SELECTION OF TEST SECTION

**Each test section over which a measurement is made shall be based on a time of 5 seconds for the same wheel path of the same lane of travel.**

**The test section shall have the same nominal material and surfacing. The surface shall extend in a perpendicular direction to travel a minimum of 1.6 ft. (0.5 m.) from the reference tire track. The test section should be dry and free of debris to the extent possible.**

**The test section should be essentially tangent (avoidance of horizontal curves when possible) Roadway geometry and grade must be documented.**

**The condition of the road should be documented and pictures included of the typical surface when possible. It is recommended to provide historical data of the roadway surface when available.**

**Test section should be located away from large roadside objects within 4 ft. (1.22 m) of the edge of pavement. If measurements must be made with objects nearby, this should be documented and reported.**

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# MEASURING PROCEDURE

**Probe Locations - At a minimum, measurements should be made at the leading edge and trailing edge of the outside tire track as shown in Figure 7.1. If measurements are taken at both locations in the same test pass, care should be taken to insure turbulence wake effects are not causing a measurable bias to the data. Multiple passes of the test section may be used with the microphones being relocated on subsequent passes.**

**Calibration - At the beginning of the test, and following all warm-up procedures specified by the manufacturer, the overall accuracy of the sound level measurement system (including the microphone) shall be checked and recorded using an acoustic calibrator or piston phone to allow accurate collection during measurements and processing of data during analysis. Calibration shall be conducted before and after the measurement period but no longer than 4 hours. It should be noted that precision does not guarantee accuracy and calibration is required for this. The measurement system shall be adjusted for accuracy according to the manufacturer's instructions. The measurement system accuracy should be verified at the end of the test and the values obtained recorded. Any deviations shall be recorded in the test report. If the calibration readings at the beginning and ending of every measurement period differ by more than 0.5 dB during a series of measurements, the test shall be considered invalid. The sound calibration device shall meet the requirements of ANSI S1.10 / IEC 9162, Class 0 or Class 1. (Note that some calibrators require correction for environmental conditions. The manufacturer**

**specifications should be consulted.) In addition to these field verifications of sound intensity calibration for the microphones certification by an appropriate lab or manufacturer every 6 months. The acoustic calibrator shall be certified at an appropriate calibration lab or manufacturer following manufacturer specifications but no longer than 12 months of the test date.**

**Sound Measurement - The signals shall be A-weighted prior to digitization in order to prevent overload of the recording system. If a single probe is used there shall be an algebraic average of leading and trailing edge measurements. If dual probes are used this average shall be for the same measurement. The measurements shall be an energy average (linear) over 5 seconds.**

**Number of Runs - At least two tests over the same test section shall be made. If any measured one-third octave band varies by more than 2.0 dB, and speed variation limitations have been met, an additional run shall be made to reach the desired measurement limits. Runs that vary more than the prescribed limits should not be used. Notwithstanding the actual number of runs, the operator shall ensure that a standard deviation of not more than 1.0 dB for each octave band shall be obtained. The final reporting will be the average of the successful runs.**

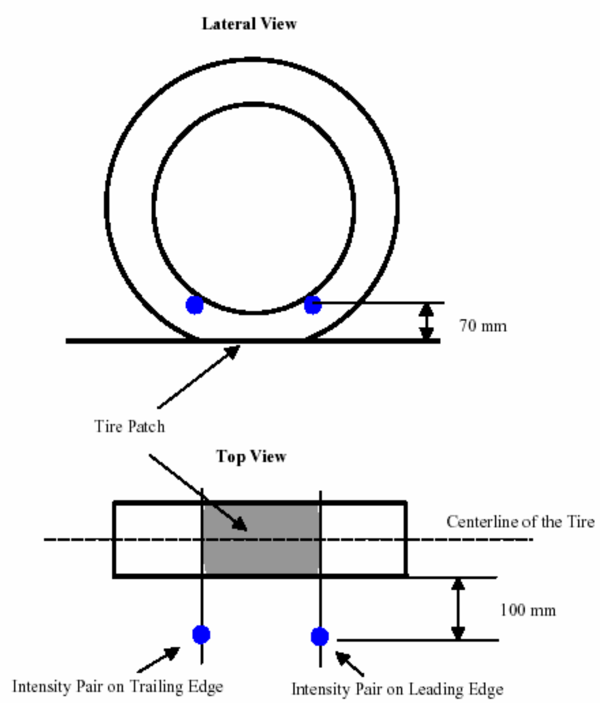


Figure 7.1. Microphone Positions: Leading/Trailing Edge Measurements.

(Courtesy of General Motors).

**Recording Data - It is recommended that the sound also be recorded for later analysis. Recording instrumentation, in combination with analyses procedures, shall be selected to meet ANSI S1.9 requirements.**

**Compromised Data - Data from measurements that are obviously influenced by any other source or that were recorded improperly shall be discarded .**

**Reporting Results - Measured values in decibels should be recorded to one decimal place**

**Frequency Spectrum Measurement - Reporting shall be done in one-third octave band frequency spectra according to ANSI S1.11 and IEC 1260. Narrower band data may be provided in addition to the one-third octave data if desired.**

**Test Vehicle Operating Conditions**

**Test speeds - During the test, the vehicle shall travel with constant speed (± 2 mph; ± 3 kph) over the test section in an appropriate gear setting. It should be noted that the reference speeds are the same for all vehicle types. Nominal test speeds will vary by facility type**

7.9.2 Standard measurements speeds include 60, 45, 35, 25 mph.

**7.9.3 Reporting Speed - For each test the actual speed shall be measured with any instrument that provides the required accuracy of ± 1 mph (3 kph).**

**Tire inflation - Cold tires should be inflated to 35 psi. Before any measurement takes place the tires shall be brought to normal operating temperature by driving for a minimum of 15 minutes. At this time the pressure should be verified and recorded.**

Tire mounting – Tires shall be installed on test vehicle while stopped at or near test location and not during travel. The SRTT shall be used with rotation in the same direction for each test for the life of the tire.

If the test tires are brand-new, run them for an additional 10 miles (16.1 kilometers) to eliminate or smoothen the mold release agents (or spikes) on the tread surface. Verification should be done to insure the spikes have been removed. Remove small stones from tread grooves prior to test runs.

**Temperature Measurement – Limitations on temperature are equipment specific and manufacture specifications should be followed.**

**The temperature of the ambient air and the surface of the pavement test section should be measured at 60-minute intervals.**

**Road Surface Temperature - Road surface temperature is recommended at a location where the temperature is representative of the temperature in the wheel tracks, and without interfering with the sound measurement.**

## Other Meteorological Conditions

**Check of Moisture in Porous Surfaces – Water in porous surfaces is known to affect measurements. For porous surfaces, procedures should be applied to verify that the pores are dry.**

**Relative Humidity – Relative Humidity shall be recorded.**

7.11.3 Barometric Pressure - Barometric pressure at the test section shall be recorded.

# REFERENCE ROAD SURFACE

**Reference Surfaces – Required only if data are to be included in national comparison.**

**General Case - The reference surface is a dense, smooth-textured asphalt concrete surface with a maximum aggregate size of 0.43 ~ 0.63 in. (11 ~ 16 mm). The surface shall have been exposed to normal traffic for at least one year when used as a reference. Macrotexture depth as measured according to ISO 10844 or ISO/CD 13473 shall be between 0.02 in. and 0.04 in. (0.50 mm and 1.00 mm). To ascertain that the surface is acoustically non-absorbing, air voids content or the sound absorption coefficient shall meet the requirements specified in ISO 10844. Reference road surfaces for State or regional analysis must be tested annually to document changes in the surface. Reference road surfaces used for national data comparisons must be tested bi-annually. Observe sample locations in accordance with ISO 108444 "Normalized Reference Case". The reference surface is a fictitious surface of which the levels are based on the average results of a great number of measurements on asphalt concrete and provides the standard surface for verification of the measurement systems.**

**"Normalized Reference Case" shall be the pavement results used for comparison when existing potential "low noise surfaces".**

**"Arbitrary Reference Case": If the reference surface is any arbitrary surface, other than above, measurements are useful only for comparisons between the particular, selected surfaces**

# REGRESSION ANALYSES

**This analysis is only required in those cases where multiple speeds have been tested for the same test section. Multiple speed testing is not**

**required. However, it is desirable to estimate sound intensities using the OBSI method as a function of the log of the speed, the regression method could be applied if sufficient data, in multiple speed ranges, are measured over the same pavement test section. This is not always practical and unless significant deviations from the nominal speed testing are possible, meaningful regression analysis is not possible and should not be used. Additionally, this method should not be applied outside of the measured speed range.**

**Regression Procedure - In those cases where a sufficient data base exists for an extended speed range, a linear regression analysis of sound levels of multiple individual passes on speed may be made utilizing data consisting of the average and maximum one-third octave band sound intensities (dependent variables) versus the logarithm of speed to the base 10 (independent variable). A least-squares regression line shall be fit to the data points for each separate vehicle category.**

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# REPORTED DATA

## The test report shall include the following data:

**General information:**

Time and date of measurement
Organization and operators responsible for the measurement
Purpose of the measurement
Vehicle speeds tested
Type of measurement equipment (including calibrator, sound measurement system, etc.)
Instrumentation used to collect speed and meteorological data.
If used, equipment for measurement of surface macrotexture.
Date of last equipment/calibration.

**Location and test site Information:**

Location of the test site
Site plan
Identification of the test section, pavement type (concrete, stone matrix asphalt, etc., including any standardized or otherwise commonly used designation of the texturing or surfacing applied)
Large object within 4 ft. (1.22 m) from the edge of pavement
Any other large objects thought to have affected test
Cross profile (vertical) of the test section
Nominal maximum aggregate size or nominal texture if appropriate
Thickness of surface layer (optional for non-porous surfaces). May be estimated from mass, density and area if not directly measured
Residual air voids content of surfacing layer according to ISO 10844, in case of porous surfaces (optional)
Sound absorption coefficient, according to ISO 10844, in case of porous surfaces (optional)

Macrotexture depth, according to ISO 10844 or ISO 13473-1 (optional)
Representative photo of the surface, covering an area approximately 16 by 8 in. (406 by 203 cm.), including a scale.

**Test surface condition and environmental information**

Age of the surface and state of maintenance
Any special surface treatment
Percent or mixture of additives or modifiers such as rubber in the binder
Any notes regarding the homogeneity of the surface
Date of latest precipitation, in case of porous surface (flexible or rigid pavement)
Average, maximum and minimum air temperatures during the measurement period
Average, maximum and minimum road temperatures during the measurement period.

**Acoustical measurement information**

Measured levels by one-third octave bands.
Calibration results.
Overall A-weighted values.
Standard deviation of results by 1/3 octave band and A-weighted levels.
Overall average of test results for a test section (one-third octave band and A-weighted).
Integration, averaging times and techniques.
Any unusual occurrences or problems during testing including possible influences from location parameters.

## Precision and Bias

**Precision – Repeatability of measured results. Precision infers obtaining the same answer for the same conditions but does not infer accuracy. (not available at this time).**

**Bias – A error trend in the data caused by procedures, equipment, or local characteristics. (not available at this time).**

## APPENDIX A:

### SUGGESTED DETAILED PROCEDURES

**Preparation - Insure the tire-wheel assembly is dynamically balanced. The appropriate adaptor should be installed on the vehicle to allow appropriate location of the microphones at the test wheel. A test vehicle must be selected that uses the reference tire.**

### Equipment Preparation

**Install microphone preamplifiers into the microphone preamplifier spacer/holder. Make certain that they are of the same depth. Care should be taken to follow the manufacturer's guidance in regards to such critical issues such as the microphone placement. By convention, channel #1 is assigned to the microphone which is closer to the test tire; channel #2 to the other**

**microphone. The microphone wind screen shall be installed to reduce the low frequency turbulence effect generated by a rotating tire and the wind. Other devices may also be used. Intensity microphones shall be phase matched as discussed in the accompanying specifications of this procedure.**

**Mount the preamplifier spacer/holder on the intensity fixture which is attached to the test vehicle. Turn on instrumentation and allow five minutes to warm up. Set microphone power supply, instrument output, and filters to the appropriate gain and follow other manufacturer specifications. Set controls as appropriate for pavement and vehicle type.**

**The DAT Recorder (or other recording device) should be setup at the same time. For each microphone, place the microphone calibrator on it and record a minimum of 30 seconds of calibration signal. The level should be verified and the gain set if there is a substantial (>2 dB) variance from calibrator level. Verify recording and headset operation.**

**Immediately prior to testing, lower the intensity probe fixture and adjust it so that the center line of the two microphones is 3 in. (76 mm) above the road surface, 4 in. (100 mm) outboard away from the sidewall of the test tire, with the microphone diaphragms in line with the leading edge of the tire contact patch, as shown in Figure 7.1. Spacing of 8.25 inches (complete as needed here). Make a test run at the defined test speed for the facility to check the system response. The signal levels should be increased to improve dynamic range but at the same time does not overload the DAT recorder, or microphone power supply.**

**Monitor the noise levels through headphones in order to identify any occurrence of unusual sound, and eliminate unusual sound. Check the DAT recorder level indicators for overloads.**

**Measuring the Sound Intensity- Procedures supplied by the equipment manufacturer should be used to operate instrumentation during the measurement and recording of the sound intensity.**

**Place the intensity probe at the appropriate position (see Figure 7.1). The sound intensity using the OBSI method should be measured at the prescribed test speed for each facility. In some cases, research may permit additional speeds to be tested. The intensity probe shall remain in the same location for all leading and trailing edge measurements as appropriate. Ensure the averaging time and test duration have been set properly. Ensure the same test section, same lane, and horizontal tire location are kept as constant as possible for each pass. This is especially important to allow the leading and trailing edge measurements to be matched if a single probe is used.**

**Ensure that the temperature measurements, wind measurement, and other local parameters have been measured or are measuring properly.**

**Ensure data is being recorded after the first test run. Equipment should be reset as needed.**

**If a single intensity probe is used, the probe fixture should be moved so that the microphone diaphragms are in line with the leading or trailing edge of the tire contact patch to begin testing (see Figure 7.1). Repeat the measurement**

**process to obtain the tire noise intensity data at the leading or trailing edge of the tire contact patch to complete testing.**

## Quality Control

**Check two runs for the same conditions to see if each one-third octave band level is within 2.0 dB. The validity of the data should also be checked by reviewing spectra to determine if the results are in an acceptable range, the coherence is correct, the direction is as specified, and pressure-to-intensity index is appropriate. Test data should be rejected if they do not meet the following requirements.**

**Direction - The negative intensity shall not occur within reported data.**

**Pressure-to-Intensity Index - The pressure-to-intensity index is the sound pressure level minus the sound intensity level and shall not exceed 5 dB.**

**Coherence – Within the reported data, values shall be between 0.8 and 1.0. In frequency bands where data are less than 0.8 the data shall not be used since it is most likely contaminated by wind gusting or non-tire related noises.**