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16. Abstract

This report presents the results of noise testing performed on Texas pavements between May of 2006 and the summer of 2008. Two field test methodologies were used: roadside noise measurement with SPL meters and on-vehicle sound intensity measurement of noise at the tire/pavement interface. Additionally, pavement samples were tested in an impedance tube. 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 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. An important part of the study focused on testing pavements corresponding to 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. 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. Measurements at the tire/pavement interface confirm the quieter characteristics of these surfaces. The study results also suggest a slight degradation of such quietness with time, but even with this small increase in noise levels the surfaces can still be considered quieter than other pavement types. Furthermore, the increase in loudness is not significant enough to assert that these PFC surfaces cannot retain their acoustic properties over time. As per the results obtained in this study, it can be said that open-graded pavements can be reliably used for noise impact avoidance and abatement.

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Noise Measurements of Highway Pavements in Texas

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Chapter 1. Introduction

Highway traffic noise has increasingly become a subject of concern for transportation agencies as well as the general public. Transportation planners, engineers, environmentalists, and researchers have sought cost-effective ways to reduce noise pollution in urban areas. For traffic noise, the most frequently used mitigation measure has been the construction of traffic noise barriers along the highways. In recent years, some porous pavement surfaces have shown to be quieter than their more common, non-porous counterparts—mostly a fortuitous property, given that these surfaces are placed for their good draining characteristics. This discovery has led to the use of such pavements as a viable alternative to traffic noise barriers. In Texas, this type of pavement is known as "Permeable Friction Course" or PFC. An open-graded asphalt with typically 18 percent or more air void content, PFC offers outstanding performance under wet conditions, significantly reducing splash and spray, improving visibility, and increasing safety. It is in use by a number of states, and is more formally known as "New Generation Open-Graded Friction Course," nationally and internationally.

PFC pavements also reduce noise, both inside the vehicle and at the roadside, because of their relatively high air void content and the occasional inclusion of crumb rubber in the mix. For the reasons discussed above, their use in Texas and several other states is increasing rapidly.

Considering the environmental concerns and the pavement technological developments, the Texas Department of Transportation devised Project 0-5185, "Noise Level Adjustments for Highway Pavements in TxDOT," in an effort to assess the potential application of "quieter" pavements for both impact avoidance and noise abatement.

The Federal Highway Administration (FHWA), the federal agency in charge of developing policies and guidelines for the national highway system, allows a state to spend federal-aid highway funds for noise abatement projects. The FHWA policy is contained in [FHWA 1995], and it establishes that pavement type or texture cannot be considered as a noise abatement measure. The policy in question also 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. The intent of this research project is to provide evidence that can address this subject. The FHWA policy applies to all federally funded projects, and it has substantial consequences on the restriction of noise reduction measures such as pavement types 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, for use only with an "Average Pavement" option. However, the program has other options—at the time, only available for research purposes—enabled for modeling pavement types that would render quieter noise levels, such as the "Open-Graded Asphalt Concrete." This applies to impact avoidance.

TxDOT addresses highway noise in its Guidelines for Analysis and Abatement of Highway Traffic Noise [TxDOT 1996]. These guidelines have been approved by FHWA. Under these guidelines, "abatement" is defined as any positive action taken to reduce the impact of highway traffic noise. A noise impact occurs when predicted traffic noise reaches a level that requires the consideration of noise abatement measures. The abatement measures that must be considered when a traffic noise analysis results in a noise impact are:

- Traffic management
- Alteration of horizontal and vertical alignments
- Acquisition of real property to serve as a buffer zone
- Insulation of public use or nonprofit institutional structures
- Construction of noise barriers

Following the FHWA regulations, no pavement consideration could be included in the guidelines for noise abatement purposes.

Notwithstanding the policies, investigating impact avoidance at the chief source of the noise, the tire/pavement interface, is a sensible endeavor. There are advantages to reducing the noise at the source rather than placing a barrier between the source and the receiver. First, all receivers, including drivers, can benefit. Second, the benefit can be achieved in situations where barrier construction is not feasible or reasonable, or when barriers may be objectionable for aesthetic reasons. If a pavement can be designed to be quieter, and it is able to retain those quiet characteristics over its service life with reasonable maintenance, then the use of quiet pavements may be approved by the FHWA in the future as a measure for impact avoidance and noise abatement. If this is accomplished, the use of quieter pavements may even eliminate the need for noise barriers in neighborhoods.

Research has concluded that a very significant component of traffic noise is produced at the tire/pavement interface. Other components of traffic noise are generated by the engine, exhaust, and aerodynamic characteristics, but at higher speeds, the dominant source is the tire/pavement noise. Evidently, the surface characteristics of the pavement have a key influence in the generation of noise. Protecting individual receivers by reducing pavement noise at the source rather than by means of traffic noise barriers may prove to be the more cost-effective way of mitigating noise.

1.1 Background and Previous Research

This is the final report for this project. Two previous reports have been produced. Report 0-5185-1 [Trevino 2006] presented the literature review, evaluated available technology for measuring pavement noise, and provided recommendations for equipment, protocols, and test sections throughout the state of Texas. Information on the candidate pavement sections was gathered at that stage, and a preliminary version of the data collection factorial was prepared. The second report of the series [Trevino 2007], documented the findings from field testing of pavement noise accomplished by two methods of testing—on-board and roadside—and presented analyses of the data as well as comparisons with TNM. Preliminary conclusions and recommendations were presented at that point, considering the results obtained up to that stage of the project. This final report documents all the testing done throughout the project, presents a detailed analysis of the results, draws final conclusions, and extends recommendations for future testing and research. The comprehensive description of this report's organization is presented in Section 1.3.

Background for this research has been developed by its predecessor, TxDOT Project 7-2957, "Use of Pavement Surfaces to Attenuate Traffic Noise." This project, documented in [DeMoss 1999], [McNerney 2000], and [McNerney 2001], devised some valuable noise testing equipment that is still in use, some of which was incorporated into the 0-5185 Project, as presented in Chapter 2. Project 7-2957 showed that there are significant differences in Texas pavements with regards to tire/pavement noise, and concluded that it would be feasible to develop quieter pavements able to provide at least a 5 dB level of traffic noise reduction, even though no pavements in the study were specifically constructed to be quiet pavements. Data gathered in the project did not provide conclusive evidence that asphalt surfaces become less quiet over time and wear, and also did not show that rigid pavements become quieter over time as traffic abrades its surface texture. Good correlations were found between noise levels measured on-board test vehicles with the roadside results. This research emphasized the importance of considering the noise absorption characteristics of the various pavement types when evaluating traffic noise.

A key event that determined the direction of the research and practice in this area in recent years and for the foreseeable future in this country was the Tire/Pavement Noise Strategic Planning Workshop, sponsored by the FHWA, held in the Fall of 2004, at Purdue University [Bernhard 2004], in which one of the researchers of this project participated. This workshop gathered the foremost experts in the traffic noise area, including engineers, researchers, environmentalists, acousticians, policy-makers, and practitioners from government entities, academia, and the private industry, to identify the needs and develop a roadmap to implement quiet highways. The decisions and initiatives undertaken as a result of this meeting laid out a comprehensive plan that has proved to be crucial in establishing new design practices, policies, construction and maintenance, analysis (measurement and prediction), and research toward the use of quieter pavements for noise mitigation.

One such decision was the creation of the Expert Task Group on Tire/Pavement Noise Measurement in charge of developing standards for consideration by AASHTO for measurement for tire/pavement noise. Some of the efforts of this group are nearing completion in regards to an upcoming standard, which will be addressed in subsequent paragraphs. The need for the establishment of standardized testing procedures was an area of opportunity identified by the experts where much progress was needed, given the existence of a variety of wayside and near field testing methods. The creation of pooled-fund projects with the state DOTs is another initiative from that meeting, with TxDOT being an active participant in those studies. Findings from this 0-5185 Project have contributed to such pooled-fund study.

NCHRP Project 1-44, “Measuring Tire/pavement Noise at the Source,” performed by Illingworth & Rodkin, Inc., and recently finalized, is another outcome of the workshop. This project evaluated potential noise-measurement procedures for measuring tire/pavement noise, applicable to light and heavy vehicles, under in-service conditions, for all pavement types [Donavan 2009]. Dr. Paul Donavan, a widely known acoustics scientist, was the Principal Investigator. This is a significant project with sizeable implications for the standardization of measurement of tire/pavement noise. Based on the exhaustive review and analysis conducted in this project, the researchers recommended a procedure for measuring tire/pavement noise by means of the sound intensity method (On-Board Sound Intensity, OBSI). This is the same method that the 0-5185 Project Committee and researchers agreed to use halfway through it, by acknowledging the national and international trends followed by the transportation noise community of researchers, scientists, practitioners and industry in recent years.

1.2 Objectives

The objectives of this research include:

Remove FHWA restrictions. The project pursues the elimination of two restrictions from the FHWA policy, namely:

1) 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 and the possible avoidance of noise impacts.
2) 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 specify 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.

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 with their acoustic properties to assist designers in predicting the noise levels generated by various mix designs.

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

The objectives of this report are as follows:

1. To present the equipment and test methods utilized throughout this research
2. To document the pavement characteristics of the sections analyzed and the basis for their selection
3. To present the experimental results obtained in the project, along with comparisons and analyses
4. To present recommendations to TxDOT for future research and noise data collection

1.3 Report Organization

This report is organized in the following way:

The details of the equipment and test procedures utilized in this project are presented in Chapter 2.

Chapter 3 is dedicated to the various data collections efforts denominated "Noise Rodeos," that were conducted at various stages of the project in cooperation with other agencies, for the comparison, validation, and calibration of the OBSI equipment.

Chapter 4 provides an analysis of the OBSI results obtained on PFC pavements.

In Chapter 5, the results of the roadside tests are presented, along with the comparisons of the actual measurements from the side of the road versus those predicted by TNM.

Several pavement sections of interest with particular characteristics that do not necessarily fall into the open-graded pavement category (such as a diamond-ground concrete pavement) were also investigated in the course of this research. Those have been labeled as Special Case Studies, and are the subject of Chapter 6.

A comprehensive statistical analysis has also been developed to evaluate the OBSI results from various standpoints, including pavement characteristics, age, traffic, climatic variables, test tires, and equipment, among others. This analysis is presented in Chapter 7.

Finally, Chapter 8 summarizes the conclusions and recommendations developed in the preceding chapters.

Chapter 2. Instrumentation and Testing

The equipment and methodology for pavement noise testing continues to evolve worldwide, and has even evolved greatly during the course of this four-year study. The driving factor for this evolution seems to be increased speed of testing while still maintaining comparability to roadside noise levels as measured with a standard decibel meter and as experienced by the receivers (homes and businesses) at the roadside. Increased testing speed reduces cost and also increases safety by using vehicle-mounted systems versus personnel exposed to traffic hazards for long periods of time.

However, because vehicle mounted systems typically measure noise at the pavement-tire interface, care must be taken to always relate on-vehicle measurements to roadside noise levels, when the data is to be used for estimation of noise impact. Otherwise, the on-board measurements simply give a “delta” between various pavements, not the absolute value of noise which would be experienced at roadside. Additionally, PFC pavements attenuate sound traveling along the drive lanes and shoulder, a “propagation effect” that further reduces the roadside noise levels. This effect is not captured by the OBSI measurement.

2.1 Test Methods Used in this Study

The noise test methods can be broadly classified in three main categories of testing equipment, each with its own standardized protocol. The categories are roadside tests, on-board methods, and impedance absorption testing. All three were used in the course of this study and are described in the sections below.

2.2 Roadside Noise Measurement using SPL Meters

The most basic (and still the most accurate) method of measuring traffic noise is to set up sound pressure meters at the roadside. All other methods used to measure road noise are simply more convenient, faster ways to approximate the wayside noise via correlation. Therefore, it’s essential to establish a relationship between the on-vehicle methods and the direct measurement, and to check that correlation periodically during the vehicle testing. It’s been observed under this study and many others that correlations between on-board and roadside measurements are unique to the vehicle configuration (primarily tires), and the pavement surface material (propagation effect).

Figure 2.1 shows a typical setup for a roadside noise measurement. One or two Class 1 sound pressure meters are set up at precise distances and elevations relative to the center of the travel lane. Initially, all requirements given in ISO 11819-1, *Measurement of the Influence of Road Surfaces on Traffic Noise* [ISO 1997] were met, including the 7.5-m horizontal distance of the microphone to the centerline of the measured traffic lane, and 1.5-m vertical elevation above the plane of the road. Later in the study, a second meter was added at 15 m distance from the centerline of the traffic lane to correspond with the distance used by Volpe Center in their measurements for validation of the FHWA’s TNM program (more information on TNM can be found in Chapter 5). A-weighted L_{eq} was used as the standard variable, as that is the sound level measurement that TNM predicts. L_{eq} is the equivalent sound pressure level that, if maintained constant over a given time, would deliver the same amount of acoustic energy as the time-varying sound pressure level measured.

Figure 2.1: Pass-by noise measurements at roadside

Another vital function roadside measurements perform is to provide as measured data for comparison with predicted roadside noise levels using the FHWA's TNM software. The TNM program is important because its use is required on federally funded projects to determine whether a noise barrier is required. TNM can predict the noise level at any location near a roadway, provided very detailed inputs are available, including vehicle counts, roadway geometry, type of surfaces, and vehicle speeds. To obtain the traffic data required for TNM, the roadside measurement procedure under this study also includes videotaping of the traffic during testing, and an inset vehicle speed reading obtained via a radar detector (Figure 2.2).

Figure 2.2: Video traffic record including vehicle speeds

At the time of this writing, a national standard for pass-by testing is being drafted by the FHWA's Expert Task Group. The new standard will specify test instrument locations at 25 and 50 ft from the center of the travel lane, which matches the 7.5 and 15 m locations used in this study. In any case, the exact locations are not important as the TNM program predicts noise levels for any receiver locations. An example output from TNM appears as Fig 2.3.

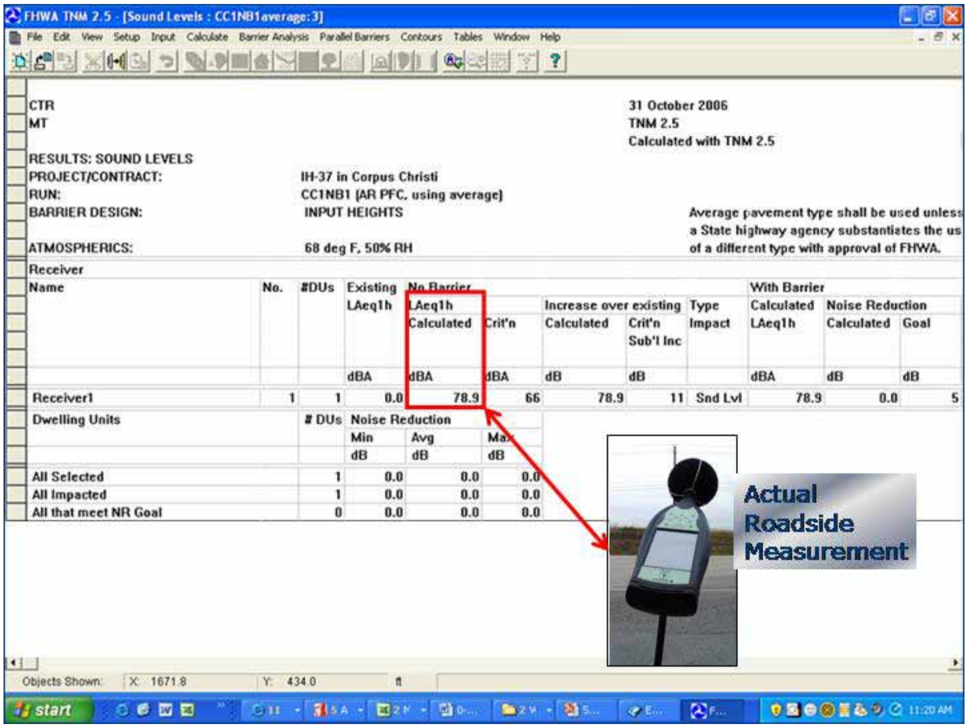

Figure 2.3: Comparison of actual roadside versus predicted noise levels using TNM

2.3 On-Board Measurement Systems

Although use of precision sound meters at roadside provides the best and most relevant measure of traffic noise, it is impractical for use on a large scale due to the set up time and the time required to take the measurements: typically 10–30 min per measurement, three replicates per section. Therefore, on the national and international level, practitioners have migrated toward vehicle-mounted measurement systems so as to be able to estimate roadside noise levels quickly, at low cost, and with low risk to personnel.

Three classes of on-board systems have emerged, which can be roughly characterized as free field close proximity devices, enclosed close proximity devices, and sound intensity devices. The former two systems are referred to as CPX (generally trailer mounted) and the latter is termed OBSI (vehicle mounted). Much work has been done with all three systems, each having specific advantages and disadvantages, with OBSI currently emerging as the dominant system.

2.3.1 Free Field CPX Trailer System

Figure 2.4 shows a typical free field, CPX trailer system that was developed under Project 7-2957 [McNerney 2001] and initially used in this study. It consists of two precision measurement microphones mounted on a hoop suspension system, designed to suspend the microphones at a precise distance from the front and rear tire contact points, as well as vertically above the pavement surface. The trailer is weighted with iron bars to closely match the axle weight of a typical passenger vehicle.

Figure 2.4: Free field CPX trailer system for pavement noise measurement

Inside the vehicle, the noise signal picked up by the microphones is not processed in real time, but rather recorded to a laptop computer and analyzed later. It is termed a "free field" system because the microphone area is not enclosed and therefore, there are no reflections or standing wave "modes" to contaminate the noise recording. This system gives very accurate and repeatable measurements, provided that there are no other nearby sources of noise (e.g., traffic, reflections from barriers, etc). Typically tests using this system were performed during very low traffic times (e.g., 3:00 a.m. on weekends) and in carefully selected locations with no nearby roadside objects (e.g., barriers) to cause reflections.

Unfortunately, most places of interest for noise data collection are in high traffic urban areas, and do include nearby barriers or other structures. For this reason, use of free field CPX trailers is very uncommon today.

2.3.2 Enclosed CPX Systems

The next step in the evolution of noise trailers was to add an enclosure around the microphones in an attempt to attenuate extraneous traffic noise and reflections from roadside barriers. Figure 2.5 shows the NCAT enclosed CPX trailer, a system that was widely used for a number of years, and initially was considered for use under this study.

Figure 2.5: Typical enclosed CPX noise measurement trailer

Although this system afforded some reduction of extraneous noise (the exact transmission loss through the thin panels has not been published), it added a new issue of acoustic reflections inside the chamber forming standing waves, and therefore created modes dependant on the enclosure dimensions, which in turn skewed the readings at various frequencies, which in turn depended on where the microphones were placed. A thin layer of Sonex foam was used to line the chamber and reduce reflections, but acoustic foam this thin can only provide a very limited amount of attenuation at the mid frequencies that are of interest in pavement noise measurement.

Figure 2.6 shows a graph prepared by Donavan (source: Dr. Donavan) showing the error introduced by the trailer enclosure. As can be seen in the figure, the maximum error introduced by the closed system and its associated standing waves occurs between 500 Hz and 1600 Hz, with a peak error of about 4-5 dB at 800 Hz. Unfortunately, this is precisely within the area of greatest interest for pavement noise. To move the standing waves down to a lower and less problematic frequency range would require using a much larger microphone enclosure, or much thicker absorptive material, neither of which is practical.

However, it was also noted by Donavan that the overall, A-weighted level measured by the NCAT trailer system was not as seriously affected as the individual frequency band measurements (Figure 2.7). It was therefore concluded in this study, and in [Donavan 2009] that the NCAT system was not optimal for measurements where frequency band was critical.

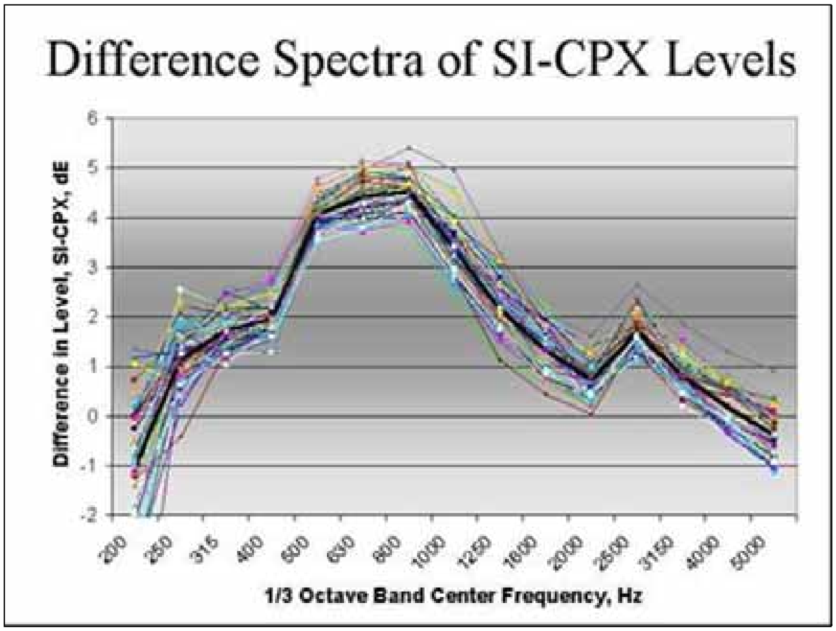

Figure 2.6: Measurement anomalies caused by microphone enclosure, NCAT trailer (source: Dr. Donavan)

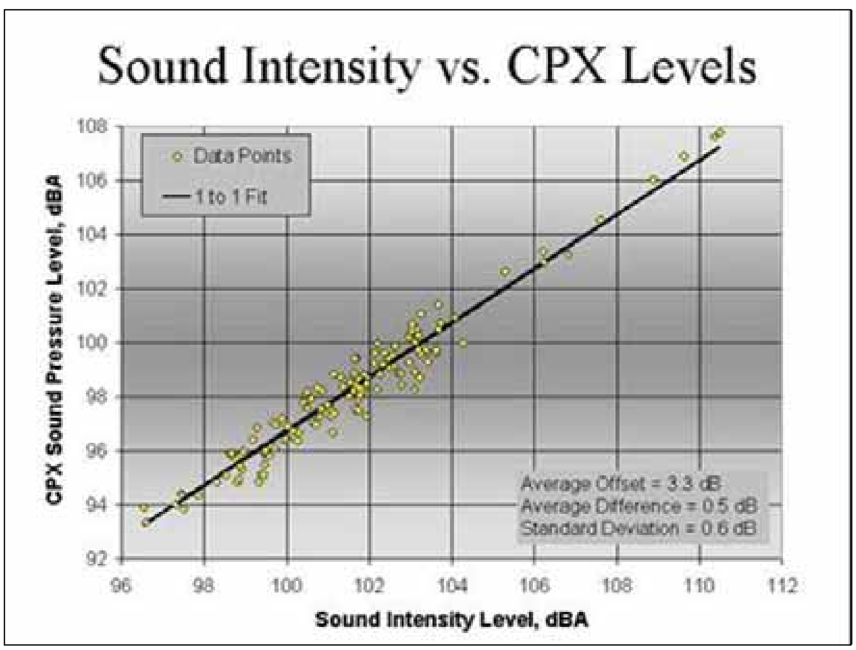

Figure 2.7: Comparison of A-weighted overall noise level between NCAT Trailer and OBSI device (source: Dr. Donavan)

2.3.3 On-Board Sound Intensity (OBSI) Device

In June of 2006, the OBSI device which had been developed by Dr. Paul Donavan of Illingworth & Rodkin, and used extensively by Caltrans, became available to this study. The OBSI system consists of a custom machined jig that bolts to the wheel rim and supports a sound intensity probe at very close proximity to either the front or rear tire/pavement contact point. Because the device is bolted to the wheel, the vertical distance from the pavement does not vary as the suspension oscillates, and because there is a robust bearing connecting the bolted on assembly to the microphone holders, the device does not rotate with the wheels. A slender vertical post affixes to the car body to steady the assembly and provide resistance to the small amount of rotational force generated by friction in the bearing. The OBSI device and vertical stabilizer bar can be seen bolted to the study test vehicle in Figure 2.8. A schematic of the system including the microphones position is shown in Figure 2.9.

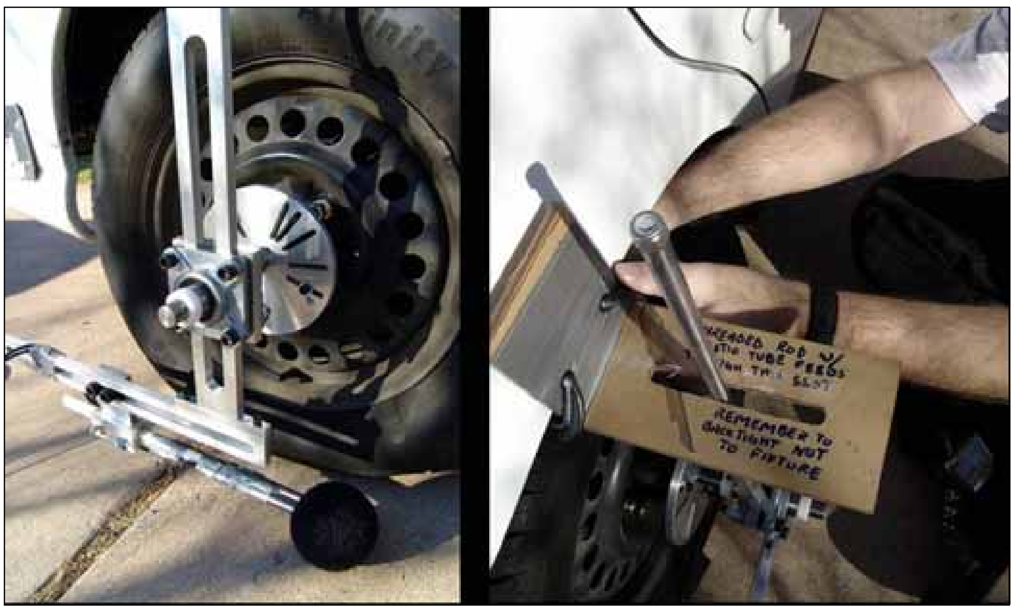

Figure 2.8: OBSI rig attached to Chevy Malibu test vehicle

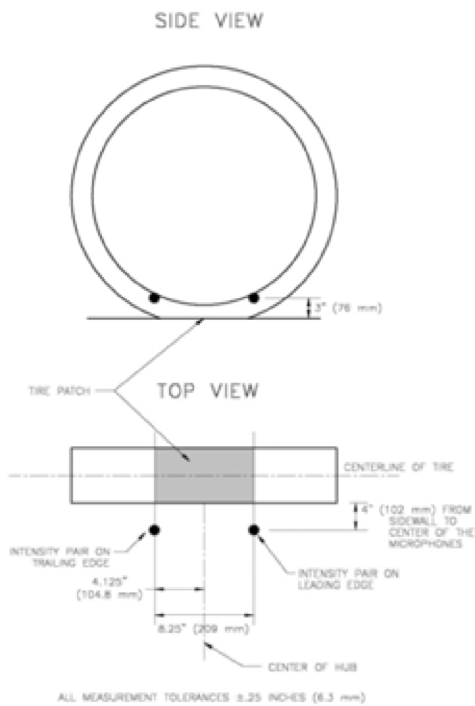

Figure 2.9: OBSI microphone position

Unlike the previous CPX trailer systems, the OBSI data is not only collected in raw form, but also analyzed in real time by an in-vehicle device, the Larson Davis 3000+ Analyzer (Figure 2.10). The analyzer requires a second vehicle passenger to operate, but affords the advantage of analyzing and displaying the sound intensity for each frequency band in real time, allows the operator to listen to the noise being recorded, and stores the processed data inside the analyzer itself. A separate, flash card audio recorder captures the raw output from the LD 3000 for reprocessing later, if needed.

Seeing the data display and hearing the noise during the test is extremely useful, as it allows the operator to immediately detect any anomalies during testing, and flag the data as suspicious for later examination. Often, mechanical problems with the jig or vehicle occur that can be easily detected by the operator and corrected in the field, so that testing can resume.

Figure 2.10: Larson Davis 3000+ sound intensity analyzer

The OBSI system provides many advantages over the CPX trailers previously used, chief among them the ability to almost totally exclude extraneous noise coming from other vehicles or roadside reflections, both of which are a serious problem in urban areas due to heavy traffic and concrete barriers. The system achieves this by using a phase matched pair of measurement microphones precisely spaced so that the analyzer can measure the phase difference and therefore the time offset between a wave front arriving at the outside microphone and the inside microphone less than a millisecond later. This allows the analyzer to discriminate between the noise coming from the tire contact point (desired) and from other sources (undesired). In addition, the unique attachment jig allows the microphones to be safely suspended 70 mm above the pavement surface and 100 mm from the tire contact point, greatly reducing extraneous noise.

Most importantly, the primary reasons that the OBSI system was selected for this study were (1) ability to accurately estimate roadside noise, and (2) compatibility with other agencies measuring road noise.

Figure 2.11 shows work performed by Donavan and Lodico [Donavan 2009] comparing enclosed CPX to OBSI in estimating roadside noise levels. The spectral distortion due to the enclosed trailer can be readily seen in the figure. By contrast, the OBSI system tracks very accurately with the roadside measurement, allowing a 24-dB overall level adjustment for the 7.5-m vs. 100-mm microphone distance (roadside sound meter vs. OBSI).

Table 2.1, also taken from [Donavan 2009], shows the correlation between the two vehicle systems vs. pass-by. Note that both systems do an excellent job of matching pass-by (slope = 0.94 for CPX vs. 0.96 for OBSI) on conventional asphalt pavements, but the OBSI device gives a closer one to one relationship when the porous pavement S4 is included, possibly due to propagation absorption observed for these open-graded pavements.

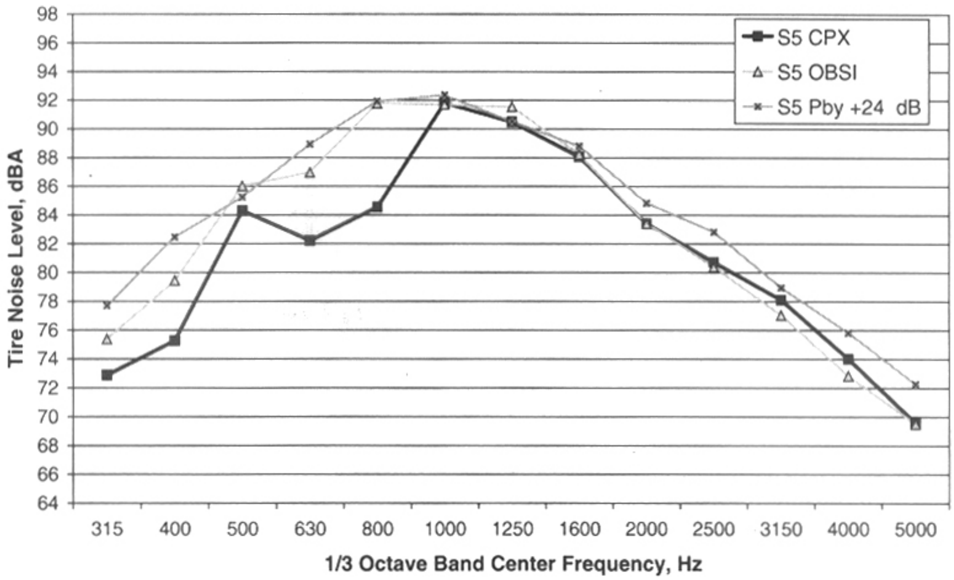

Figure 2.11: Comparison of CPX and OBSI systems to pass-by levels [Donavan 2009]

Table 2.1: Correlation indicators for CPX and OBSI to Pass-by [Donavan 2009]

Metric	Sections S1, S5, W3		Sections S1, S4, S5, W3		All Sites	
	CPX	OBSI	CPX	OBSI	CPX	OBSI
Slope	0.94	0.96	0.87	0.94	0.80	0.87
r^2	0.94	0.95	0.94	0.93	0.79	0.87
Offset, dB	21.9	23.7	21.7	24.0	22.4	24.6
Std Dev, dB	1.2	0.9	1.1	1.1	1.8	1.7
Avg. Dev, dB	1.0	0.7	0.8	0.9	1.4	1.3

Similar comparisons of OBSI to controlled pass-by levels were made during this study. Although only a minority of the sections we tested with the on-board system were also tested using roadside noise meters (primarily due to geometric or safety issues), enough data was gathered to garner confidence that (a) the OBSI system was doing a good job of predicting roadside noise levels, and (b) our results supported Donavan's findings from his more extensive study.

Figure 2.12 shows the result of the CTR testing. Note that the roadside levels observed had a wide range, and that a good linear relationship was found with an average offset of about 25 dBA, very similar to the offset found at the 7.5-m microphone position in the previously mentioned NCHRP study [Donavan 2009]. A more detailed analysis of the correlations found in the CTR data between OBSI and roadside measurements is presented in Section 5.5 of this report. Also note that an experiment using a single probe position at the center of the tire contact patch rather than separate measurements at the leading and trailing edges was conducted on one of the Yoakum sections (Yoakum 5 on IH10), and on one of the Waco sections (SH 6), which are included in the graph. The experiment was also conducted on SH 130 in Austin. More information on this experiment is presented in Section 6.3.3.

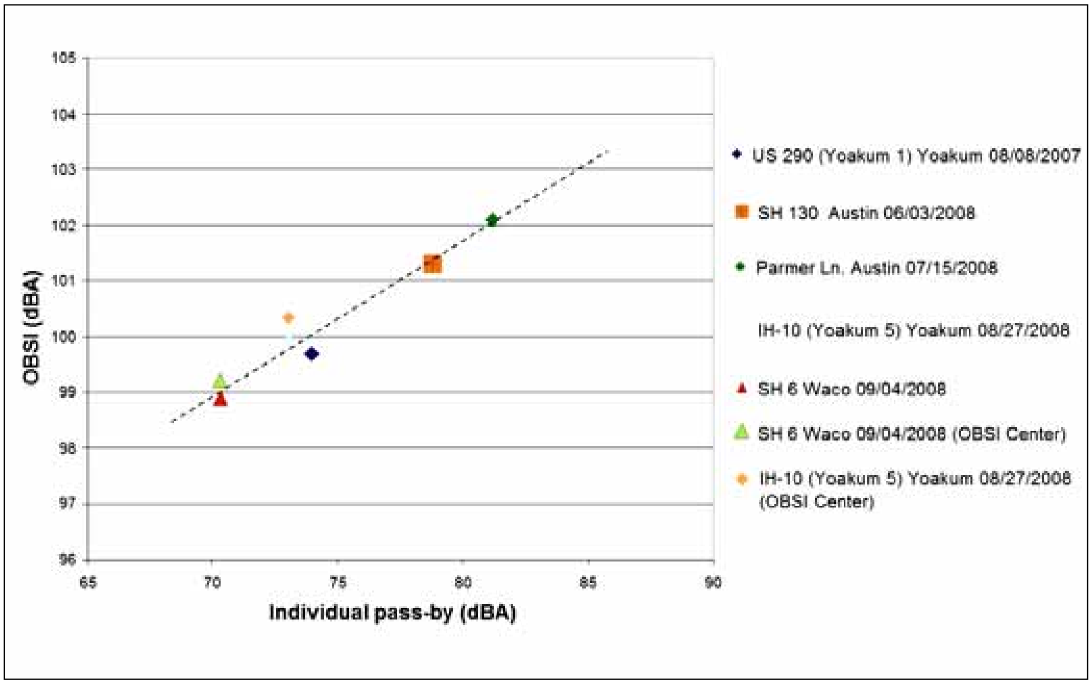

Figure 2.12: Comparison of OBSI levels to pass-by

For all the reasons noted above, the OBSI system was chosen as the primary measurement system used in this study. The OBSI method, at the time of producing this report, is about to become an AASHTO standard, as the draft has just been submitted (AASHTO Designation TP 76-10), which the researchers from this study participated in drafting. A new standard for pass-by testing is also under development at this time.

Because the OBSI method requires testing at the leading tire contact point, then repeating the many replicate tests after setting the device to the trailing contact point, efforts have been made to combine the testing passes, including mounting two pairs of intensity probes simultaneously testing both contact points, or, under this project, testing at the center of the tire/pavement contact patch. These will be discussed further in Chapter 6 and in the recommendations chapter (Chapter 8).

In an experiment to evaluate the amount of engine noise measured by the OBSI device, a set of runs was performed on FM 620 in Austin, in which the vehicle remained parked while the engine RPMs were raised to an equivalent level to that of the OBSI method testing speed (60 mph). The noise measured with the stationary test was then compared to a run on the pavement section at 60 mph demonstrating that the engine noise contribution to the measured level was insignificant compared to the overall tire/pavement noise (Figure 2.13).

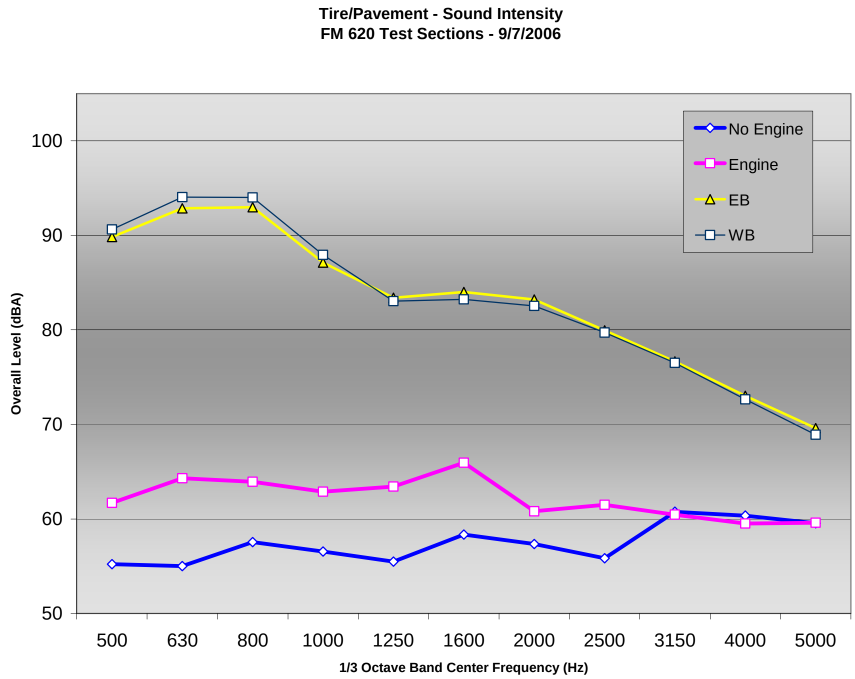

Figure 2.13: Engine noise contribution to OBSI overall noise level measurement

2.4 Impedance Tube Absorption Testing

The third and final system used for testing in this study was a standard impedance tube, a test device commonly used for testing either the acoustic absorption or transmission loss of a material specimen. The tube used in this study was designed and built under TxDOT project 7-2957, documented in [DeMoss 1999]. It consists of a 40-in. long aluminum tube with 4-in. inside diameter designed to accept 4-in.-diameter pavement cores commonly available at the time it was made. Three holes have been machined into the side of the tube to allow two precision microphones to be inserted. A full range speaker is mounted at one end of the tube to generate broadband noise, and a specimen holder is arranged at the other end to hold the core or mold under test (Figure 2.14).

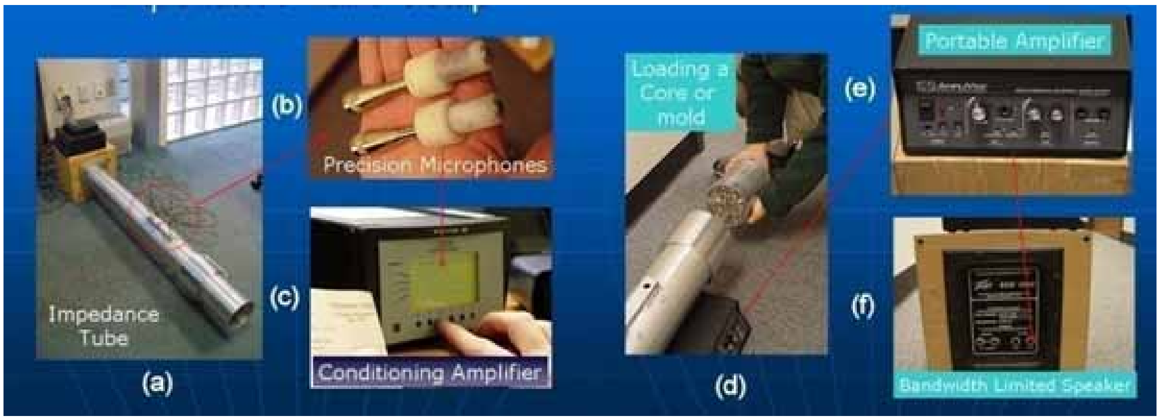

Figure 2.14: Impedance tube testing system for pavement cores

The principle behind the impedance tube is that standing waves are formed in the tube, and the absorption coefficient at any desired frequency for the material under test is determined using the cross spectral density observed at the two inserted microphones. From this, the reflection coefficient can be determined and the absorption coefficient is simply defined as 1— the square of the reflection coefficient. The equations used are:

$$R = \frac{H_{12} - e^{-jks}}{e^{+jks} - H_{12}},$$

where:
R = pressure reflection coefficient
S = microphone separation distance
H_{12} is the transfer function defined as

$$H_{12} = \frac{S_{12}}{S_{11}}.$$

where:
S_{12} = cross spectral density between the two microphones
S_{11} = auto spectral density of the microphone nearer the sound source

Under this study, superior analog to digital converters were purchased (compared to those available to the 7-2957 project researchers), and new analysis software was developed with the assistance of a consultant audio engineer. Consequently, the ease of use for the system and the accuracy of the results have been greatly improved. The upper frequency limit of the tube remains at 1950 Hz as determined by the 4-in. inside diameter.

Using the impedance tube is very simple. The tube is first calibrated using an open cell (acoustic) foam target. A 30-second burst of bandwidth limited pink noise is played through the tube and the output from the microphones recorded digitally (a 24-bit, 95-kHz stereo flash memory recorder was used in this study). The two microphones are swapped and the process is repeated, resulting in two sound files that form the calibration data for the tube. Performing this process before each set of tests compensates for any slight phase or amplitude difference between the two microphones, as well as any extrinsic factors such as temperature and humidity.

After the calibration data has been obtained and stored, specimens can be prepared and tested.

A 4-in. molded or cored specimen is placed in the receiver (Figure 2.14d) and loaded into the impedance tube. To best simulate a real pavement, the core is backed up by material similar to what would be found under the thin PFC layer, i.e., generally a thicker section of dense-graded asphalt. The same pink noise source is then played into the tube, the noise reflects off the composite pavement sample instead of the (very) absorbent acoustic foam calibrator, and the results are recorded to a digital file, as with the calibration data.

The new analysis software is then used to post process the stored data; it is not capable of processing the date in real time, nor is that needed. Figure 2.15 shows the initial data entry screen, where file names, ambient conditions and notes are entered, to be saved in the output Excel spreadsheet.

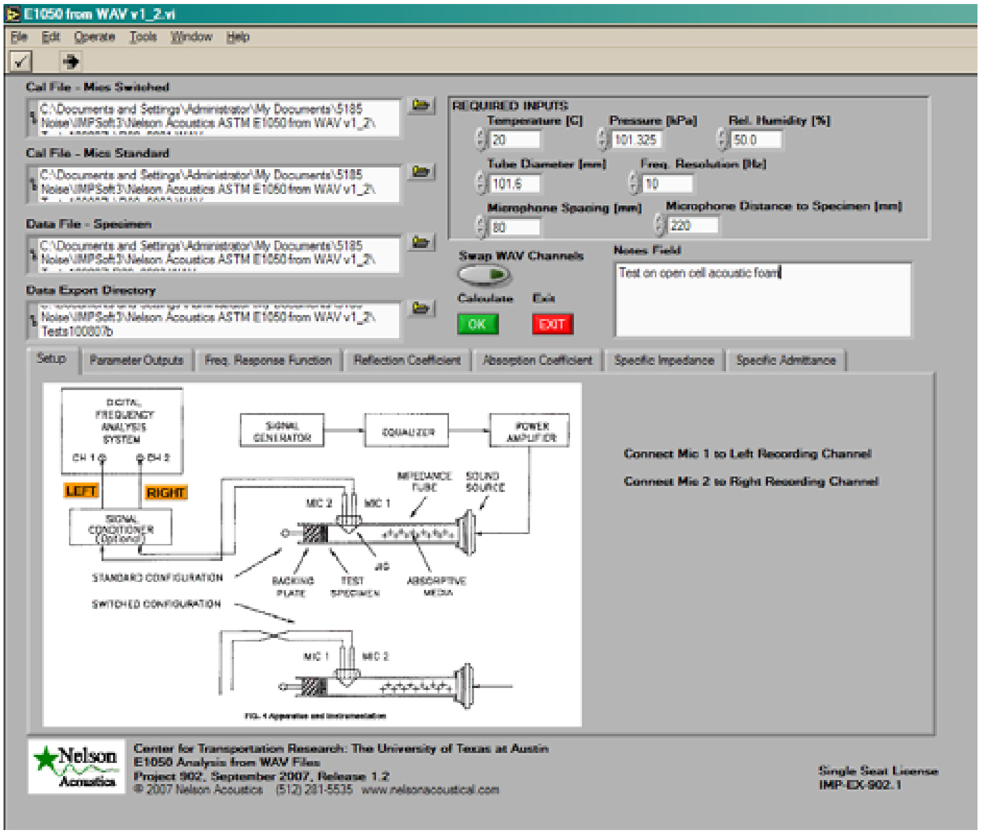

Figure 2.15: Impedance tube analysis software—data entry screen

As a reasonableness check, Figure 2.16 shows the results of testing a sample of acoustic foam (above) and the results for a polished aluminum cylinder (bottom); the absorption of the foam is very high, while the absorption of the plug is very low.

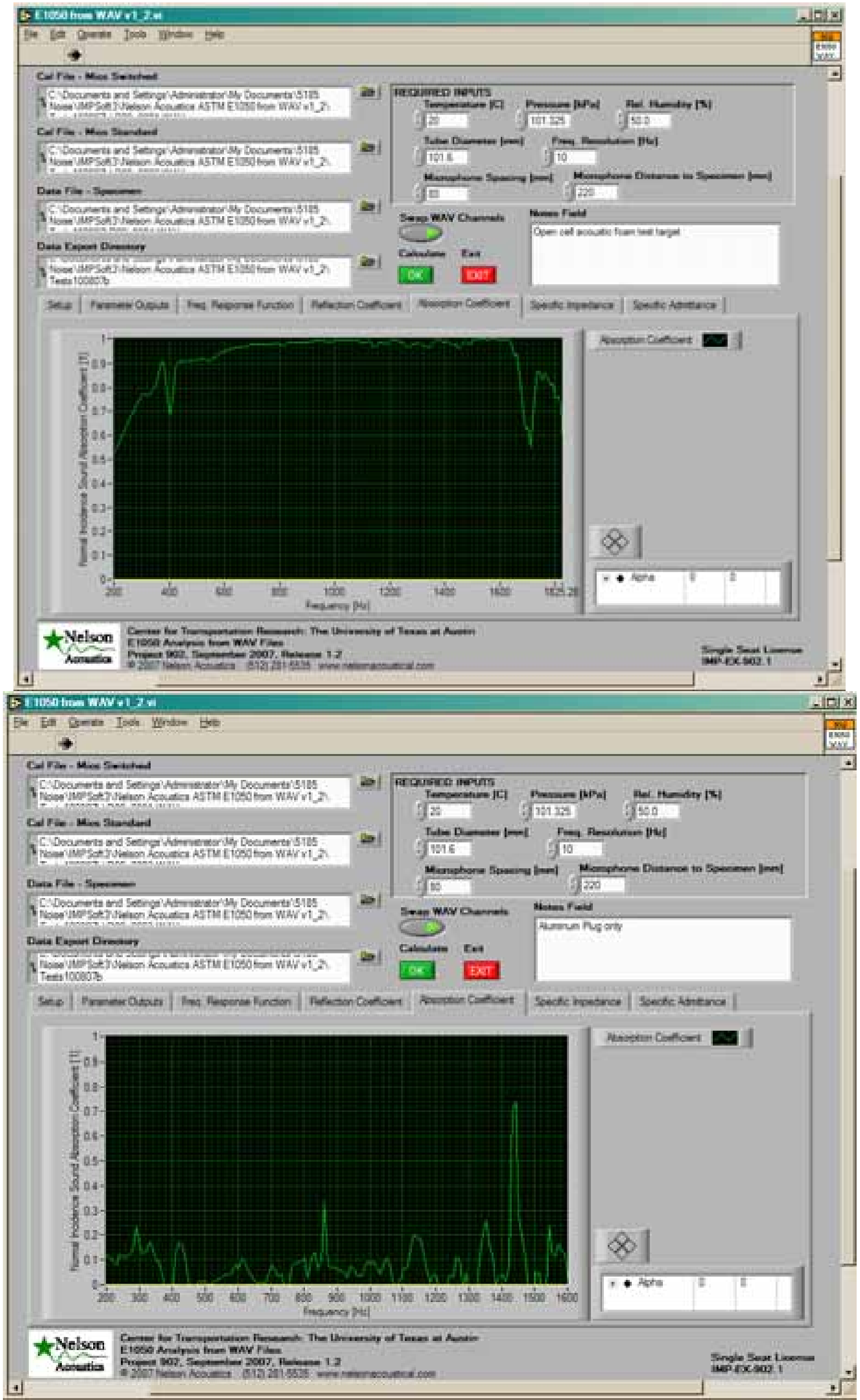

Figure 2.16: Impedance tube results for (a) foam and (b) metal plug

The results for the pavement specimens tested are more interesting. Figure 2.17 shows the absorption spectra for a uniformly-tined portland cement concrete (PCC) specimen (top) and for a dense-graded asphalt specimen (bottom). Note that the concrete is almost completely reflective, whereas the ACP absorbs well around 300 Hz.

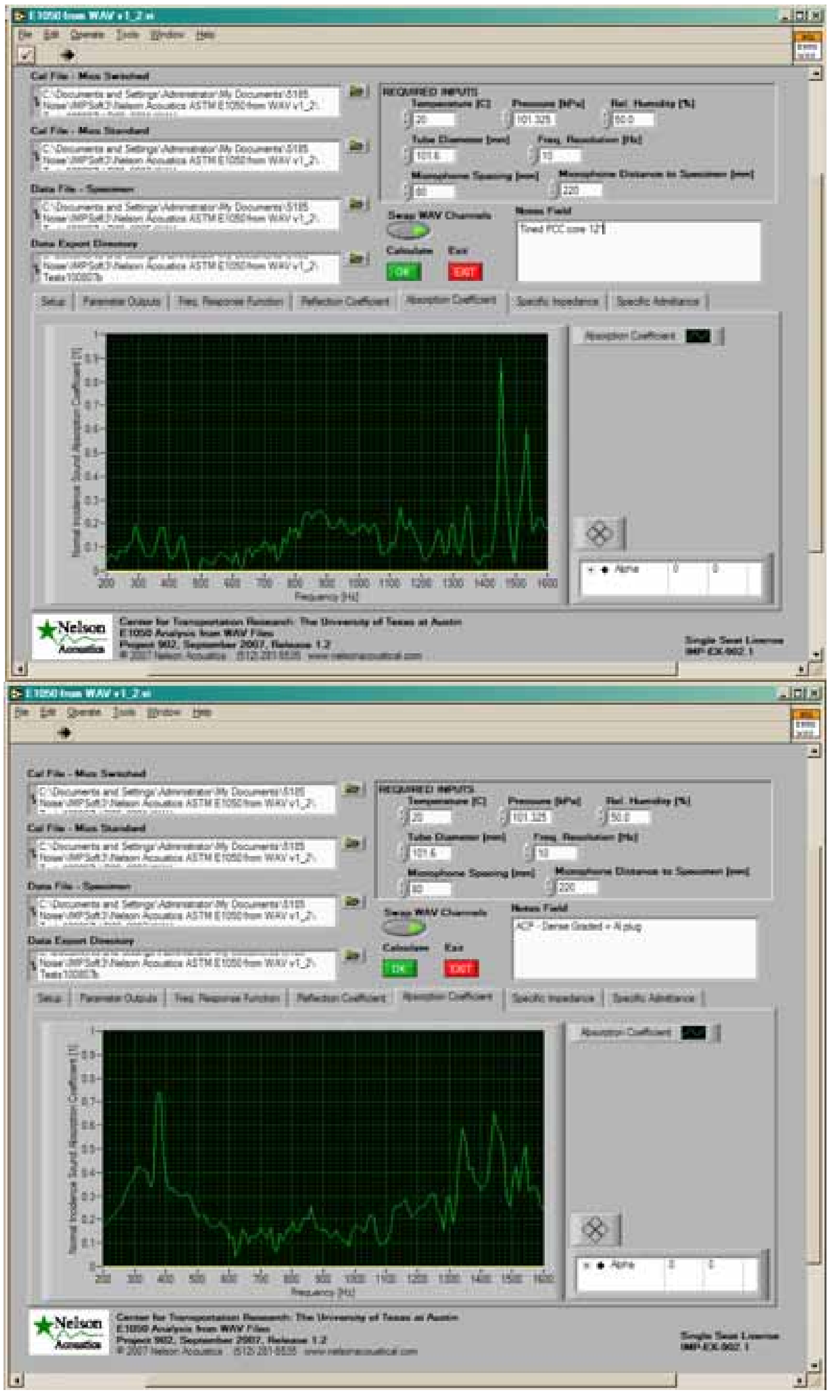

Figure 2.17: Absorption results for PCC (top) and ACP (bottom)

Figure 2.18 shows the result from two PFC samples, the top being a lab mold, and the bottom being a thin core from an overlay. The thicker molded specimen shows good broadband absorption, and the core, a strong absorption spike around 1 kHz.

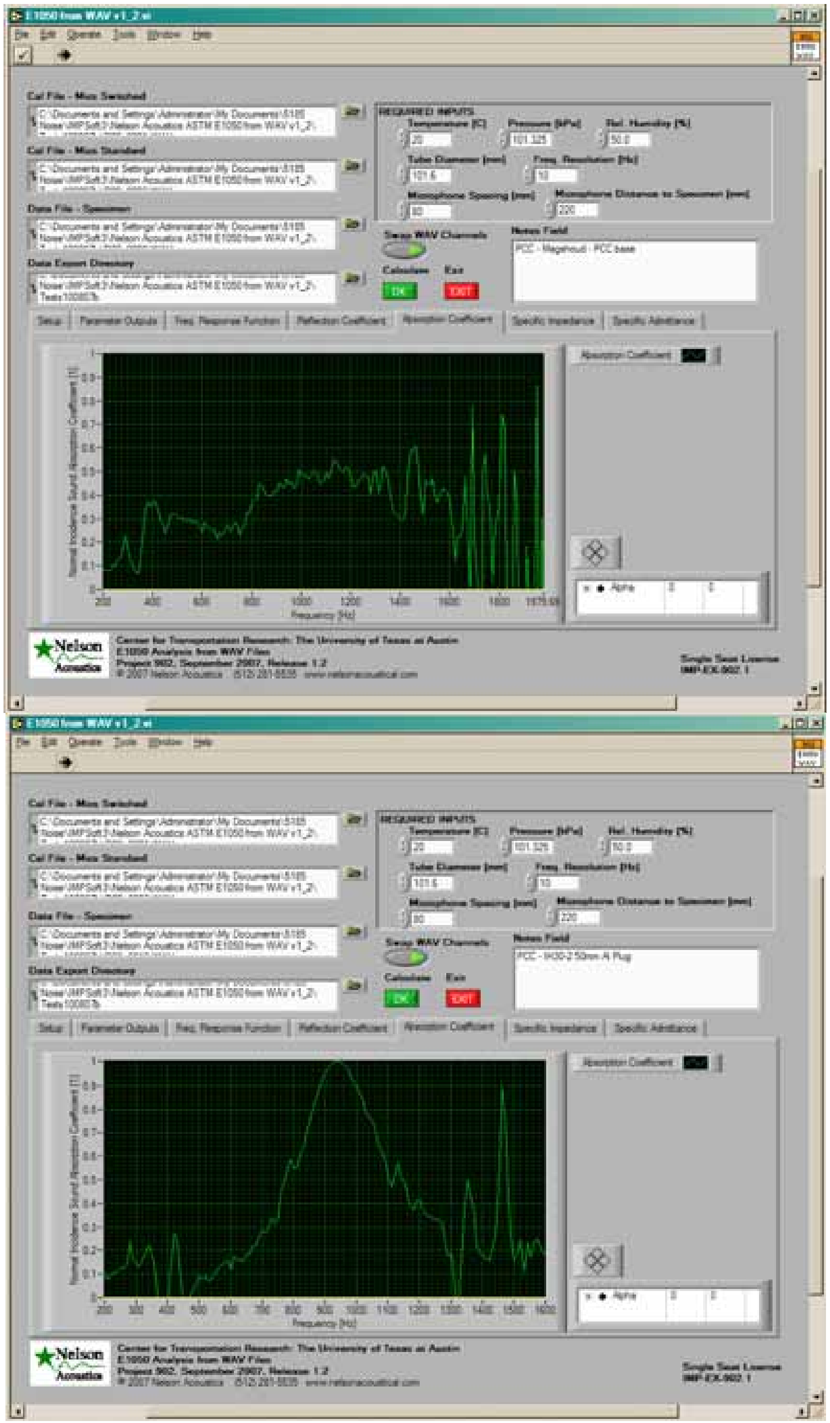

Figure 2.18: Absorption for a 100-mm PFC mold (top) and a 50-mm PFC core

The above example results serve to demonstrate how powerful a tool the impedance tube may prove to be for measuring the absorptive properties of permeable pavements. Although absorption is not the sole characteristic determining tire noise on PFC pavements, it is a significant component. Additionally, the absorption spectra constitute a key component of propagation absorption, which the recent NCHRP 1-44 study [Donavan 2009] found very significant in determining roadside noise.

Although the impedance tube is presented above as strictly a tool for destructive measurements of pavement (cores must be taken), it can also be used to test molded specimens in order to evaluate candidate mix designs for noise performance before constructing the sections. Additionally, as shown in Figure 2.19, all the impedance tube system components are field-portable (battery-powered) and can be used (as were used in Project 7-2957) with a custom stand to be placed on porous pavements to check absorption characteristics in situ. This latter use may even prove to be a means to estimate loss of permeability over time due to clogging or compaction, as air void content and connectivity of air voids can reasonably be assumed to be correlated to acoustic absorption.

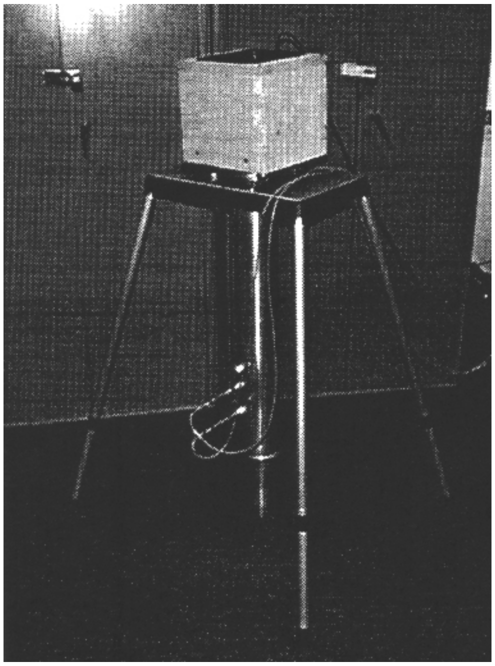

Figure 2.19: Vertical mounting of the impedance tube for in situ field measurements

Chapter 3. Noise Rodeos

3.1 Background

When performing measurements of any kind, variability is a key element that should not be overlooked. Noise measurements can be influenced by many factors, such as equipment, environment, pavement characteristics, and data collection procedures all of which are sources of variability.

Comparisons of results from different times, measured by different persons, using different equipment (vehicles, tires, microphones), and processed and analyzed in different ways present a challenge, as each component contributes its own variability. Researchers from different agencies, states, and countries have attempted to compare their results, as the procedures and technology for measuring noise become more standardized, and as evaluating noise characteristics of pavements becomes a more widespread practice all over the world. However, the variability involved in the measurements might make these efforts meaningless.

On the national level, regarding OBSI testing, there have been various gatherings involving several agencies that meet at certain location, bringing their respective equipment and vehicles, to test the same pavement sections and compare results. These have been named "noise rodeos." CTR has been involved in some of such efforts.

Before participating in any one of these rodeos involving other agencies, CTR and TxDOT did some comparisons with their equipment, given that all the OBSI gear and vehicles used for testing by CTR and TxDOT are virtually the same, and the data processing is done in identical way. An adequate highway location with good characteristics for identifying suitable test sections was selected in the Austin area. 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 3.1.

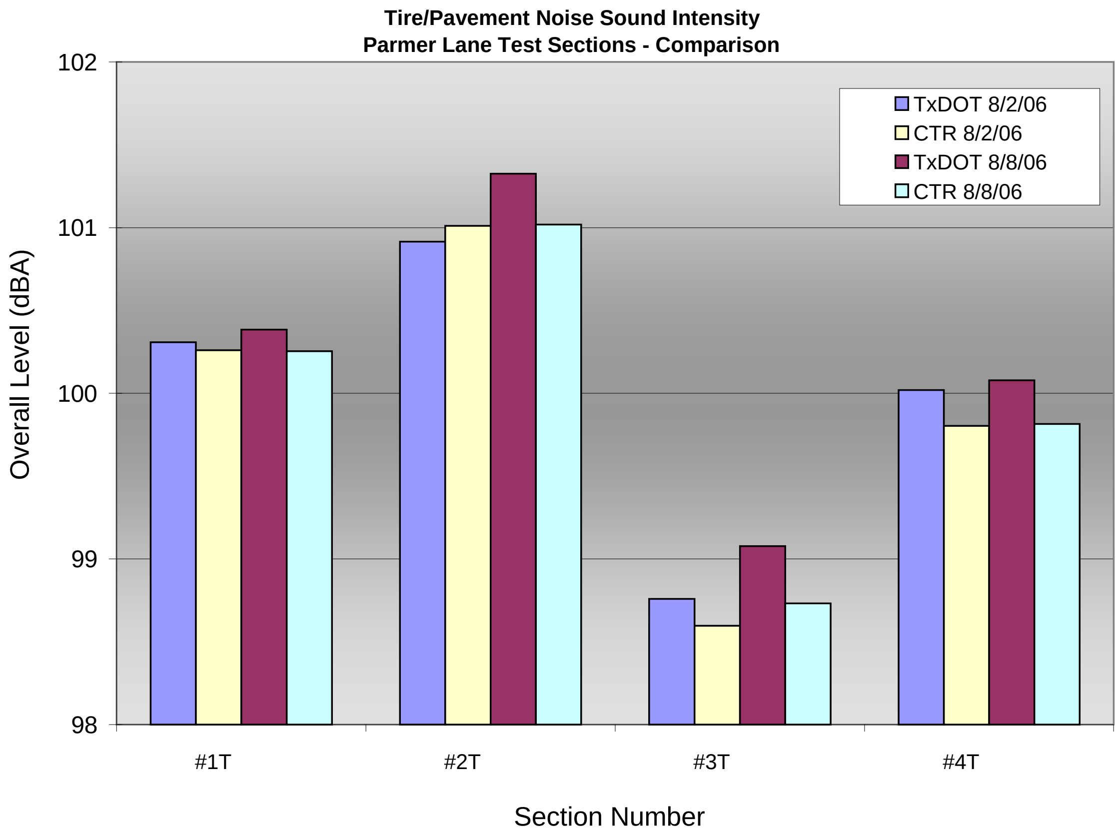

Figure 3.1: Comparison of equipment and vehicle between CTR and TxDOT on Parmer Ln.

Even though the TxDOT data from August 8, 2006 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 3.2) also present little variability among the dates and the vehicles, and the patterns of the graphs are the same in every case, which was an encouraging indication that both sets of equipment and vehicles could be considered equivalent for every aspect needed in this research. The information gathered during the month of August 2006 was the basis for CTR's and TxDOT participation in subsequent, more comprehensive efforts oriented toward OBSI results comparisons.

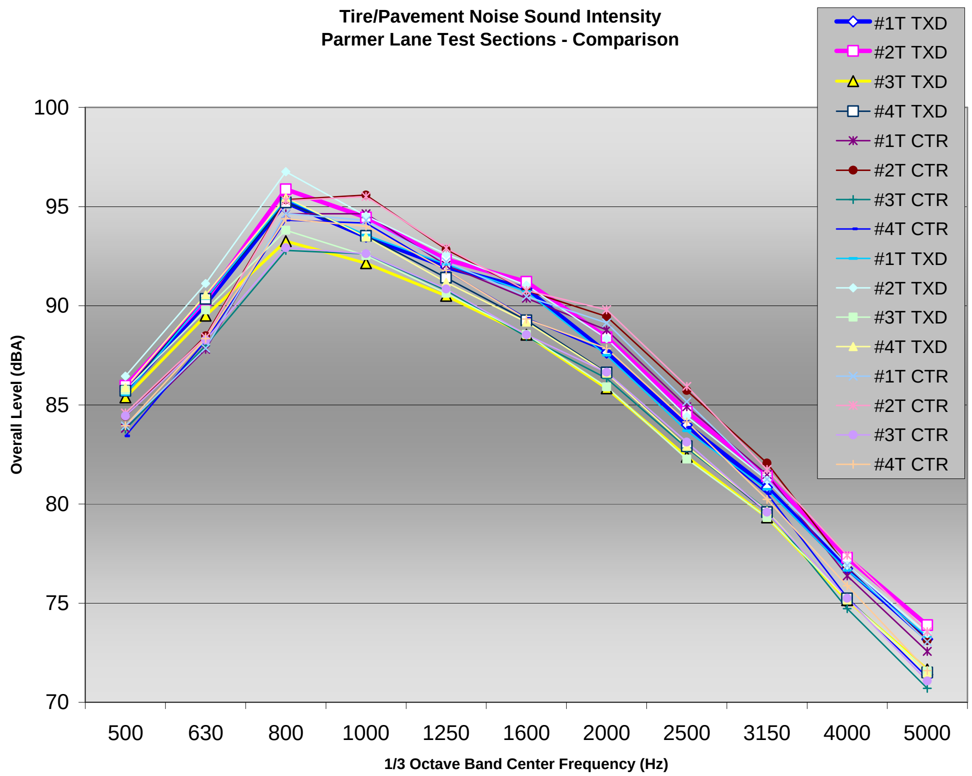

Figure 3.2: Sound spectra for Parmer Ln. tests comparing TxDOT and CTR equipment

3.2 First Rodeo: September 2007

The first Texas Rodeo took place on September 6th and 7th, 2007. The objective was to compare and validate tire/pavement noise measurements using the OBSI method, on different types of pavements, with different vehicles and different equipment. The participants were TxDOT, Transtec, a local consulting firm, and CTR. Other out-of-state agencies were invited, but declined. John Wirth, of TxDOT, organized this rodeo.

Three groups of sections in the Austin area were selected for these tests, corresponding to the three common pavement types targeted in this research:

- FM 734 (Parmer Ln.)—Conventional, dense-graded AC (DGAC)
- US 183—New and old CRCP
- IH-35—PFC

A map of the test sites for this first rodeo is shown in Figure 3.3.

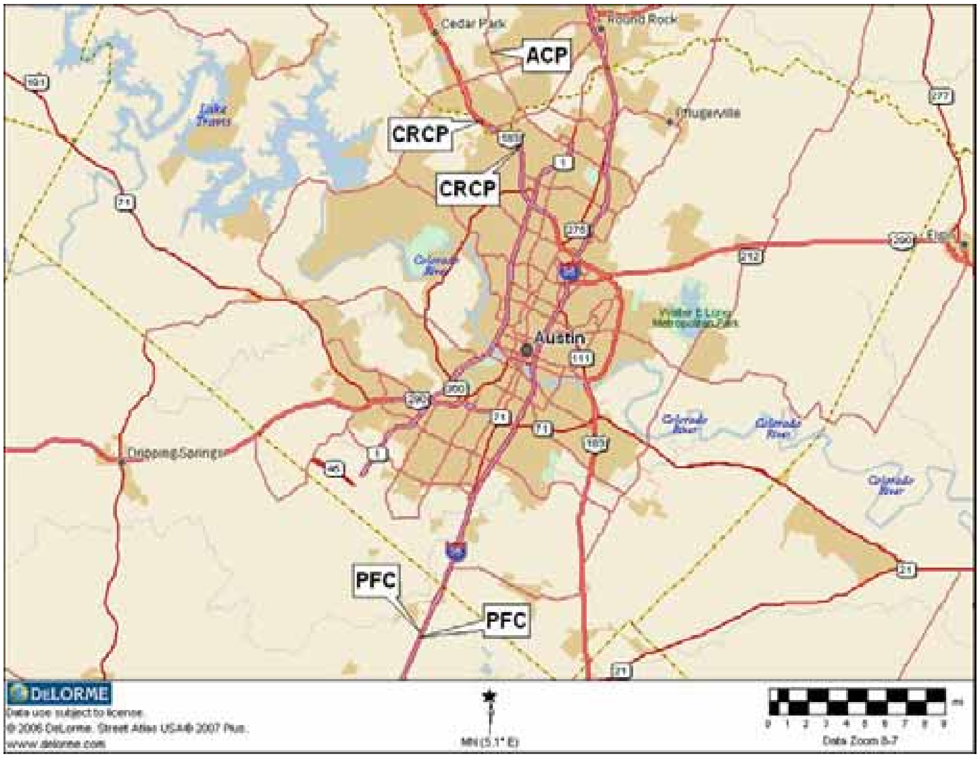

Figure 3.3: Test sites for the first Texas Rodeo

3.2.2 Parmer Lane

The same group of four subsections that were previously used by TxDOT and CTR in the first round of OBSI results comparisons in September 2006 was tested on this occasion during the rodeo (Figure 3.4). The use of this group of sections was convenient, given the familiarity of the researchers with them, the fact that they were already marked, and further comparisons could be performed on the same site.

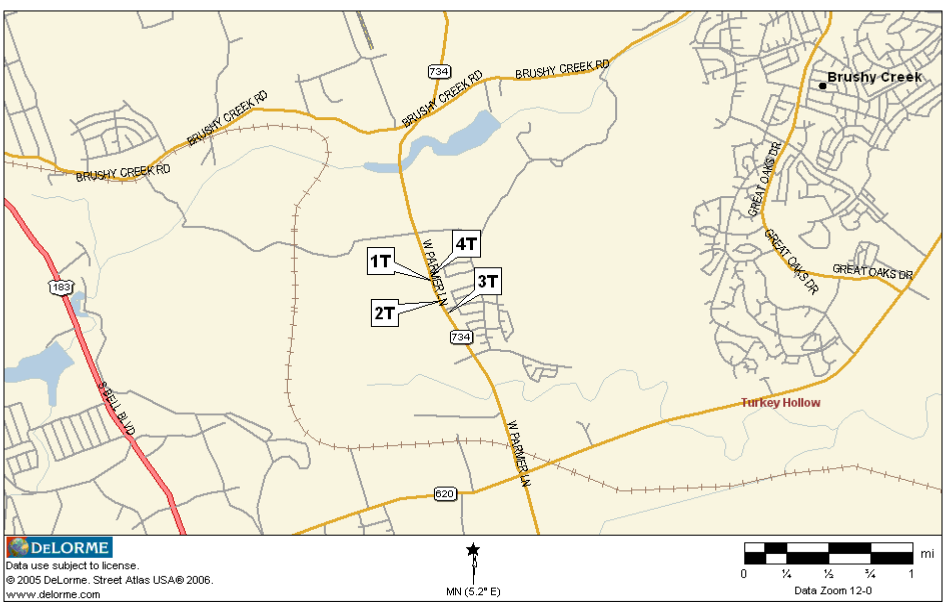

Figure 3.4: Parmer Ln. test sections

Figure 3.5 shows the results from the Parmer Ln. sections.

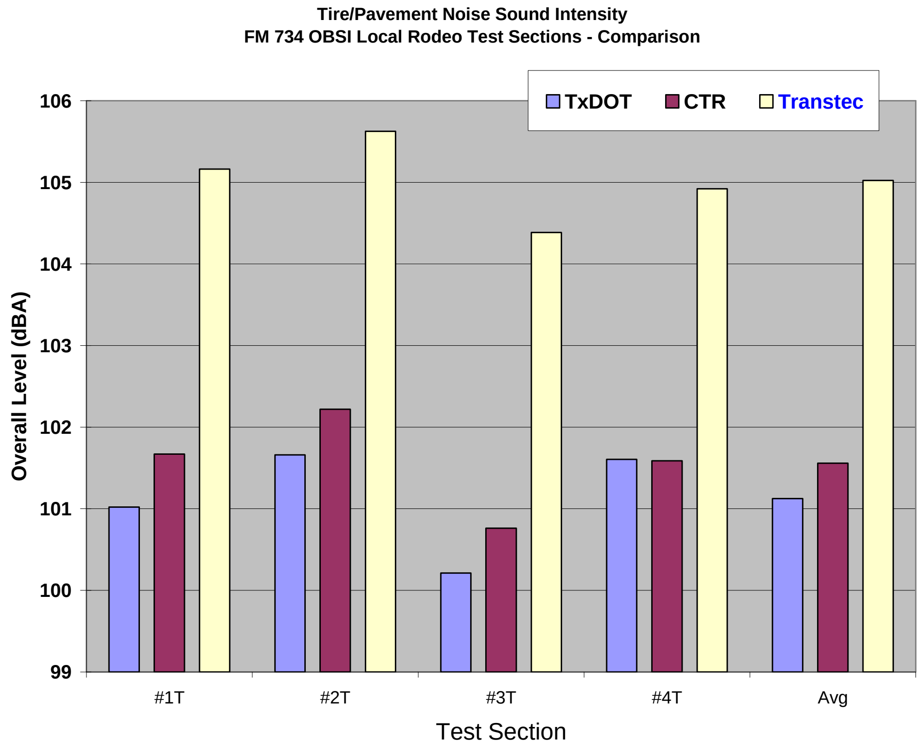

Figure 3.5: Parmer Ln. overall rodeo results

3.2.3 US 183

Two groups of sections were identified on US 183, with concrete pavements of different ages: north of McNeil Dr., subsections 5, 6, 7, 8 and 9, which correspond to newer CRCP were marked, and south of McNeil Dr., subsections 10, 11, 12, 13, and 14, were identified, which are the older pavements. Both groups are uniformly, transversely tined pavements (Figure 3.6).

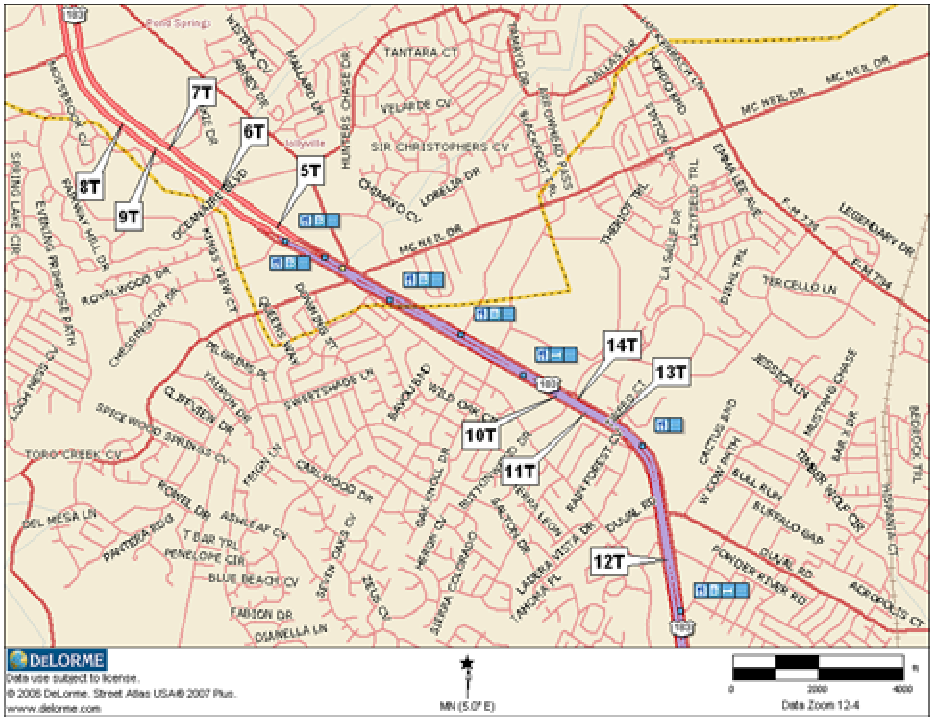

Figure 3.6: CRCP sections on US 183

The results of the newer and older pavements are shown in Figures 3.7 and 3.8, respectively.

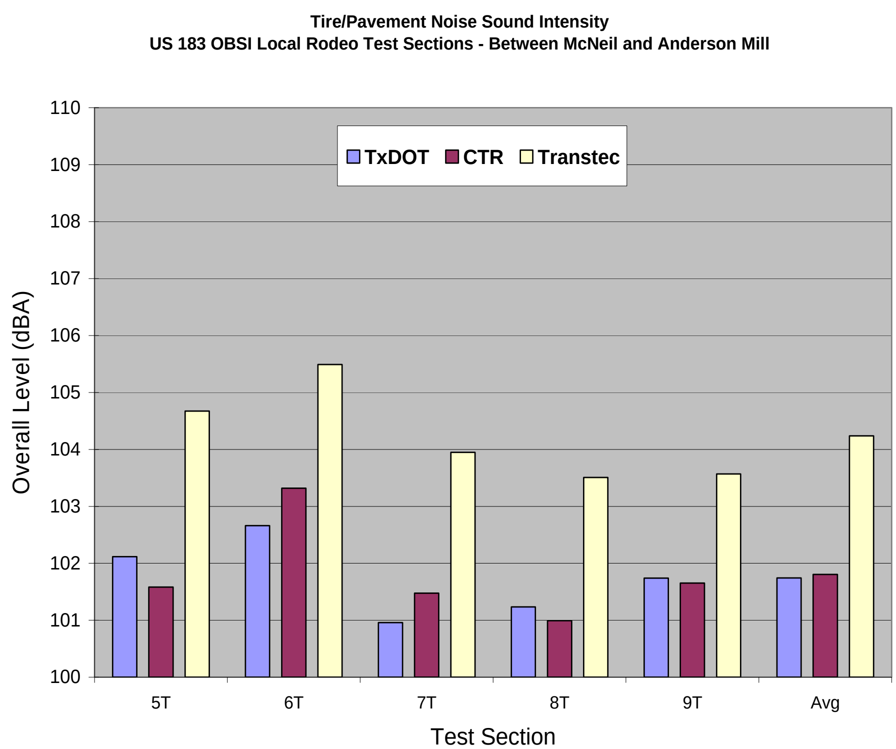

Figure 3.7: US 183 results—newer CRCP

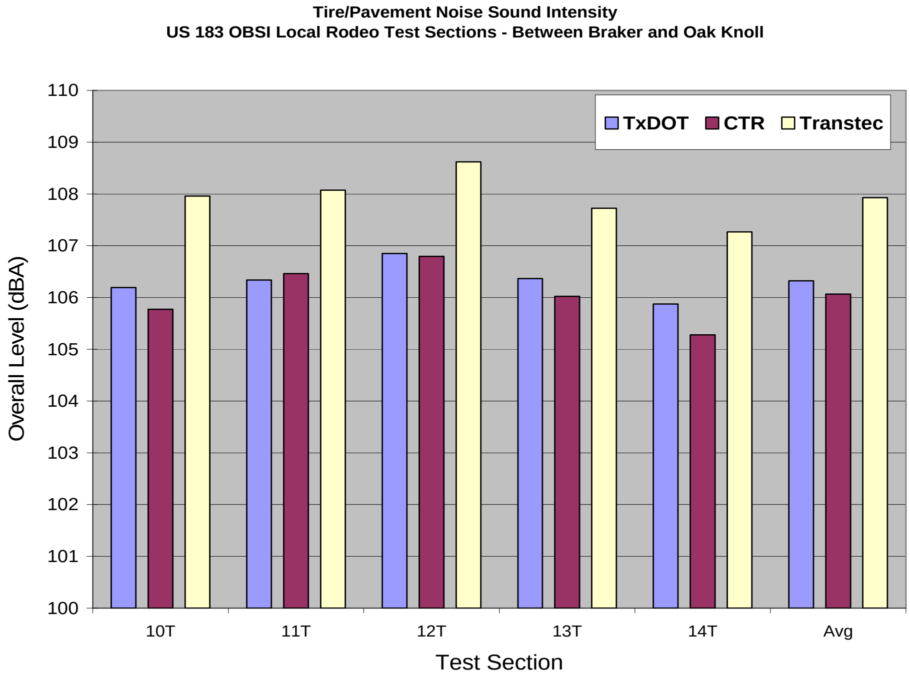

Figure 3.8: US 183 results—older CRCP

3.2.4 IH-35

The IH-35 sections chosen for the rodeo are located in Buda, south of Austin, in a stretch between Loop 4 and Yarrington Rd. Two segments were tested, each paved with a different type of PFC: the northbound direction includes subsections 11, 12 and 13, corresponding to PFC 76-22TR, and the southbound segment is comprised of subsections 7, 8, 9, and 10, consisting of PFC 76-22S (Figure 3.9).

Figure 3.9: IH-35 sections in Buda

The overall results are show in Figure 3.10.

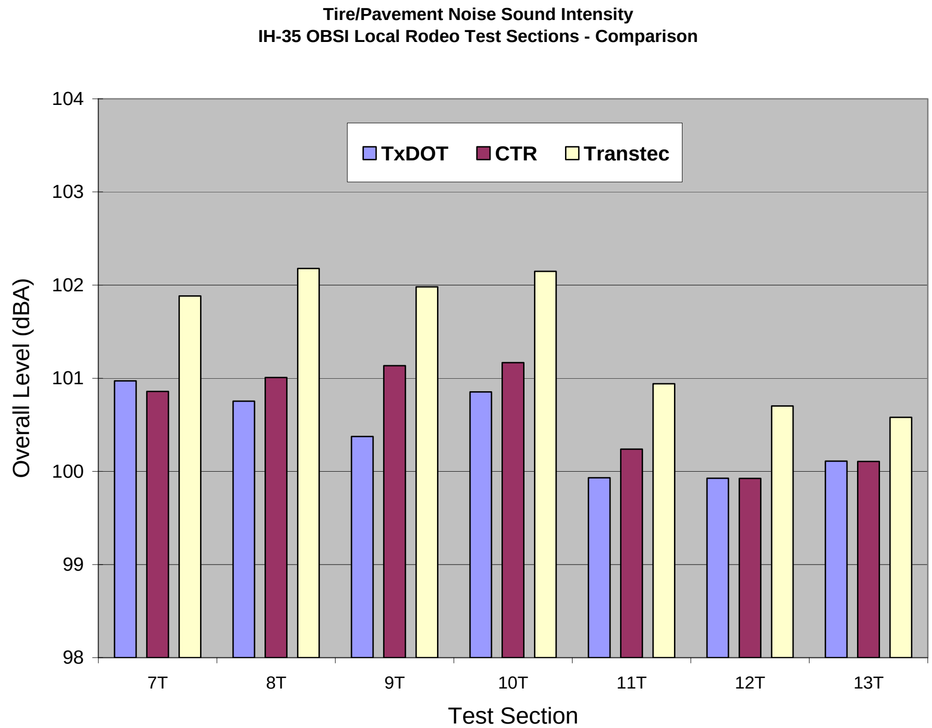

Figure 3.10: IH35 rodeo results

3.2.5 Summary of First Rodeo

The average measurements obtained by each agency, by test section are shown in Table 3.2.

Table 3.2: Average measurements by agency, by section (dBA)

Section	FM 734 DGAC	US 183 New CRCP	US 183 Old CRCP	IH-35 SB PFC	IH-35 NB PFC
TxDOT	101.1	101.7	106.3	100.7	100.0
CTR	101.6	101.8	106.1	101.0	100.1
Transtec	105.0	104.2	107.9	102.0	100.7

While TxDOT and CTR results were very similar, the results of these agencies relative to Transtec's present much larger differences, and these occurred consistently in all the sections measured. The largest differential occurred in the FM 734 results, the dense-graded AC, in which Transtec was almost 4 dBA higher than its counterparts. Transtec's averages were higher in all cases than those of TxDOT and CTR.

Between CTR and TxDOT, the largest differential happened also on FM 734, but it is quite a small amount: 0.4 dBA, which underscores how similar the results were.

The higher noise levels obtained by Transtec might be explained by differences in their OBSI equipment, vehicle, tire, and data processing. Figures 3.11 and 3.12 compare the OBSI equipment utilized by CTR and TxDOT with the Transtec rig.

Figure 3.11: CTR and TxDOT OBSI fixture

Figure 3.12: Transtec OBSI fixture

The first obvious difference is that TxDOT and CTR use a single-probe OBSI rig, while Transtec's is dual-probe, meaning that it is capable of measuring the leading and trailing edges of the tire/pavement contact patch simultaneously. The second difference is that the Transtec fixture is attached to the suspension of the vehicle, and therefore, the microphones move with it, and this causes that the distance of the microphones to the ground is not consistent throughout the runs. Even in Figure 3.12 with the vehicle stationary, it appears that the left-side probe microphones are closer to the ground than the microphones on the right side. Also, the microphones are set at an angle from the ground instead of being completely horizontal. Finally, the position of the four microphones as held by the rig might cause wind issues affecting the measured noise. Besides the rig, CTR and Transtec used a 15-in. Uniroyal Tiger Paw AWP test tire, mounted on their 2001 Chevrolet Malibu vehicles, as opposed to Transtec's 16-in. Standard Reference Test Tire mounted on their Buick test vehicle. The tread pattern for the test tires is shown in Figure 3.13.

Regarding the data analysis, Transtec records its data and post-processes it, while TxDOT and CTR process it in real-time with a Larson Davis analyzer (see Figure 2.10). Transtec utilizes proprietary software to analyze their noise data. All these differences may account for the discrepancies in results obtained in this rodeo. The inconclusive results led the researchers to plan a future rodeo, with more homogeneous procedures among the participants.

Figure 3.13: Uniroyal Tiger Paw AWP(left) and SRTT (right)

3.3 Rodeo Follow-up

In early 2008, TxDOT procured new 16-in. SRTTs for their Malibu vehicle. This offered the opportunity to repeat some of the rodeo measurements with their new tires and find out if the results could resemble Transtec's from the first rodeo, while the CTR vehicle was still equipped with the AWP tires used in the first rodeo. On March 28th 2008, TxDOT and CTR repeated some of their tests from the rodeo. For this one-day rodeo follow-up, only the sites of Parmer Ln. and US 183 were tested. The results of the Parmer Ln. sections are summarized in Figure 3.14, in which the values from the first rodeo are also plotted for comparison. In this graph it can be seen that a new section was added to the tests, denominated #5T. This section was intended as a substitute for section #4T, because section #4T is very close to a traffic light, which makes it difficult to test at 60 mph, even though still a few runs were performed on it by TxDOT.

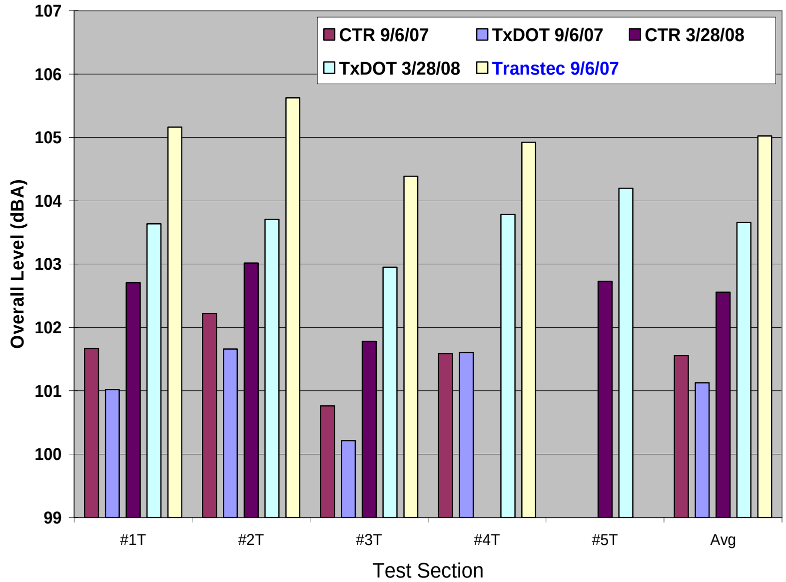

Figure 3.14: Rodeo Follow-up and First Rodeo results, Parmer Ln.

The results shown in Figure 3.14 indicate that the measurements obtained by TxDOT in the follow-up are higher than CTR's, and get slightly closer to Transtec's results from the first rodeo. This suggests that part of the discrepancies with Transtec's higher results from that occasion could be attributed to the tire. The hypothesis that would complement this assumption is that the other part of the difference is due to their particular rig and vehicle. CTR's results were higher this time when compared with CTR measurements during the first rodeo, and this could be explained by the lower temperatures occurring in March compared to those from September.

When looking at the spectra (Figure 3.15), it can be seen that the curves stayed reasonably consistent, and that the new SRTTs appear to produce similar curves as the Tiger Paw tires, only slightly higher. In this graph, only the results of one subsection (#3T) are presented for simplicity and clarity, but the remaining sections produced similar outputs.

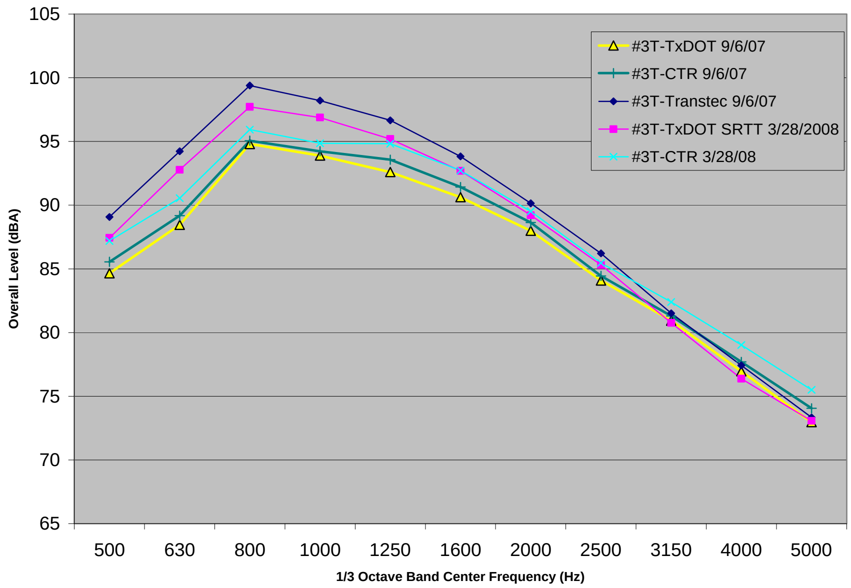

Figure 3.15: Spectral analysis for Parmer Ln., Section #3T

The results of the US 183 test sections are presented in Figure 3.16, which also includes the comparison with the First Rodeo results.

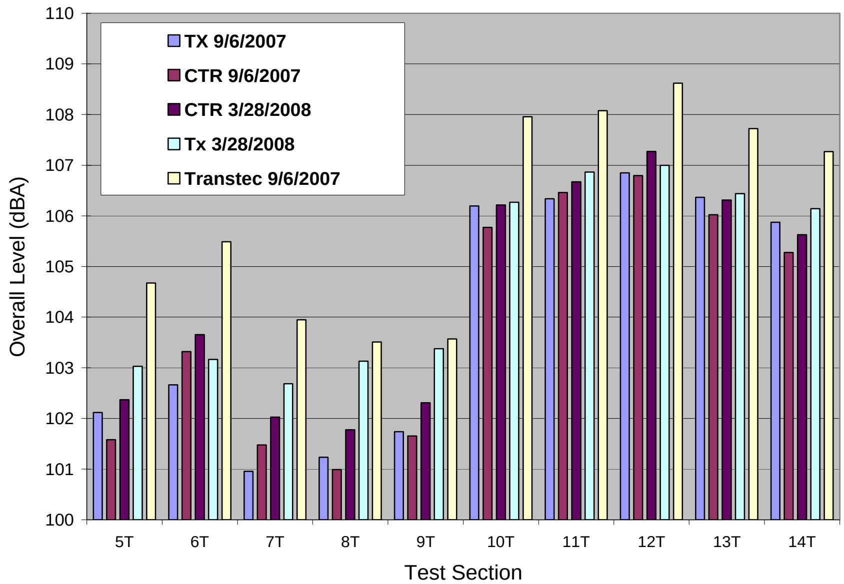

Figure 3.16: Rodeo Follow-up and First Rodeo results, US 183

Besides the OBSI tests, some individual pass-by tests were run at the Parmer Ln. site, with the purpose of finding out if differences in loudness could be attributed solely to the tires, given that the vehicles are virtually identical. In these tests, each vehicle, driven at 60 mph, passed by a microphone, set on a tripod 7.5 m away from the center of the outside lane and 1.2 m above the pavement surface level, while no other vehicles passed by the area surrounding the sound meter. The results of these runs are shown in Table 3.2.

Table 3.3: Individual Pass-By Tests on Parmer Ln.

Vehicle / Run	TxDOT	CTR
1	79.9	82.3
2	80.7	82.4
3	81.5	82.7
4	80.0	81.9
Average	80.5	82.3
Difference	1.8	

The results indicate that the passes by the CTR vehicle with the AWP tires were louder than those of the TxDOT car with the SRTTs. This was not expected, as during the rodeo, it was the car equipped with the SRTTs (Transtec's) that produced the louder sound levels.

3.4 Second Rodeo: July 2008

TxDOT, Transtec, and CTR participated in the Second Rodeo, conducted on July 15, 2008, with the purpose of repeating some of the measurements performed on September 6th and 7th, 2007, when the first rodeo took place.

In this rodeo, just two of the roadways from the first rodeo were tested: Parmer Ln., a dense-graded AC pavement, and US Highway 183, a rigid pavement section. The sections from the first rodeo that were eliminated in this case were the IH-35 sections south of Austin, in the interest of time, to be able to perform all the testing within one day. Figure 3.17 shows the three test vehicles being prepared for testing, prior to the start of the Second Rodeo, near the US 183 test sections.

Figure 3.17: CTR, TxDOT and Transtec (L to R) vehicles before starting the Second Rodeo

Transtec acquired a new OBSI rig for their vehicle in preparation for this rodeo. A picture of their new rig is shown in Figure 3.18. This new equipment is a dual probe vertical rig which, unlike the previous one, does not attach to the suspension of the car, but to the tire, keeping the distances from the microphones to the tire consistent.

Figure 3.18: Transtec new OBSI rig for the Second Rodeo

3.4.2 Parmer Lane

Four sections were originally identified by John Wirth on the Parmer Ln. segment, which served initially to compare TxDOT's and CTR's equipment during various experimental runs in August 2006. Those four sections were also utilized in the first rodeo, back in September 2007. As mentioned before, section #4T has been replaced by an additional section (named #5T) since the March 2008 measurements, because of the proximity of section #4T to a traffic light, which makes it difficult to test at 60 mph. Figure 3.19 presents CTR's results from the two rodeos, the March 2008 follow-up, and the August 2006 experiment.

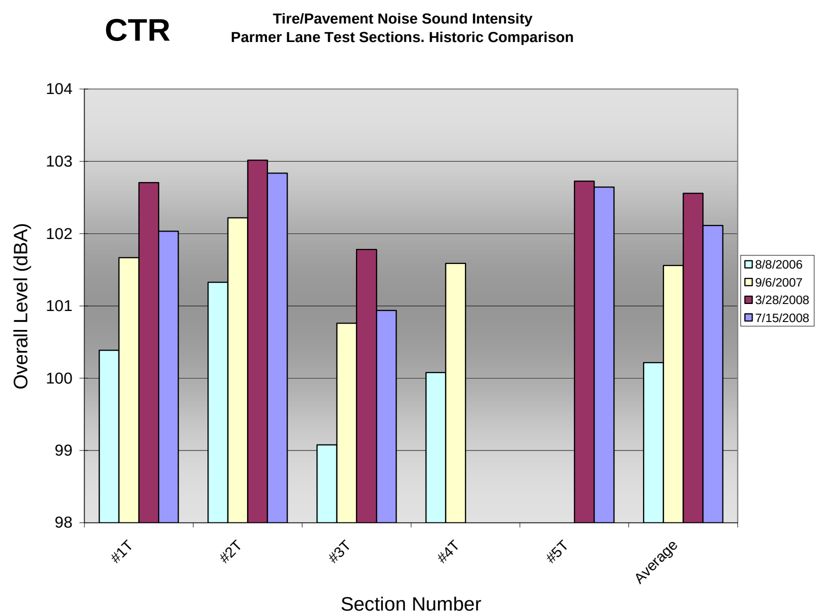

Figure 3.19: Parmer Ln. overall level comparison, CTR results

The graph shows that the Parmer Ln. sections are getting slightly louder over time. As in the case of US 183, the March 2008 measurements are the highest, and this can be attributed to the lower temperatures during the tests. Table 3.3 summarizes the weather conditions for the Parmer Ln. tests.

Table 3.4: Summary of weather conditions for Parmer Ln. tests

	8/8/2006	**9/6/2007**	**3/28/2008**	**7/15/2008**
Air Temperature (°F)	83.3	85	69	95
Relative Humidity (%)	88	66	66.5	76
Wind Speed (mph)	6	7	4	3

Figure 3.20 presents the frequency spectra for the Parmer Ln. tests, showing uniformity among the four sections, and a shape typical of conventional AC pavements.

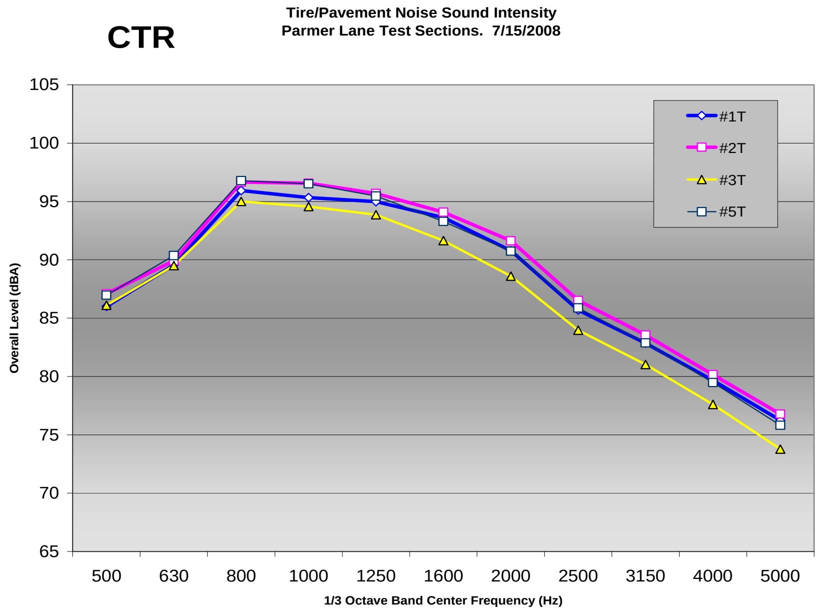

Figure 3.20: Parmer Ln. frequency spectra

The overall results for the rodeo including Transtec's and TxDOT's numbers are presented in Figure 3.21. This chart shows that the highest results are still those from Transtec, but their levels were lower in the case of the second rodeo when compared to the first. This reduction (between 0.5 and 1 dBA, approximately) could be due, in part at least, to their new equipment. The other factor contributing to this reduction, as noted earlier, is the temperature. Still CTR presented the lower levels, followed by TxDOT and then by Transtec. CTR's lower results are explained by the different tire with which the CTR vehicle is equipped, as opposed to the SRTT tires on the TxDOT and Transtec cars.

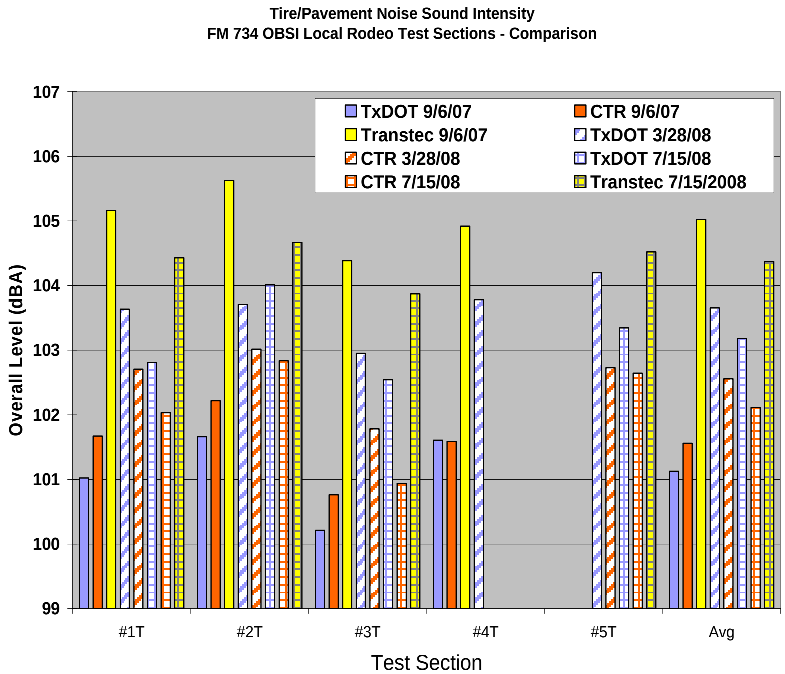

Figure 3.21: Parmer Ln. results of both rodeos and rodeo follow-up

3.4.3 US Highway 183

The segment of interest on US 183 consists of two groups of different CRCP segments. From Braker Ln. to Oak Knoll (sections 10 to 14) the CRCP is an older pavement, and from McNeil to Anderson Mill (sections 5-9) the CRCP is newer. Figure 3.22 shows CTR's results from this rodeo, along with those from the two previous occasions.

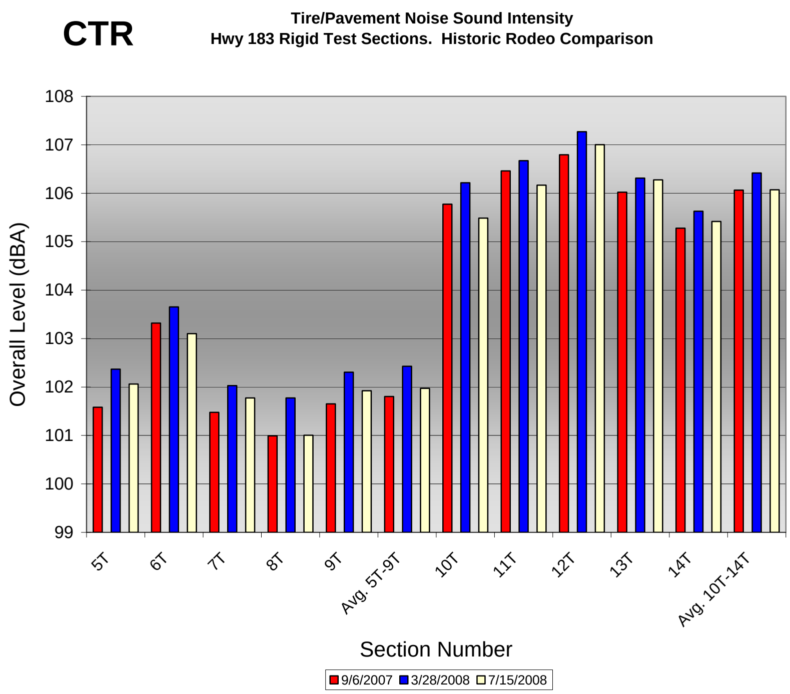

Figure 3.22: CTR's US 183 Overall level comparison

There is a clear difference in levels between the older and the newer pavements, with the newer ones being significantly quieter (about 4 dBA on average), and the difference is consistent over time. The older CRCP has some shallow spalling, while the newer sections show no apparent spalling. The sections' levels have also remained very consistent in the time span of these measurements. The fact that the measurements from March 2008 are slightly higher than the other two sets of results can be attributed mainly to the lower temperature prevailing at the time of the test, as compared to the temperatures during the other two dates. The weather conditions recorded during the tests are shown below (Table 3.4).

Table 3.5: Summary of weather conditions for US 183 tests

	9/6/2007	3/28/2008	7/15/2008
Air Temperature (°F)	83	69	79.9
Relative Humidity (%)	77	85	76
Wind Speed (mph)	5	4	2.7

The conditions during the September 2007 and July 2008 tests were very similar, which explains the analogous results from those dates. Figure 3.23 shows the frequency spectra for the recent rodeo tests, where the two groups of pavements are also very distinguishable, and where the peak corresponding to the 1000-Hz frequency band, which is characteristic of tined CRCP, can be observed for all sections.

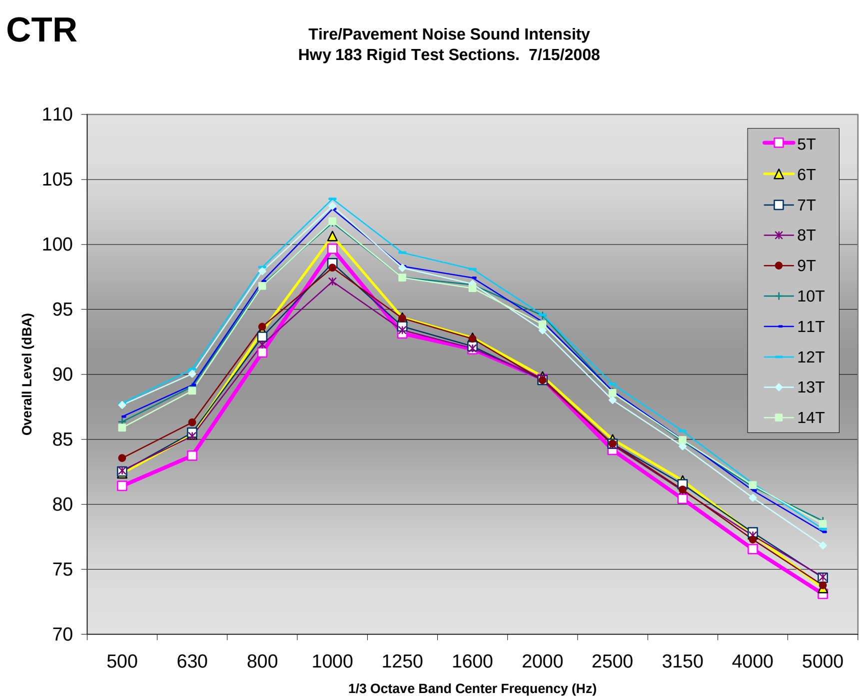

Figure 3.23: US 183 frequency spectra

Figure 3.24 shows the overall levels obtained in the US 183 tests by all agencies in the second rodeo, along the values from the previous efforts.

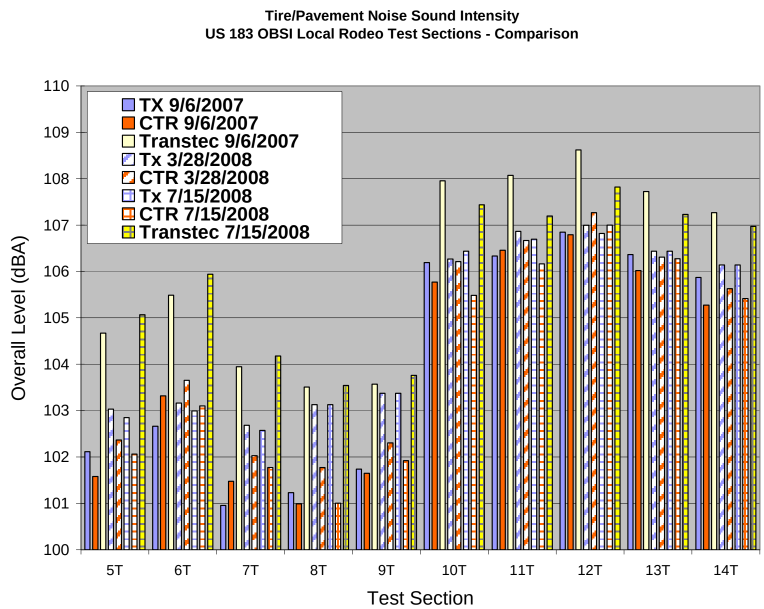

Figure 3.24: US 183 results of both rodeos and rodeo follow-up

This graph also shows a reduction in Transtec's results from the previous rodeo, similar to the Parmer Ln. reduction. TxDOT's results are almost identical to what they measured in March when their vehicle was outfitted with the new SRTTs, and CTR's results are also very similar to what was obtained in March. CTR's levels remained lower than TxDOT's, and Transtec still got the highest measurements in every subsection during both rodeos.

3.5 Conclusion

The "noise rodeos" were valuable efforts to compare OBSI results obtained on different pavement surfaces by the participating agencies, in this case, TxDOT, Transtec, and CTR, which have similar testing equipment. Among the participants, TxDOT's and CTR's sets of equipment are virtually identical, while Transtec's equipment differs from TxDOT's and CTR's. The same is true for Transtec's analysis procedure. Those differences are reflected in the results of the noise measurements. Results from TxDOT and CTR diverted slightly from each other when TxDOT acquired a new set of tires for their vehicle, the SRTT, to be in line with what the OBSI community is recommending, and soon standardizing, for this kind of tests. The results show that the SRTT gives higher results than the AWP tire with which the CTR vehicle is still equipped.

On average, the SRTT resulted in louder sound intensity levels than the AWP tire by 1.1 dBA on dense graded AC (FM 734); between 0.7 and 1 dBA louder on new CRCP (US 183); and between 0.1 and 0.4 dBA on older CRCP (US 183).

During these efforts, CTR was the agency that introduced less variability in its equipment, as it remained unchanged throughout all the testing. The results showed this as well. However, it is expected that eventually the CTR vehicle will be equipped with SRTTs, in order to be able to deliver results that can be compared with other agencies, according to what has been observed in the national and international trends. Transtec introduced a new, improved OBSI rig for their vehicle, which brought their results closer to what the other two participants obtained, but still their OBSI values remained the highest for all surfaces and subsections.

Consistency in OBSI results reassures that the measurements are being conducted following the same protocols, and gives credibility to the testing process, as the results can be compared with other values obtained by other agencies elsewhere which follow the same procedures.

Chapter 4. OBSI Tests and PFC Aging

4.1 Introduction

This chapter presents the results of the on-board sound intensity (OBSI) tests performed in this project on several sections of porous asphalt that were selected to be tested over time. As mentioned in other sections of this report, an important part of this project focused on testing open-graded friction course (OGFC) pavements, also known in Texas as permeable friction courses (PFC). These pavements have delivered excellent results in terms of their acoustic characteristics, even though in Texas they have not been designed and constructed with this purpose in mind. Most of the testing in this project was dedicated to PFC pavements.

One of the main objectives of this research is to evaluate the acoustic performance over time of this type of surfaces, which are commonly regarded as quieter than conventional asphalt and concrete pavements. The question that this study attempted to address is whether such quietness can be sustained over time, as a well-known hypothesis indicates that these porous asphalt pavements get louder with time and traffic, as the voids in the surface get clogged. In order to confirm or refute the hypothesis, tests on PFC had to be repeated over a long period of time on the same pavements, and that is what this research intended. One of the variables utilized to classify the pavements in this study is age.

It should also be emphasized that to obtain more definitive conclusions on this matter, it would have been optimal to have a longer time frame to conduct the testing. The OBSI testing in this project started in May 2006 and concluded in the summer of 2008. Hopefully, future research endeavors will enable the continuation of this work over time, to provide results that can cover the lifespan of a PFC overlay, which is normally considered to be between 6 and 8 years.

The selection of the test sections was performed according to the factorial prepared for this project.

4.2 Factorial

4.2.1 Factorial Variables

The design of the PFC factorial experiment includes variables that have an effect on the acoustic properties of the surface, such as binder type, pavement age, and geographic location.

Binder Type

Two main categories of binder types were identified to classify the PFCs in Texas: polymer modified binders and crumb rubber binders. The polymer modified category includes all the PG 76-22 and PG 76-22 TR.

Pavement Age

It is generally accepted that as a pavement surface ages it becomes louder, but this general perception is not necessarily true. The common hypothesis supporting this premise is that, with time, the pavement air voids become clogged with dust and other debris, and when the voids are filled with material, they can no longer absorb sound, making the surface louder. This is true in many cases, and if that is the case, it could be assumed that the desirable acoustic properties can be restored with cleaning of the porous surface. However, the usefulness of cleaning procedures is the subject of debate.

It should be mentioned that the less porous the riding surface is, the less susceptible it is to clogging. This brings up an instance in which an aging pavement does not become louder with time is when a non-porous riding surface (e.g., a concrete pavement) gets polished with use and loses its texture, making it smoother and hence, quieter.

Besides clogging, another change that the pavement surfaces exhibit with time and wear that has an effect on noise generation is compaction. Compaction of a pavement layer might occur in a more noticeable way in newer porous surfaces, such as a recently placed PFC. The loads imposed by traffic on the pavement reduce the air voids' sizes, and the particles of coarse aggregate might change their position and orientation when subjected to such loads, partially diminishing the effectiveness of the air voids to absorb noise.

The change in acoustic properties with age is a foremost research subject in this study. For FHWA to accept that "pavement type" can be used for noise mitigation purposes, it has to be demonstrated that such properties can be maintained in "perpetuity," i.e., that a pavement that is constructed quiet will remain quiet.

Three age categories were established:

- New: pavements two years old and newer
- Medium: pavements between two and five years old
- Old: pavements five years old and older

It should be noted that as the project progressed, naturally some of the study sections changed from one age category to the next. The results of the tests are reported and classified according to the pavement age at the time of each particular test, thus, some sections may provide results that fall into various pavement ages throughout the duration of this study.

Pavement Location

The geographic location of the sections has an influence on the weather conditions, mainly regarding precipitation and temperature. These two environmental aspects have an impact on tire/pavement noise. There is a wide variety of climatic conditions that occur in the State of Texas. However, for the purpose of this study, to simplify the factorial, the climatic conditions within the state have been grouped into four categories, which also correspond to four regions within the state:

1. Wet and freeze
2. Wet and no freeze
3. Dry and no freeze
4. Dry and freeze

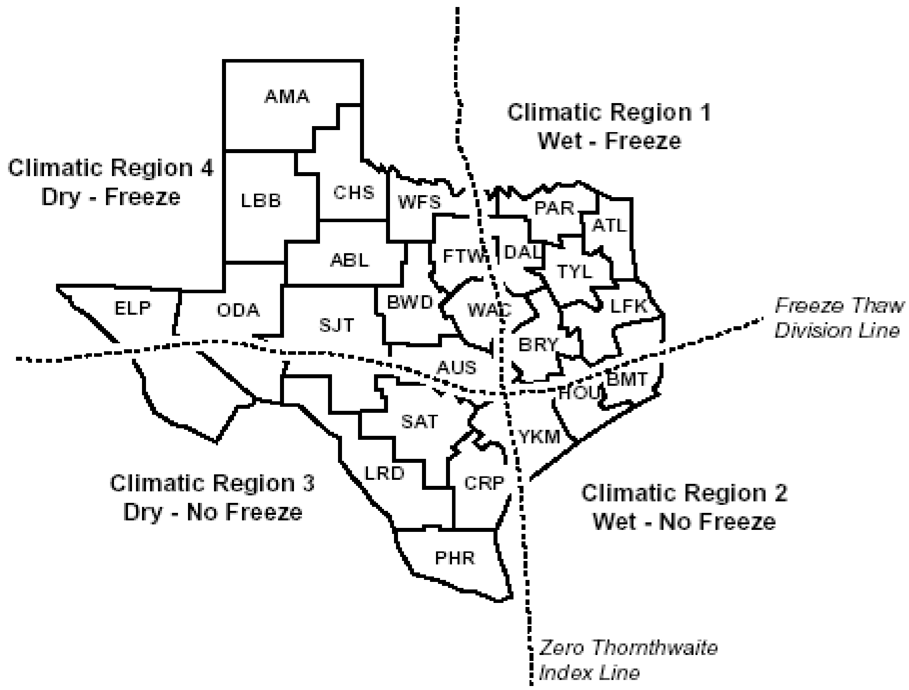

Figure 4.1: Climatic region classification in Texas, showing TxDOT districts

The geographic location of the four regions is determined by two lines dividing the state into quadrants. One line, close to a horizontal line, separates the region prone to freezing temperatures from the region in which temperatures remain above freezing for the most part, while the other line divides the state into wet and dry regions as shown in Figure 4.1. This line is based on the Zero Thornthwaite Index, which separates regions with water deficiency from regions with water surplus. Thus, in general, it can be seen that the northern part of the state is prone to freezing while the southern part of the state is not; similarly, the eastern part of the state falls into the wet classification, while the west part corresponds to the dry classification.

It should be noted that the boundaries of the four regions are not absolute, meaning that given the variability of climatic conditions with time, the location of the lines that determine the quadrants may change. Also, the locations of those lines sometimes fall within districts, making some districts have areas in two or more climatic regions.

The PFC factorial, indicating the number of sections that were initially identified for this research, is presented in Table 4.1.

Table 4.1: PFC Factorial

Age		Age ≥ 5 Years		2<Age<5		Age ≤ 2 Years	
Binder Type		Polymer Modified	Crumb Rubber	Polymer Modified	Crumb Rubber	Polymer Modified	Crumb Rubber
Climate	Dry-Freeze	5	0	8	0	5	0
	Dry- No Freeze	1	1	4	2	0	4
	Wet-Freeze	0	0	3	0	2	0
	Wet- No Freeze	2	0	4	0	10	0
	Total	8	1	19	2	17	4

The sections identified by climatic region and district are as follows (Table 4.2):

Table 4.2: PFC Factorial by climatic region and district

Age		Old		Medium		New	
Climate	**Asphalt Rubber**	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**
Dry-Freeze	Amarillo		1				
	Austin				2		4
	Fort Worth		1				
	Waco				1		1
	Wichita Falls		3		5		
Dry- No Freeze	Corpus Christi			1	1		
	El Paso		1				
	Odessa					2	
	Pharr				3		
	San Antonio	1		1		2	
Wet-Freeze	Dallas						1
	Lufkin				2		
	Tyler				1		1
Wet- No Freeze	Houston			1	1		3
	Yoakum		2		2		7

As it turned out, not all of the initially identified sections were suitable for noise testing. For instance, some were not true PFCs, such as the Fort Worth pavements, which were similar mixes to PFC, but not designed under the current PFC specification, others were in urban areas in which the OBSI testing speed was not attainable, e.g., one section in downtown Waco, and others, such as the El Paso and Amarillo sections were not practical to test because of their distance from Austin. The final number of sections tested is presented in Table 4.3.

Table 4.3: Final factorial of PFC test sections

Age		Age ≥ 5 Years		2<Age<5		Age ≤ 2 Years	
Binder Type		Polymer Modified	Crumb Rubber	Polymer Modified	Crumb Rubber	Polymer Modified	Crumb Rubber
Climate	Dry-Freeze	1	0	4	0	7	0
	Dry- No Freeze	0	0	1	2	0	2
	Wet-Freeze	0	0	0	0	1	0
	Wet- No Freeze	1	0	2	1	4	0
	Total	2	0	7	4	12	2

4.3 PFC Test Sections

The PFC sections that were tested in this project, with their factorial classification are shown in Table 4.4.

Table 4.4: PFC Test sections by district, climatic region, binder and age

District	Highway	Type	Year Constructed	Site Description	Factorial Classification		
					Climate	Binder	Age
Austin	US 183	PFC	2003	North Fork San Gabriel R. to Seward Junction (SH 29)	Dry-Freeze	Polymer Modified	Medium
	IH 35	PFC	2006	Colorado River to Ben White	Dry-Freeze	Polymer Modified	New
	IH 35 South	PFC	2005	Loop 4 to Yarrington Rd.	Dry-Freeze	Polymer Modified	New
	IH 35 North	PFC	2005	Loop 4 to Yarrington Rd.	Dry-Freeze	Polymer Modified	New
	FM 1431	Item 3231 - PFC	2005	From Trails End rd. to 0.2 mi West of Vista Ridge	Dry-Freeze	Polymer Modified	New
	FM 620	PFC	2004	From Parmer Ln. to IH-35	Dry-Freeze	Polymer Modified	New, Medium
	Loop 360	PFC		US 183 to FM 2222	Dry-Freeze	Polymer Modified	New
Dallas	IH 30	PFC	2006	Sylvan Ave. to Loop 12	Wet-Freeze	Polymer Modified	New
Corpus Christi	IH 37	PFC	2004	(CC1: Asphalt rubber mix w/ limestone). From downtown Corpus Christi at US 181 to north of the Nueces River Bridge.	Dry- No Freeze	Crumb Rubber	New
	IH 37	PFC	2004	(CC2: fibers and limestone). From Nueces River Bridge to Atascosa County line.	Dry- No Freeze	Polymer Modified	New
Houston	US 90	PFC	2003	from IH 10 east of Peach Ridge rd. to FM 359, West Harris Area Office	Wet- No Freeze	Crumb Rubber	Medium
	SH 6	PFC	2004	from Harris Co. Line to US 90A, let in January 2004; Fort Bend Area Office	Wet- No Freeze	Polymer Modified	Medium
	IH 45	PFC	2005	from Loop 336 to FM 1097, let in February 2005; Montgomery Area Office	Wet- No Freeze	Polymer Modified	New
	SH 242	PFC	2005	from San Jacinto River to US 59, let in February 2005; Montgomery Area Office	Wet- No Freeze	Polymer Modified	New
	SH 146	PFC	2005	FM 518 to FM 1764	Wet- No Freeze	Polymer Modified	New
San Antonio	IH 35	PFC	2003	Weidner Road to Loop 1604 or Thousand Oaks to Topperwein	Dry- No Freeze	Crumb Rubber	Medium
	US 281	TY PFC_AR1	2006	Bass Rd to 0.40 Miles North of Hildebrand	Dry- No Freeze	Crumb Rubber	New
	US 281	TY PFC_AR2	2006	0.40 Miles North of Hildebrand to Pearl Parkway	Dry- No Freeze	Crumb Rubber	New
Waco	IH 35	PFC	2003	Main lanes at Craven Ave, placed in 2003, 1 ½ inches of PFC, McLennan County	Dry-Freeze	Polymer Modified	Medium, Old
	SH 6	PFC	2005	from BU 77 to SH 164, McLennan County	Dry-Freeze	Polymer Modified	New, Medium
Yoakum	US 290	PFC	2004	from Washington County Line to Lee County Line, Fayette County	Wet- No Freeze	Polymer Modified	Medium
	IH 10	PFC	2001	from FM 609 to US 90 at Waelder, Fayette and Gonzales Counties	Wet- No Freeze	Polymer Modified	Old
	IH 10	PFC	2006	from US 90 at Waelder to US 183, Gonzales and Caldwell Counties	Wet- No Freeze	Polymer Modified	New

The age in the rightmost column corresponds to the classification at the time each particular test was conducted, therefore, as mentioned before, some sections fall under various age classifications.

The subsequent paragraphs are dedicated to present the results for some of the PFC pavements with most outstanding features that have been monitored over time in this project, followed by the summary of all the sections and their results as they pertain to aging of the PFCs.

4.3.2 US 281 in San Antonio

The acoustic performance of the US 281 PFC section in San Antonio has been monitored in this research project almost since the construction of this pavement. This has been a valuable opportunity to evaluate the noise levels generated by traffic at various stages of a PFC life. Among the test sections measured in this project, this one was consistently identified as the quietest. This pavement, labeled as PFC1, consists of a 2-in thick asphalt rubber PFC overlay on concrete pavement, constructed in 2006 over 2.4 miles. It has been tested on several occasions both by TxDOT and by CTR, the first time being in October 2006, shortly after construction, when TxDOT got the first opportunity to perform OBSI tests on this surface. Another important feature of this pavement is that there is another similar PFC section adjacent to it, which is about the same age, and which has been tested several times as well. This one was labeled PFC2, and it is also a rubberized overlay on concrete pavement, 1 ½ in. thick, placed in 2006 over 2.5 miles. Besides the PFC sections, other conventional AC sections were identified and tested, specifically some Type C mix, which offered the opportunity to compare a conventional AC pavement with the PFCs.

The subsections that correspond to the US 281 pavements analyzed are summarized in Table 4.5, and a map showing the sections' location is presented in Figure 4.2.

Table 4.5: Subsections of US 281 in San Antonio

Section	Thickness (in.)	Aggregate Type	Year of Construction	Northbound Subsections	Southbound Subsections
PFC1	2	Traprock	2006	12T, 13T, 14T	3T, 4T, 5T
PFC2	1.5	Sandstone	2006	9T, 10T, 11T	6T, 7T, 8T, 17T
Type C	1.5	Limestone	2000	15T, 16T	1T, 2T

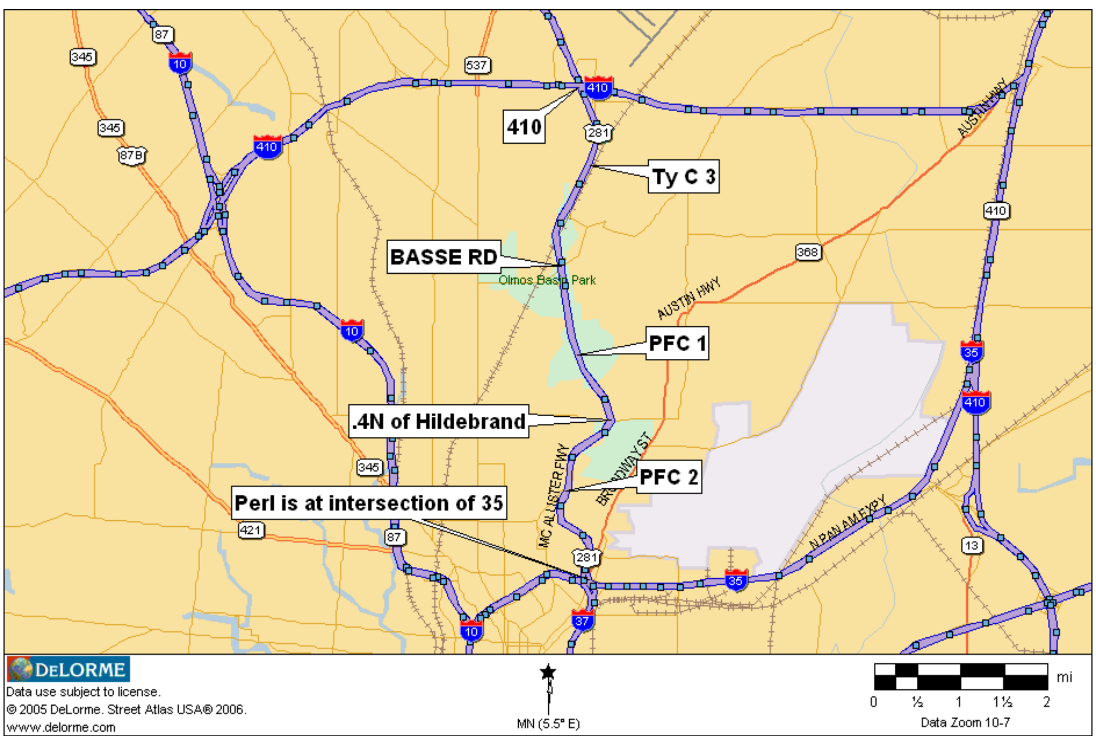

Figure 4.2: San Antonio test sections on US 281

The sound levels for US 281 pavements from October 2006 are shown in Figure 4.3. As expected, the PFC sections were considerably lower than those for the Type C mix, but there was also a significant difference between PFC1 and PFC2. In fact, PFC1 had the lowest sound levels of all the sections tested throughout this project, with an average level of 94.9 dBA. The variability within the section is small, showing that the quiet level was consistent throughout that segment. This quiet level prompted repeated visits for additional testing to confirm the results, both from TxDOT and CTR, and the section has proved to remain quiet on every occasion.

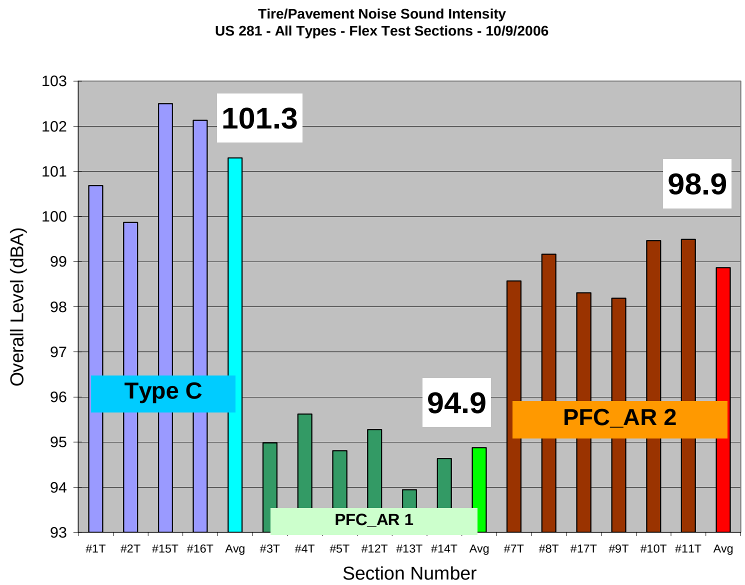

Figure 4.3: Overall OBSI levels for US 281 sections in San Antonio

The spectra for the sections (Fig. 4.4) show that the subsections within the same type of pavement present similar patterns, which is a sign of consistency between the tests and the pavements themselves. The spectra show that the dense-graded AC surfaces have a peak at the 800 to 1000 Hz bands, whereas PFCs stay more uniform in the lower-frequency bands. Subsections of the three pavements (Type C, PFC1, and PFC2) are clearly distinguishable as the curves tend to group within each main section.

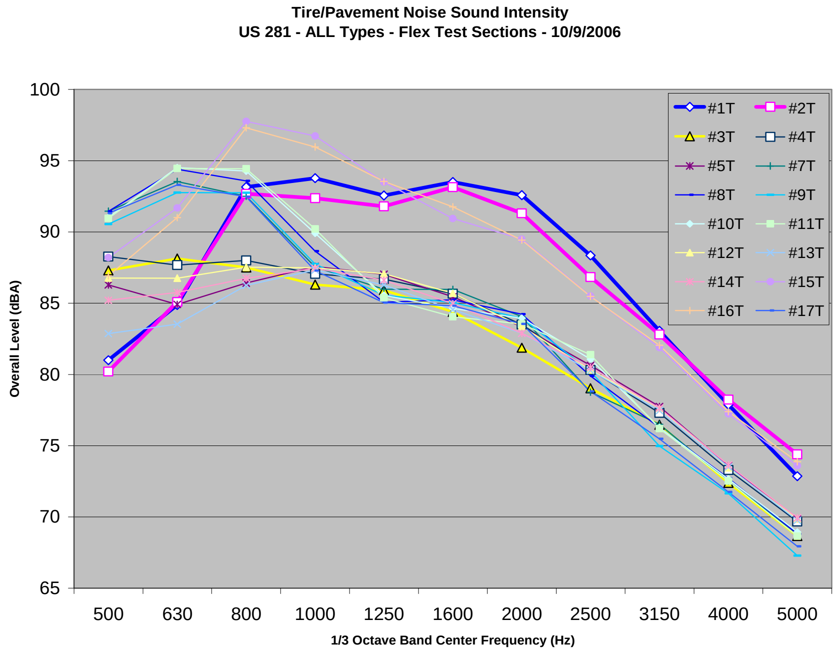

Figure 4.4: Spectra for US 281 sections in San Antonio

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.

The overall results of the November 29 tests indicate it is indeed a quiet pavement, even when 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 same trend in the results continued in the following three rounds of tests, which were performed by TxDOT on December 6, 2006, by CTR on September 26, 2007, and by CTR on September 3, 2008. The results of the five sets of tests are presented in Figure 4.5.

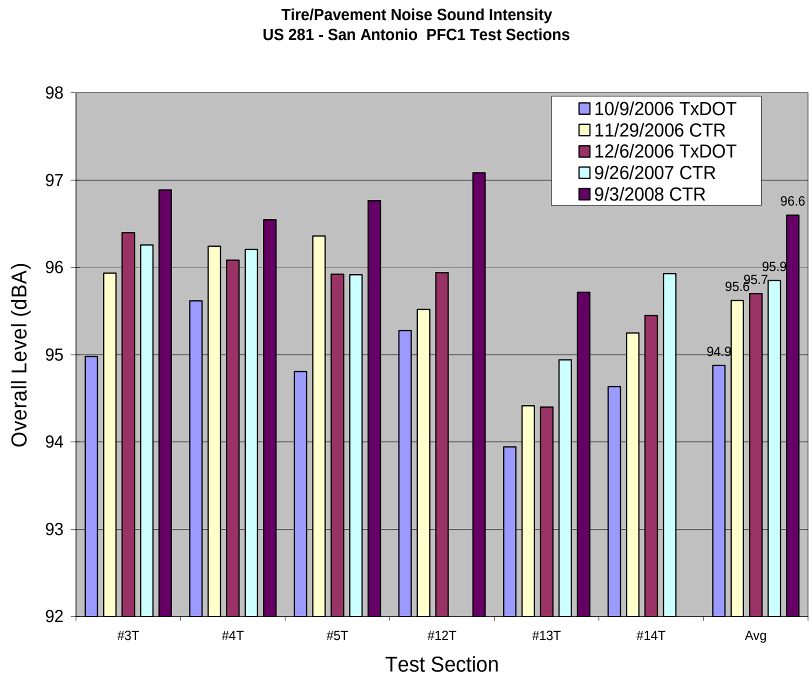

Figure 4.5: Comparison of OBSI results on PFC1 section on US 281 in San Antonio

In most of the subsections, the levels are slightly louder in the most recent tests, indicating that the surface might be getting louder with time. However, the differences are small, and in some cases, negligible. On average, the difference between the minimum and maximum noise levels recorded is 1.7 dBA, which is indeed a small amount for a time span of almost two years.

An element that can influence sound test results is the climatic conditions prevailing during the test. Table 4.6 summarizes the weather conditions for the five dates of testing at the site.

Table 4.6: Weather Conditions During OBSI Testing on PFC1 section on US 281 in San Antonio

Date of Test	Wind Speed (mph)	Air 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
September 26, 2007	1.9	91.0	53
September 3, 2008	5.2	89.1	46

The temperature was very similar for the first two rounds of testing, whereas the December test, with the lowest temperature, had higher sound levels up to that point in time. The levels remained similar or increased slightly in the September 2007 tests, when the temperature was the highest. The conditions during the September 2008 were very similar to those during the September 2007. 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. Several empirical studies indicate that tire/pavement noise increases about 1 dB per decrease in temperature of 10° C [Sandberg 2002]. Therefore, in this case, the temperature itself does not entirely explain the fact that the surface is slightly louder, plus if this were the decisive factor, the levels should have dropped back for the September 2007 tests, when it was about 20° F warmer than during the December 2006 tests. Plus, the steepest increase in noise levels occurred between the September 2007 and September 2008, when the weather conditions were similar, suggesting that the pavements acoustic properties are changing with time. Thus, the small increase in noise levels might be attributed to void reduction due to clogging or compaction, both of which are normal occurrences in this type of pavement with traffic and time. Clogging of the voids with dust and debris, and compaction caused by traffic loads might diminish the quieter characteristics of PFCs, as it is those open spaces that provide the acoustic absorption of these surfaces. However, the acoustic changes observed in this case are small, and even with the slight increase in noise levels over time, the section remains within the quietest range among those measured in this project. Even the loudest measurement on this section, which is also the most recent, is lower than any other OBSI result from any other pavement in this project.

4.3.3 Waco SH 6

The PFC segment of SH 6 from BU 77 to SH 164, in McLennan County, was constructed in 2005, and it was a significant test site for this research because its age classification changed during the time frame of this project. This pavement was visited on two occasions, during which its age classification changed from new to medium. Its location is shown in Figure 4.6

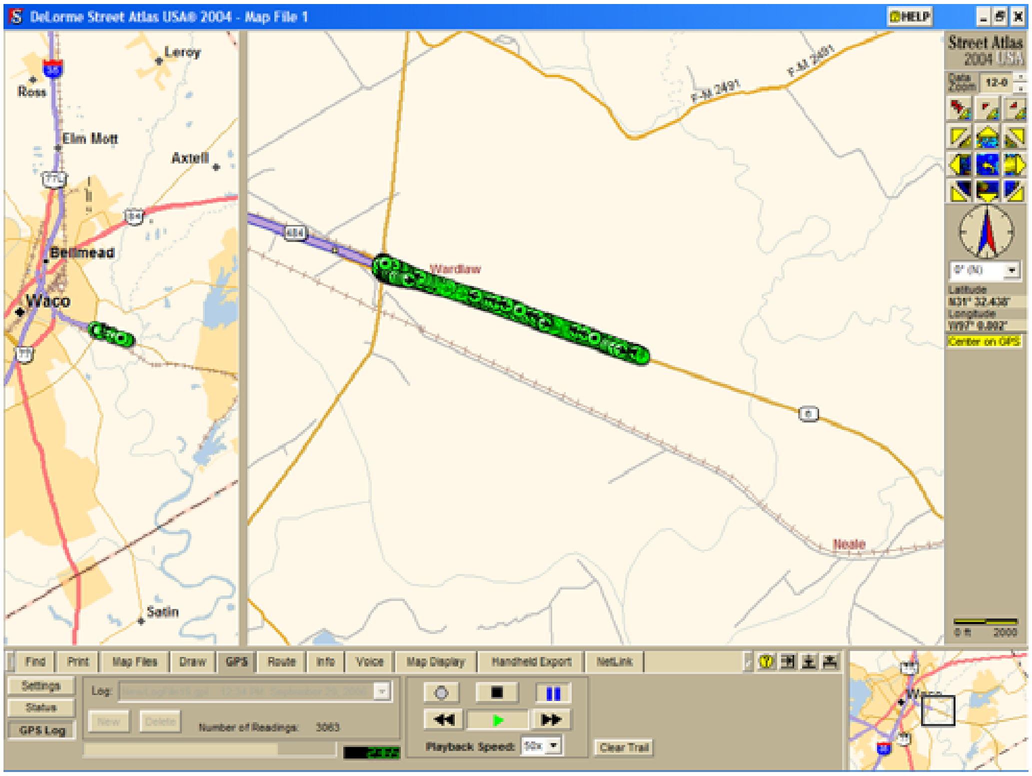

Figure 4.6: SH 6 PFC section location in Waco

The first set of tests on this road was performed on September 29, 2006. On that occasion, 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 4.7 and 4.8, respectively.

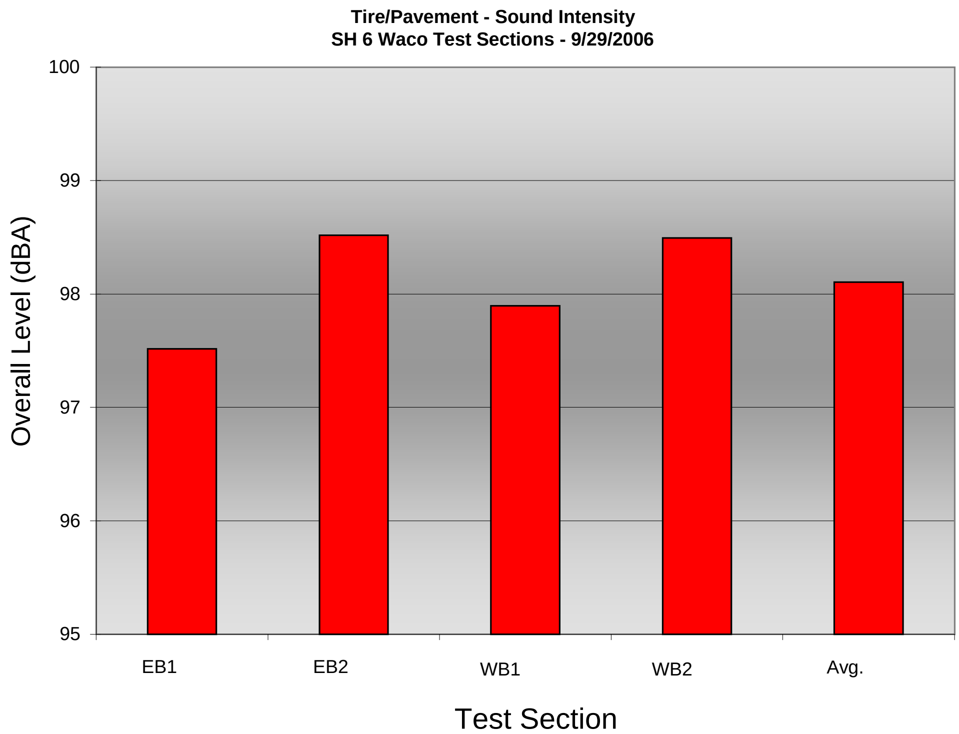

Figure 4.7: Overall sound levels for SH 6 in Waco (classified as new)

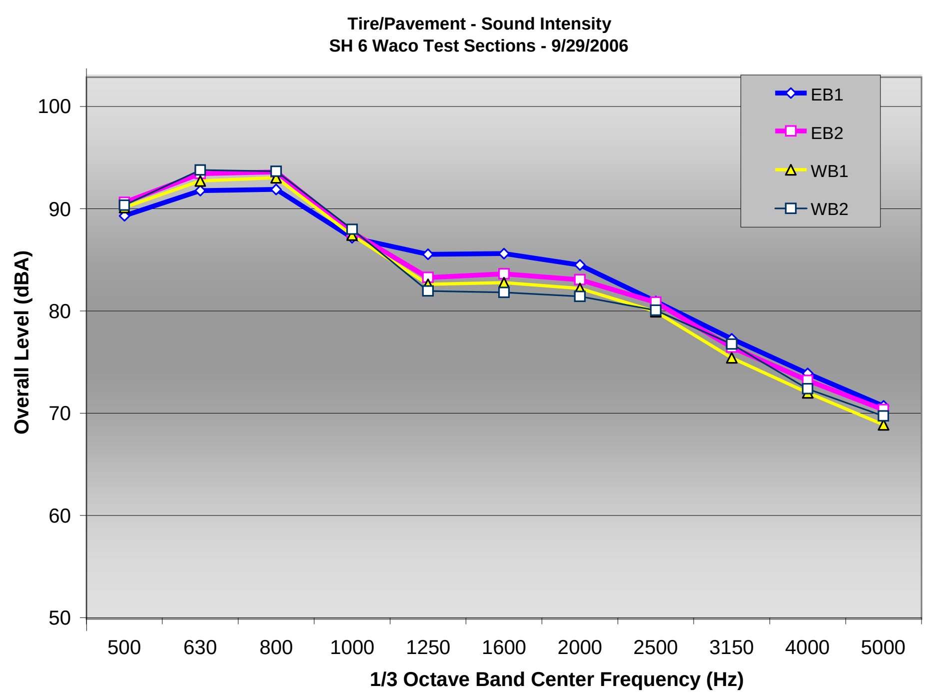

Figure 4.8: Spectral analysis for the PFC on SH 6 in Waco (classified as new)

By the next time the section was visited, on September 8, 2008, almost two years after the first visit, the section's age was classified as medium. The results comparing both test dates are presented in Figure 4.9.

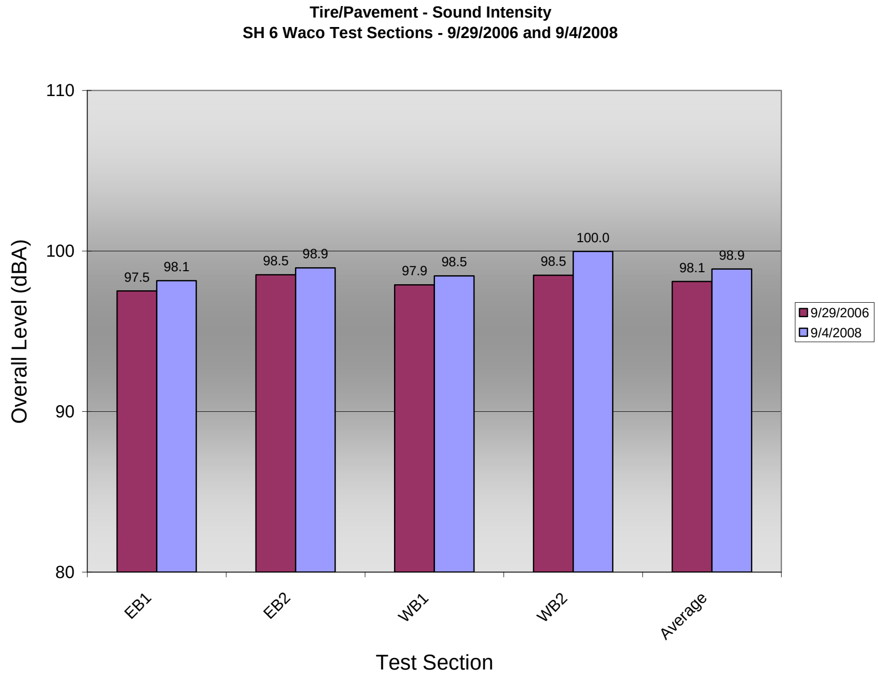

Figure 4.9: Overall sound levels for SH 6 in Waco from 2006 and 2008

It can be seen that the section got slightly louder, but the difference on average does not account for even 1 dBA. The spectra from the 2008 tests are presented in Figure 4.10, showing a very similar pattern as in the previous round of tests. With aging, this section might have experienced some clogging, and every subsection turned relatively louder, but the acoustic performance reflects minimal differences in two years. Considering that during the last set of tests the section was three years old, at which point most of the effects of compaction and clogging could have already occurred, it can be said that this section has retained its favorable acoustic properties as a PFC.

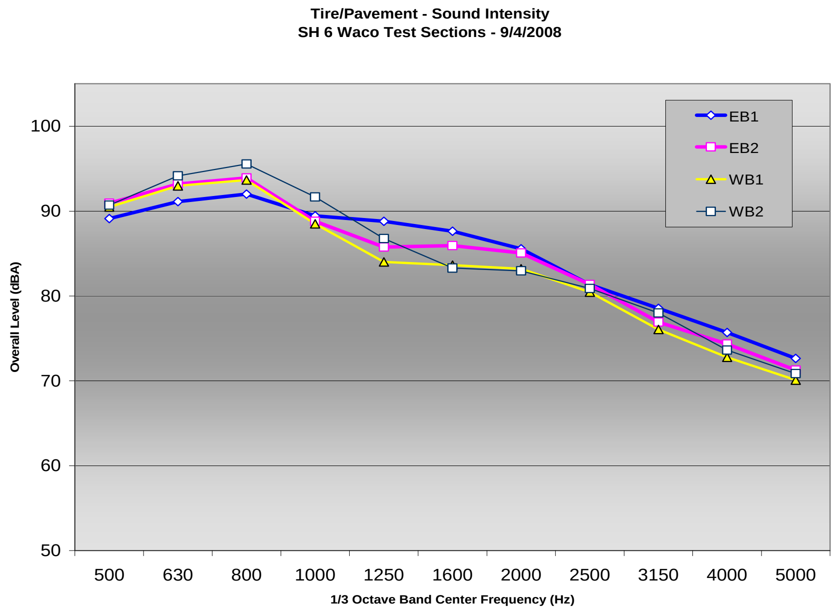

Figure 4.10: Spectral analysis for the PFC on SH 6 in Waco (classified as medium)

4.3.4 IH-10 in Yoakum

The PFC segment on IH-10 in Yoakum District, from FM 609 to US 90 at Waelder, in Fayette and Gonzales Counties was constructed in 2001, which makes this one the older PFC segment that could be tested in Texas for the purposes of this project. The only older PFC section that could be located in the state is in downtown Waco, and it is close to a traffic light, at a place not suitable to attain the testing speed required for OBSI. The location of the Yoakum tests sections is shown in Figure 4.11.

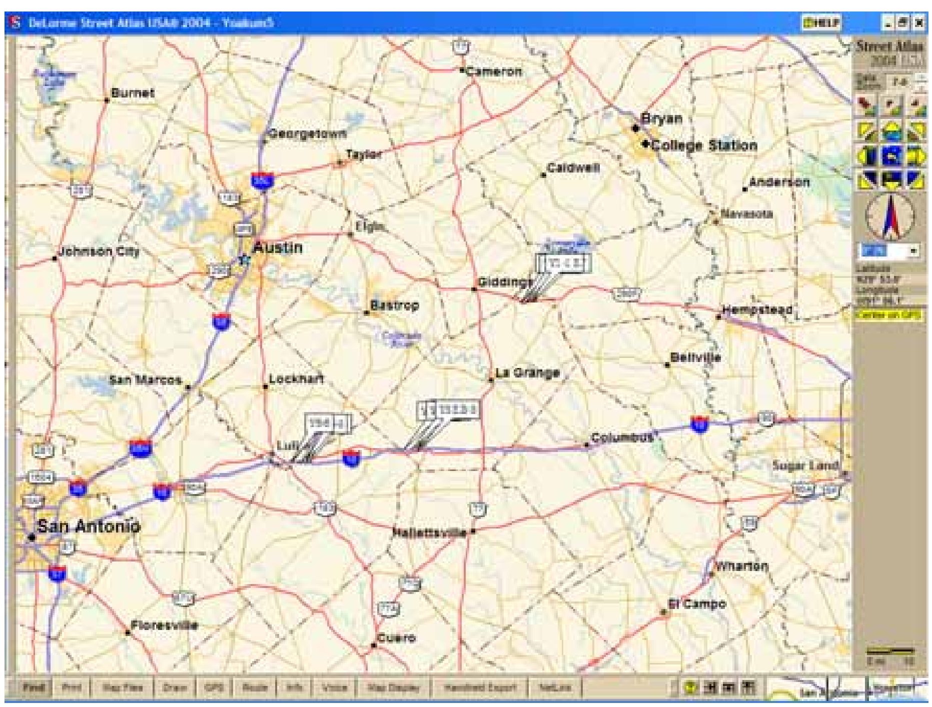

Figure 4.11: Yoakum 5 test sections on IH-10 (classified as old)

The Yoakum section was visited on August 9, 2007 for the first time. The second time it was measured was almost a year after, on August 7, 2008. The results from both times (Figure 4.12) indicate that the section got louder, but the difference is again negligible, on average about 1 dBA.

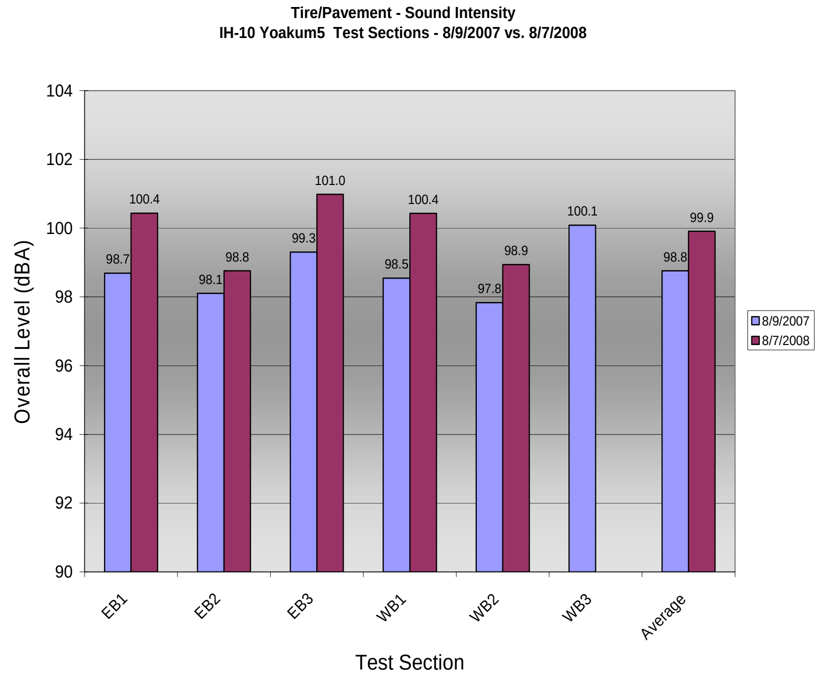

Figure 4.12: Overall sound levels for IH-10 Yoakum 5 test sections from 2007 and 2008.

The spectral analysis (Figure 4.13) also shows minimal changes with time. Being an old section, and the oldest one found for testing, it can be concluded that it has performed adequately from the acoustical standpoint over time.

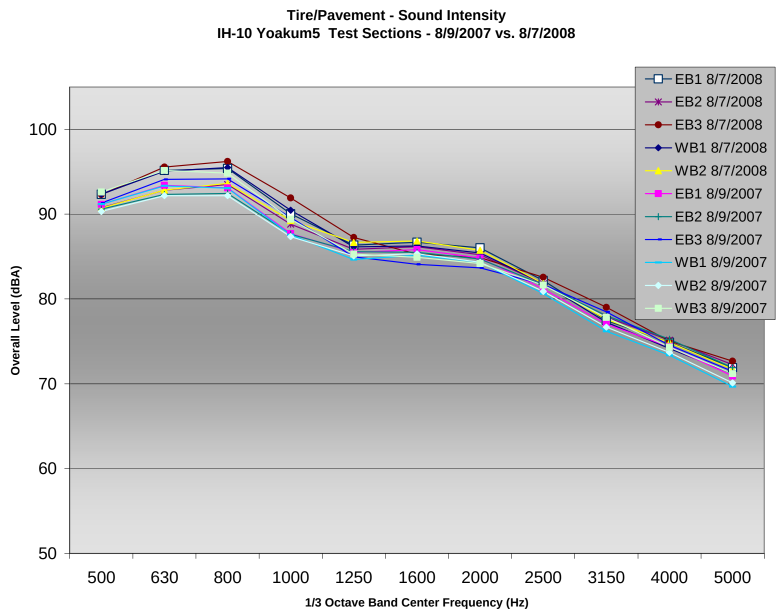

Figure 4.13: Spectral analysis for the PFC on IH-10 in Yoakum (classified as old)

4.4 Discussion of PFC Results

In this section, the relationship between aging of PFC surfaces and their noise measurements is further analyzed by presenting the results of all the OBSI tests performed in this type of pavements, following the age classification introduced at the beginning of this chapter.

4.4.1 PFC Overall Results

The OBSI results of the PFC measurements in this project, sorted from quietest to loudest are summarized in Figure 4.14.

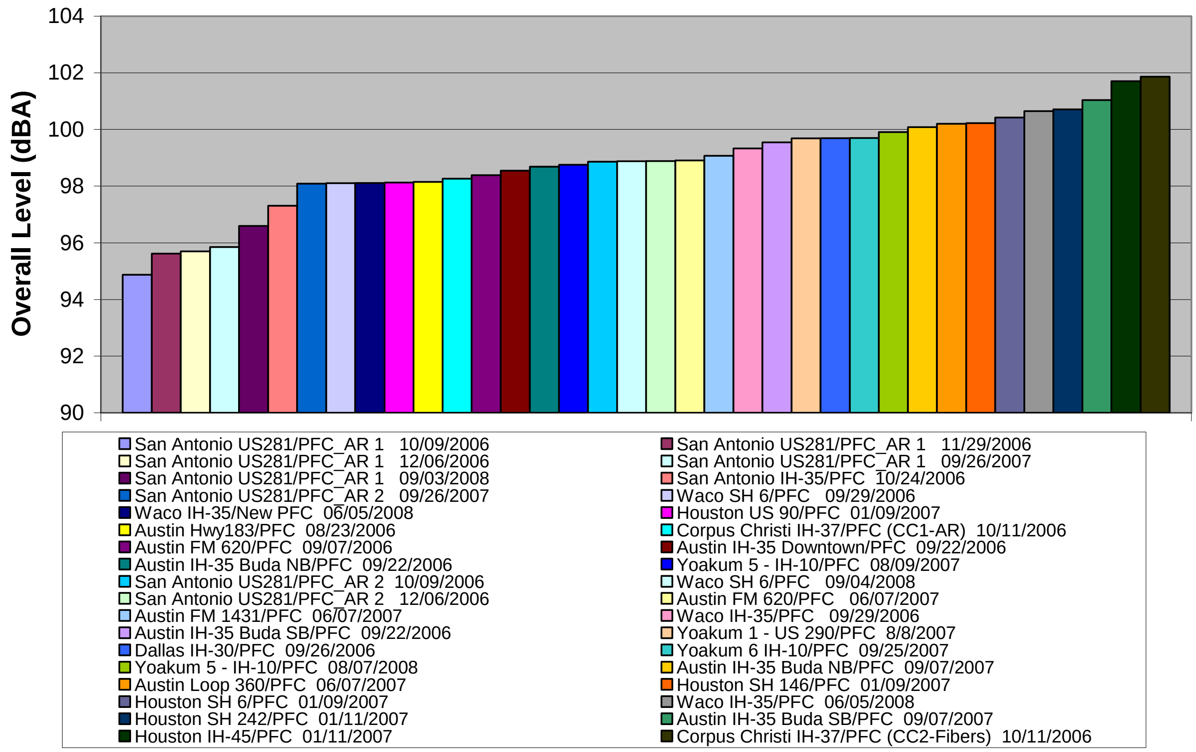

Figure 4.14: PFC OBSI measurements

The data used to create the chart, along with the pavement characteristics that the researchers were able to compile for all the PFCs tested in this project, are presented in Appendix A (Table A.1). The results in Figure 4.14 show that the five quietest measurements in this project were obtained from the US 281 PFC 1 section in San Antonio discussed above. The lowest overall measurement was 94.9 dBA; the loudest one was 101.9 dBA, recorded on IH-37 in Corpus Christi, on a section constructed in 2004 with limestone aggregate and fibers. This section was approximately two years old when the test took place, on October 11, 2006.

Other quiet measurements coincidentally, originated from other sections in San Antonio, such as the aforementioned PFC2 on US 281, and the IH-35 section. Among all the measurements collected, the range of overall levels is 7 dBA. The graph shows that the majority of the measurements (58%) are between 98 and 100 dBA. Only six measurements (17%) were below 98 dBA (with five of those corresponding to US 281 PFC 1), and 25% of them were above 100 dBA. The average measurement was 98.8 dBA, while the median is 98.9 dBA and the standard deviation is 1.6 dBA.

4.4.2 PFCs and Other Pavement Types

The majority of the tests in this project was conducted on PFC pavements. However, there were some other tests performed on conventional AC as well as concrete pavements. The graph in Figure 4.15 illustrates how the PFCs fared against all the pavement types tested by means of the OBSI procedure in this project. The pavement types are classified as CRCP, PFC, and conventional AC. This chart shows that PFC was the quietest pavement type in general. There were some loud CRCP sections, but there were others that were as quiet as, or even quieter than some PFCs, while the AC sections also had some loud measurements, but remain mostly in the medium range within the chart.

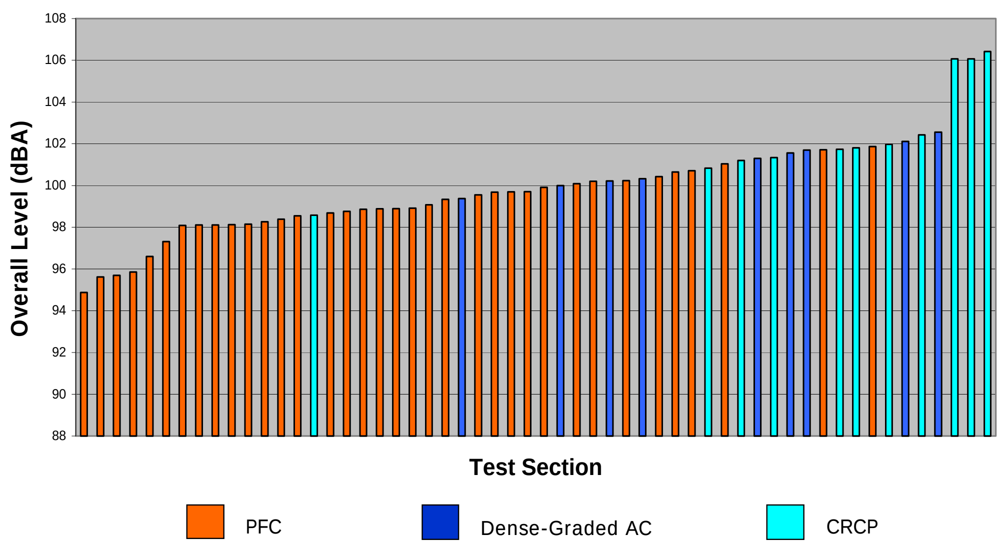

Figure 4.15: OBSI Tests by pavement type

4.4.3 PFC Results by Age

The effect of age on PFCs acoustic properties is presented in Figure 4.16, in which the PFC results have been grouped according to the age classification described before in this chapter.

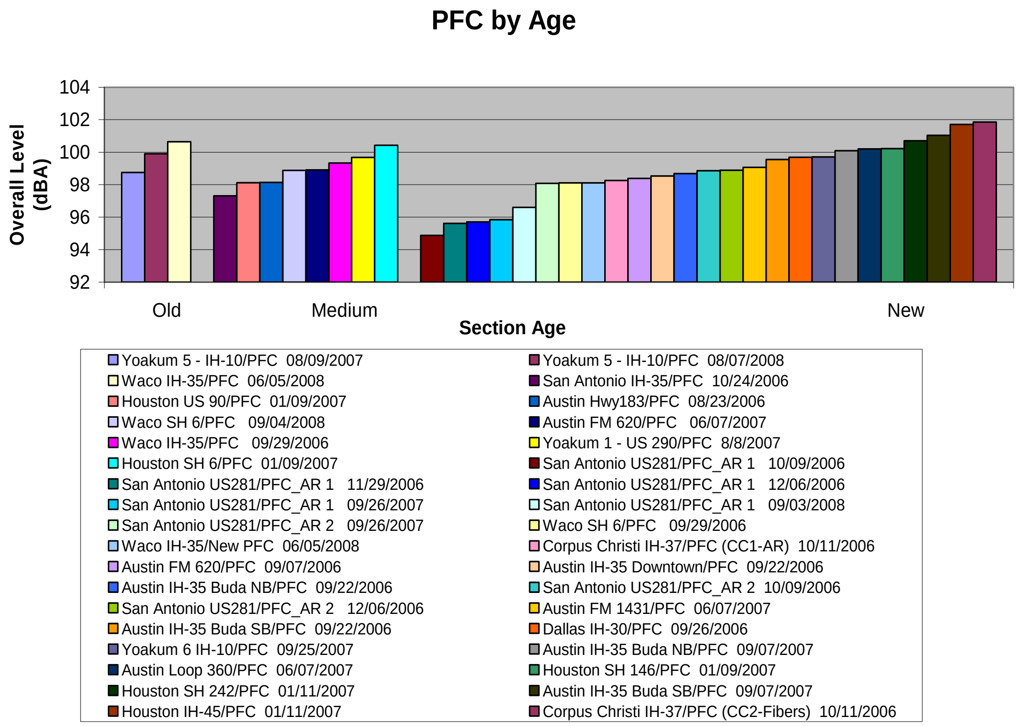

Figure 4.16: PFC OBSI results by age classification

The old PFCs seem to be louder, but there were only three measurements that could be performed on sections classified as old. As Table 4.4 shows, only a handful of test sections were available under this classification. The old sections average is 99.8 dBA, the medium sections average is 98.9 dBA, and the new sections average is 98.7 dBA. Therefore, the averages correspond with what is expected from evaluating the effect of age on PFC surfaces, but the differences are almost negligible, especially between medium and new sections.

4.5 Summary

From the results presented in this chapter, it can be concluded that the PFC pavements analyzed have gotten louder with age, as this is a definite trend in every case studied, perhaps due to clogging and compaction, reducing the size of the voids that are present in these pavement surfaces. However, the acoustical changes do not represent large variations over time, and in most cases are very minimal. Surfaces that have been in service for a period of time long enough to be classified as old relatively to the life span of a PFC are still performing acoustically in such a way that they can still be considered quiet when compared to other pavements. This leads to the conclusion that if the voids clogging action occurs as expected, and compaction happens on the PFCs as well, the amount and rate at which these changes take place do not preclude the PFCs from adequately dissipating and absorbing traffic noise. In general, it can be concluded that PFCs are the quietest pavement type.

Chapter 5. Roadside Measurements and Comparison to Traffic Noise Model Results

5.1 Introduction

Roadside noise measurements and modeling 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.

Even though a considerable amount of effort and time on this project was dedicated to OBSI testing, roadside measurements constitute a very significant portion of the research because of their comparison with TNM (Traffic Noise Model), the FHWA approved traffic noise and barrier modeling software. 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, performing comparisons between roadside measurements and the corresponding modeling of the road conditions with TNM is a sensible endeavor.

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 [FHWA 1995]. 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 in 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.

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.

Accordingly, several states are making a strong effort to address these concerns, and this research project is part of that effort in the state of Texas. The research attempts to provide evidence that can remove the FHWA existing restrictions against using pavement design for impact avoidance and abatement. This would allow the use of the "open graded" pavement option in the TNM program. Thus, this study focuses on PFC pavements, as it is deemed that this type of pavement can be indeed quieter, and therefore can demonstrate that not all pavements are acoustically equivalent. Some other surfaces including portland cement concrete (PCC) and dense-graded asphalt have also been tested, and have provided valuable results for comparisons.

Given the significance of roadside measurements, from the practical standpoint, another essential goal of this project is to be able to predict noise on the side of the road from OBSI tests. OBSI tests are less labor-intensive and less time-consuming than roadside tests: the amount of sound intensity data gathered in the time a roadside noise test is completed would allow for the characterization of several sections. Therefore, one of the relevant characteristics of OBSI testing is that it can be used as a reasonable predictor of roadside values, as OBSI is a measurement more likely to be performed at the network level. Thus, the correlation obtained between OBSI and roadside measurements for PFC pavements is presented in this chapter.

5.2 Roadside Noise Measurement Procedure

In devising the roadside noise measurement procedure, the researchers 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, which is a handheld or tripod-mounted sound pressure level (SPL) meter, such as the one illustrated in Figure 5.1.

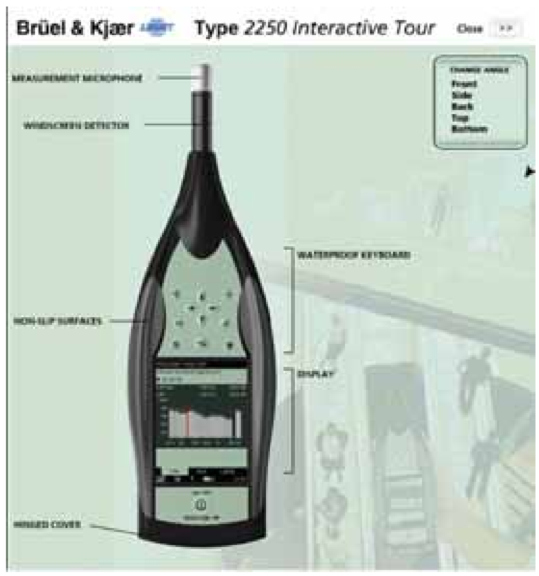

Figure 5.1: B&K Handheld Recording SPL Meter.

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 1997].

As specified by the standard, the SPL 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. In many instances, whenever possible, an additional microphone was placed at 15 meters (49.2 ft) from the center of the lane, and at the same height as the other microphone, to provide data directly comparable to the REMELs utilized to characterize pavement types within TNM. Other restrictions in the standard establish that measurement is not possible during windy conditions or when the roadway is wet. The primary SPL 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 were 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 was 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. Another input of the TNM program is the vehicle speed as listed in the next section. In the field, the researchers mounted a radar and placed it in such a way that each vehicle speed is registered by the same video camera that recorded the traffic (Figure 5.3). This setup produces video images such as the capture shown in Figure 2.2. The speeds were averaged for each vehicle classification and these numbers were used as inputs for the TNM program.

Figure 5.3: Equipment setup for traffic recording for pass-by tests

There are some requirements that should be assessed for the selection of the test sections. 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).

However, the proposed procedure for the test utilized by the researchers does not entirely follow the aforementioned standard, because SPB data and TNM results are not directly comparable, as the former is for individual vehicles, while the latter predicts levels for a traffic stream averaged over time. One of the main differences between the standard and what the researchers performed involves 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 performed pass-by tests in two different 10-minute periods and used both noise levels in the modeling and calculations. Evidently, the time of day would have an effect on the noise level that is measured in the test, as the traffic levels are likely to vary within the day; 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. Currently, an FHWA Expert Task Group is working on the standardization of a roadside method that can satisfy the purposes of this test. In the case of this TxDOT Project, the researchers took some guidelines from the Statistical Pass-by standard, and devised a procedure, but there is no standard that can accomplish the measurements that the researchers developed for this project. The researchers in this project have collaborated in that FHWA group.

5.3 TNM Modeling

TNM is the FHWA approved traffic noise and barrier modeling software developed for the use of state transportation agencies in addressing highway traffic noise. This program, created as a replacement for STAMINA 2.0/OPTIMA, is a state-of-the-art computerized model capable of predicting noise impacts in the vicinity of highways. TNM Version 1.0 was released in March 1998, then Version 1.1 came out in September 2000, and Version 2.0 in 2002. Version 2.5 was issued in April 2004. The Volpe National Transportation Systems Center Acoustics Facility has been in charge of the TNM validation study, which started in July 1999 and is an ongoing project. Version 2.5 is required for all new traffic noise analyses initiated on or after May 2005. For the case of this project, TNM 2.5 was used to predict the noise levels that correspond to the conditions observed in the field during the roadside tests. This was done for each of the locations measured, using the roadside procedure described in the preceding section.

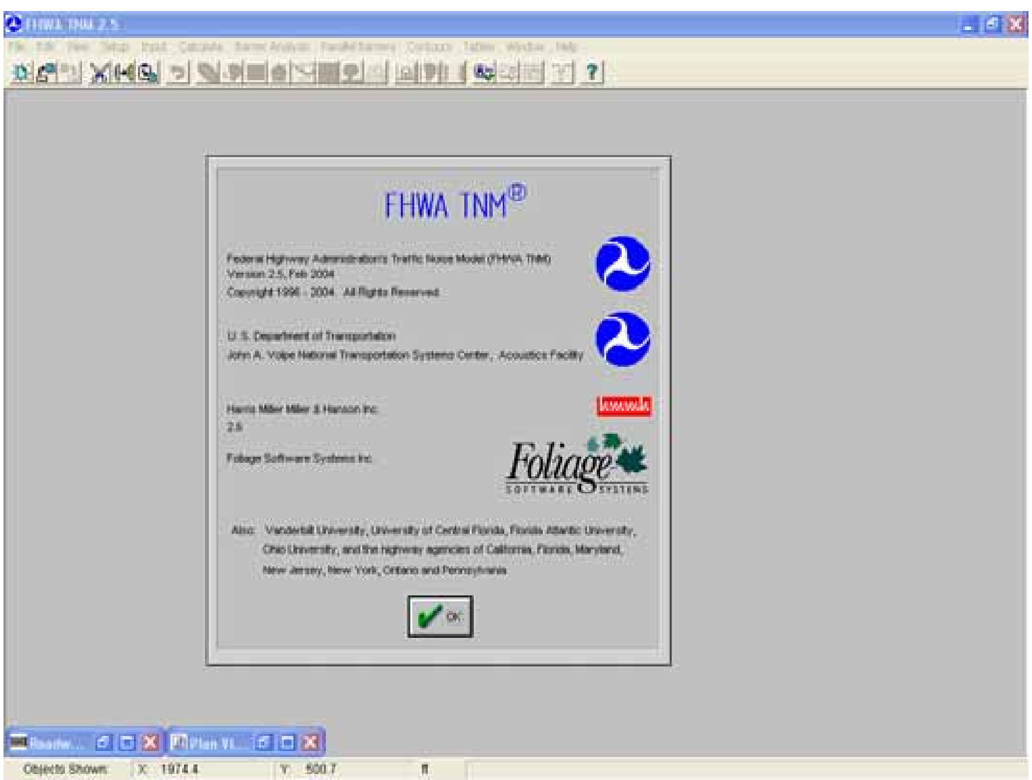

Figure 5.4: TNM Introductory screen

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 "average", and the specific pavement type, i.e., "open-graded" or "PCC" or "dense-graded" were performed; see Figures 5.5, 5.6, and 5.7, respectively)
6. Location of receivers

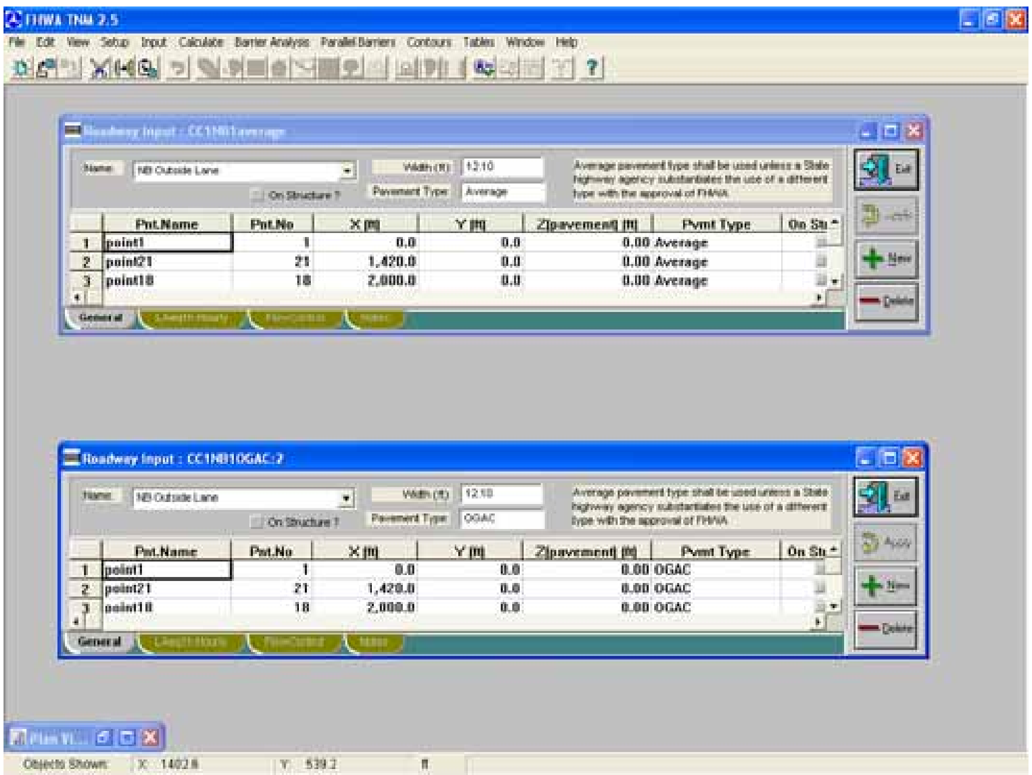

Figure 5.5: Runs using both "Average" (top window) and "OGAC" (bottom window) pavement type options are performed for PFC pavements

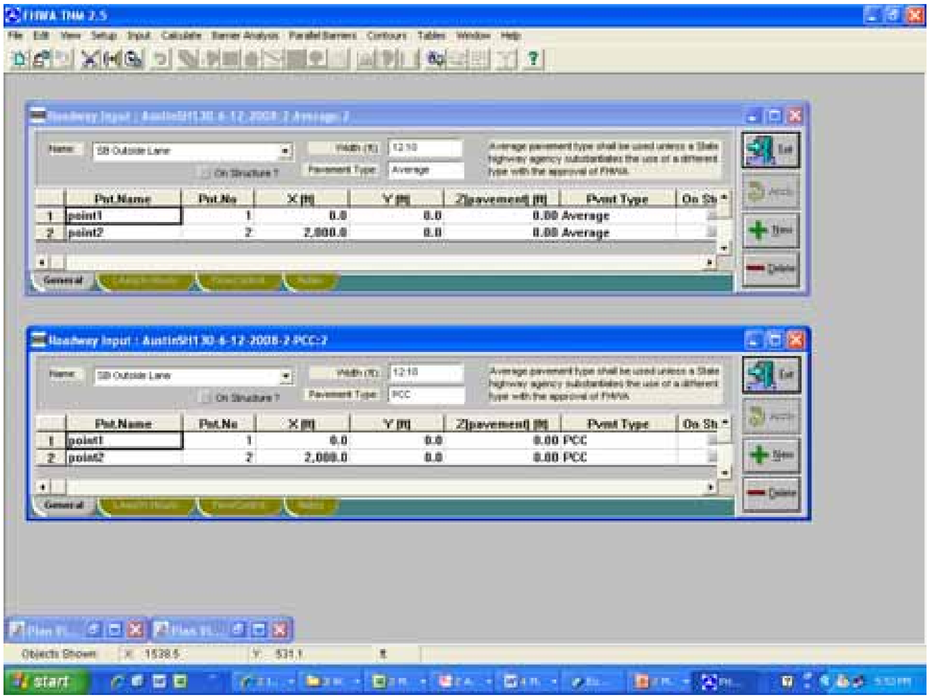

Figure 5.6: Runs using both "Average" (top window) and "PCC" (bottom window) pavement type options are performed for rigid pavements

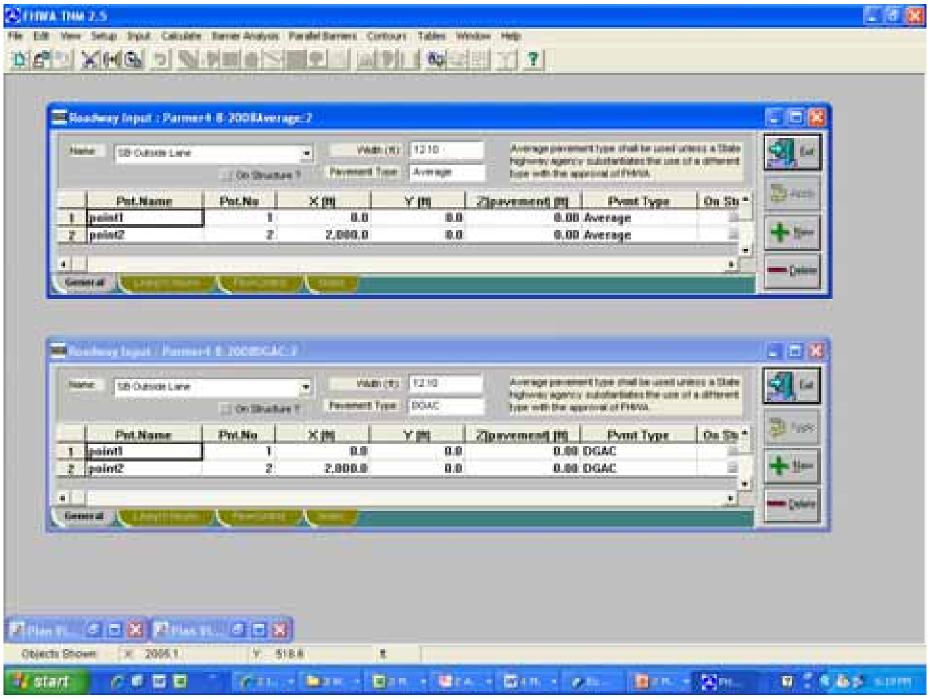

Figure 5.7: Runs using both "Average" (top window) and "DGAC" (bottom window) pavement type options are performed for dense-graded pavements

For the purpose of the comparison model with roadside tests, only one or two receivers are required, which correspond to the microphone positions, but from the program's standpoint, the receiver could be positioned anywhere, and the program would deliver the results according to whichever location is chosen.

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

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

Data for these two inputs were recorded with the video camera and radar arrangement described in the previous section.

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 need to be 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. If the test site has been selected properly for the purposes of the roadside test, none of these elements are necessary.

The comparison between roadside noise levels and the results obtained with TNM is performed in the following manner. 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.

5.4 Roadside Test Results and Discussion

The following PFC sections were tested for roadside noise levels: FM 620 in Austin, IH-30 in Dallas, SH 6 and IH-35 in Waco, IH-37 in Corpus Christi, IH-35 and US 281 in San Antonio, US 290 in Yoakum, and two different PFCs on IH-10 in Yoakum. Some of these sections were tested on different dates. Table 5.1 presents the results in chronological order, with the last three columns showing the noise levels: first, the measured level, followed by the TNM calculation using the "Average" pavement option and finally, the TNM calculation using the "OGAC" pavement option. Several sections were measured on more than one occasion within the same test date, i.e., more than one 10-minute period.

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 69.9	75.0	73.4
IH30	Dallas	WB @ exit 43A	9/26/2006	78.2 78.0 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 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 74.1	79.3 79.7	77.7 78.0
US 290	Yoakum	Yoakum 1	8/8/2007	70.4 69.5	74.0 74.8	72.5 73.3
IH-10	Yoakum	Yoakum 6	9/25/2007	71.2 72.8	76.5 77.2	75.0 75.8
IH-10	Yoakum	Yoakum 5	9/25/2007	70.5 69.8	75.1 76.0	73.7 74.5
IH-10	Yoakum	Yoakum 5	8/27/2008	73.2 72.4	77.5 77.7	76.0 76.2
US 281	San Antonio	NB12	9/3/2008	74.5 73.7	79.7 79.0	78.1 77.4
SH 6	Waco	WB1	9/4/2008	69.1 66.7	75.8 75.0	74.4 73.5

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 actual levels recorded with the meter. Figure 5.8 illustrates the pass-by results and the comparison with the TNM predictions.

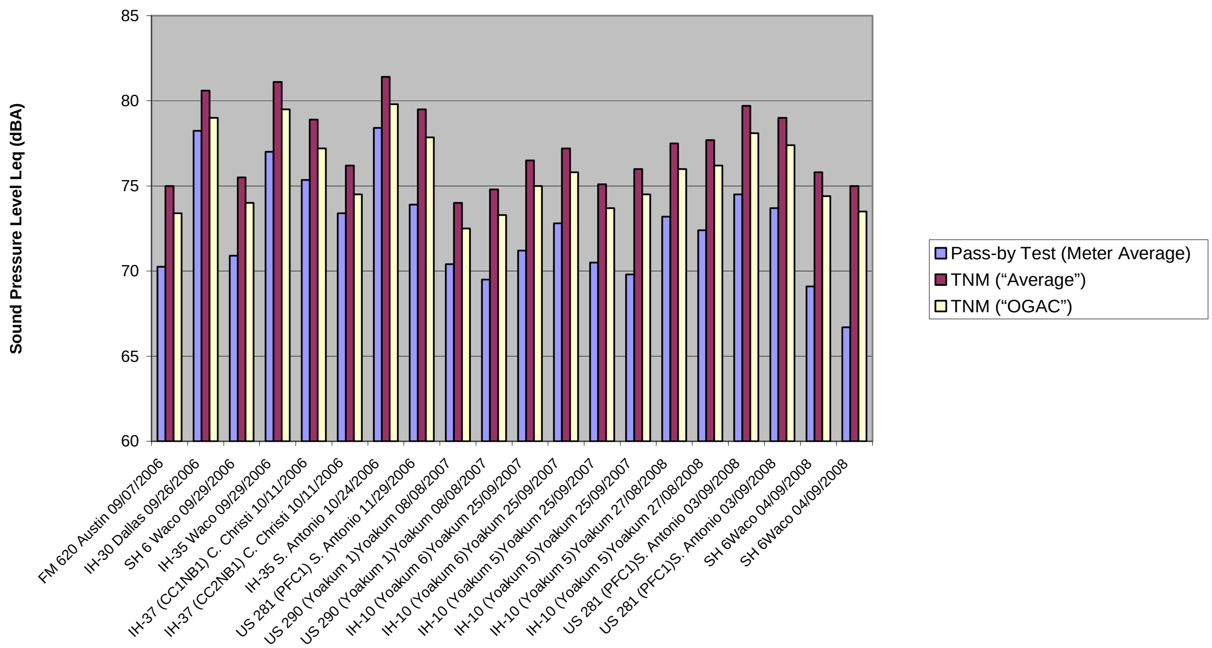

Figure 5.8: Pass-by results versus TNM predictions

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; Differences (in dBA) between Predicted Noise Level and Actual Pass-by Level

Roadway	District	Pass-by Test (Meter Average)	TNM (“Average”)	TNM (“OGAC”)	TNM "Average" - Pass-by (dBA)	TNM "OGAC" - Pass-by (dBA)
FM 620	Austin	70.3	75.0	73.4	4.7	3.1
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	3.5	1.8
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 (PFC1)	S. Antonio	73.9	79.5	77.9	5.6	4.0
US 290 (Yoakum 1)	Yoakum	70.4	74.0	72.5	3.6	2.1
US 290 (Yoakum 1)	Yoakum	69.5	74.8	73.3	5.3	3.8
IH-10 (Yoakum 6)	Yoakum	71.2	76.5	75.0	5.3	3.8
IH-10 (Yoakum 6)	Yoakum	72.8	77.2	75.8	4.4	3.0
IH-10 (Yoakum 5)	Yoakum	70.5	75.1	73.7	4.6	3.2
IH-10 (Yoakum 5)	Yoakum	69.8	76.0	74.5	6.2	4.7
IH-10 (Yoakum 5)	Yoakum	73.2	77.5	76.0	4.3	2.8
IH-10 (Yoakum 5)	Yoakum	72.4	77.7	76.2	5.3	3.8
US 281 (PFC1)	S. Antonio	74.5	79.7	78.1	5.2	3.6
US 281 (PFC1)	S. Antonio	73.7	79.0	77.4	5.3	3.7
SH 6	Waco	69.1	75.8	74.4	6.7	5.3
SH 6	Waco	66.7	75.0	73.5	8.3	6.8
Mean					4.8	3.2
Std. Deviation					1.4	1.4
C. of Variation (%)					29.3	44.6

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 5 dBA, while the "OGAC" pavement option over predicts noise levels by about 3 dBA, on average. These differences are illustrated in Figures 5.9 and 5.10. Figure 5.9 shows the relationship between TNM using the "Average" pavement option and the actual measured values, and Figure 5.10 represents the relationship between TNM using the "OGAC" pavement option and the actual measured values. If the program predictions in both cases were to match the actual measurements, those charts trend lines would be one-to-one relations.

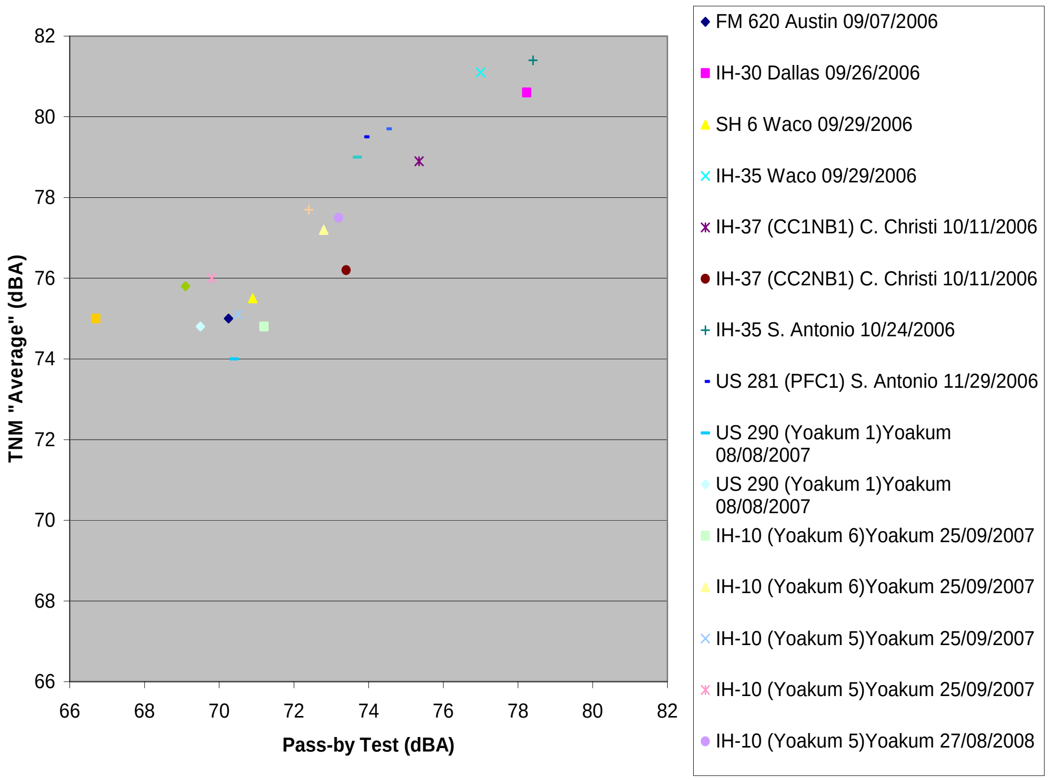

Figure 5.9: Relationship between TNM "Average" prediction and actual pass-by measurements

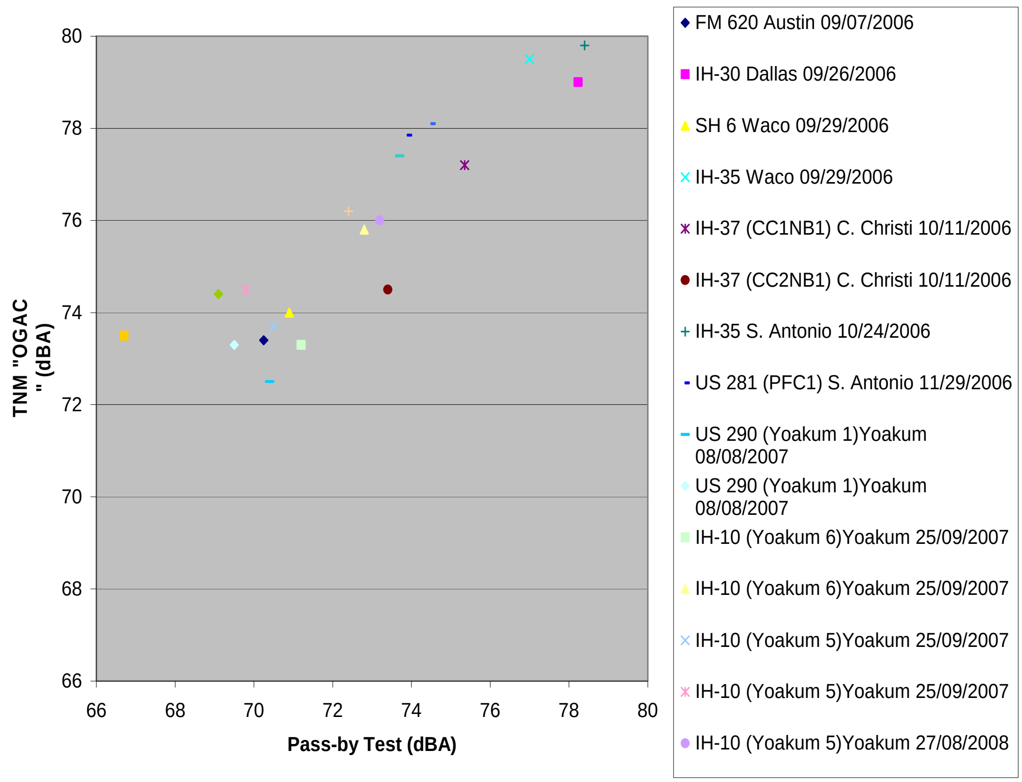

Figure 5.10: Relationship between TNM "OGAC" prediction and actual pass-by measurements

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. Over-predicting noise levels by almost 5 dBA is a considerable amount, and it is an indication that the "average" pavement type option should not be used for PFCs, especially when there is another option already built-in the program that delivers better results which represent more closely what was measured in the field. The fact that even the "OGAC" pavement option over-predicts for the case of all the PFCs studied would suggest that such pavement option in the program could be further adjusted with this type of results to be a better predictor. The results of pass-by measurements obtained in this research should be analyzed towards incorporating them into the REMELs database to improve the TNM program's prediction of open-graded pavements.

The general outcome of these comparisons provide an encouraging basis 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 and impact avoidance. The data gathered in this project offers evidence that the restrictions could be lifted.

5.5 Roadside and OBSI Measurements Correlation

As mentioned in the introduction to this chapter, a foremost objective in this project is to analyze the correlation between roadside measurements and OBSI measurements. If a consistent and meaningful correlation between both types of measurements is established, it will allow OBSI tests, which are faster and easier to perform than pass-by tests, to be used as a predictor of roadside traffic noise. Figure 5.11 presents a plot of OBSI versus pass-by results. As the graph shows, most of the values correspond to PFC surfaces, but as it was observed that values obtained from other pavement types follow a similar pattern that do not deviate from establishing a correlation, it was decided to include them. Thus, the points from US 183 (CRCP), SH 130 (CRCP), and Parmer Ln. (AC) are included in the chart. The fact that these points blend in with the pattern of the PFC points suggests that a correlation between the two methods is independent of the pavement type.

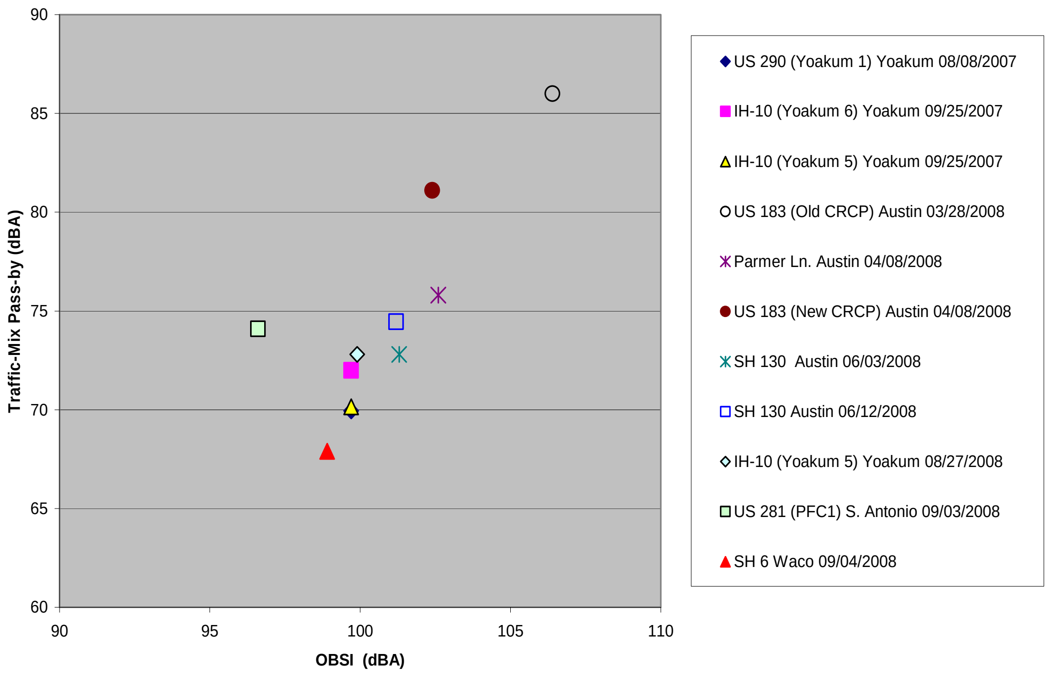

Figure 5.11: OBSI versus pass-by results on various pavement types

In analyzing this graph, it seems that the points describe close to a linear relationship. Interestingly enough, the value that appears to be an outlier in this plot is the one that corresponds to the quietest section measured in the project, US 281 in San Antonio (PFC1). It is its quietness in the OBSI results that make it depart from an otherwise linear behavior exhibited by the other data points. Two linear regression equations were calculated for the data from Figure 5.11, using two different approaches, relationships which are shown in Figure 5.12.

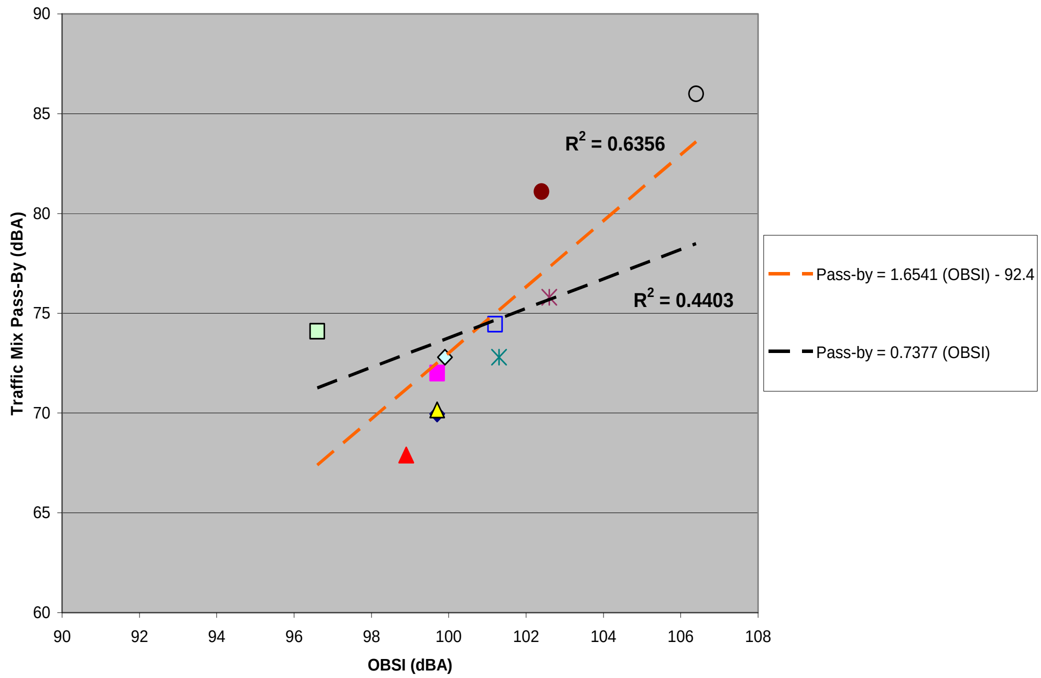

Figure 5.12: Linear regression of traffic mix pass-by and OBSI

On average, the offset between the OBSI and the traffic mix pass-by sets of data is 26.5 dBA. If this offset were used to predict the pass-by results from the OBSI data, the measurements that deviate more from such prediction would be those taken on CRCP, from US 183 (for both the old and the new groups of sections). If the two CRCP segments are not taken into account for the computation of the offset, the new number would be 27.7 dBA.

Another field noise test that was performed on occasion to contribute to analyze the correlation in question was the individual pass-by run, which can also be referred as a controlled pass-by. For this test, the setup of the equipment was the same as described for the pass-by tests, but the difference is that instead of measuring the traffic noise generated by the traffic mix traversing the test section for a period of time, only a single vehicle, in this case, the CTR test vehicle, passed by the microphones at a known speed (60 mph). A single, instantaneous reading on the noise meter is taken for this individual event. The reason this test could not be performed in every road on every occasion is because in many of the busy roads it was impossible to find a suitable gap in the traffic that would allow isolating the noise generated by a single vehicle without having traffic control. Only on five roadways could this test be performed, namely, US 290 (Yoakum 1), SH 130 in Austin, Parmer Ln. in Austin, IH10 Yoakum 5, and SH 6 in Waco. The graph displaying these results compared to their respective OBSI measurements is shown in Figure 5.13. Again, this chart includes a CRCP (SH 130) as well as an AC pavement (Parmer Ln.) among the other values of PFCs, showing that the relationship can include any pavement type without affecting the outcome in any significant way.

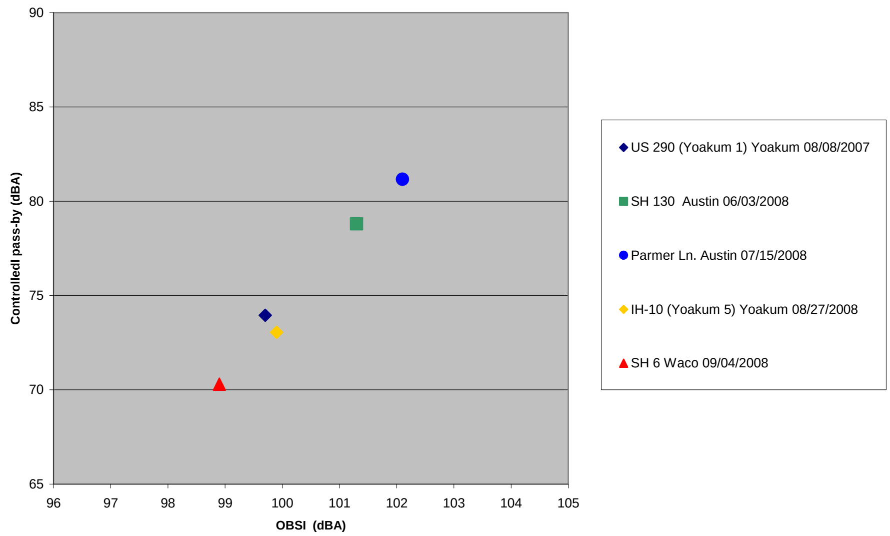

Figure 5.13: OBSI vs. Controlled pass-by tests

The graph of OBSI versus individual pass-by events shows that the data points are aligned in a very linear fashion, which predicts a good correlation. The regression equation is shown in Figure 5.14, in which R^2 is 0.98.

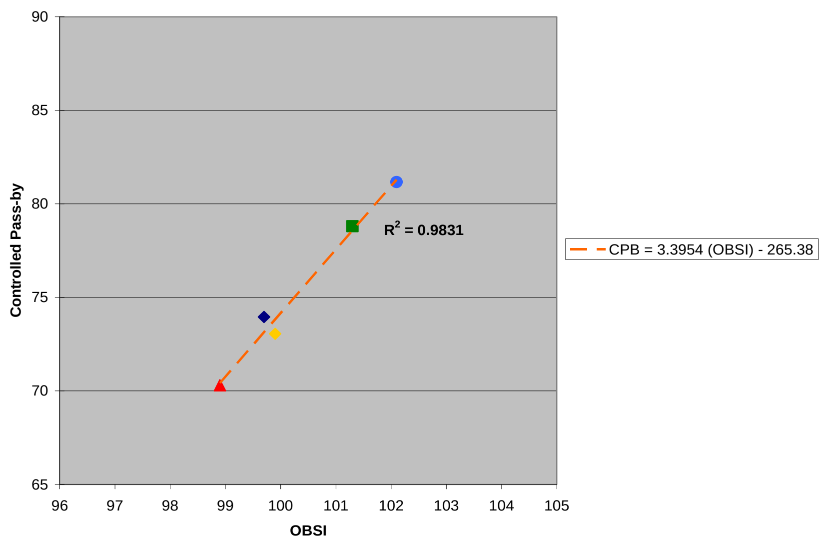

Figure 5.14: Linear regression of controlled pass-by and OBSI

The previous correlation shows that OBSI can be used to predict the results of controlled pass-by tests with a high degree of certainty. There is a fairly consistent offset between both sets of measurements which on average is 24.9 dBA. It is interesting to notice that if the pass-by results were to be predicted from this offset and the OBSI tests, the measurements on PFC surfaces, in this case, are the ones that remain closer to such prediction, while those that correspond to CRCP and AC pavements depart slightly more from the prediction based on the offset.

5.6 Summary

In this chapter, the results of the comparisons performed between the actual roadside measurements and the predictions of such measurements calculated with the TNM program have been presented. Under current FHWA policies, only one of the TNM pavement type characterization options is available, which is denominated as “Average” pavement. However, for research purposes, an additional option has been made available within TNM for open-graded pavements, called “OGAC.” Comparisons of the actual measurements were analyzed utilizing both pavement type options. The experimental results obtained on PFC pavements in this project indicate that the TNM program over-predicts noise levels with either program option. The “Average” pavement option in TNM over predicts noise levels by almost 5 dBA, while the “OGAC” pavement option over predicts noise levels by about 3 dBA, on average. These figures suggest that the “Average” option is not optimal for calculations corresponding to PFC pavements and also that, while the “OGAC” option represents an improvement toward a more accurate prediction, the values within the program on which the calculations are based (REMELs) could be adjusted with results such as those gathered in this study.

The results of this study support the use of pavements such as PFC as “OGAC” in TNM, which could result in the avoidance of noise impacts.

Chapter 6. Special Case Studies

6.1 Introduction

This chapter presents the experimental work that was performed on several pavement sections that were not necessarily considered as the primary focus of this research project, but that offered valuable insight both on noise measurements and pavement acoustic performance. The first part of this chapter analyzes the work conducted on three highways which offered the opportunity to evaluate the acoustic performances of different pavement surfaces. The second part of this chapter presents a summary of the work conducted on rigid pavements throughout this project.

For the first part, the roads in question in the case studies were a segment on IH-30 in downtown Dallas that, at the time was a CRCP about to be overlaid with a PFC; the other two pavements were a fairly new rigid pavement in the Austin area, SH 130, and a segment on IH-35 that goes through downtown Waco, which includes various sections of different types of pavements. The noise measurements conducted included the two main tests that were implemented throughout this project, the on-board sound intensity (OBSI) measurements, and pass-by tests from the side of the road, performed on SH 130. Roadside measurements from SH 130 were compared with the results predicted by a computer program, the Traffic Noise Model (TNM), by means of the procedure explained in detail in Chapter 5 of this report.

The highway segment of IH-30 going through downtown Dallas is a very busy road that had noise problems as a uniformly transversely tined CRCP surface. In an effort to mitigate such problem, it was suggested to overlay a short segment of it with a PFC, situation which offered the researchers an opportunity to test both surfaces.

The new SH 130 is a 49-mile toll road that extends from IH-35, just north of Georgetown to US 183 southeast of Austin, passing through Williamson and Travis Counties. The segment that was tested is the northernmost. The pavement is also uniformly transversely tined CRCP. This roadway was visited on several occasions. This offered the opportunity to compare the various results and verify their repeatability. For some time, the researchers have been tinkering with an idea that might expedite the way OBSI tests are normally conducted, by introducing slight modification to tests, with encouraging results so far. This modification, involving the positioning of the microphones during the measurements, was experimented again on this road.

The IH-35 segment in Waco is a busy downtown set of sections of rigid pavement that has had different overlays and surface treatments. Part of this section is a PFC that was visited and measured in 2006. Next to this older PFC is a brand new PFC. Also adjacent to these sections are short segments of the old CRCP that have been treated by diamond grinding to improve its texture, as well as untreated concrete segments that show some distresses. Thus, the loop that was tested includes old PFC, new PFC, old CRCP, and textured CRCP sections.

The following paragraphs present the work conducted on each of the highway sections, including the work conducted on the Dallas pavement both prior to the PFC overlay as a CRCP surface, and after the overlay, the OBSI and roadside results for SH 130, the OBSI microphone positioning experiment on SH 130, as well as the results from the IH-35 OBSI measurements. Finally, comparisons between the SH 130 and Waco CRCP sections are also shown, followed by a summary of measurement on rigid pavements.

6.2 IH-30 in Dallas

The first pavement tested in this project by means of the OBSI Method 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 6.1 shows the map of the project location.

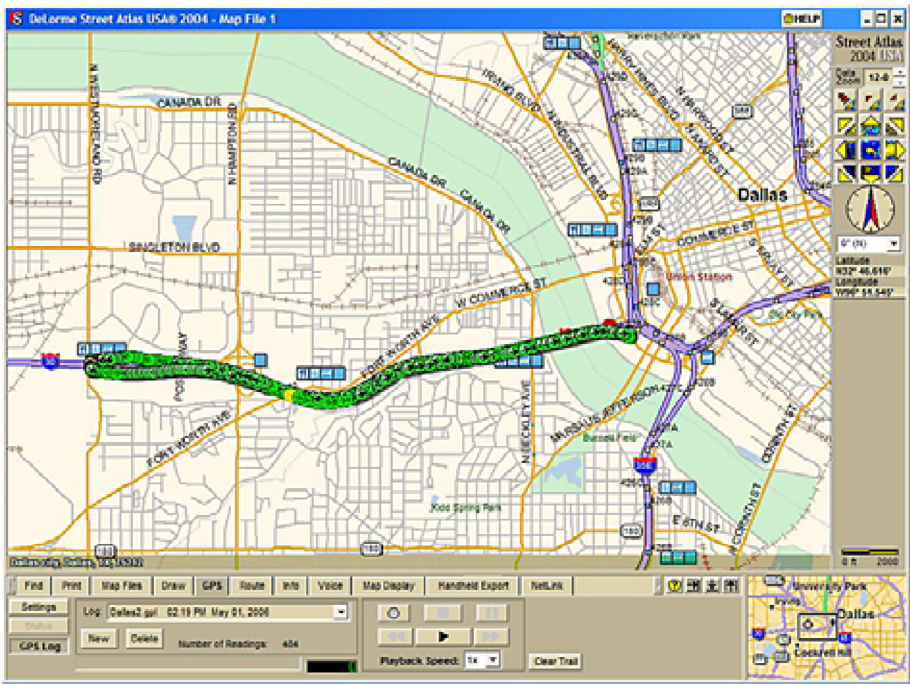

Figure 6.1: Map of IH-30 in Dallas, showing the loop driven while performing the OBSI tests

A picture of the beginning of the westbound segment, west of Sylvan Ave., at exit 43 A, is presented in Figure 6.2, where the change in pavement type can be seen, from AC to CRCP.

Figure 6.2: Beginning of IH-30 CRCP westbound section

6.2.2 Tests on CRCP

Three subsections were tested, two in the westbound direction and one in the eastbound lanes. 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 6.3.

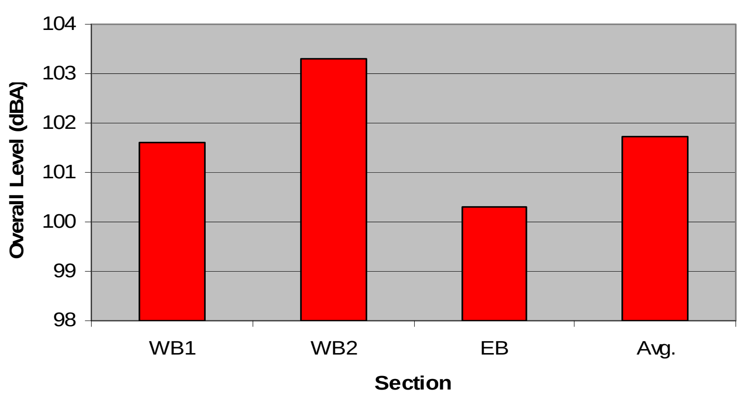

Figure 6.3: Overall noise levels for IH-30 CRCP Sections in Dallas

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. Perhaps the results of this subsection are influenced by a noise reflection problem.

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 6.4.

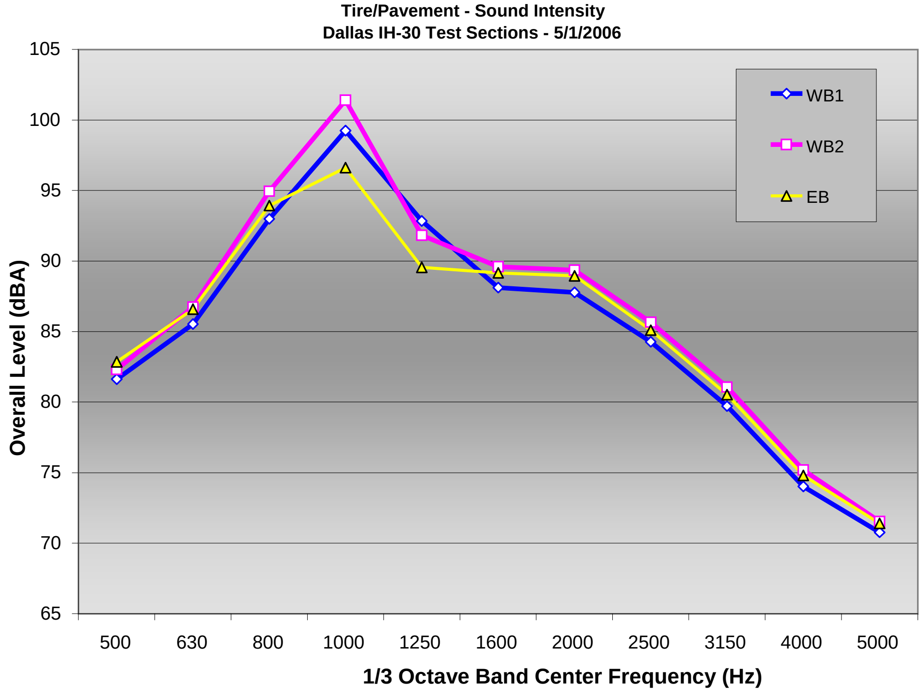

Figure 6.4: Spectral analysis for the Dallas IH-30 CRCP sections

6.2.3 Tests on PFC

The pavement was overlaid on May 11, 2006, shortly after the first round of tests was completed on the CRCP. The research team visited the section once the PFC overlay was already in place, on September 26, 2006, to conduct the OBSI tests on the new surface (Figures 6.5 and 6.6).

Figure 6.5: Texture of the new PFC overlay on IH-30 in Dallas

Figure 6.6: 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 for the September 2006 tests are shown in Figure 6.7.

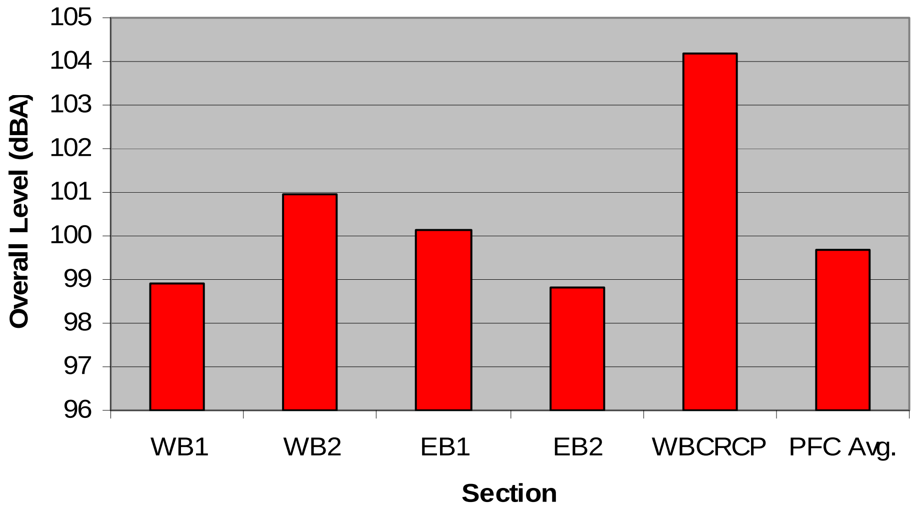

Figure 6.7: Overall noise levels from IH-30 PFC in Dallas

The spectra for each subsection are presented in Figure 6.8, where, as expected, the pattern of the PFC spectra are quite different from that of the CRCP, which, as observed in the various tests conducted on uniformly transversely tined CRCP throughout this project, has a characteristic peak in the 1000-Hz frequency band.

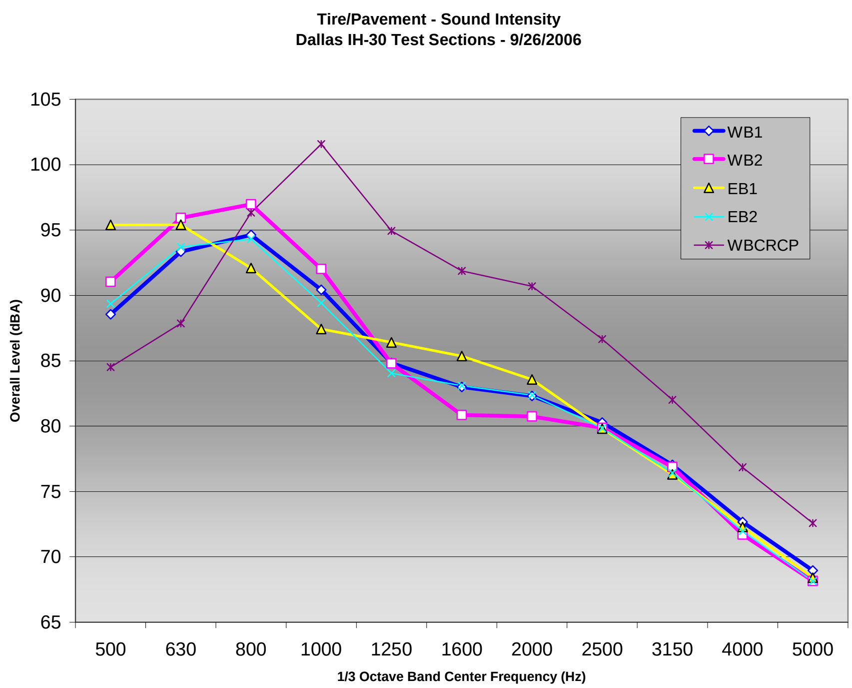

Figure 6.8: Spectra for the IH-30 Dallas PFC project and the additional CRCP section

The overall sound level comparison from before (CRCP) and after (PFC) is illustrated in Figure 6.9, which shows that the PFC fulfilled its purpose of making the pavement quieter, especially in the westbound lanes, which experienced a reduction of more than 2 dBA. The eastbound direction PFC was quieter as well, but the original CRCP in this direction was not as loud as the westbound, so the attenuation provided by the PFC overlay was not so significant. As expected, the WBCRCP section had a high measured value (higher than 104 dBA) because it was still a concrete pavement segment, which extends beyond the limits of the rehabilitation project, and therefore, such value is comparable to those obtained on the CRCP during the May 2006 tests. The noise reflection issue by the adjoining retaining wall could still be occurring with the new PFC in subsection WB2, as that subsection remains as the loudest among the subsections in this project, but the PFC has provided significant attenuation.

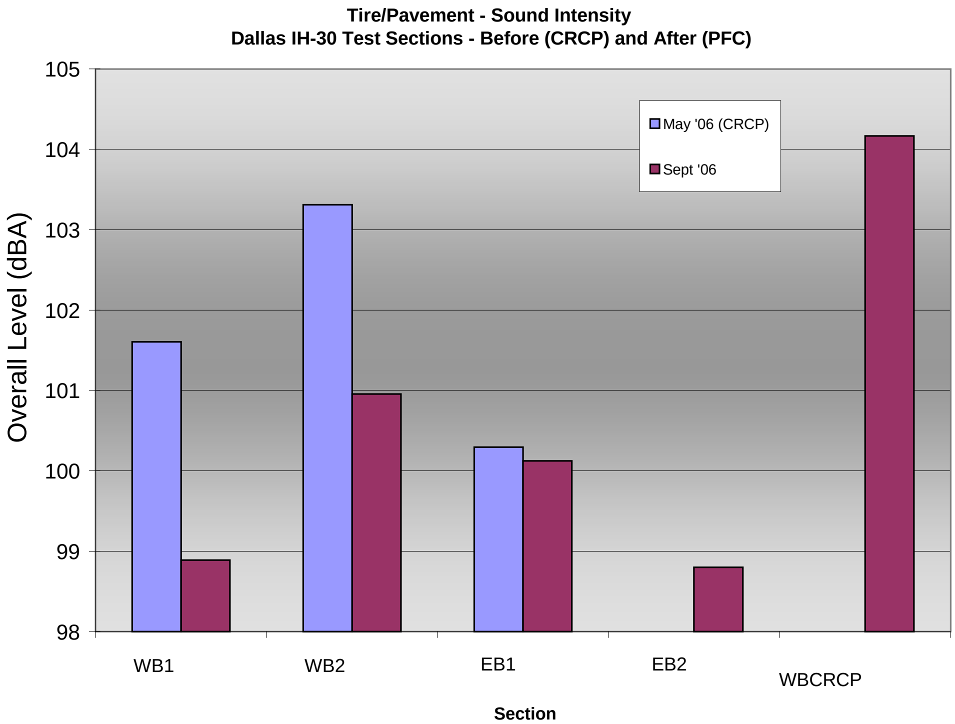

Figure 6.9: Overall level comparison for the IH-30 Dallas project before and after PFC overlay

In comparing the 1/3-octave band spectra for the two occasions (Figure 6.10), 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.

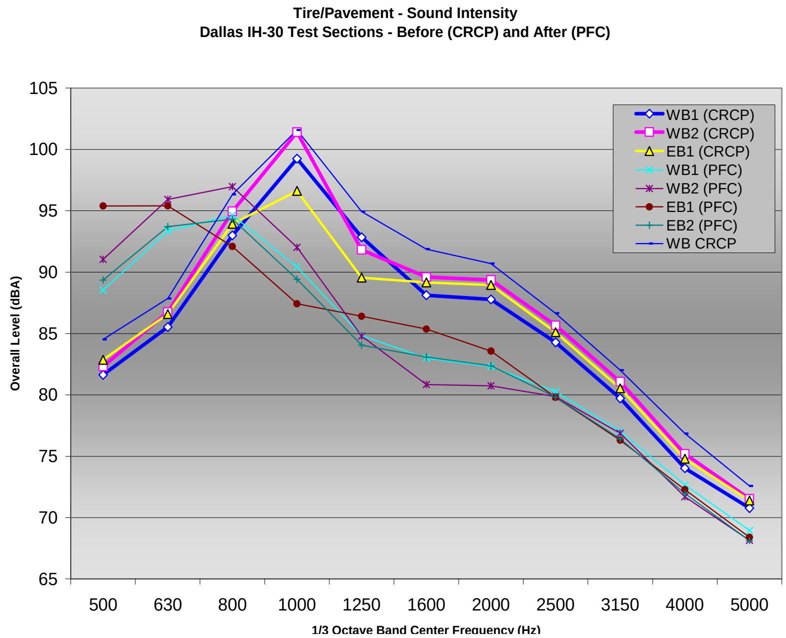

Figure 6.10: Spectra comparison for the IH-30 Dallas project before and after PFC overlay

The porous texture of the PFC is very different from the stiff, slicker texture of the CRCP and this explains their different spectra. The peak of the CRCP in the 1000-Hz band is associated to the whining sound caused by the uniform transverse tining that these pavements normally feature on their surfaces in Texas. Thus, it is not just the overall levels that are attenuated when a PFC pavement is in place as opposed to a CRCP, but mainly, the different frequency distribution that changes the perception of the sound from the receiver standpoint that, in general, makes these pavements quieter.

As a reference, the IH-30 PFC overall level average (99.7 dBA) leans toward the louder range among the PFCs measured in this project. Of a total of 36 overall averages, when sorted from quietest to loudest, this PFC ranks as the 25th, ranking in which the quietest average is 94.7 dBA and the loudest is 101.7 dBA. However, it can still be considered an average PFC, as it is part of the vast majority of measurements that lie between 98 and 100 dBA, which encompasses 58 percent of the PFCs measured in this project (see Section 4.4.1 for the discussion on overall PFC rankings).

6.3 State Highway 130

On May 28, 2008, a first scouting trip was taken to identify some sections within the segment between US 290 and Georgetown, i.e., the north segment of the highway. This segment opened to traffic in late 2006. Figure 6.11 shows a map of SH 130. Figure 6.12 shows a general view of the roadway, its geometry and traffic.

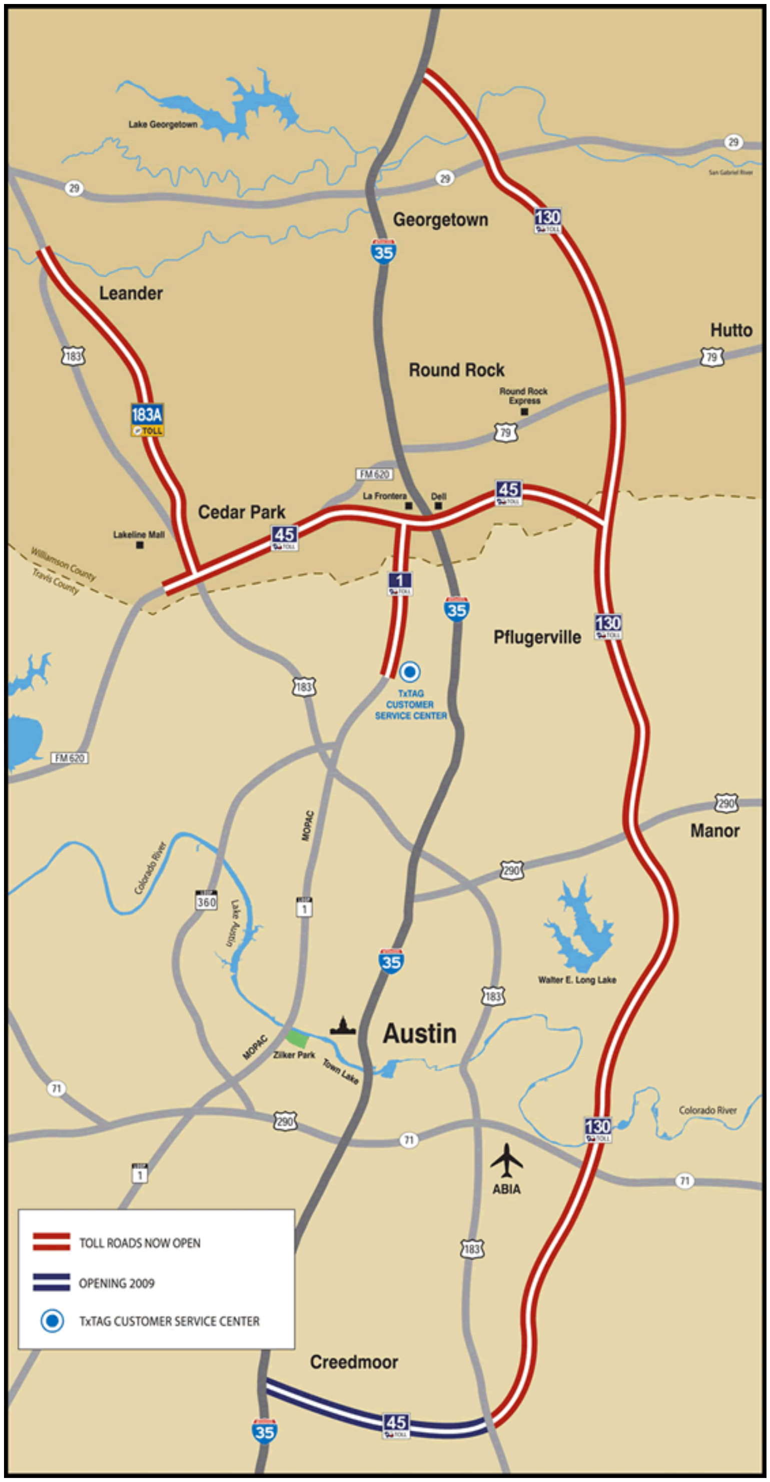

Figure 6.11: Map of SH 130

Figure 6.12: View of SH 130

The pavement in all sections identified is uniformly transversely tined CRCP, and it is in very good condition. As the picture shows, the traffic on the road can be considered light. Figure 6.13 shows a close view of the pavement condition, which is representative of the overall condition of the roadway.

Figure 6.13: Uniformly transversely tined CRCP on SH 130 in Austin

The sections were selected based on the criteria for OBSI, which include adequate length, fairly straight and flat, no walls or other objects that could reflect noise, and away from other sources of noise such as frontage roads. These criteria also suit the needs of an adequate location for pass-by tests, especially the distance to frontage roads. This was a problem with the other CRCP highway that was tested in the Austin area as part of this project, US 183 (which results will be presented in the second part of this chapter), where the frontage roads are so close and are also so busy that the sound meters record the noise coming from that traffic as well. The sections that were finally chosen lie from just north of Highway 79 and IH-35 near Georgetown. Two sections were chosen in the northbound direction, NB1 and NB2, and three in the southbound direction: SB3, SB1, and SB2.

6.3.2 OBSI Tests

On June 2, 2008, the first set of OBSI tests was performed on SH 130. The overall results of this set of tests are shown in Figures 6.14 and 6.15. The average level for all five sections was 101.3 dBA.

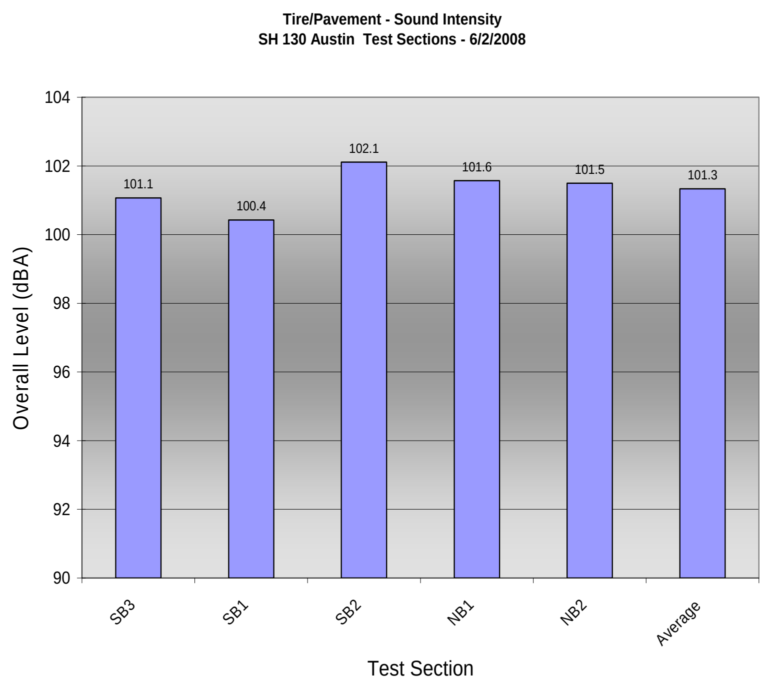

Figure 6.14: SH 130 overall sound levels for June 2, 2008 tests

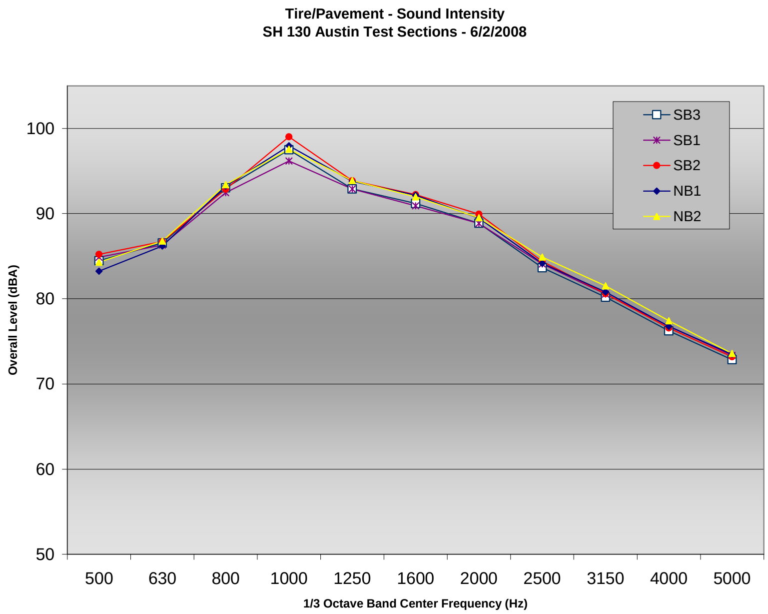

Figure 6.15: SH 130 OBSI spectra for June 2, 2008 tests

The shape of the spectra is very similar for all the sections, and it is also consistent with that of other uniformly transversely tined CRCP sections: they all have a peak for the 1000 Hz frequency.

On June 12, 2008, a second set of OBSI tests was conducted on the same five sections, to verify the consistency and repeatability of the previous results, and also to conduct some additional testing, trying a slight variation in the OBSI procedure. The results of the OBSI standard procedure tests are shown in Figure 6.16, where it can be seen that the average of all sections was 101.2 dBA, i.e., there was only 0.1 dBA difference from the previous set of tests. Figure 6.17 compares the data from both dates of OBSI tests on SH 130, showing very little difference between them. These are positive results from the standpoint of the repeatability of the tests.

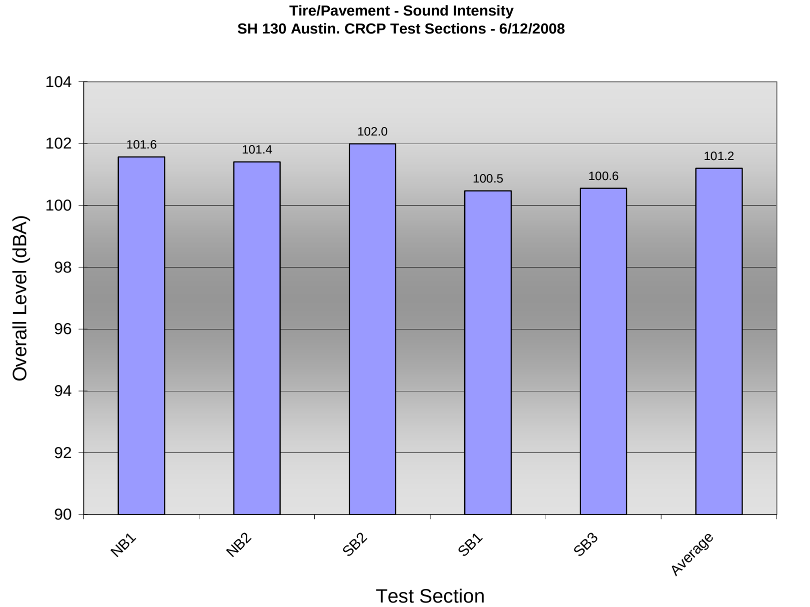

Figure 6.16: SH 130 overall sound levels for June 12, 2008 tests

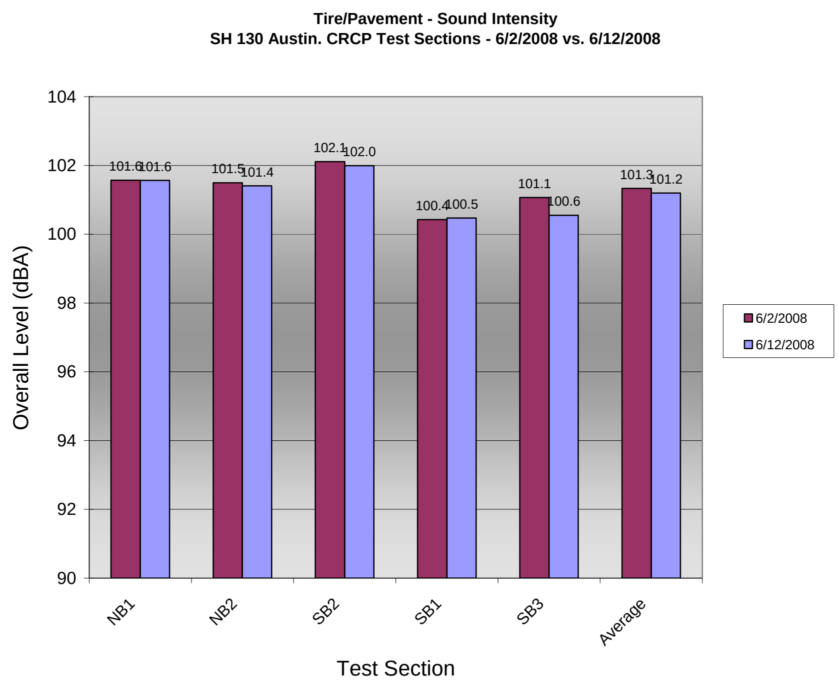

Figure 6.17: SH 130 overall sound levels for 6/2/2008 and 6/12/2008

6.3.3 Microphone Position Experiment

Normally, for OBSI, the microphone probe is placed at two different positions relative to the tire: at the leading edge of the tire/pavement contact patch and at the trailing edge of the patch. Leading edge runs and trailing edge runs are then averaged, resulting in the "tire average," which is reported as the outcome of the test. In the field, a series of runs are performed first with the microphones in either position, while the loop encompassing the test sections is driven on several occasions, until at least two or three sets of runs are collected for each test section. Then, the microphone position is switched to the other edge, and the procedure is repeated. This makes conducting OBSI tests a time consuming endeavor. The researchers have thought about conducting the tests at a single position, at the center of the tire/pavement contact patch and checking how the results would compare to a tire average of both edges. If the results are comparable, this alternative could save time and resources while conducting these tests, especially if the intent is testing at a network level, in which performing a large number of tests in shorter time is a priority. In the past, this alternative was experimented in a series of PFC sections in Yoakum, on IH-10, back in September of 2007, with very encouraging results. As a reference, the overall sound level comparison between the average of leading and trailing edges measurements and the center of the tire/pavement patch from the Yoakum sections is shown in Figure 6.18.

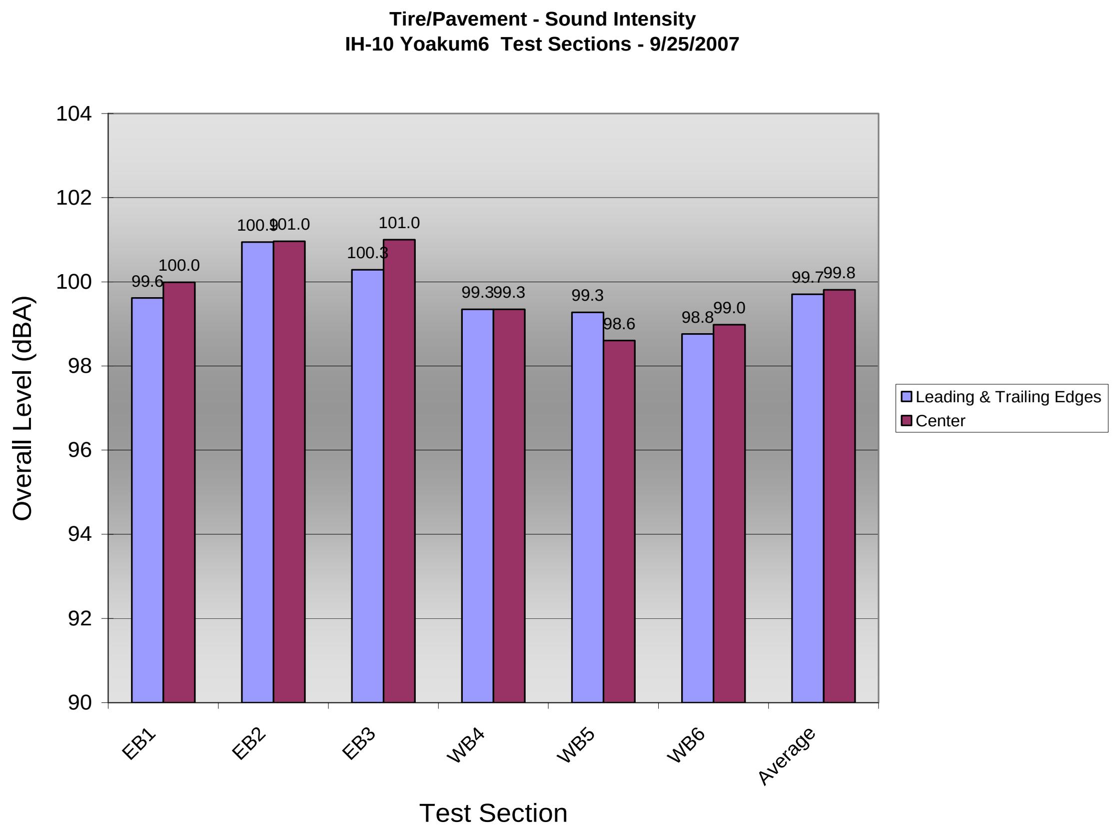

Figure 6.18: IH-10 Yoakum microphone probe position comparison between leading and trailing edges and the center of the tire/pavement patch

The maximum difference between leading and trailing edges and the center of the tire/pavement patch on that occasion was 0.7 dBA, and it occurred in Section WB5. The average difference for all sections was 0.1 dBA.

The microphones at the center of the tire/pavement patch experiment was performed again on SH 130 during the June 12th, 2008 OBSI runs. The results are not as close to the tire average as the Yoakum experiment was, but are still very reasonable and show that this could be a viable alternative in the interest of saving time. Figure 6.19 presents the comparison, showing that the measurements at the center of the tire patch were lower than the leading and trailing edges measurements, indicating that at least for the case of this pavement, the tire/pavement interface has the edges as the louder spots.

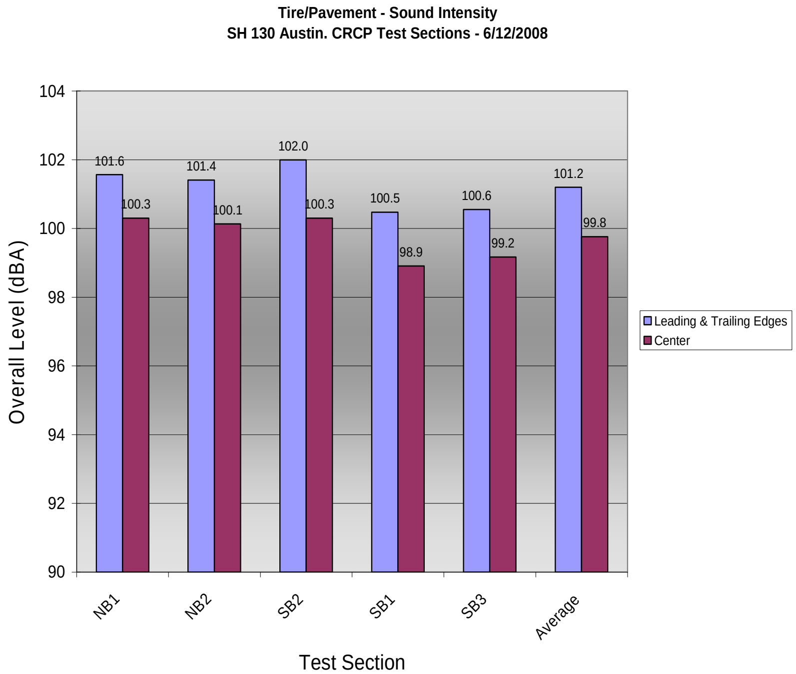

Figure 6.19: SH 130 microphone probe position comparison between leading and trailing edges and the center of the tire/pavement patch

The differences between leading and trailing edges and the center of the tire/pavement patch for the case of each section are illustrated in Figure 6.20, where the maximum difference was 1.7 dBA, for Section SB2, and the average difference was 1.4 dBA.

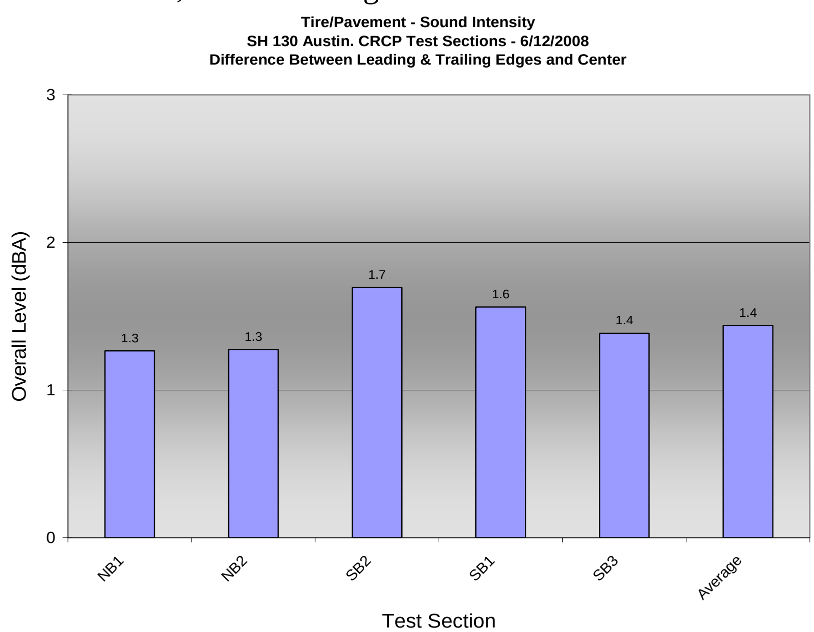

Figure 6.20: SH 130 differences between leading and trailing edges and the center of the tire/pavement patch

6.3.4 Roadside Tests

Two sets of roadside tests were performed on SH 130 following the procedure described in Chapter 5: on June 3, 2008, one 10-minute period of pass-by was recorded, and on June 12, 2008, two 10-minute periods were recorded. Traffic was counted with the aid of a video camera, and the speed of every vehicle was registered by the radar, which was taped as well. The equipment set-up is presented in Figure 6.21, where two sound meters, the video camera and the speed radar can be seen. The two sound meters are placed at 7.5 m and 15 m, respectively, from the center of the outside traffic lane.

Figure 6.21: Equipment set-up for pass-by tests on SH 130

An example of how the individual speeds are recorded is shown in a screen capture from the video taken during the roadside test (Figure 6.22).

Figure 6.22: Speed recoding for pass-by test on SH 130

On June 3, only the 7.5-m microphone measurement could be obtained. Table 6.1 shows the summary of the traffic information gathered both days.

Table 6.1: Traffic information from roadside tests on SH 130

6/3/2008	Autos		Medium Trucks		Heavy Trucks		Motorcycles	
	V veh/hr	S mph	V veh/hr	S mph	V veh/hr	S mph	V veh/hr	S mph
NB Outside Lane	72	69.1	12	60.5	6	65	0	0
NB Inside Lane	84	66.6	0	0	24	61	0	0
SB Inside Lane	84	66.6	0	0	24	61	0	0
SB Outside Lane	72	69.1	12	60.5	6	65	0	0

6/12/2008 1st Measurement	Autos		Medium Trucks		Heavy Trucks		Motorcycles	
	V veh/hr	S mph	V veh/hr	S mph	V veh/hr	S mph	V veh/hr	S mph
NB Outside Lane	60	63.4	6	55	36	59.5	12	61
NB Inside Lane	78	61	12	64	6	56	6	66
SB Inside Lane	78	61	12	64	6	56	6	66
SB Outside Lane	60	63.4	6	55	36	59.5	12	61

6/12/2008 2nd Measurement	Autos		Medium Trucks		Heavy Trucks		Motorcycles	
	V veh/hr	S mph	V veh/hr	S mph	V veh/hr	S mph	V veh/hr	S mph
NB Outside Lane	66	61.9	24	61	36	57.7	6	51
NB Inside Lane	78	66.8	0	0	18	62.7	0	0
SB Inside Lane	78	66.8	0	0	18	62.7	0	0
SB Outside Lane	66	61.9	24	61	36	57.7	6	51

The results of the roadside tests were compared to those predicted by the computer model. The FHWA's Traffic Noise Model (TNM) is used for this purpose. The roadway's geometric configuration, traffic type and counts, and vehicle speeds are all inputs for the computer program. The program has options to characterize the pavement type: a rigid pavement can be modeled as "average," or as "PCC." However, at this stage, because of the current FHWA restriction on the use of pavement type as a noise-reduction alternative, only the "average" selection is available to the public. For research purposes, the "PCC" pavement option is enabled in the program, and was investigated in this case. The detailed results from TNM are contained in Appendix B.

Table 6.2 summarizes the results of the roadside tests on SH 130 and the comparison with the TNM results utilizing both average and PCC as pavement types.

Table 6.2: Roadside measurements and comparison with TNM

Date	Measurement	Pass-by		TNM		Difference Pass-by vs. TNM	
		Microphone Distance (m)	Measured Leq (dBA)	TNM "Average" (dBA)	TNM "PCC" (dBA)	Measured - "Average" (dBA)	Measured - "PCC" (dBA)
6/3/2008	1	7.5	72.8	70.6	72.3	2.2	0.5
		15	-	66.5	68.1	-	-
6/12/2008	1	7.5	73.7	71.9	73.1	1.8	0.6
		15	68.4	68.1	69.1	0.3	0.7
	2	7.5	75.2	72.3	73.6	2.9	1.6
		15	69.9	68.2	69.4	1.7	0.5
					Mean	1.8	0.8
					Std. Dev.	1.0	0.5
					C. of V. (%)	53.5	59.7

As Table 6.2 shows, in all cases, the PCC pavement option delivered results that are closer to the actual measurements obtained with the sound meters, while the average option always underestimated the actual sound pressure levels. Given that the "PCC" option is not enabled yet to use by the general public, these results support making it available. This is an analogous case to the observations detailed in Chapter 5 of this report, regarding the use of the open graded option of the TNM program to characterize PFC pavements. In both cases, the use of the more specific pavement type option provides better results that more accurately characterize the pavement type than the more general "average" pavement type option.

6.4 IH-35 in Waco

The pavement section in Waco was first visited in September 2006. On that occasion, the focus was the measurement of the PFC near downtown. This pavement section is located on IH-35 at Craven Ave., in McLennan County, and was placed in 2003, consisting of 1 ½ in.-thick PFC. On June 5, 2008, the section was visited again, but this time the objective was twofold: measuring the diamond-ground CRCP adjacent to the aforementioned PFC, and following up on the measurements of the PFC from 2006. Dr. German Claros, from TxDOT, had recommended the researchers to get measurements on this textured segment. However, the scouting of the section prior to the actual tests to identify sections indicated that the textured section was very short and there were not many suitable subsections that could be identified for OBSI tests, and also that a segment of the old PFC placed in 2003 had been overlaid with a newer PFC. This was an interesting finding, because in addition to the original PFC, measurements could be taken on the new PFC, as well as on textured and non-textured CRCP sections. Figure 6.23 shows a map of the Waco sections on IH-35.

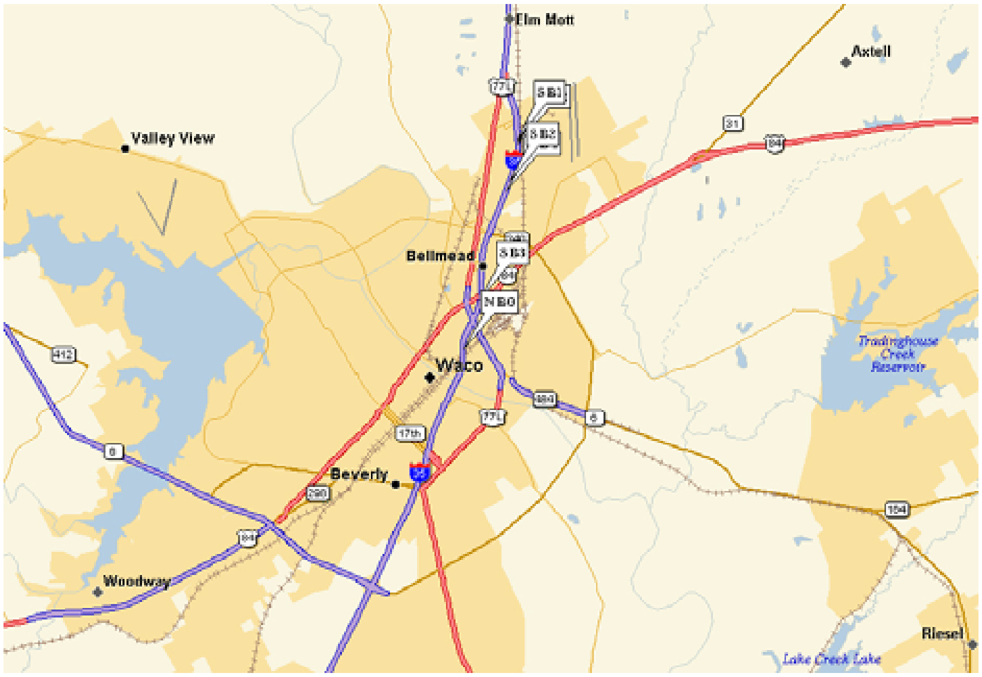

Figure 6.23: Map of the Waco sections on IH-35

The textured CRCP sections on IH-35 occur in both directions, beginning at the Brazos River and ending at Behrens Circle. The texturing work was performed in the summer of 2007, according to information obtained from Mr. Billy Pigg, District Materials/Pavement Engineer, in Waco.

For comparison purposes, the OBSI results from the September 2006 tests on the original PFC are presented in Figures 6.24 and 6.25 (overall sound levels and frequency spectra, respectively). On that occasion, two northbound and two southbound sections, and an additional northbound section of dense-graded AC were tested.

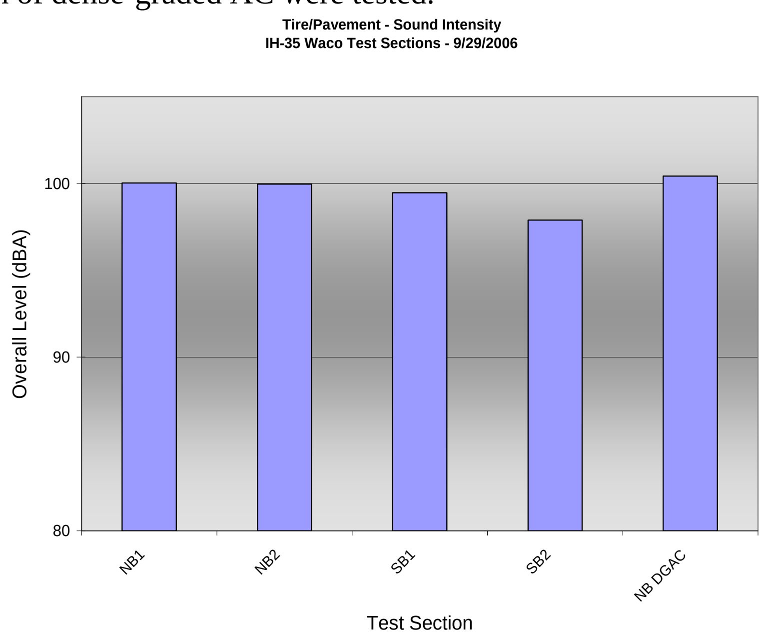

Figure 6.24: Waco IH-35 overall levels from September 2006

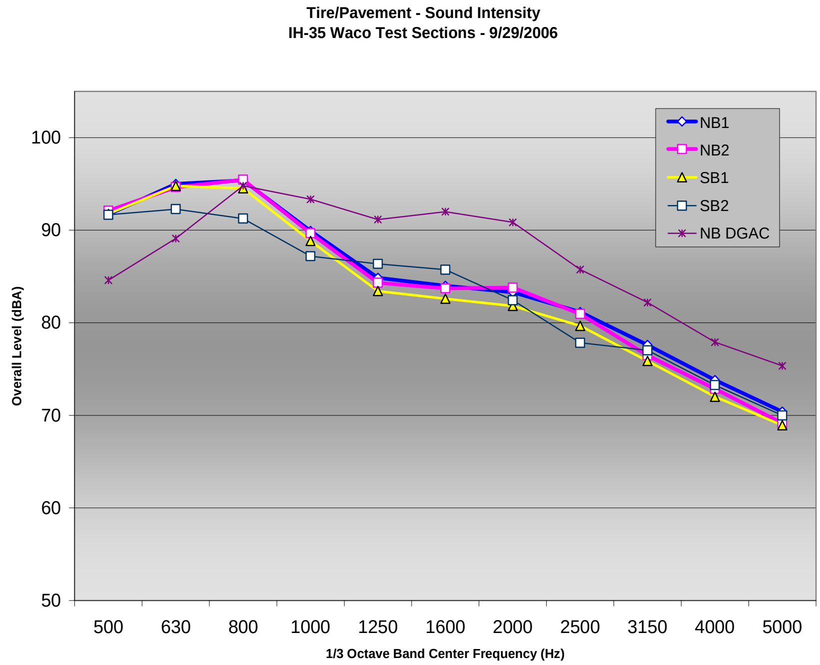

Figure 6.25: Waco IH-35 frequency spectra from September 2006

Table 6.3 shows the sections that were tested on June 5, 2008 and their corresponding pavement type.

Table 6.3: IH-35 Waco sections tested on June 5, 2008

Section	Pavement Type
NB0	Diamond Ground CRCP
NB OC	Non-milled CRCP
NB1	New PFC
NB2	Old PFC
SB1	Old PFC
SB2	New PFC
SB3	Diamond Ground CRCP

From the sections measured in September 2006, only the old PFC sections, NB2 and SB1, could be measured again, as the others had changed due to the placement of a new PFC. The placement date of the new PFC is unknown, and so is the age of the old CRCP. Figure 6.26 illustrates the texture of the old PFC, from a September 2006 picture, and Figure 6.27 presents the comparison of the results from that occasion and the recent tests, which indicates that the PFC was slightly louder in the most recent tests (0.6 and 1.2 dBA, respectively for NB2 and SB1). These differences are small, and might be caused by clogging of the voids of the PFC by debris, possibly compaction, as well as the wear of the surface that occurs with time and traffic, considering that the tests were conducted almost two years apart.

Figure 6.26: Old PFC on IH-35 in Waco, from September 2006

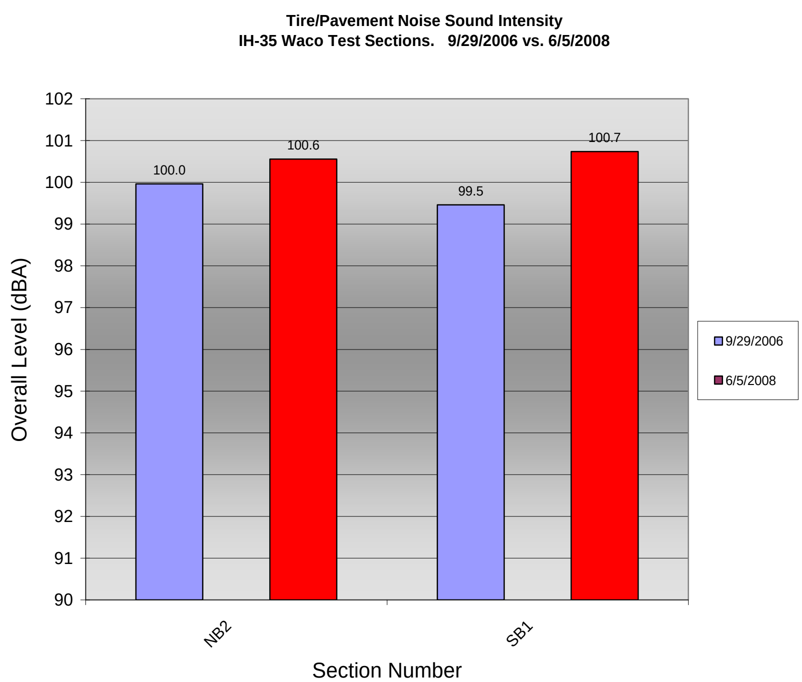

Figure 6.27: Waco IH-35 tests on original PFC

Figure 6.28 illustrates the appearance and distresses of the old concrete pavement section. Notice that the surface is not tined.

Figure 6.28: Old CRCP on IH-35 in Waco

The beginning of the textured concrete pavement is shown on the right side of the photograph in Figure 6.29, while the left side shows non-milled concrete pavement. Figure 6.30 shows a closer view of the improved texture of the diamond-ground surface, which removed the superficial distresses.

Figure 6.29: Beginning of IH-35 northbound diamond-ground section in Waco

Figure 6.30: Texture of the diamond-ground section on IH-35 in Waco

The overall level results and the spectra from the June 2008 tests are shown in Figures 6.31 and 6.32, respectively. The overall levels indicate that the milling on the CRCP had a very positive effect on the loudness of the pavement, as the treated surface was about 2 dBA quieter. The old PFC was as loud as the old CRCP (100.6 dBA on average), which could be considered as a surprising result, given that concrete pavements, in general, are regarded as louder than PFCs. The new PFC was quieter than the old PFC, about 2.5 dBA on average. Regarding the spectra, the CRCP in these cases do not show the characteristic peak that normally occurs at 1000 Hz because the surfaces were not tined. The spectra for the two diamond-ground sections are virtually identical, which indicates that the rehabilitation had the same effect on both sides of the road; also, the milled CRCP shows to be quieter in all frequencies than the non-milled CRCP. This suggests that it is the practice of tining the pavements which gives CRCP that typical whining sound. Even though in this case the CRCP was not originally tined, the tests indicate that diamond grinding could be a viable option to make tined pavements quieter, even if this is only a side effect of what might otherwise be the purpose of such repair.

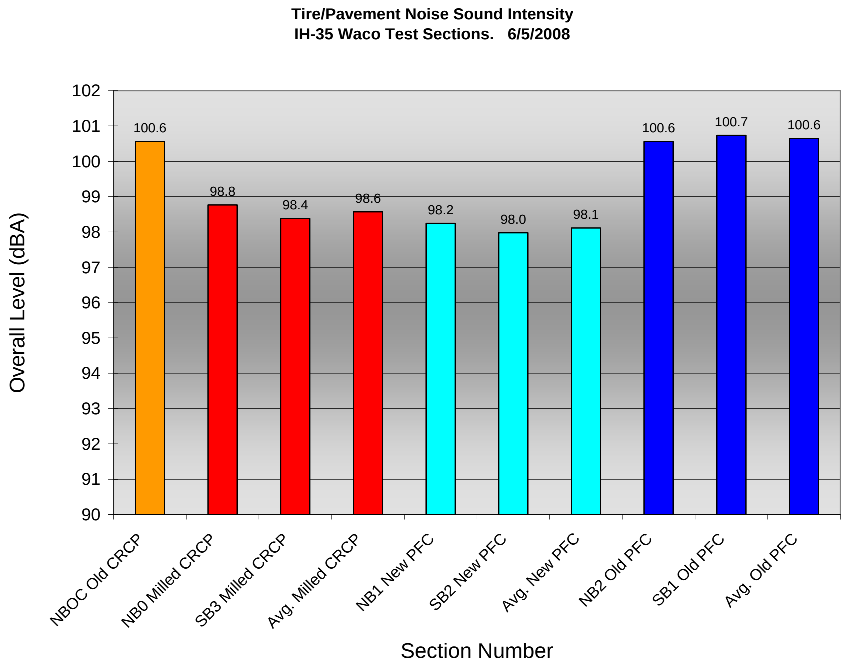

Figure 6.31: Waco IH-35 overall sound levels from June 5, 2008

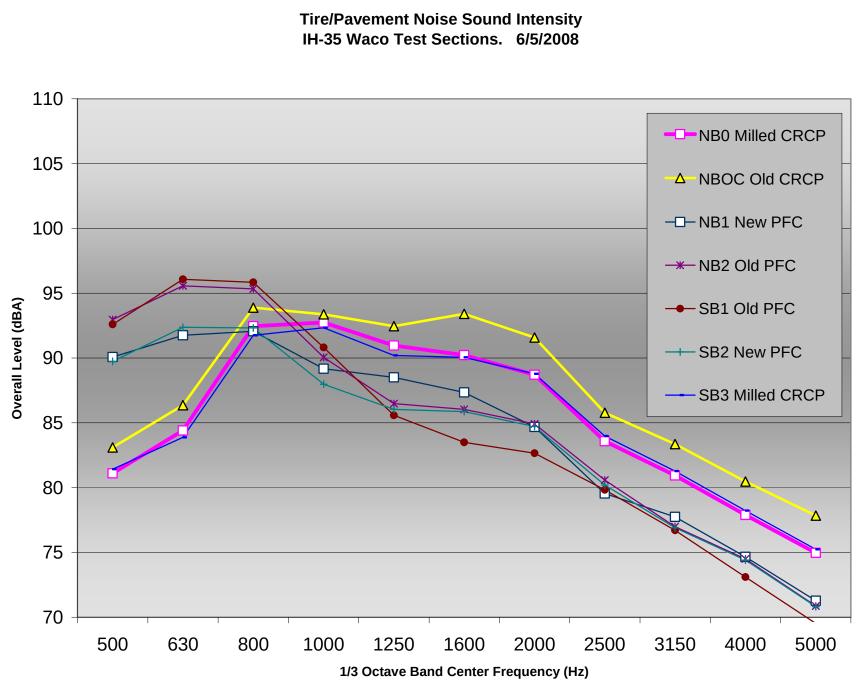

Figure 6.32: Waco IH-35 frequency spectra from June 5, 2008

6.5 SH 130 and IH-35 Waco CRCP Comparison

The tests conducted on these two roads featuring rigid pavements offered the opportunity to compare an almost new uniformly transversely tined concrete pavement with and old, distressed, and heavily-trafficked one with no tining, and also to see what the effect of the diamond grinding that was applied to it has caused to its acoustic behavior (Figure 6.33).

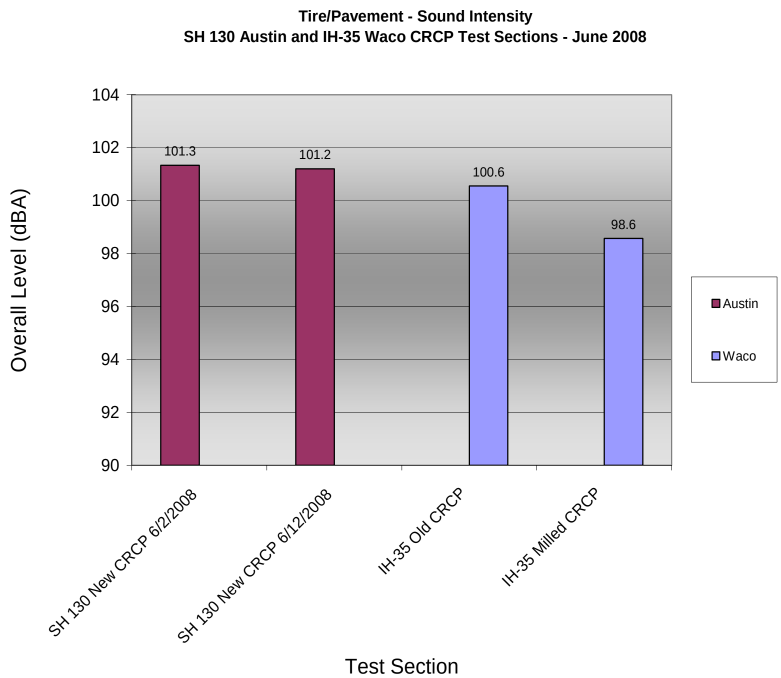

Figure 6.33: SH 130 Austin and IH-35 Waco average sound level comparison

It is interesting to notice that the old CRCP on IH-35 in Waco is quieter than the new uniformly transversely tined CRCP on SH 130, and that the milling that took place on part of the Waco pavement has made it significantly quieter. This implies that the common practice of tining CRCP might be responsible for most of its loudness, as the pavements in question on IH-35 in Waco do not exhibit this pattern in their texturing (Figure 6.34).

Figure 6.34: Non-milled, old concrete pavement texture on IH-35 in Waco

6.6 Summary of OBSI Results on Concrete Pavement Sections

Even though the focus of this project was the acoustic performance of PFCs, it also presented the opportunity to conduct traffic noise measurements on several rigid pavements. Some of those have already been presented in the first part of this chapter. Other concrete pavement sections that were tested as part of this research besides those on IH-30 in Dallas, IH-35 in Waco and SH 130 in Austin, include the various old and new CRCP segments on US 183 on Austin that were part of the Noise Rodeos presented in Chapter 3. Unfortunately, the ages of the CRCP sections studied are not known, except for the newest one, the SH 130 pavement.

The detailed description of the US 183 sections is presented in Section 3.2.3 of this report.

The average OBSI measurements on concrete pavement sections are summarized in Figure 6.35, where the sections have been sorted from low to high overall levels, and have been identified by colors so that tests conducted on different dates for the same sections can be compared. This graph is based on the total averages calculated for each test date for all the subsections involved.

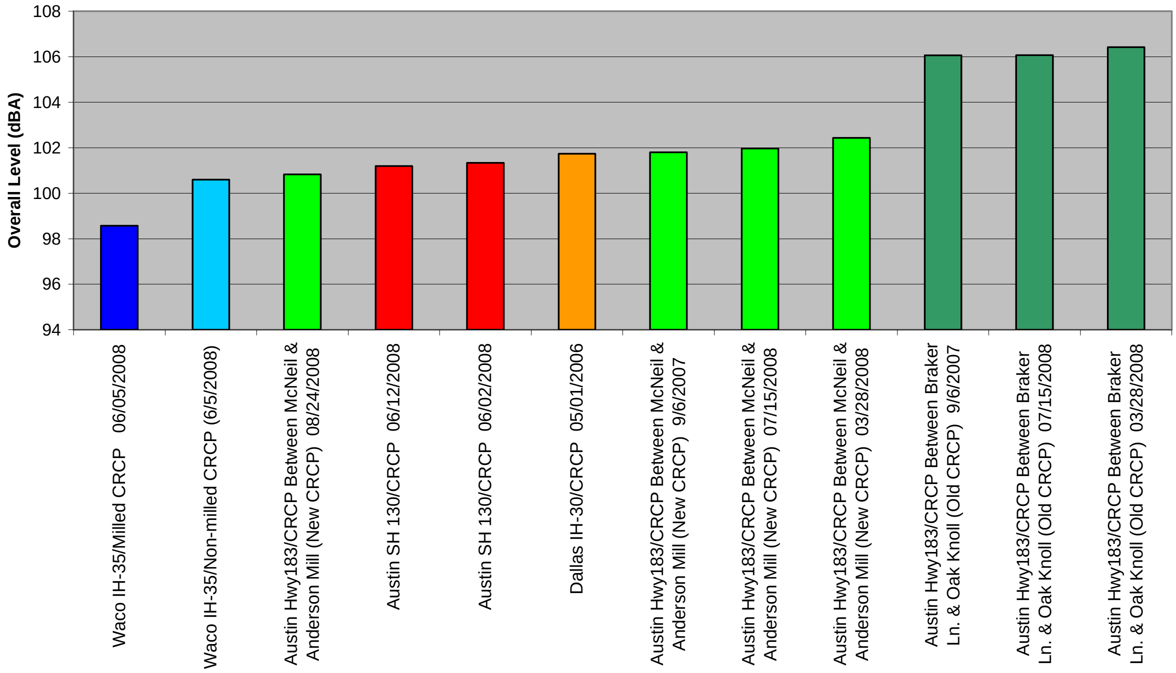

Figure 6.35: OBSI Concrete pavement section comparison

It is interesting to note that the quietest measurement on rigid pavement was obtained from the lone diamond-ground pavement that was tested. Another remarkable finding is that the two quietest measurements on rigid pavements were recorded on surfaces that are not tined. Tining might be responsible for a significant component of the loudness of such pavements as the spectra suggests, and as discussed in the previous paragraphs. Both of those quieter concrete surfaces are the sections on IH-35 in Waco, and as could be seen in the previous sections dedicated to the analysis of those pavements, the non-milled, non-tined pavement is old and exhibited several distresses, facts that apparently are not reflected in the noise levels. Because the diamond-ground section is part of this distressed, old pavement, it can be assumed that the milling treatment applied to it accounts for the 2-dBA reduction when comparing both adjacent segments, making the textured section as quiet, and even quieter than many PFCs. This underscores the effectiveness of the diamond grinding as a noise attenuation treatment for concrete pavements.

The loudest of the measurements on rigid pavements were recorded on the old CRCP sections of US 183, during the rodeo tests. The results from those sections remained very consistent over time, which is true also for the newer CRCP sections of US 183.

6.7 Conclusions

This chapter presented the results of various roadway segments that enabled the comparison of the acoustic behavior of sections of different pavement types. The Dallas IH-30 project is particularly interesting because it showcased the results of two different surfaces on the same road stretch at two different stages: the roadway was originally a concrete pavement (uniformly, transversely tined CRCP), which was overlaid with a PFC, in an attempt to make it quieter. OBSI tests were conducted on the CRCP before it was overlaid, and on the new PFC overlay.

The two sets of test sections on SH 130 and IH-35 in Waco represented a unique opportunity to conduct a series of comparisons between different kinds of pavements, including old and new PFC, old and new CRCP, and textured and non-textured CRCP, as well as to experiment with the OBSI microphone position, and to perform roadside tests and compare their results to those obtained with a computer model (TNM).

From the results and discussion presented in this chapter, the following conclusions can be drawn:

- OBSI tests on IH-30 in Dallas on uniformly transversely tined CRCP, first, and then on PFC, showed that the PFC accomplished its purpose of reducing the noise levels.
- Besides the noise level reduction, the frequency spectra of both surfaces are very different, which might account for a significant reduction in the perceived noise by the receivers.
- Tests on SH 130 conducted within a 10-day span showed good consistency and repeatability of the results
- The microphone position experiment (center of tire/pavement patch instead of leading/trailing edges) produced reasonable and encouraging results. The center position resulted in an average of 1.4 dBA quieter levels as compared to the leading/trailing positions. A similar experiment on the PFC in Yoakum from 2007 resulted in even smaller, almost negligible differences. This indicates that the alternative microphone position results might be closer to the leading/trailing position results for porous pavements, such as the PFC, as opposed to the rigid, less porous counterparts, such as the CRCP.
- The TNM "PCC" option resulted in accurately predicted sound levels in relation to actual roadside measurements. The "average" option underestimated the actual sound pressure levels. Given that the "PCC" option is not enabled yet to use by the general public, these results support making it available. This is an analogous situation to what occurs in TNM with PFCs and the "OGAC" option discussed in Chapter 5, in which the more specific pavement type option .
- The PFC in Waco (placed in 2003) got slightly louder in less than 2 years time. The new PFC adjacent to it is significantly quieter (about 2.5 dBA on average).
- Diamond-grinding of the CRCP in Waco resulted in even quieter overall levels, and eliminated the whining noise produced by the tire/pavement contact. This is illustrated by the absence of the 1000-Hz peak in the frequency spectra, which is characteristic of the tined CRCP. Removal of superficial distresses through the diamond-grinding process has also contributed to the improved acoustic performance.
- The overall noise levels of the diamond-ground CRCP in Waco are very similar to those of the new PFC next to it. On average, the textured CRCP is only about 0.5 dBA louder than the new PFC. This is another good indication that the texturing of an old CRCP is beneficial toward reducing its loudness, making its loudness comparable to that of a PFC.

- The old PFC in Waco is as loud as the old CRCP (100.6 dBA, on average). Unfortunately, there is no history of noise measurements available for either section to quantify their rates of increase in loudness.
- The old CRCP on IH-35 in Waco is quieter than the new CRCP on SH 130. This was an unexpected result, considering that the Waco pavement is distressed as opposed to the very good condition of the SH 130. The reason could be that the old pavement in Waco is not tined, and also has been polished by traffic and age, while the tines on SH 130 are sharp and new. However, the SH 130 ranks as one of the quietest tined pavements measured in this study.
- The quietest rigid pavement sections measured in this project correspond to two untined CRCP sections: the diamond-ground section on IH-35 in Waco, and the old CRCP next to it.

Chapter 7. Statistical Analysis

Although the OBSI data and analyses have already been presented graphically in Chapters 3 and 4, it is also useful to employ statistics to characterize and quantify certain aspects of the data that might not be immediately clear or definitive from the charts. Specifically, this chapter will examine variance between test vehicles, between the leading edge, trailing edge, and center of the tire patch in regards to the OBSI probe placements, and finally the variance between overall pavement noise measurements due to mix design, aging, traffic, and environmental variables.

Figure 7.1 presents a sample sheet from the combined dataset, assembled to facilitate the t-tests and analysis of variance (ANOVA). The data includes 240 observations from seven TxDOT Districts, each observation containing up to three replicates, each for trailing edge OBSI, leading edge OBSI, and center OBSI, as well as their averaged values—approximately 1400 independent road noise measurements. This subset of the data comprises the dependent variable set for the analysis. The independent variables (which are used to explain variance in the dependent variables) include pavement age at time of testing, location, climatic zone, binder type, pavement type, functional highway classification, and selected environmental variables obtained from the National Climatic Data Center's comprehensive weather history database.

The complete dataset is presented in Appendix A (Table A.2).

7.1 Comparison of the TxDOT and CTR Test Vehicles

Except for minor variation in vehicle weight due to personnel, the TxDOT and CTR test vehicles and their OBSI gear are identical, using the same vehicle tire type up until the final noise rodeo, as explained in Chapter 3. Any variation due to aging of the precision microphones used by the two systems over time is compensated for by strict calibration of the system before and after every series of runs. Therefore it would be expected that the results from testing the same sections at the same time using the two vehicles would be essentially identical, and indeed the charts and analysis in Chapter 3 do support that conclusion. However, to be thorough, a brief statistical analysis is used to confirm this as well as examine variability between vehicles and between runs.

7.1.1 T-Test for CTR vs. TxDOT Results

Simply put, a t-test can be used to determine with some degree of confidence whether two sets of data have the same mean value. In this case, a paired t-test is used because each pair of observations (CTR system versus TxDOT system) is dependant, taken on the same pavement section at the same time (within a few minutes of each other). The data used for this analysis is taken from the first rodeo result, comparing the TxDOT and CTR systems when both vehicles were using the Tiger Paw tire, testing performed on the Parmer Lane and US 183 test sections in Austin. Figure 7.2 shows the result of the analysis.

OBSI and Selected Climate Data

HWY	City	ID	Type	Const_Y	Climate	Binder	Test_YR	Agency	T1	T2	T3	Tavg	L1	L2	L3	Lavg	AVG	Center	TotRain	AvgMaxT	AvgMinT	TFP	MaxT	MinT	Day32	AvgT
FM143	Aus	EB1	PFC	2005	DF	P	2007.5	CTR	99.7	99.2	99.0	99.3	99.5	99.5	99.6	99.5	99.4	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM143	Aus	EB2	PFC	2005	DF	P	2007.5	CTR	100.2	100.4	100.8	100.5	99.7	100.0	99.3	99.8	100.2	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM143	Aus	WB1	PFC	2005	DF	P	2007.5	CTR	97.8	97.8	98.0	97.9	97.5	97.4	97.3	97.4	97.6	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM620	Aus	EB1	PFC	2004	DF	P	2006.8	CTR	98.4	98.2	97.9	98.2	98.1	97.8	97.3	97.7	98.0	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM620	Aus	EB1	PFC	2004	DF	P	2006.8	CTR	98.3	98.1	98.0	98.1	98.7	98.4	98.4	98.5	98.3	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM620	Aus	WB1	PFC	2004	DF	P	2006.8	CTR	98.8	98.9	99.2	99.0	99.1	98.3	0.0	98.7	98.8	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM620	Aus	WB1	PFC	2004	DF	P	2006.8	CTR	99.5	99.4	99.7	99.5	99.7	99.5	99.4	99.5	99.5	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM734	Aus	1	ACP	0	DF	N	2007.7	CTR	101.7	101.6	102.3	101.9	102.0	101.7	100.6	101.4	101.7	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM734	Aus	2	ACP	0	DF	N	2007.7	CTR	101.5	102.6	102.2	102.1	102.3	102.4	102.3	102.3	102.2	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM734	Aus	3	ACP	0	DF	N	2007.7	CTR	101.6	101.1	101.0	101.2	100.2	100.3	100.3	100.3	100.8	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM734	Aus	4	ACP	0	DF	N	2007.7	CTR	101.8	101.3	101.4	101.5	102.1	101.1	101.8	101.7	101.6	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM734	Aus	1	ACP	0	DF	N	2008.3	CTR	102.5	103.3	103.2	103.0	102.0	102.5	102.7	102.4	102.7	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM734	Aus	2	ACP	0	DF	N	2008.3	CTR	102.3	103.6	103.1	103.0	102.8	103.1	103.2	103.0	103.0	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM734	Aus	3	ACP	0	DF	N	2008.3	CTR	101.8	101.7	102.3	101.9	101.6	101.6	101.7	101.6	101.8	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM734	Aus	5	ACP	0	DF	N	2008.3	CTR	102.6	102.7	103.4	102.9	102.1	102.8	102.9	102.6	102.7	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	10	PFC	2005	DF	P	2006.8	TxDOT	101.4	101.2	101.4	101.2	100.9	100.9	101.0	100.9	101.6	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	11	PFC	2005	DF	P	2006.8	TxDOT	100.2	100.3	100.3	100.2	100.3	99.9	100.3	100.2	100.4	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	12	PFC	2005	DF	P	2006.8	TxDOT	99.8	99.6	99.8	99.9	100.1	100.2	99.9	100.1	99.9	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	13	PFC	2005	DF	P	2006.8	TxDOT	100.2	100.0	100.1	100.1	100.0	100.1	100.2	100.1	100.1	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	7	PFC	2005	DF	P	2006.8	TxDOT	101.1	101.1	101.1	100.9	100.6	100.7	100.5	100.6	101.1	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	8	PFC	2005	DF	P	2006.8	TxDOT	101.1	101.3	101.2	101.0	100.8	101.0	100.6	100.8	101.3	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	9	PFC	2005	DF	P	2006.8	TxDOT	101.3	101.2	101.3	101.1	101.1	100.8	100.9	101.0	101.4	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	10	PFC	2005	DF	P	2006.8	TxDOT	100.1	99.9	99.8	99.9	99.4	99.3	99.2	99.3	99.6	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	11	PFC	2005	DF	P	2006.8	TxDOT	99.1	98.6	98.8	98.8	98.0	98.1	98.0	98.0	98.4	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	12	PFC	2005	DF	P	2006.8	TxDOT	99.2	99.1	98.9	99.0	98.0	98.5	98.4	98.3	98.7	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	13	PFC	2005	DF	P	2006.8	TxDOT	99.4	99.1	99.3	99.3	98.5	98.5	98.6	98.5	98.9	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	7	PFC	2005	DF	P	2006.8	TxDOT	99.6	99.9	100.1	99.9	99.4	99.3	99.3	99.3	99.6	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	8	PFC	2005	DF	P	2006.8	TxDOT	100.2	100.0	99.9	100.0	99.3	99.1	99.1	99.2	99.6	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	9	PFC	2005	DF	P	2006.8	TxDOT	100.0	100.0	100.0	100.0	98.7	98.7	98.2	98.6	99.3	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	10	PFC	2005	DF	P	2007.8	CTR	101.4	101.2	101.4	101.2	100.9	100.9	101.0	100.9	101.6	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	11	PFC	2005	DF	P	2007.8	CTR	100.2	100.3	100.3	100.2	100.3	99.9	100.3	100.2	100.4	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	12	PFC	2005	DF	P	2007.8	CTR	99.8	99.6	99.8	99.9	100.1	100.2	99.9	100.1	99.9	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	13	PFC	2005	DF	P	2007.8	CTR	100.2	100.0	100.1	100.1	100.0	100.1	100.2	100.1	100.1	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	7	PFC	2005	DF	P	2007.8	CTR	101.1	101.1	101.1	100.9	100.6	100.7	100.5	100.6	101.1	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	8	PFC	2005	DF	P	2007.8	CTR	101.1	101.3	101.2	101.0	100.8	101.0	100.6	100.8	101.3	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	9	PFC	2005	DF	P	2007.8	CTR	101.3	101.2	101.3	101.1	101.1	100.8	100.9	101.0	101.4	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2

**0 indicates missing values*

Page 1

Figure 7.1: Sample sheet from the consolidated OBSI and environmental data (full set in Appendix A)

Paired Comparison t Test for CTR vs TxDOT Vehicles			
The MEANS Procedure			
Analysis Variable : diff			
Mean	Std Error	t Value	Pr > |t|
-0.5807831	0.1596476	-3.64	0.0030

Figure 7.2: T-Test paired comparison results for TxDOT vs. CTR vehicles

It can be seen from the figure above that the mean difference between the CTR and TxDOT vehicles using the Tiger Paw tire is about 0.6 dBA, with a standard error of 0.16, giving a 95% confidence interval ranging from -0.28 dBA to -0.88 dBA, an insignificant difference. Therefore, measurements taken using the two vehicles can safely be used interchangeably; in fact, TxDOT noise measurements using the Tiger Paw tires have been incorporated into the database.

Another method of comparing the two vehicles uses the ANOVA analysis. ANOVA reveals the correlation between independent variables and dependant variables, showing the statistical significance for the each variable in predicting the dependant variables, as well as what percentage of the overall variability in the dependant variable is explained by the independent variables. Figure 7.3 shows the result for CTR vs. TxDOT: 97% correlation between the two vehicles.

ANOVA Analysis Comparing TxDOT and CTR Vehicles with Tiger Paw Tires

The GLM Procedure

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	65.23316820	65.23316820	407.33	<.0001
Error	12	1.92176282	0.16014690		
Corrected Total	13	67.15493102			

R-Square	Coeff Var	Root MSE	CTR Mean
0.971383	0.387564	0.400184	103.2560

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TxDOT	1	65.23316820	65.23316820	407.33	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TxDOT	1	65.23316820	65.23316820	407.33	<.0001

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	10.27449902	4.60827765	2.23	0.0456
TxDOT	0.90096899	0.04464110	20.18	<.0001

Figure 7.3: ANOVA for CTR vs. TxDOT results using Tiger Paw Tire

As detailed in Chapter 3, Transtec participated in two noise rodeos, using a very different system from CTR and TxDOT to test the same sections on the same day. In the first rodeo, CTR and TxDOT used the Uniroyal Tiger Paw tire (TP), whereas Transtec used the newer, Standard Reference Test Tire (SRTT). In addition, Transtec used a dual probe system (connected to the vehicle body in the first rodeo, and to the tire rim in the second), a different vehicle, and a proprietary data analysis program. TxDOT switched to the SRTT tire in the second rodeo. Combining all this information and performing an ANOVA gives the results shown in Figure 7.4.

ANOVA Comparison Between SRTT and TP Tires, CTR & TxDOT Vehicles

The GLM Procedure

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	45	485.7122685	10.7936060	40.76	<.0001
Error	67	17.7426982	0.2648164		
Corrected Total	112	503.4549666			

R-Square	Coeff Var	Root MSE	Avg Mean
0.964758	0.493734	0.514603	104.2269

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Loc*Date*Sect	42	395.8244581	9.4243919	35.59	<.0001
Agency	2	84.1645277	42.0822638	158.91	<.0001
Tire	1	5.7232827	5.7232827	21.61	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Loc*Date*Sect	42	395.7708850	9.4231163	35.58	<.0001
Agency	2	24.2658364	12.1329182	45.82	<.0001
Tire	1	5.7232827	5.7232827	21.61	<.0001

Figure 7.4: ANOVA for both rodeos, showing significance of tire and agency

It can be seen in the figure that the most significant variable found was Loc*Date*Sect, which is a composite variable that precisely identifies the section tested and date the section was tested. As expected (and hoped), it is the most significant variable found in the analysis. However, the test tire used is also significant, as is the agency variable, meaning there are differences in measurement not attributable strictly to the tire, i.e. the Transtec microphone suspension and/or vehicle used. The Transtec results from the first rodeo were significantly higher using their body mount suspension system, possibly indicating that oscillation of the vehicle suspension varied the distance between the microphones and the pavement, a factor which the noise measurement is highly sensitive to.

Because the SRTT has been selected as the test tire of choice in the AASHTO draft specification, it would be very useful to have a model correlating SRTT to Tiger Paw tires. Figure 7.5 uses ANOVA to produce such a model, confined to data where every other variable is controlled except the tire type. A 93% correlation was obtained, and a useful model generated. Figure 7.6 shows the fit through the data used in the analysis.

ANOVA Analysis Comparing TxDOT and CTR Vehicles with SRTT Tires

The GLM Procedure

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	50.98656822	50.98656822	187.16	<.0001
Error	12	3.26904499	0.27242042		
Corrected Total	13	54.25561321			

R-Square	Coeff Var	Root MSE	CTR Mean
0.939747	0.502397	0.521939	103.8898

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TxDOT	1	50.98656822	50.98656822	187.16	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TxDOT	1	50.98656822	50.98656822	187.16	<.0001

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	-21.05995412	9.13435487	-2.31	0.0398
TxDOT	1.19602817	0.08742454	13.68	<.0001

Figure 7.5: SRTT tire vs. Tiger Paw correlation, all other variables controlled

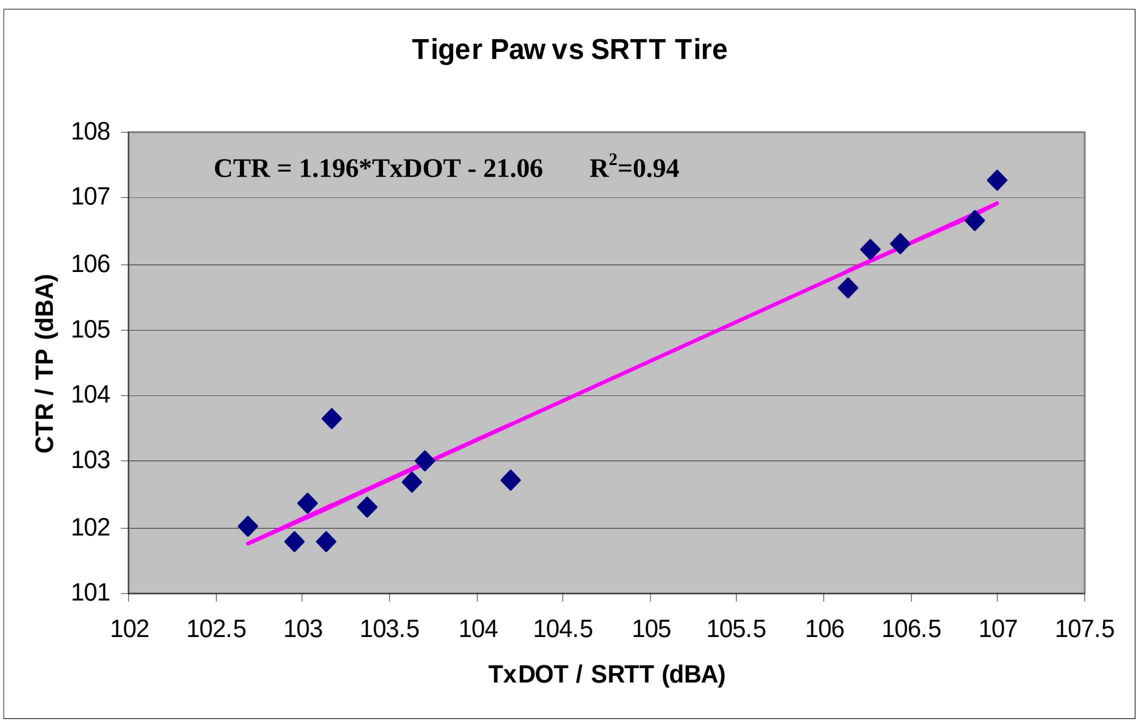

Figure 7.6: Fit for Tiger Paw vs. SRTT model

In Figure 7.6, it can be seen that there are two clumps of data, the louder being from tests on US 183 (CRCP) and the quieter from FM 734 (dense-graded AC). On average, the SRTT was 0.6 dBA louder than the Tiger Paw tire; however, the mean difference between the tires on the AC pavement was 1.07 dBA and 0.39 dBA for the CRCP, probably due to different spectral characteristics between the two types of pavement, as explained in Chapter 3.

For ACP, the differences at various frequencies can be directly investigated using data obtained during the March 2008 and July 2008 rodeos. Although Transtec took part in the July 2008 rodeo, that data has been excluded from the analysis to eliminate any extraneous variables such as vehicle type, data analysis procedure, or use of dual probe. The differences presented strictly compare the CTR vehicle with Tiger Paw tires to the identical TxDOT vehicle with SRTT tires. Figure 7.7 shows the comparisons graphically.

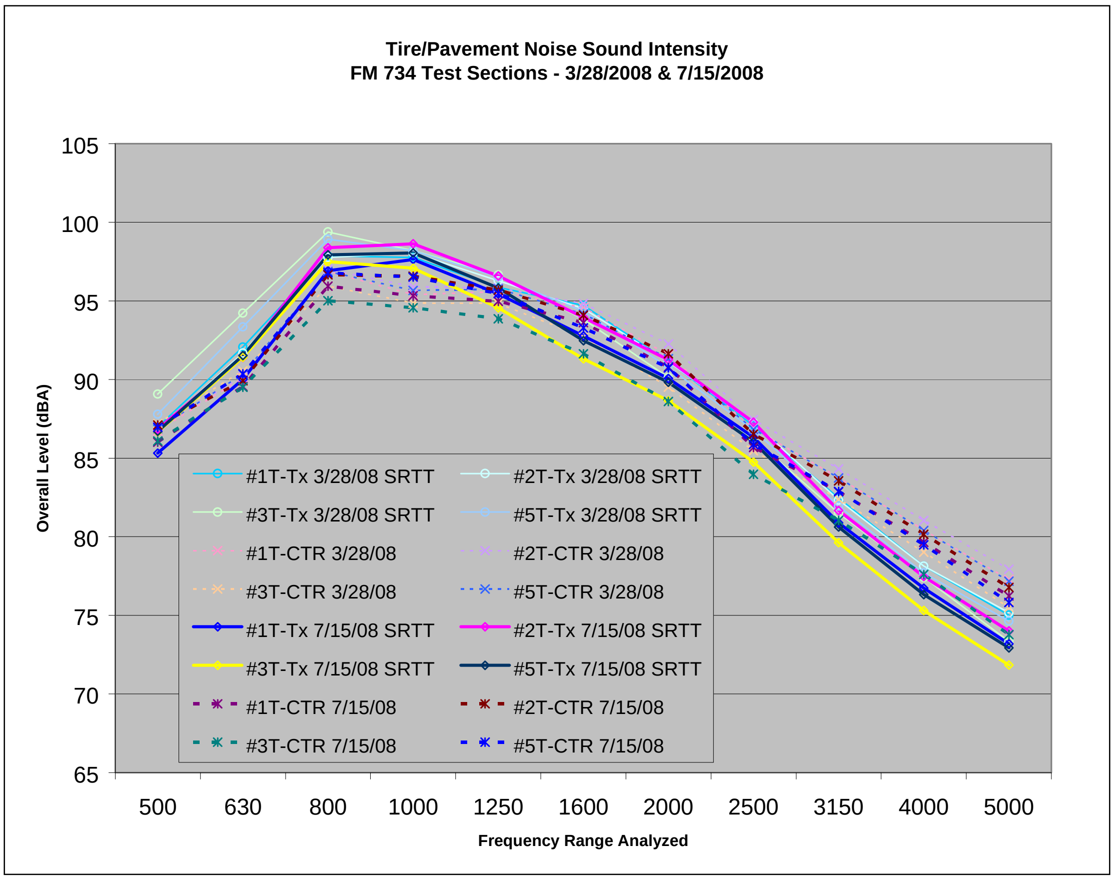

Figure 7.7: Comparison of SRTT to TP tires, all other variables excluded, Parmer Lane ACP

As can be seen from the figure, the newer SRTT tire is slightly louder at the lower frequencies, then becomes quieter at frequencies above 3 kHz. The SRTT tire being louder at the key midrange frequencies around 1 kHz explains the slightly louder overall A-weighted values observed in the previous analysis.

A table can be prepared, listing these differences at the various frequencies reported in the standard noise analysis Table 7.1 shows the average differences in dB between the SRTT and TP tires, using direct paired comparisons on the same dates and sections.

Table 7.1: Spectral differences between SRTT and TP tires (n = 264)

Frequency (Hz)	Difference (dB) SRTT-TP
500	0.460059
630	2.152551
800	1.718371
1000	2.449625
1250	0.941946
1600	0.050363
2000	-0.32001
2500	0.532136
3100	-1.47315
4000	-2.44946
5000	-2.3596

If it is desired to calibrate between tires at intermediate frequencies, a simple linear regression can be used. A regression analysis was performed using SAS to fit a linear model to the 88 paired comparisons (11 frequencies, 2 test dates, 4 ACP sections) resulting in the fit presented in Figure 7.8. The average error in prediction is 0.64 dB with the largest residual of -1.3 dB observed at 500 Hz.

Although the frequency analysis presented is sound, it must be remembered that only 88 paired observations were available for the analysis and that the pavement project tested was conventional asphalt (ACP). The frequency differences observed for rigid (CRCP) pavement on the US183 portion of the rodeo were considerably different than for ACP, so it's likely that conventional ACP spectral differences are somewhat different from PFC pavements as well. This is consistent with the understanding that the total noise generated via tire / pavement contact arises from a number of mechanisms (impact, adhesion, air displacement, resonances, etc) that are unique to the specific tire design and the surface / void content of the pavement it contacts.

These conversions should therefore be used with caution until more comparison data becomes available from the new 0-5836 study. In any case, work at the national level supports our finding that the a-weighted levels for the SRTT tires and TP tires aren't significantly different and can be used interchangeably.

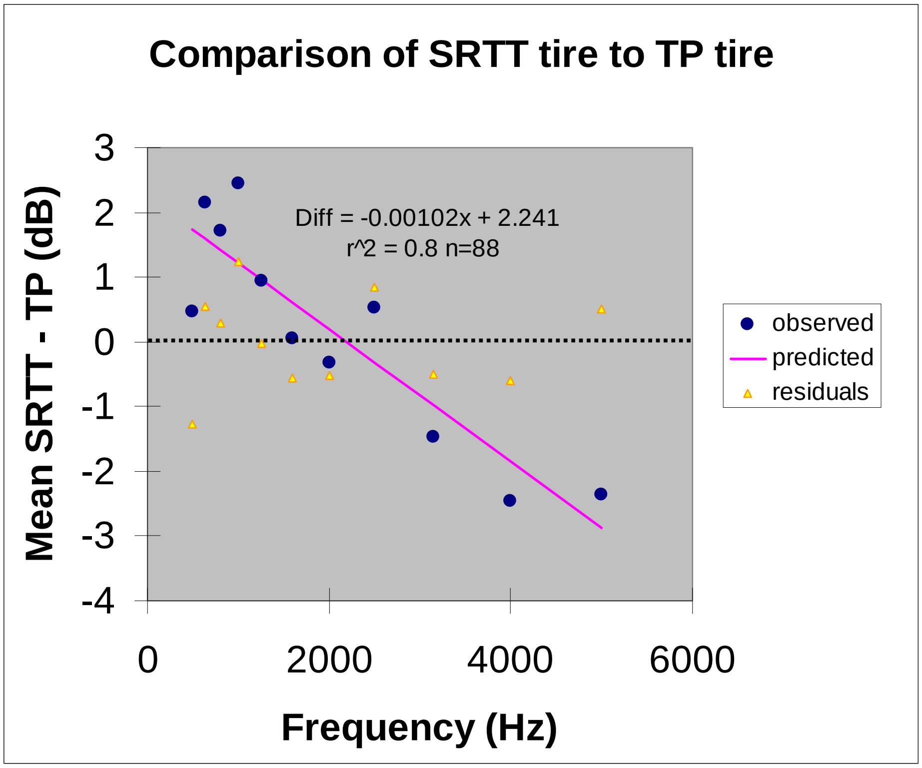

Figure 7.8: Frequency calibration model for SRTT vs TP tires

7.2 Comparison of Center, Leading Edge, and Trailing Edge for OBSI Measurements

Traditionally, noise measurements at the tire/pavement contact area have been taken at both the leading and trailing edges for OBSI tests. This practice assumes that noise at the two contact points are significantly different, and that the overall noise measurement cannot be adequately captured using a single microphone placement—say, at the center of the tire contact patch. If leading and trailing edge measurements are required using a single probe OBSI device, the probe position must be switched, and the runs must be repeated. Given that in some locations the loop distance may be ten miles or more, and driven at least three times for each probe position, this effectively doubles the time and cost associated with measuring noise on a test section and can be very significant.

A probe positioned at the center of the tire contact patch is just inches away from both the leading and trailing points. In such position, it is able to record noise levels which are a mixture of the two traditional measurement points. Given that the OBSI data is presented as a single A-weighted average of the leading and trailing edge values, the hypothesis of the researchers was that perhaps the center position could be accurate enough to serve. This section investigates that possibility. Figure 7.9 shows the raw, averaged data for leading vs. trailing edge.

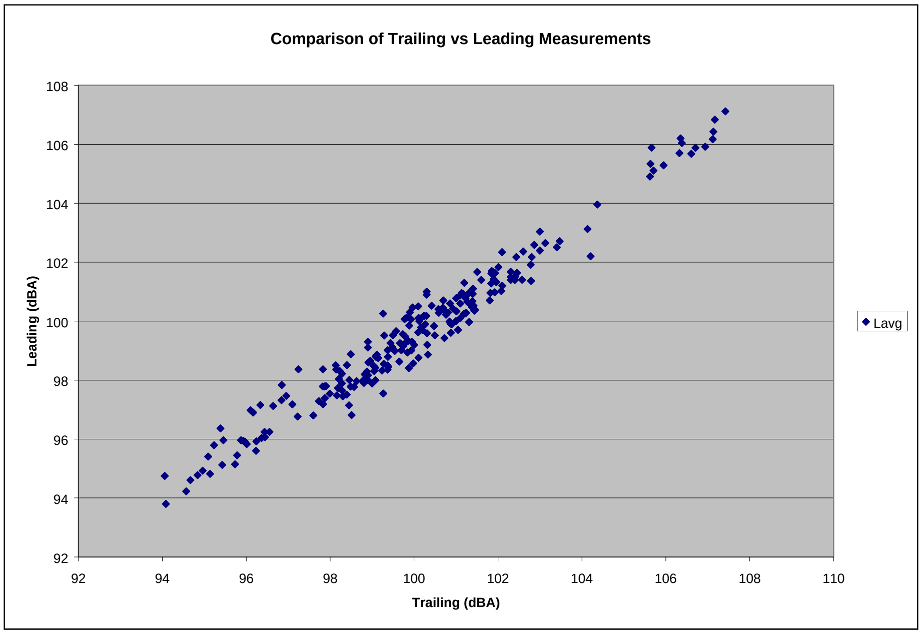

Figure 7.9: Comparison of average leading vs. trailing edges, averaged

7.2.2 Paired t-test of leading vs. trailing

The first statistical method employed is the paired t-test, which determines if the mean difference between two measurements taken at the same time is significantly different from zero. This test is ideal for comparing leading and trailing edge measurements, as every observation in the dataset has an average for trailing and leading edge OBSI noise, taken within a few minutes of each other. Figure 7.10 shows the results of the t-test and related ANOVA.

Comparison of Leading Edge to Trailing Edge

The GLM Procedure

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	1593.049102	1593.049102	5692.83	<.0001
Error	236	66.040903	0.279834		
Corrected Total	237	1659.090005			

R-Square	Coeff Var	Root MSE	Tavg Mean
0.960195	0.528623	0.528994	100.0702

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Lavg	1	1593.049102	1593.049102	5692.83	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Lavg	1	1593.049102	1593.049102	5692.83	<.0001

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	-3.105333514	1.36788317	-2.27	0.0241
Lavg	1.035381439	0.01372260	75.45	<.0001

Paired Comparison t Test

The MEANS Procedure

Analysis Variable : diff

Mean	Std Error	t Value	Pr > |t|
0.4204180	0.0346957	12.12	<.0001

Figure 7.10: T-test and ANOVA relating leading to trailing edge measurement

It can be seen in the figure that the leading and trailing averages have a high probability of having the same underlying mean, i.e., are insignificantly different from each other. On the average, the trailing edge was 0.42 dBA louder, with a very small standard error of 0.035 giving a 95% confidence interval ranging from 0.49 to 0.35 dBA. For PFC pavement, at least, these two measures are insignificantly different.

An ANOVA was also performed, modeling the trailing edge measurement as a function of the leading edge. An R^2 of 0.96 was obtained, again showing a very tight correlation. Figure 7.11 shows the fit to the data.

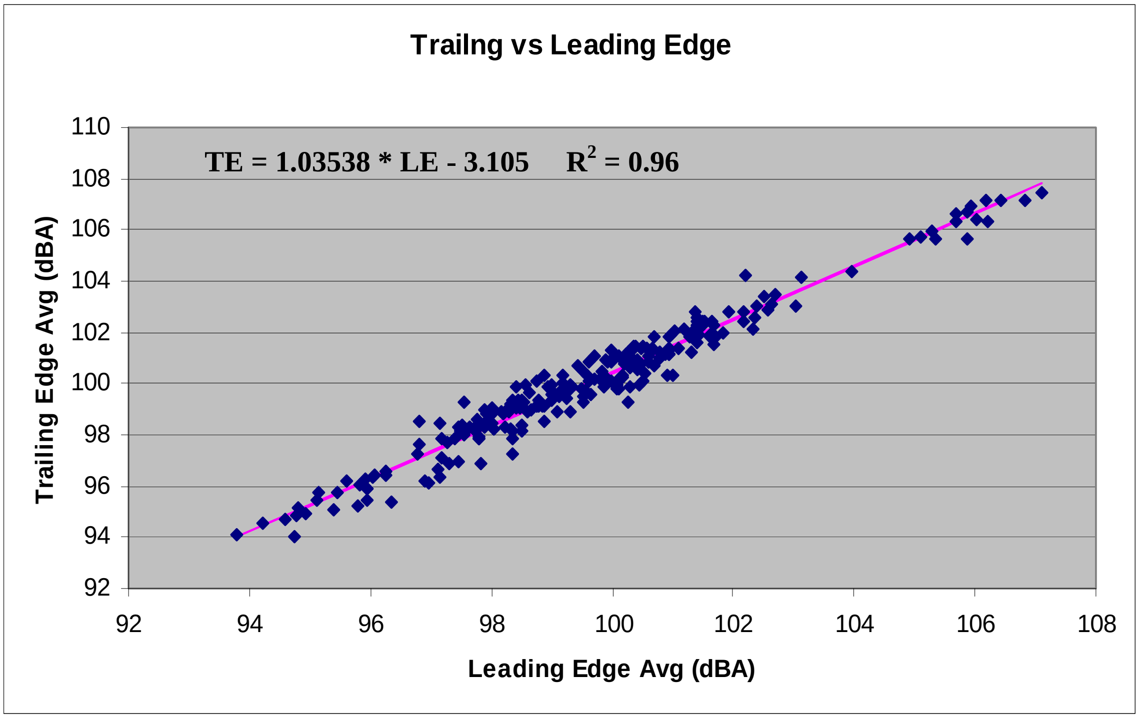

Figure 7.11: Regression predicting trailing edge from leading edge

7.2.3 ANOVA comparing center and average of leading and trailing edges

Now that it has been established that the leading and trailing edge measurements (at least for PFC pavements) are not significantly different, there is some support for the idea that a single, center contact measurement may be sufficiently related to the average of leading and trailing values to serve in their stead, which for the purposes of this analysis will be termed AVG. ANOVA establishes how much of the variability in the dependent variable (in this case, AVG) can be attributed to the independent variable, which is the center measurement that is termed CTR. Figure 7.12 shows the ANOVA and associated model to correlate center measurements to the average of leading and trailing edge measurements currently reported. The regression gives an R^2 of 0.95, and the fit is shown in Figure 7.13.

Comparison of Center to Average

The GLM Procedure

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	42.15475156	42.15475156	183.03	<.0001
Error	11	2.53342313	0.23031119		
Corrected Total	12	44.68817469			

R-Square	Coeff Var	Root MSE	Center Mean
0.943309	0.486376	0.479907	98.67012

Source	DF	Type I SS	Mean Square	F Value	Pr > F
AVG	1	42.15475156	42.15475156	183.03	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
AVG	1	42.15475156	42.15475156	183.03	<.0001

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	-35.56765795	9.92311624	-3.58	0.0043
AVG	1.35914639	0.10046169	13.53	<.0001

Figure 7.12: Regression model estimating AVG noise using only a single center probe placement

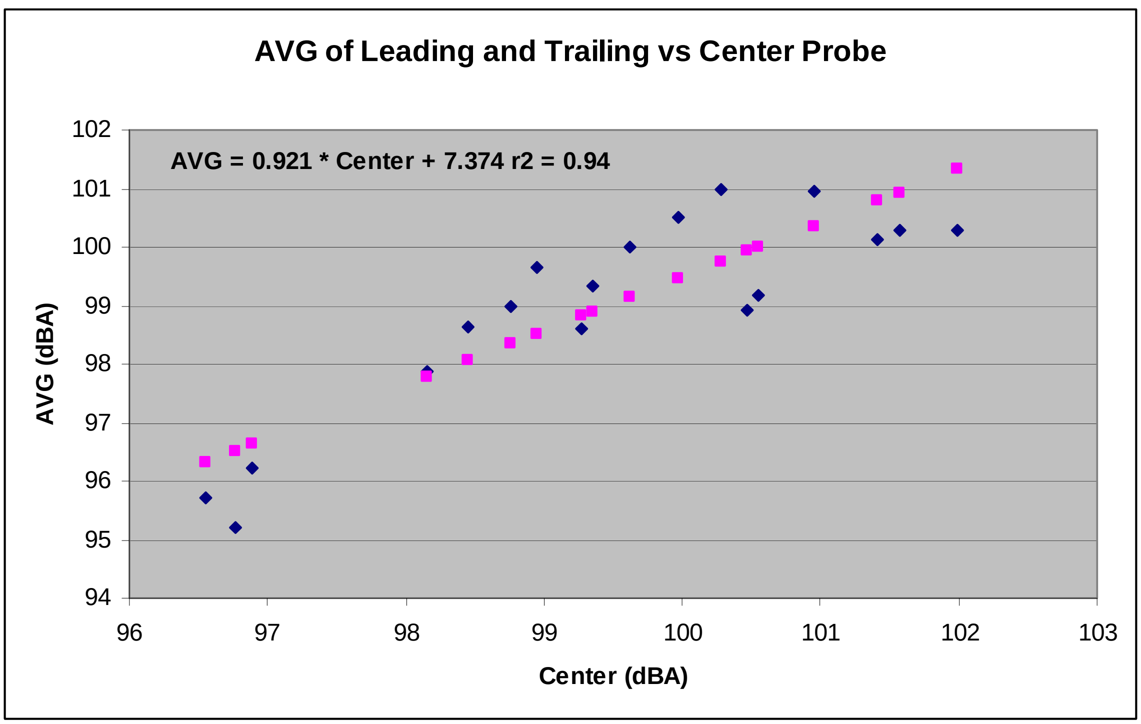

Figure 7.13: Regression model predicting AVG measure using center probe

The average error using the center measurement to predict the average of leading and trailing was found to be about 0.7 dB, which may be close enough for some measurements on the network level, or for targeting sections for more detailed study.

7.3 Evaluation of Factors Related to Pavement Noise Levels

Noise data has been collected under this study using an experimental factorial (Table 4.3). The factorial was designed using levels of age (new, medium, old), mix design (rubber or polymer binder), and four combinations of environment (freeze/no freeze, wet/dry). It is hoped that by monitoring noise on the selected sections over time, a better understanding of how the noise levels change and why can be obtained. However, there are relatively few "old" PFC sections at the time of this writing, and PFC is used widely in some areas of the state but not at all in others. Additionally, one variable that is known to be very significant, PFC layer thickness, was not collected during this study, as "as built" thickness varies greatly, requiring taking of cores. However, the findings and data from this project can serve as history and guidance for the new, long term PFC performance monitoring project.

For now, an analysis can be performed to determine which variables collected have proven to be significant thus far.

7.3.1 ANOVA Investigating Age, Design, and Environmental Factors

The data collection factorial attempts to characterize all environmental effects by dividing the state into four zones: wet freeze, dry freeze, wet no-freeze, and dry no-freeze. Of course, the actual conditions are not as simple as that; San Antonio is considered dry no-freeze, but actually freezes occasionally, and of course rainfall is experienced in varying amounts throughout the state. The four-area characterization is adequate for data collection, but there is no reason not to use more accurate rainfall and temperature variables matching the actual pavement section locations, and even for those locations over time. The idea is to generate variables that characterize each pavement's experience since construction, i.e. degree days of heating, total water flow, etc. Accordingly, the National Climatic Center Database was used to extract various climatic variables for use in the analysis. Figure 7.14 shows a sample environmental summary sheet for one section.

An average of the last three years was used for all environmental variables, then multiplied by the age of each pavement section to estimate the environmental stress experienced by the pavement over its lifetime. The variables found to be must significant in predicting pavement noise levels were TotRain (total rainfall in inches), AvgMaxT (serving as a summer heating experience variable).

The only available design variable was Binder (polymer vs. rubber), and traffic was estimated using Age*HwyTyp, which attempts to very roughly estimate ESALS by combining age with the functional class (IH, FM, Loop, SH, US) of the roadway. Figure 7.15 shows the result of the ANOVA using these variables.

U.S. Department of Commerce
National Oceanic & Atmospheric Administration

ANNUAL CLIMATOLOGICAL SUMMARY (2007)

National Climatic Data Center
Federal Building
151 Patton Avenue
Asheville, North Carolina 28801

Station: **410429/13904, AUSTIN BERGSTROM AP, Texas** Elev. 480 ft. above sea level Lat. 30°11'N, Lon. 97°41'W

Date	Temperature (° F)													
Elem->	MMXT	MMNT	MNTM	DPNT	HTDD	CLDD	EMXT		EMNP		DT90	DX32	DT32	DT00
											Number of Days			
2007 Month	Mean Max.	Mean Min.	Mean	Depart. from Normal	Heating Degree Days	Cooling Degree Days	Highest	High Date	Lowest	Low Date	Max >=90°	Max <=32°	Min <=32°	Min <=0°
1	55.2	36.3	45.8	-5.3	593	2	78	5	24	29	0	2	14	0
2	64.6	38.1	51.4	-4.1	381	5	83	27	20	16	0	0	10	0
3	73.8	51.6	62.7	0.1	149	84	83	10	23	5	0	0	5	0
4	73.8	51.4	62.6	-6.3	124	58	84	29	34	8	0	0	0	0
5	83.5	64.4	74.0	-1.6	0	286	90	13	56	18	1	0	0	0
6	88.7	70.4	79.6	-1.9	0	443	93	19	63	6	14	0	0	0
7	87.6	71.5	79.6	-5.0	0	458	93	16	67	18	13	0	0	0
8	93.2	72.7	83.0	-1.5	0	567	99	13	68	28	30	0	0	0
9	90.1	67.3	78.7	-0.8	0	417	94	27	60	25	23	0	0	0
10	84.8	55.3	70.1	-0.7	55	219	93	17	36	26	13	0	0	0
11	72.5	47.5	60.0	-0.5	205	61	86	21	29	26	0	0	3	0
12	67.5	36.7	52.1	-0.8	419	26	85	2	21	27	0	0	14	0
Annual	77.9	55.3	66.6	-2.4	1926	2626	99	Aug	20	Feb	94	2	46	0

Date	Precipitation (inches)									
Elem->	TPCP	DPNP	EMXP		TSNW	MXSD		DP01	DP05	DP10
			Greatest Observed		Snow, Sleet			Number of Days		
2007 Month	Total	Depart. from Normal	Day	Date	Total Fall	Max Depth	Max Date	>=.10	>=.50	>=1.0
1	7.66	5.45	4.28	13	0.1	0T	17	10	2	1
2	0.12	-1.90	0.06	1	0.0	0		0	0	0
3	6.00	3.64	1.62	12	0.0	0		7	4	4
4	3.71	1.08	1.55	4	0.0T	0T	8	7	3	1
5	6.73	1.61	1.67	28	0.0T	0T	5	9	4	3
6	7.49	4.07	3.54	20	0.0	0		8	4	2
7	7.62	5.59	1.46	20	0.0	0		13	6	2
8	2.19	-0.32	1.38	16	0.0	0		3	1	1
9	0.73	-2.15	0.28	11	0.0	0		3	0	0
10	1.80	-2.19	1.69	22	0.0	0		2	1	1
11	1.26	-1.76	0.72	24	0.0	0		3	1	0
12	0.60	-1.93	0.24	15	0.0T	0T	28	3	0	0
Annual	45.91	11.19	4.28	Jan	0.1	0	Dec	68	26	15

Notes

(blank) Not reported.

\+ Occurred on one or more previous dates during the month. The date in the Date field is the last day of occurrence. Used through December 1983 only.

X Monthly means or totals based on incomplete time series. 1 to 9 days are missing. Annual means or totals include one or more months which had 1 to 9 days that were missing.

M Used to indicate data element missing.

Figure 7.14: NCDC Environmental summary sheet for 2007, Austin Bergstrom Airport

ANOVA for AVG noise level

The GLM Procedure

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	391.0858379	48.8857297	35.82	<.0001
Error	173	236.1296727	1.3649114		
Corrected Total	181	627.2155105			

R-Square	Coeff Var	Root MSE	AVG Mean
0.623527	1.180353	1.168294	98.97841

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TotRain	1	174.0004790	174.0004790	127.48	<.0001
Age*AvgMaxT	1	0.2965604	0.2965604	0.22	0.6417
Binder	1	160.8768390	160.8768390	117.87	<.0001
Age*htyp	5	55.9119594	11.1823919	8.19	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TotRain	1	63.1536700	63.1536700	46.27	<.0001
Age*AvgMaxT	1	41.2211615	41.2211615	30.20	<.0001
Binder	1	116.9711260	116.9711260	85.70	<.0001
Age*htyp	5	55.9119594	11.1823919	8.19	<.0001

Parameter		Estimate		Standard Error	t Value	Pr > |t|
Intercept		94.78385960	B	0.40155906	236.04	<.0001
TotRain		0.06952295		0.01022071	6.80	<.0001
Age*AvgMaxT		0.17597140		0.03202095	5.50	<.0001
Binder	P	2.24963892	B	0.24301088	9.26	<.0001
Binder	R	0.00000000	B	.	.	.
Age*htyp	FM	-14.39518624		2.56300730	-5.62	<.0001
Age*htyp	IH	-13.93892491		2.52396310	-5.52	<.0001
Age*htyp	Lo	-13.96345225		2.57642141	-5.42	<.0001
Age*htyp	SH	-14.25249878		2.55517684	-5.58	<.0001
Age*htyp	US	-14.25669041		2.54671997	-5.60	<.0001

Figure 7.15: ANOVA showing significance of age, design, traffic, and environmental variables on pavement noise

From the ANOVA, it can be seen that the strongest predictor of pavement noise is the use of asphalt rubber binder, which, on average, results in a 2.25 dBA noise reduction over polymer binder; this is the clearest finding from the analysis. The second most significant variable was rainfall amount, followed by degree days of heating in summer, with Age*htyp being slightly significant, perhaps serving as intended, a rough indicator of traffic and possibly ESALs. Clearly, more precise traffic data is needed for each test section.

Overall, the fit is only $R^2 = 0.62$, but that improves somewhat if the US 281 sections in San Antonio are removed from the analysis, as those sections were measured extensively and are the quietest pavements in the state. More analysis will be needed to determine why that is.

7.4 Summary and Recommendations

- The CTR and TxDOT vehicles, when using the same tire type, produce essentially identical measurements. Therefore, all data collected by CTR and TxDOT using the Tiger Paw tire can be combined for analysis purposes, such as it was done in the analyses performed in this project. This also indicates that the OBSI device, protocol, and operator training insure low variability.
- The leading and trailing positions for the OBSI device produce remarkably correlated data, the trailing edge being generally louder by a very small amount. However the difference is insignificant.
- The new OBSI standard test tire, the SRTT tire, though it produces a different spectrum of noise compared to the former tire, the Tiger Paw, does give a comparable A-weighted composite measurement, generally slightly louder than the Tiger Paw tire, but affected by the pavement type due to the spectral differences. The SRTT measurement can be more closely calibrated to the Tiger Paw measurement (or vice versa) using the model of the sort presented in Figure 7.5, though more data is needed than was available to the researchers from the two noise rodeos. *This is a crucial finding as being able to model the two tires allows historical data and new data to be combined*.
- Using a single probe position near the center of the tire/pavement contact point approximates and is highly correlated to the average of the trailing and leading edge measurements now commonly used for reporting OBSI measurements. Whenever speed and cost are factors (possible network level work), the OBSI probe can be mounted at the center location and reasonably accurate measurements can be taken, and/or improved using the model shown in Figure 7.11. However, this finding requires more data to be taken to substantiate it, as only limited data was available from this project.
- The use of specific, location precise environmental data for each test section over its lifetime improved the model for predicting pavement noise over time. This data is easy and free to obtain from NCDC, and could be made even more useful by compiling this data from “cradle to grave” for each test section from the nearest city if such data is available. Cumulative rainfall shows a strong effect, and the degree-days variable does also, especially in the summer when the asphalt would be softer and more subject to compaction and therefore void reduction / clogging / sealing. This effect should be followed up on.
- Age/traffic data shows significance, but more data needs to be collected to separate age and traffic effect, specifically ESAL data if available, or, if not, percentage trucks and ADT.
- It is essential that further noise testing include coring to determine the as-built thicknesses of PFC sections, as this variable is known from several other studies to affect noise very significantly.

Chapter 8. Conclusions and Recommendations

This chapter synthesizes the most relevant aspects of this investigation. The first part is focused on general conclusions, followed by various recommendations for future research and data collection procedures for TxDOT.

8.1 Conclusions

8.1.1 Equipment and Testing Protocols; Repeatability of Results

Traffic noise has been a subject of escalating concern, which has prompted the development of several procedures for measuring noise, as well as the advancement of quiet pavement technology. Regarding noise-measuring techniques, the latest proceedings in the industry aim toward the standardization of the on-board sound intensity method, utilization of which was one of the major thrusts of this project. The advantages of this testing technique are numerous; the most outstanding are its ease of use and its good correlation with other, more elaborate methods such as the pass-by tests, besides its ability to measure tire/pavement noise at the source, without the influence of other noise sources (engine, aerodynamic, exhaust, reflections, etc.).

In order to ascertain the reproducibility and consistency of the OBSI measurements, various "noise rodeos" were conducted throughout the duration of this project, under the valuable coordination provided by TxDOT. These were worthwhile efforts in which OBSI results were obtained on different pavement surfaces by the participating agencies— in this case, TxDOT, Transtec, and CTR, which have similar testing equipment. Among the participants, TxDOT's and CTR's sets of equipment were virtually identical, while Transtec's had higher variability both in their equipment and data analysis procedure; their results clearly reflected this. Results from TxDOT and CTR diverged slightly from each other when TxDOT installed a new type of test tire for their vehicle, the SRTT. The results show that the new SRTT produced slightly higher noise levels than the AWP tire with which the CTR vehicle is still equipped.

The CTR and TxDOT vehicles, when using the same tire type, produce essentially identical measurements. Therefore, all data collected by CTR and TxDOT using the Tiger Paw tire can be combined for analysis purposes, as was done in this report. This also indicates that the OBSI device, protocol, and operator training have resulted in low variability.

The new OBSI standard test tire, the SRTT produces a different spectrum of noise compared to the former tire, the Tiger Paw, but gives a roughly comparable A-weighted composite measurement, generally slightly louder than the Tiger Paw tire. The level shift is dependent on pavement type due to the spectral differences. The SRTT measurement can be closely calibrated to the Tiger Paw measurement (or vice versa) using the model of the sort devised in this project. Thus, historical data obtained with both tires could be combined to create a continuous noise history despite changes in the specified measurement tire type.

The leading and trailing positions for the OBSI device produce remarkably correlated data, the trailing edge being generally louder by a very small amount—especially for PFC pavement. The difference is minimal and can easily be modeled for a specific pavement type as demonstrated in Chapter 7.

The microphone position experiment (center of tire/pavement patch instead of leading/trailing edges) produced reasonable and encouraging results. As expected, the center position resulted in slightly quieter levels (a constant linear shift) as compared to the leading/trailing positions, and this was true for both PFC and CRCP. The differences were even smaller, almost negligible when the experiment was conducted on PFC pavements.

These two experiments raise the issue of whether measurements at both the leading and trailing edges are needed, and the answer clearly depends on what level of precision is needed compared to what expenditure of time and effort for the testing is possible.

8.1.2 Open-Graded Pavements' Performance

On the topic of quieter paving surfaces, those of the open-graded type (in Texas, commonly known as PFC) have demonstrated advantageous acoustic characteristics which explain their excellent performance in regards to noise, among other safety benefits. These properties, when tied to experimental results such as those presented in this report, indicate that open-graded pavements could be considered a viable means of reducing traffic noise at the source, rather than trying to diminish its effects by placing traffic noise barriers. This matter is tied to FHWA policies, for which the corresponding conclusions will be addressed in subsequent paragraphs.

One of the goals of the project was to investigate the performance of PFC pavements with time, as the issue of whether these types of surfaces can keep their quietness over time is a key aspect for their applicability as quieter pavements. The PFC pavements analyzed in this project indeed got louder with age, and this was an unquestionable trend in every case studied, perhaps due to clogging and compaction, both of which reduce the size of the voids that are present in these pavement surfaces. The presence of those air voids is the fundamental principle for their noise absorption capabilities.

An important finding of this study is that the increase in noise levels on PFC pavements with time and traffic does not seem to be linear; early indications are that changes in the first year after construction are more rapid, perhaps due to the initial compaction of the pavement structure when traffic is turned onto the pavement. Year-to year-changes in older PFC pavements are much more gradual, as was shown for middle-aged PFC sections in Waco and Yoakum Districts.

It should be emphasized, however, that all the acoustical changes measured during the course of this study found no significant variations over time; changes in most cases were negligible. PFC surfaces that can be considered relatively old are still showing low noise levels, levels that continue to render them quieter than other pavement types. The evidence gathered strongly suggests that whatever void clogging is occurring and whatever compaction is taking place on PFCs as a consequence of traffic loads, the amount and rate at which these changes take place do not significantly diminish the PFCs' ability to dissipate and absorb traffic noise. In general, it can be concluded that PFC surfaces represent the quietest pavement type currently in use and appear to maintain that distinction over their reasonable service life.

Given that the OBSI equipment first came available for use in June of 2006 (meaning the maximum time between measurements on the same pavement section was limited to 2 years), and given that the oldest PFC pavement that could be measured under this study was in service for just 7 years, additional research is required to establish a comprehensive cradle-to-grave noise performance history for PFC. The findings from this project will focus any subsequent research and the data collected under this study will serve as historical data for changes in noise levels over time.

Early results also seem to suggest that the small changes in noise levels over time vary with age, traffic, and environmental variables such as degree days of heating and total annual rainfall. More specific data must be collected over a longer period of time to support these findings conclusively, as the current data is limited and the changes being modeled are slight.

8.1.3 Comparisons of Roadside Measurements to TNM Predictions; FHWA Policies

On the subject of roadside measurements and the specific intent that this project had of conducting comparisons with TNM to substantiate the statement that some pavement types can be placed to purposely reduce noise, it can be said that the results presented herein for PFC pavements support this objective. There is no current noise measuring standard that can accomplish the type of roadside measurements required for the TNM comparisons, so the researchers devised a procedure. An Expert Task Group organized by FHWA is currently addressing this issue and working on developing a standard, which will be relevant to subsequent research.

Under the current FHWA policies, only one of the TNM pavement type characterization options is available, which is denominated as "Average" pavement. However, for research purposes, an additional option has been made available within TNM for open-graded pavements, which is called "OGAC." Comparisons of the actual measurements were performed utilizing both pavement type options. The experimental results obtained on PFC pavements in this project indicate that the TNM program over-predicts noise levels, with both the "Average" and the "OGAC" options. The "Average" pavement option in TNM over predicts noise levels by almost 5 dBA, while the "OGAC" pavement option over predicts noise levels by about 3 dBA, on average. These numbers imply that the "Average" option is not the best alternative for calculations corresponding to PFC pavements. The "OGAC" option represents a definite improvement toward a more accurate prediction; however, the analysis performed indicates that the values within the program on which the calculations are based (REMELs) could be further adjusted with results such as those gathered in this study to fine-tune the program's predictions even more. In general, based on research conducted to date, the results of this study support a change in the current FHWA policy, change which could remove the restriction on using pavement type as a noise abatement. This analysis, also suggests that the modeling capabilities of TNM could be improved for PFCs by enabling the use of the "OGAC" pavement type option, as these open-graded pavements differ substantially in their results when compared to those obtained using the "Average" option. This supports removing the restriction on the use of these surfaces for the purpose of impact avoidance.

For the case of rigid pavements, the TNM "PCC" option resulted in predicted sound levels that were very close compared to actual roadside measurements. The "average" option underestimated the actual sound pressure levels. Given that the "PCC" option is not enabled other than for research purposes, these (limited) results support making it available, in an analogous case to PFCs and the "Average" TNM option.

8.1.4 Case Studies

Several tests and analyses on pavement types other than PFCs were also developed within this research. These studies emphasized the significance of the frequency spectral analysis when evaluating noise results.

The application of uniform transverse tining on concrete pavements as a texturing method for safety purposes produces higher overall noise levels, and a peak around 1000 Hz in the frequency spectra. The analyses show that tining is responsible for a significant component of the loudness of such pavements. The use of diamond-grinding results in quieter overall levels than those exhibited by tined sections. Diamond-grinding makes the noise levels comparable to those of PFCs, and eliminates the whining noise produced by the uniform transverse tining. This manifests in the reduction of the 1000-Hz peak in the frequency spectra. Removal of superficial distresses through the diamond-grinding process also contributes to the improved acoustic performance.

The quietest rigid pavement sections measured in this project correspond to two untined CRCP sections: one was a diamond-ground section, and the other one was an old pavement next to it.

The other case study, which involved the successful application of a thin PFC overlay to reduce roadside noise levels for old, very noisy CRCP sections in high traffic urban areas was effectively demonstrated by the before and after case study on IH-30 in downtown Dallas. It should be noted, however, that this example showcased a comparison of pavements of different ages, in which the old CRCP is compared to a brand new PFC overlay. Nevertheless, two options for reducing CRCP noise levels that show promise are diamond grinding and PFC overlay.

8.2 Recommendations

It is recommended to follow up this study with further, long-term testing, to thoroughly assess the influence of aging on noise levels, especially for PFCs. Up to the conclusion of this project, as mentioned in the previous statements, the aging effect has been deemed as inconsequential in the overall acoustic performance of the pavements—shown both graphically in Chapter 4 and through statistical analysis in Chapter 7. Accordingly, a new four-year TxDOT study on PFCs is underway, Project 0-5836, “Performance of Permeable Friction Courses (PFC) Over Time,” which should provide a proper time frame to follow-up on some of the sections studied in Project 0-5185.

The results obtained in this project support the recommendation of modifying the FHWA policy to allow the use of pavement surfaces such as PFCs for noise avoidance and abatement. This would require enabling non-Average pavement types in TNM. Because PFC pavements in Texas may incorporate unique design elements compared to open graded pavement elsewhere in the nation, it is important to collect a substantial database of noise measurements for TxDOT PFC pavement designs. This data may be used at some point to establish classes (bins) of permeable pavements within the TNM analysis program.

If network-level OBSI measurements are to be performed in the future by TxDOT, and if the testing program faces limitations in regards to time or other resources, the alternative microphone position at the center of the tire patch is a viable option, as not much accuracy is lost and the results have shown to be reliable.

Two environmental variables that appear to affect PFC noise performance are total rainfall (perhaps affecting clogging) and heating (perhaps affecting compaction). The former variable is collected by NCDC, but the latter variable, also collected by NCDC, might serve as a surrogate variable for pavement temperature, which would be better represented by a direct measurement of the surface temperature over time. Therefore, it is recommended that further study include embedded Thermochron devices to record pavement temperature history.

An area of traffic noise that needs to be considered for future research involves sound propagation effects. Sound propagates differently above different types of surfaces, depending on the materials properties. For instance, acoustic waves propagate differently through porous materials, such as PFC, as they do through a more reflective one, as could be the case of a CRCP. Thus, if there is a shoulder or a traffic lane of different material in relation to the pavement being measured between the noise source and the reference microphone, the results would not be the same compared to the case of the surface being homogeneous. The acoustical properties of various road surfaces could be measured and compared to theoretical models.

One method seen in the literature involves placing a pink noise emitter on or near the pavement surface to be investigated, to be measured at a specified distance across the pavement surface. The roadside measurement then shows the differential absorption spectra characteristic for the pavement being measured.

Work under this study suggests that two alternate methods of measuring propagation absorption are available, using existing equipment. The first simply uses the frequency spectra recorded by the roadside meters during controlled pass by testing. Any difference in spectral characteristics between the tire/pavement contact noise measured using OBSI and the roadside spectral measurements can be attributed to differential absorption as the acoustic wave propagates over the pavement surface. This method has the great advantage of not requiring traffic control, but does require a brief period of time where there are no other vehicles near the test vehicle.

The second method (which has been tried on a very limited basis but shows promise) is to use the field portable impedance tube system to measure the in-situ spectral absorptivity of the pavement. This method provides a definitive result without requiring destructive coring, but does require lane closure and traffic control for the duration of the measurement.

Tests of this nature could impart further insight into the absorptive characteristics of porous pavements such as PFC. By placing the source and the reference microphone close to the surface, the measured level difference spectra can provide a suitable in situ method to assess the evolution of clogging in the voids of the pavements.

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Appendix A: PFC Test Sections Summary and All OBSI Results

This appendix presents a summary of the properties of all the PFC sections tested in this project and their average OBSI results, which are shown in Table A.1. The sections are shown grouped by district, and are classified according to the factorial variables: climatic region, binder type, and age. A description of the factorial experiment is presented in Chapter 4.

Table A.1 shows the several test dates for each of the sections and the average OBSI noise level calculated on each occasion. Such averages were calculated considering all the subsections that comprised each section, and both directions of travel.

Table A.2 presents the detailed OBSI data and selected climatic information for all the pavement sections investigated in this project, as explained in Chapter 7.

Table A.1: PFC Test sections and OBSI results

District	Highway	Type	Year Constructed	Site Description	Factorial Classification			Test Date 1	Test Date 2	Test Date 3	Test Date 4	Test Date 5	Average Test Date 1 (dBA)	Average Test Date 2 (dBA)	Average Test Date 3 (dBA)	Average Test Date 4 (dBA)	Average Test Date 5 (dBA)
					Climate	Binder	Age										
Austin	US 183	PFC	2003	North Fork San Gabriel R. to Seward Junction (SH 29)	Dry-Freeze	Polymer Modified	Medium	8/23/2006					98.1				
	IH 35	PFC	2006	Colorado River to Ben White	Dry-Freeze	Polymer Modified	New	9/22/2006					98.5				
	IH 35 South	PFC	2005	Loop 4 to Yarrington Rd.	Dry-Freeze	Polymer Modified	New	9/22/2006	9/7/2007	9/7/2007			98.7	100.7	101.0		
	IH 35 North	PFC	2005	Loop 4 to Yarrington Rd.	Dry-Freeze	Polymer Modified	New	9/22/2006	9/7/2007	9/7/2007			99.5	100.0	100.1		
	FM 1431	Item 3231 - PFC	2005	From Trails End rd. to 0.2 mi West of Vista Ridge	Dry-Freeze	Polymer Modified	New	6/7/2007					99.1				
	FM 620	PFC	2004	From Parmer Ln. to IH-35	Dry-Freeze	Polymer Modified	New, Medium	9/7/2006	6/7/2007				98.4	98.9			
	Loop 360	PFC		US 183 to FM 2222	Dry-Freeze	Polymer Modified	New	6/7/2007					100.2				
Dallas	IH 30	PFC	2006	Sylvan Ave. to Loop 12	Wet-Freeze	Polymer Modified	New	9/26/2006					99.7				
Corpus Christi	IH 37	PFC	2004	(CC1: Asphalt rubber mix w/ limestone). From downtown Corpus Christi at US 181 to north of the Nueces River Bridge.	Dry- No Freeze	Crumb Rubber	New	10/11/2006					98.3				
	IH 37	PFC	2004	(CC2: fibers and limestone). From Nueces River Bridge to Atascosa County line.	Dry- No Freeze	Polymer Modified	New	10/11/2006					101.9				
Houston	US 90	PFC	2003	from IH 10 east of Peach Ridge rd. to FM 359, West Harris Area Office	Wet- No Freeze	Crumb Rubber	Medium	1/9/2007					98.1				
	SH 6	PFC	2004	from Harris Co. Line to US 90A, let in January 2004; Fort Bend Area Office	Wet- No Freeze	Polymer Modified	Medium	1/9/2007					100.4				
	IH 45	PFC	2005	from Loop 336 to FM 1097, let in February 2005; Montgomery Area Office	Wet- No Freeze	Polymer Modified	New	1/11/2007					101.7				
	SH 242	PFC	2005	from San Jacinto River to US 59, let in February 2005; Montgomery Area Office	Wet- No Freeze	Polymer Modified	New	1/11/2007					100.7				
	SH 146	PFC	2005	FM 518 to FM 1764	Wet- No Freeze	Polymer Modified	New	1/9/2007					100.2				
San Antonio	IH 35	PFC	2003	Weidner Road to Loop 1604 or Thousand Oaks to Topperwein	Dry- No Freeze	Crumb Rubber	Medium	10/24/2006					97.3				
	US 281	TY PFC_AR1	2006	Bass Rd to 0.40 Miles North of Hildebrand	Dry- No Freeze	Crumb Rubber	New	10/9/2006	11/29/2006	12/6/2006	9/26/2007	9/3/2008	94.9	95.6	95.7	95.9	96.6
	US 281	TY PFC_AR2	2006	0.40 Miles North of Hildebrand to Pearl Parkway	Dry- No Freeze	Crumb Rubber	New	10/9/2006	12/6/2006	9/26/2007			98.9	98.9	98.1		
Waco	IH 35	PFC	2003	Main lanes at Craven Ave, placed in 2003, 1 ½ inches of PFC, McLennan County	Dry-Freeze	Polymer Modified	Medium, Old	9/29/2006	6/5/2008				99.3	100.6			
	SH 6	PFC	2005	from BU 77 to SH 164, McLennan County	Dry-Freeze	Polymer Modified	New, Medium	9/29/2006	9/4/2008				98.1	98.9			
Yoakum	US 290	PFC	2004	from Washington County Line to Lee County Line, Fayette County	Wet- No Freeze	Polymer Modified	Medium	8/8/2007					99.7				
	IH 10	PFC	2001	from FM 609 to US 90 at Waelder, Fayette and Gonzales Counties	Wet- No Freeze	Polymer Modified	Old	8/9/2007	8/7/2008				98.8	99.9			
	IH 10	PFC	2006	from US 90 at Waelder to US 183, Gonzales and Caldwell Counties	Wet- No Freeze	Polymer Modified	New	9/18/2007 (Rain)	9/25/2007				99.7	99.7			

Table A.2: Detailed OBSI results and climatic information for 0-5185 Project sections

OBSI and Selected Climate Data

HWY	City	ID	Type	Const_Y	Climate	Binder	Test_YR	Agency	T1	T2	T3	Tavg	L1	L2	L3	Lavg	AVG	Center	TotRain	AvgMaxT	AvgMinT	TFP	MaxT	MinT	Day32	AvgT
FM143	Aus	EB1	PFC	2005	DF	P	2007.5	CTR	99.7	99.2	99.0	99.3	99.5	99.5	99.6	99.5	99.4	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM143	Aus	EB2	PFC	2005	DF	P	2007.5	CTR	100.2	100.4	100.8	100.5	99.7	100.0	99.3	99.8	100.2	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM143	Aus	WB1	PFC	2005	DF	P	2007.5	CTR	97.8	97.8	98.0	97.9	97.5	97.4	97.3	97.4	97.6	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM620	Aus	EB1	PFC	2004	DF	P	2006.8	CTR	98.4	98.2	97.9	98.2	98.1	97.8	97.3	97.7	98.0	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM620	Aus	EB1	PFC	2004	DF	P	2006.8	CTR	98.3	98.1	98.0	98.1	98.7	98.4	98.4	98.5	98.3	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM620	Aus	WB1	PFC	2004	DF	P	2006.8	CTR	98.8	98.9	99.2	99.0	99.1	98.3	0.0	98.7	98.8	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM620	Aus	WB1	PFC	2004	DF	P	2006.8	CTR	99.5	99.4	99.7	99.5	99.7	99.5	99.4	99.5	99.5	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM734	Aus	1	ACP	0	DF	N	2007.7	CTR	101.7	101.6	102.3	101.9	102.0	101.7	100.6	101.4	101.7	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM734	Aus	2	ACP	0	DF	N	2007.7	CTR	101.5	102.6	102.2	102.1	102.3	102.4	102.3	102.3	102.2	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM734	Aus	3	ACP	0	DF	N	2007.7	CTR	101.6	101.1	101.0	101.2	100.2	100.3	100.3	100.3	100.8	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM734	Aus	4	ACP	0	DF	N	2007.7	CTR	101.8	101.3	101.4	101.5	102.1	101.1	101.8	101.7	101.6	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM734	Aus	1	ACP	0	DF	N	2008.3	CTR	102.5	103.3	103.2	103.0	102.0	102.5	102.7	102.4	102.7	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM734	Aus	2	ACP	0	DF	N	2008.3	CTR	102.3	103.6	103.1	103.0	102.8	103.1	103.2	103.0	103.0	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM734	Aus	3	ACP	0	DF	N	2008.3	CTR	101.8	101.7	102.3	101.9	101.6	101.6	101.7	101.6	101.8	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
FM734	Aus	5	ACP	0	DF	N	2008.3	CTR	102.6	102.7	103.4	102.9	102.1	102.8	102.9	102.6	102.7	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	10	PFC	2005	DF	P	2006.8	TxDOT	101.4	101.2	101.4	101.2	100.9	100.9	101.0	100.9	101.6	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	11	PFC	2005	DF	P	2006.8	TxDOT	100.2	100.3	100.3	100.2	100.3	99.9	100.3	100.2	100.4	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	12	PFC	2005	DF	P	2006.8	TxDOT	99.8	99.6	99.8	99.9	100.1	100.2	99.9	100.1	99.9	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	13	PFC	2005	DF	P	2006.8	TxDOT	100.2	100.0	100.1	100.1	100.0	100.1	100.2	100.1	100.1	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	7	PFC	2005	DF	P	2006.8	TxDOT	101.1	101.1	101.1	100.9	100.6	100.7	100.5	100.6	101.1	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	8	PFC	2005	DF	P	2006.8	TxDOT	101.1	101.3	101.2	101.0	100.8	101.0	100.6	100.8	101.3	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	9	PFC	2005	DF	P	2006.8	TxDOT	101.3	101.2	101.3	101.1	101.1	100.8	100.9	101.0	101.4	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	10	PFC	2005	DF	P	2006.8	TxDOT	100.1	99.9	99.8	99.9	99.4	99.3	99.2	99.3	99.6	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	11	PFC	2005	DF	P	2006.8	TxDOT	99.1	98.6	98.8	98.8	98.0	98.1	98.0	98.0	98.4	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	12	PFC	2005	DF	P	2006.8	TxDOT	99.2	99.1	98.9	99.0	98.0	98.5	98.4	98.3	98.7	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	13	PFC	2005	DF	P	2006.8	TxDOT	99.4	99.1	99.3	99.3	98.5	98.5	98.6	98.5	98.9	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	7	PFC	2005	DF	P	2006.8	TxDOT	99.6	99.9	100.1	99.9	99.4	99.3	99.3	99.3	99.6	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	8	PFC	2005	DF	P	2006.8	TxDOT	100.2	100.0	99.9	100.0	99.3	99.1	99.1	99.2	99.6	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	9	PFC	2005	DF	P	2006.8	TxDOT	100.0	100.0	100.0	100.0	98.7	98.7	98.2	98.6	99.3	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	10	PFC	2005	DF	P	2007.8	CTR	101.4	101.2	101.4	101.2	100.9	100.9	101.0	100.9	101.6	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	11	PFC	2005	DF	P	2007.8	CTR	100.2	100.3	100.3	100.2	100.3	99.9	100.3	100.2	100.4	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	12	PFC	2005	DF	P	2007.8	CTR	99.8	99.6	99.8	99.9	100.1	100.2	99.9	100.1	99.9	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	13	PFC	2005	DF	P	2007.8	CTR	100.2	100.0	100.1	100.1	100.0	100.1	100.2	100.1	100.1	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	7	PFC	2005	DF	P	2007.8	CTR	101.1	101.1	101.1	100.9	100.6	100.7	100.5	100.6	101.1	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	8	PFC	2005	DF	P	2007.8	CTR	101.1	101.3	101.2	101.0	100.8	101.0	100.6	100.8	101.3	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH35	Aus	9	PFC	2005	DF	P	2007.8	CTR	101.3	101.2	101.3	101.1	101.1	100.8	100.9	101.0	101.4	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2

**0 indicates missing values*

OBSI and Selected Climate Data

HWY	City	ID	Type	Const_Y	Climate	Binder	Test_YR	Agency	T1	T2	T3	Tavg	L1	L2	L3	Lavg	AVG	Center	TotRain	AvgMaxT	AvgMinT	TFP	MaxT	MinT	Day32	AvgT
Loop3	Aus	EB1	PFC	0	DF	P	2007.5	CTR	100.3	100.3	99.9	100.2	99.8	99.7	99.9	99.8	100.0	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
Loop3	Aus	WB1	PFC	0	DF	P	2007.5	CTR	101.0	100.8	100.9	0.0	100.1	100.0	99.6	99.9	100.4	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
SH130	Aus	NB1	CRC	0	DF	N	2008.5	CTR	102.4	101.3	0.0	101.8	101.2	101.3	0.0	101.3	101.6	100.3	31.5	80.9	56.1	0.1	103	21	36	68.2
SH130	Aus	NB2	CRC	0	DF	N	2008.5	CTR	102.4	101.3	0.0	101.8	101.0	101.0	0.0	101.0	101.4	100.1	31.5	80.9	56.1	0.1	103	21	36	68.2
SH130	Aus	SB1	CRC	0	DF	N	2008.5	CTR	100.6	100.2	0.0	100.4	100.5	100.6	0.0	100.5	100.5	98.9	31.5	80.9	56.1	0.1	103	21	36	68.2
SH130	Aus	SB2	CRC	0	DF	N	2008.5	CTR	102.3	102.5	0.0	102.4	101.4	101.6	0.0	101.5	102.0	100.3	31.5	80.9	56.1	0.1	103	21	36	68.2
SH130	Aus	SB3	CRC	0	DF	N	2008.5	CTR	100.9	100.5	0.0	100.7	100.3	100.4	0.0	100.4	100.6	99.2	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	1	PFC	2003	DF	P	2006.7	TxDOT	98.7	99.1	98.9	98.5	98.1	97.9	97.9	98.0	98.7	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	2	PFC	2003	DF	P	2006.7	TxDOT	97.9	97.6	97.6	97.2	96.7	96.6	97.0	96.8	97.5	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	3	PFC	2003	DF	P	2006.7	TxDOT	99.6	99.2	99.4	99.1	99.1	98.7	98.6	98.8	99.4	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	4	PFC	2003	DF	P	2006.7	TxDOT	98.0	97.6	97.9	97.8	97.6	98.1	97.7	97.8	98.0	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	1	PFC	2003	DF	P	2006.8	TxDOT	98.7	98.7	99.1	98.9	98.1	97.9	97.9	98.0	98.5	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	2	PFC	2003	DF	P	2006.8	TxDOT	97.5	97.9	97.6	97.6	96.7	96.6	97.0	96.8	97.2	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	3	PFC	2003	DF	P	2006.8	TxDOT	99.4	99.6	99.2	99.4	99.1	98.7	98.6	98.8	99.1	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	4	PFC	2003	DF	P	2006.8	TxDOT	98.0	98.0	97.6	97.9	97.6	98.1	97.7	97.8	97.8	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	10	CRC	0	DF	N	2007.8	CTR	105.6	105.7	105.7	105.7	105.7	106.0	105.9	105.9	105.8	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	11	CRC	0	DF	N	2007.8	CTR	106.9	106.9	107.0	106.9	105.7	106.2	0.0	105.9	106.5	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	12	CRC	0	DF	N	2007.8	CTR	107.2	107.0	107.2	107.1	106.4	106.5	0.0	106.4	106.8	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	13	CRC	0	DF	N	2007.8	CTR	106.4	106.4	106.2	106.3	105.1	106.0	106.0	105.7	106.0	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	14	CRC	0	DF	N	2007.8	CTR	105.7	105.6	105.6	105.6	105.0	104.9	104.8	104.9	105.3	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	5	CRC	0	DF	N	2007.8	CTR	102.3	101.9	102.1	0.0	101.0	100.8	101.2	101.0	101.6	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	6	CRC	0	DF	N	2007.8	CTR	104.5	103.9	104.2	0.0	101.9	102.5	102.3	102.2	103.3	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	7	CRC	0	DF	N	2007.8	CTR	102.2	101.6	101.9	0.0	101.0	100.9	101.0	101.0	101.5	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	8	CRC	0	DF	N	2007.8	CTR	101.7	101.2	101.3	101.4	100.6	100.6	100.4	100.5	101.0	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	9	CRC	0	DF	N	2007.8	CTR	102.1	102.0	101.8	102.0	101.4	101.2	101.4	101.3	101.7	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	10	CRC	0	DF	N	2008.3	CTR	106.7	105.9	106.6	106.4	106.0	106.1	106.0	106.0	106.2	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	11	CRC	0	DF	N	2008.3	CTR	107.1	107.1	107.2	107.1	105.6	106.1	106.9	106.2	106.7	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	12	CRC	0	DF	N	2008.3	CTR	107.4	107.4	107.4	0.0	106.9	107.3	107.2	107.1	107.3	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	13	CRC	0	DF	N	2008.3	CTR	106.6	106.9	106.6	106.7	105.7	105.7	106.3	105.9	106.3	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	14	CRC	0	DF	N	2008.3	CTR	106.0	105.9	105.9	0.0	104.9	105.5	105.5	105.3	105.6	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	5	CRC	0	DF	N	2008.3	CTR	102.5	103.0	102.9	102.8	102.1	101.7	101.9	101.9	102.4	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	6	CRC	0	DF	N	2008.3	CTR	103.6	104.2	104.7	104.1	102.7	103.7	103.0	103.1	103.7	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	7	CRC	0	DF	N	2008.3	CTR	102.4	102.7	102.7	102.6	100.7	101.9	101.7	101.4	102.0	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	8	CRC	0	DF	N	2008.3	CTR	101.7	101.7	102.2	101.9	101.5	101.6	101.9	101.7	101.8	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	9	CRC	0	DF	N	2008.3	CTR	102.5	102.5	102.3	102.4	102.0	102.3	102.2	102.2	102.3	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	10	CRC	0	DF	N	2008.6	CTR	105.8	105.5	105.5	105.6	105.5	105.0	105.4	105.3	105.5	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2

**0 indicates missing values*

OBSI and Selected Climate Data

HWY	City	ID	Type	Const_Y	Climate	Binder	Test_YR	Agency	T1	T2	T3	Tavg	L1	L2	L3	Lavg	AVG	Center	TotRain	AvgMaxT	AvgMinT	TFP	MaxT	MinT	Day32	AvgT
US183	Aus	11	CRC	0	DF	N	2008.6	CTR	106.7	106.8	106.3	106.6	105.8	0.0	105.6	105.7	106.2	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	12	CRC	0	DF	N	2008.6	CTR	106.9	107.3	107.2	107.2	106.8	107.0	106.8	106.8	107.0	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	13	CRC	0	DF	N	2008.6	CTR	106.1	106.2	106.7	106.3	106.3	106.1	106.1	106.2	106.3	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	14	CRC	0	DF	N	2008.6	CTR	105.7	105.8	105.7	105.7	105.1	104.9	105.3	105.1	105.4	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	5	CRC	0	DF	N	2008.6	CTR	102.3	102.8	102.3	102.5	101.2	102.1	101.7	101.6	102.1	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	6	CRC	0	DF	N	2008.6	CTR	103.2	103.1	104.2	103.5	103.0	103.2	102.0	102.7	103.1	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	7	CRC	0	DF	N	2008.6	CTR	102.0	101.5	102.1	101.8	101.6	101.7	101.8	101.7	101.8	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	8	CRC	0	DF	N	2008.6	CTR	100.9	101.0	101.4	101.1	100.9	100.9	100.9	100.9	101.0	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
US183	Aus	9	CRC	0	DF	N	2008.6	CTR	102.0	102.1	101.9	102.0	102.2	101.5	101.8	101.8	101.9	0.0	31.5	80.9	56.1	0.1	103	21	36	68.2
IH37	Crp	CC1N	PFC	2004	DN	R	2006.8	CTR	100.1	100.1	0.0	100.1	98.5	99.1	98.6	98.8	99.5	0.0	33.6	82.7	63.4	0.0	102	29	2	73.1
IH37	Crp	CC1S	PFC	2004	DN	R	2006.8	CTR	99.0	99.8	99.0	99.3	97.6	97.5	97.6	97.5	98.5	0.0	33.6	82.7	63.4	0.0	102	29	2	73.1
IH37	Crp	CC1S	PFC	2004	DN	R	2006.8	CTR	98.9	98.1	98.4	98.5	97.0	96.3	97.3	96.8	97.7	0.0	33.6	82.7	63.4	0.0	102	29	2	73.1
IH37	Crp	CC2N	PFC	2004	DN	P	2006.8	CTR	102.0	101.7	0.0	101.8	101.5	102.1	101.3	101.6	101.7	0.0	33.6	82.7	63.4	0.0	102	29	2	73.1
IH37	Crp	CC2N	PFC	2004	DN	P	2006.8	CTR	102.4	102.2	102.3	102.3	101.9	100.9	102.2	101.7	102.0	0.0	33.6	82.7	63.4	0.0	102	29	2	73.1
IH37	Crp	SBDG	ACP	0	DN	N	2006.8	CTR	98.6	98.2	98.6	98.5	96.9	97.1	97.4	97.1	97.8	0.0	33.6	82.7	63.4	0.0	102	29	2	73.1
IH30	Dal	C1	CRC	0	WF	N	2006.8	CTR	105.1	103.6	0.0	104.4	104.1	103.5	0.0	104.0	104.2	0.0	35.1	78.3	58.7	0.4	105	19	20	68.5
IH30	Dal	EB1	PFC	2006.5	WF	P	2006.8	CTR	101.3	100.4	100.5	100.7	100.4	99.0	99.0	99.4	100.1	0.0	35.1	78.3	58.7	0.4	105	19	20	68.5
IH30	Dal	EB2	PFC	2006.5	WF	P	2006.8	CTR	99.4	99.4	99.0	99.2	98.5	98.1	0.0	98.3	98.8	0.0	35.1	78.3	58.7	0.4	105	19	20	68.5
IH30	Dal	WB1	PFC	2006.5	WF	P	2006.8	CTR	99.1	99.0	100.0	99.4	98.7	98.0	98.4	98.3	98.9	0.0	35.1	78.3	58.7	0.4	105	19	20	68.5
IH30	Dal	WB2	PFC	2006.5	WF	P	2006.8	CTR	101.3	101.4	101.4	101.4	100.7	100.4	100.4	100.5	101.0	0.0	35.1	78.3	58.7	0.4	105	19	20	68.5
IH45	Hou	1	PFC	2005	WN	P	2007	TxDOT	102.6	102.4	101.8	102.3	101.2	101.8	101.2	101.4	101.9	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
IH45	Hou	2	PFC	2005	WN	P	2007	TxDOT	102.2	102.5	102.3	102.3	101.6	101.7	101.3	101.5	102.0	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
IH45	Hou	3	PFC	2005	WN	P	2007	TxDOT	101.2	101.3	100.6	101.0	100.1	99.8	100.2	100.0	100.6	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
IH45	Hou	4	PFC	2005	WN	P	2007	TxDOT	100.9	101.5	101.0	101.1	100.3	100.1	99.9	100.1	100.6	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
IH45	Hou	5	PFC	2005	WN	P	2007	TxDOT	102.4	102.5	102.4	102.4	101.3	101.7	101.3	101.5	102.0	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
IH45	Hou	6	PFC	2005	WN	P	2007	TxDOT	103.5	103.5	103.2	103.4	102.4	102.5	102.5	102.5	103.0	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
IH45	Hou	7	PFC	2005	WN	P	2007	TxDOT	102.2	102.4	102.5	102.4	101.8	101.3	101.1	101.4	101.9	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
IH45	Hou	8	PFC	2005	WN	P	2007	TxDOT	102.2	102.3	101.9	102.1	101.5	101.3	100.9	101.2	101.7	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
SH146	Hou	1	PFC	2005	WN	P	2007	TxDOT	100.4	100.3	99.6	100.1	100.1	101.7	99.7	100.5	100.3	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
SH146	Hou	2	PFC	2005	WN	P	2007	TxDOT	97.7	98.9	100.2	98.9	99.5	100.1	98.2	99.3	99.1	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
SH146	Hou	3	PFC	2005	WN	P	2007	TxDOT	101.6	101.7	102.0	101.8	101.1	100.7	100.2	100.7	101.2	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
SH146	Hou	4	PFC	2005	WN	P	2007	TxDOT	100.0	100.0	99.7	99.9	100.0	100.6	100.4	100.3	100.1	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
SH146	Hou	5	PFC	2005	WN	P	2007	TxDOT	100.5	100.5	100.0	100.3	100.4	101.9	100.9	101.0	100.7	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
SH146	Hou	6	PFC	2005	WN	P	2007	TxDOT	100.0	100.0	99.7	100.2	99.9	99.4	99.8	99.7	99.9	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
SH242	Hou	1	PFC	2005	WN	P	2007	TxDOT	100.9	101.3	101.3	101.2	101.2	101.1	101.6	101.3	101.2	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
SH242	Hou	2	PFC	2005	WN	P	2007	TxDOT	100.7	100.6	100.9	100.7	100.8	100.7	100.6	100.7	100.7	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2

**0 indicates missing values*

OBSI and Selected Climate Data

HWY	City	ID	Type	Const_Y	Climate	Binder	Test_YR	Agency	T1	T2	T3	Tavg	L1	L2	L3	Lavg	AVG	Center	TotRain	AvgMaxT	AvgMinT	TFP	MaxT	MinT	Day32	AvgT
SH242	Hou	3	PFC	2005	WN	P	2007	TxDOT	100.3	100.5	100.1	100.3	101.0	100.8	100.8	100.9	100.6	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
SH242	Hou	4	PFC	2005	WN	P	2007	TxDOT	98.8	98.7	99.0	98.9	99.1	99.1	99.0	99.1	99.0	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
SH242	Hou	5	PFC	2005	WN	P	2007	TxDOT	101.5	101.5	101.8	101.6	101.3	101.5	101.2	101.4	101.5	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
SH242	Hou	6	PFC	2005	WN	P	2007	TxDOT	101.3	101.5	101.5	101.4	101.4	101.2	100.8	101.1	101.3	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
SH6	Hou	1	PFC	2004	WN	P	2007	TxDOT	101.2	101.5	101.6	101.4	100.7	100.5	99.9	100.4	100.9	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
SH6	Hou	2	PFC	2004	WN	P	2007	TxDOT	101.5	101.1	101.5	101.4	100.7	100.8	100.5	100.7	101.0	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
SH6	Hou	3	PFC	2004	WN	P	2007	TxDOT	100.5	101.0	101.2	100.9	99.4	100.3	100.0	99.9	100.4	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
SH6	Hou	4	PFC	2004	WN	P	2007	TxDOT	100.1	100.4	100.5	100.3	98.3	98.7	99.6	98.9	99.7	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
SH6	Hou	5	PFC	2004	WN	P	2007	TxDOT	100.6	100.1	100.3	100.3	99.1	99.5	99.0	99.2	99.8	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
SH6	Hou	6	PFC	2004	WN	P	2007	TxDOT	101.4	101.3	101.2	101.3	99.6	100.4	99.9	100.0	100.7	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
US90	Hou	1	PFC	2003	WN	R	2007	TxDOT	98.2	98.3	98.4	98.3	97.6	97.7	97.6	97.6	98.0	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
US90	Hou	2	PFC	2003	WN	R	2007	TxDOT	99.3	99.1	99.0	99.1	99.1	99.0	98.5	98.8	99.0	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
US90	Hou	3	PFC	2003	WN	R	2007	TxDOT	97.7	98.2	98.1	98.0	97.7	97.9	97.0	97.5	97.8	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
US90	Hou	4	PFC	2003	WN	R	2007	TxDOT	97.4	97.7	98.1	97.7	97.3	97.2	97.3	97.3	97.5	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
US90	Hou	5	PFC	2003	WN	R	2007	TxDOT	98.5	98.8	99.0	98.8	98.0	97.9	98.1	98.0	98.4	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
US90	Hou	6	PFC	2003	WN	R	2007	TxDOT	101.2	101.4	101.1	101.2	100.4	100.2	100.3	100.3	100.8	0.0	54.9	80.3	60.5	0.0	101	29	18	70.2
IH35	San	NB1	PFC	2003	DN	R	2006.8	CTR	96.1	96.0	96.2	96.1	97.0	96.9	0.0	97.0	96.6	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
IH35	San	NB2	PFC	2003	DN	R	2006.8	CTR	96.1	97.7	97.7	96.8	98.3	97.1	98.1	97.8	97.4	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
IH35	San	SB1	PFC	2003	DN	R	2006.8	CTR	97.2	97.4	97.2	97.2	98.3	98.5	96.1	98.4	97.8	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
IH35	San	SB2	PFC	2003	DN	R	2006.8	CTR	97.0	96.9	0.0	97.0	97.6	97.4	0.0	97.5	97.2	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	1	ACP	2006	DN	R	2006.8	TxDOT	101.0	101.1	101.0	101.0	100.1	100.4	100.6	100.3	100.7	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	10	PFC	2006	DN	R	2006.8	TxDOT	99.8	99.7	0.0	99.7	99.3	99.2	99.0	99.2	99.5	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	11	PFC	2006	DN	R	2006.8	TxDOT	99.9	100.0	0.0	99.9	99.1	98.8	99.1	99.0	99.5	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	12	PFC	2006	DN	R	2006.8	TxDOT	95.8	95.0	95.4	95.4	95.2	95.3	94.9	95.1	95.3	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	13	PFC	2006	DN	R	2006.8	TxDOT	94.1	94.1	94.1	94.1	93.7	93.8	93.8	93.8	93.9	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	14	PFC	2006	DN	R	2006.8	TxDOT	94.4	94.5	95.1	94.7	94.7	94.4	94.8	94.6	94.6	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	15	ACP	2006	DN	R	2006.8	TxDOT	102.3	103.1	103.0	102.8	102.1	102.2	102.2	102.2	102.5	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	16	ACP	2006	DN	R	2006.8	TxDOT	102.4	102.9	103.0	102.8	101.6	101.1	101.5	101.4	102.1	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	17	PFC	2006	DN	R	2006.8	TxDOT	98.5	98.8	0.0	98.6	97.8	98.1	98.1	98.0	98.3	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	2	ACP	2006	DN	R	2006.8	TxDOT	100.0	100.1	100.2	100.1	99.6	99.7	99.5	99.6	99.9	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	3	PFC	2006	DN	R	2006.8	TxDOT	94.7	95.4	95.3	95.1	94.7	94.7	95.1	94.8	95.0	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	4	PFC	2006	DN	R	2006.8	TxDOT	95.6	95.9	95.9	95.8	95.4	95.5	95.5	95.4	95.6	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	5	PFC	2006	DN	R	2006.8	TxDOT	94.8	94.8	94.9	94.8	94.4	95.0	95.0	94.8	94.8	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	6	PFC	2006	DN	R	2006.8	TxDOT	97.1	0.0	0.0	97.1	97.2	97.3	97.0	97.2	97.1	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	7	PFC	2006	DN	R	2006.8	TxDOT	99.4	99.0	98.9	99.1	97.7	98.2	98.1	98.0	98.6	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	8	PFC	2006	DN	R	2006.8	TxDOT	99.5	99.7	99.8	99.7	98.4	98.6	98.9	98.6	99.2	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4

**0 indicates missing values*

OBSI and Selected Climate Data

HWY	City	ID	Type	Const_Y	Climate	Binder	Test_YR	Agency	T1	T2	T3	Tavg	L1	L2	L3	Lavg	AVG	Center	TotRain	AvgMaxT	AvgMinT	TFP	MaxT	MinT	Day32	AvgT
US281	San	9	PFC	2006	DN	R	2006.8	TxDOT	98.7	98.5	98.6	98.6	97.8	97.7	97.8	97.8	98.2	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	NB12	PFC	2006	DN	R	2006.9	CTR	95.2	95.2	0.0	95.2	95.6	95.7	96.1	95.8	95.5	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	NB13	PFC	2006	DN	R	2006.9	CTR	94.0	94.2	94.5	94.1	94.8	94.7	94.7	94.7	94.4	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	NB14	PFC	2006	DN	R	2006.9	CTR	95.2	95.0	95.3	95.1	95.2	95.3	95.7	95.4	95.3	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	SB3	PFC	2006	DN	R	2006.9	CTR	96.0	96.4	95.5	95.9	95.9	96.0	95.8	95.9	95.9	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	SB4	PFC	2006	DN	R	2006.9	CTR	96.3	96.6	96.4	96.4	96.5	96.0	96.4	96.2	96.3	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	SB5	PFC	2006	DN	R	2006.9	CTR	95.6	95.3	96.0	95.4	96.8	96.8	95.7	96.4	95.9	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	1	ACP	2006	DN	R	2006.9	TxDOT	101.2	101.4	101.2	101.3	100.7	100.7	100.6	100.7	101.0	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	10	PFC	2006	DN	R	2006.9	TxDOT	99.9	99.7	99.5	99.7	98.6	99.8	0.0	99.2	99.5	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	11	PFC	2006	DN	R	2006.9	TxDOT	99.6	100.2	99.6	99.8	99.1	99.6	99.8	99.5	99.6	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	12	PFC	2006	DN	R	2006.9	TxDOT	96.1	95.8	96.0	96.0	95.6	96.3	95.9	95.9	95.9	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	13	PFC	2006	DN	R	2006.9	TxDOT	94.8	94.4	94.5	94.6	94.2	94.4	94.1	94.2	94.4	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	14	PFC	2006	DN	R	2006.9	TxDOT	95.8	95.7	95.7	95.7	95.0	95.3	95.1	95.1	95.4	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	15	ACP	2006	DN	R	2006.9	TxDOT	102.9	103.2	103.2	103.1	102.6	102.7	102.7	102.6	102.9	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	16	ACP	2006	DN	R	2006.9	TxDOT	102.0	103.1	102.7	102.6	102.4	102.3	102.4	102.4	102.5	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	17	PFC	2006	DN	R	2006.9	TxDOT	99.2	99.2	98.9	99.1	98.9	98.8	0.0	98.9	99.0	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	2	ACP	2006	DN	R	2006.9	TxDOT	100.7	100.5	100.7	100.6	100.3	100.3	100.2	100.3	100.4	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	3	PFC	2006	DN	R	2006.9	TxDOT	96.6	96.7	96.5	96.6	96.1	96.4	96.2	96.2	96.4	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	4	PFC	2006	DN	R	2006.9	TxDOT	96.2	96.3	96.3	96.2	95.8	96.1	95.9	95.9	96.1	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	5	PFC	2006	DN	R	2006.9	TxDOT	96.0	95.6	96.5	96.0	95.7	96.2	95.7	95.8	95.9	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	6	PFC	2006	DN	R	2006.9	TxDOT	97.8	98.0	97.8	97.9	97.6	98.1	97.9	97.8	97.9	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	7	PFC	2006	DN	R	2006.9	TxDOT	99.2	99.2	99.0	99.1	98.6	98.9	0.0	98.7	99.0	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	8	PFC	2006	DN	R	2006.9	TxDOT	98.7	99.7	99.7	99.4	98.6	99.4	0.0	99.0	99.2	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	9	PFC	2006	DN	R	2006.9	TxDOT	98.6	98.2	97.9	98.2	97.7	98.1	98.4	98.0	98.1	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	NB11	PFC	2006	DN	R	2007.8	CTR	0.0	0.0	0.0	0.0	98.1	98.0	97.4	97.8	97.7	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	NB13	PFC	2006	DN	R	2007.8	CTR	95.0	95.0	94.9	95.0	94.8	94.9	95.0	94.9	94.9	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	NB14	PFC	2006	DN	R	2007.8	CTR	96.3	96.2	96.2	96.2	95.6	96.0	95.3	95.6	95.9	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	SB17	PFC	2006	DN	R	2007.8	CTR	98.4	98.3	98.0	98.2	98.4	98.2	0.0	98.3	98.3	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	SB3	PFC	2006	DN	R	2007.8	CTR	96.4	96.7	96.5	96.4	95.9	96.2	96.1	96.1	96.3	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	SB4	PFC	2006	DN	R	2007.8	CTR	96.2	96.2	96.8	96.4	96.0	96.2	96.3	96.0	96.2	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	SB5	PFC	2006	DN	R	2007.8	CTR	96.4	95.8	95.5	95.9	95.9	95.9	95.9	96.0	95.9	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	SB7	PFC	2006	DN	R	2007.8	CTR	98.4	98.2	98.3	0.0	97.9	97.9	97.8	97.9	98.1	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	SB8	PFC	2006	DN	R	2007.8	CTR	98.1	0.0	0.0	98.1	98.4	0.0	0.0	98.4	98.3	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	NB12	PFC	2006	DN	R	2008.8	CTR	96.7	96.9	0.0	96.8	97.2	97.5	0.0	97.3	97.1	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	NB13	PFC	2006	DN	R	2008.8	CTR	95.5	95.4	0.0	95.5	95.6	96.3	0.0	96.0	95.7	0.0	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	SB3	PFC	2006	DN	R	2008.8	CTR	96.6	96.7	0.0	96.6	97.2	97.1	0.0	97.1	96.9	96.2	28.4	81.2	59.6	0.0	105	25	12	70.4

**0 indicates missing values*

OBSI and Selected Climate Data

HWY	City	ID	Type	Const_Y	Climate	Binder	Test_YR	Agency	T1	T2	T3	Tavg	L1	L2	L3	Lavg	AVG	Center	TotRain	AvgMaxT	AvgMinT	TFP	MaxT	MinT	Day32	AvgT
US281	San	SB4	PFC	2006	DN	R	2008.8	CTR	95.7	96.6	96.3	96.2	96.9	96.9	0.0	96.9	96.5	95.7	28.4	81.2	59.6	0.0	105	25	12	70.4
US281	San	SB5	PFC	2006	DN	R	2008.8	CTR	96.5	96.2	96.4	96.3	97.3	97.0	0.0	97.2	96.8	95.2	28.4	81.2	59.6	0.0	105	25	12	70.4
IH35	Wac	NB1	PFC	2003	DF	P	2006.8	CTR	100.5	100.6	100.4	100.5	99.8	98.8	100.0	99.5	100.0	0.0	31.7	79.6	56.4	1.2	107	19	31	68.1
IH35	Wac	NB2	PFC	2003	DF	P	2006.8	CTR	100.5	100.1	0.0	100.3	100.0	99.4	99.4	99.6	100.0	0.0	31.7	79.6	56.4	1.2	107	19	31	68.1
IH35	Wac	SB1	PFC	2003	DF	P	2006.8	CTR	100.0	99.6	99.4	99.7	99.2	99.3	0.0	99.2	99.5	0.0	31.7	79.6	56.4	1.2	107	19	31	68.1
IH35	Wac	SB2	PFC	2003	DF	P	2006.8	CTR	98.6	99.4	0.0	99.0	97.7	97.9	98.0	97.9	98.5	0.0	31.7	79.6	56.4	1.2	107	19	31	68.1
IH35	Wac	SB2	ACP	0	DF	N	2006.8	CTR	100.9	0.0	0.0	100.9	100.7	100.2	0.0	100.4	100.7	0.0	31.7	79.6	56.4	1.2	107	19	31	68.1
IH35	Wac	NB0	CRC	0	DF	P	2008.5	CTR	0.0	98.7	99.4	99.0	0.0	98.1	98.9	98.5	98.8	0.0	31.7	79.6	56.4	1.2	107	19	31	68.1
IH35	Wac	NB1	PFC	2008	DF	P	2008.5	CTR	97.8	98.6	98.4	98.3	98.3	98.1	98.3	98.2	98.2	0.0	31.7	79.6	56.4	1.2	107	19	31	68.1
IH35	Wac	NB2	PFC	2003	DF	P	2008.5	CTR	101.1	100.3	101.0	100.8	100.6	100.5	99.8	100.3	100.6	0.0	31.7	79.6	56.4	1.2	107	19	31	68.1
IH35	Wac	NBOC	CRC	0	DF	P	2008.5	CTR	0.0	100.7	100.7	100.7	0.0	100.9	100.0	100.4	100.6	0.0	31.7	79.6	56.4	1.2	107	19	31	68.1
IH35	Wac	SB1	PFC	2003	DF	P	2008.5	CTR	101.4	101.3	100.9	101.2	100.6	100.1	100.0	100.2	100.7	0.0	31.7	79.6	56.4	1.2	107	19	31	68.1
IH35	Wac	SB2	PFC	2008	DF	P	2008.5	CTR	98.5	98.2	98.4	98.4	97.8	96.9	97.8	97.5	98.0	0.0	31.7	79.6	56.4	1.2	107	19	31	68.1
IH35	Wac	SB3	CRC	0	DF	P	2008.5	CTR	99.3	98.3	98.8	98.8	0.0	97.6	98.2	97.9	98.4	0.0	31.7	79.6	56.4	1.2	107	19	31	68.1
SH6	Wac	EB1	PFC	2005	DF	P	2006.8	CTR	98.2	97.9	97.3	97.8	96.9	97.3	97.4	97.2	97.5	0.0	31.7	79.6	56.4	1.2	107	19	31	68.1
SH6	Wac	EB2	PFC	2005	DF	P	2006.8	CTR	98.9	98.9	98.6	98.8	98.1	98.5	98.0	98.2	98.5	0.0	31.7	79.6	56.4	1.2	107	19	31	68.1
SH6	Wac	WB1	PFC	2005	DF	P	2006.8	CTR	98.3	98.2	98.5	98.3	97.9	97.3	97.2	97.4	97.9	0.0	31.7	79.6	56.4	1.2	107	19	31	68.1
SH6	Wac	WB2	PFC	2005	DF	P	2006.8	CTR	99.4	99.3	99.4	99.4	98.4	98.5	98.6	98.5	99.0	0.0	31.7	79.6	56.4	1.2	107	19	31	68.1
SH6	Wac	EB1	PFC	2005	DN	P	2008.8	CTR	97.9	98.9	98.7	98.5	97.5	97.4	98.6	97.8	98.1	97.9	31.7	79.6	56.4	1.2	107	19	31	68.1
SH6	Wac	EB2	PFC	2005	DN	P	2008.8	CTR	99.2	98.6	99.6	99.1	98.2	99.4	98.7	98.8	98.9	99.6	31.7	79.6	56.4	1.2	107	19	31	68.1
SH6	Wac	WB1	PFC	2005	DN	P	2008.8	CTR	98.6	98.2	98.4	98.4	98.4	98.8	98.3	98.5	98.5	98.6	31.7	79.6	56.4	1.2	107	19	31	68.1
SH6	Wac	WB2	PFC	2005	DN	P	2008.8	CTR	99.8	100.0	99.7	99.8	100.1	100.2	100.1	100.1	100.0	100.5	31.7	79.6	56.4	1.2	107	19	31	68.1
IH10	Ykm	EB1	PFC	2001	WN	P	2007.7	CTR	98.1	98.9	98.4	98.5	98.8	99.0	98.9	98.9	98.7	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	EB2	PFC	2001	WN	P	2007.7	CTR	97.0	98.7	98.0	97.8	98.6	98.3	98.2	98.4	98.1	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	EB3	PFC	2001	WN	P	2007.7	CTR	99.1	99.5	99.8	99.5	98.7	99.2	99.4	99.1	99.3	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	WB1	PFC	2001	WN	P	2007.7	CTR	98.6	98.4	99.8	98.9	98.0	98.4	98.1	98.2	98.5	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	WB2	PFC	2001	WN	P	2007.7	CTR	98.3	98.1	98.1	98.2	97.5	97.4	98.1	97.5	97.8	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	WB3	PFC	2001	WN	P	2007.7	CTR	100.2	100.3	100.4	100.3	100.1	99.8	99.8	99.9	100.1	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	EB1	PFC	2006	WN	P	2007.8	CTR	100.1	0.0	0.0	100.1	99.8	100.2	100.0	100.0	100.1	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	EB1	PFC	2006	WN	P	2007.8	CTR	99.8	99.4	99.7	99.6	99.5	99.7	99.7	99.7	99.6	100.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	EB2	PFC	2006	WN	P	2007.8	CTR	99.3	0.0	0.0	99.3	100.8	99.0	101.0	100.3	99.8	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	EB2	PFC	2006	WN	P	2007.8	CTR	101.5	101.4	100.3	101.4	100.6	100.4	100.1	100.4	100.9	101.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	EB3	PFC	2006	WN	P	2007.8	CTR	100.8	0.0	0.0	100.8	100.8	98.9	101.0	100.2	100.5	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	EB3	PFC	2006	WN	P	2007.8	CTR	99.8	0.0	0.0	99.8	98.9	98.2	99.7	98.9	99.4	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	EB3	PFC	2006	WN	P	2007.8	CTR	101.4	99.9	101.4	100.9	99.7	99.6	99.5	99.6	100.3	101.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	WB4	PFC	2006	WN	P	2007.8	CTR	99.8	0.0	0.0	99.8	99.1	99.4	98.6	99.3	99.5	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4

**0 indicates missing values*

OBSI and Selected Climate Data

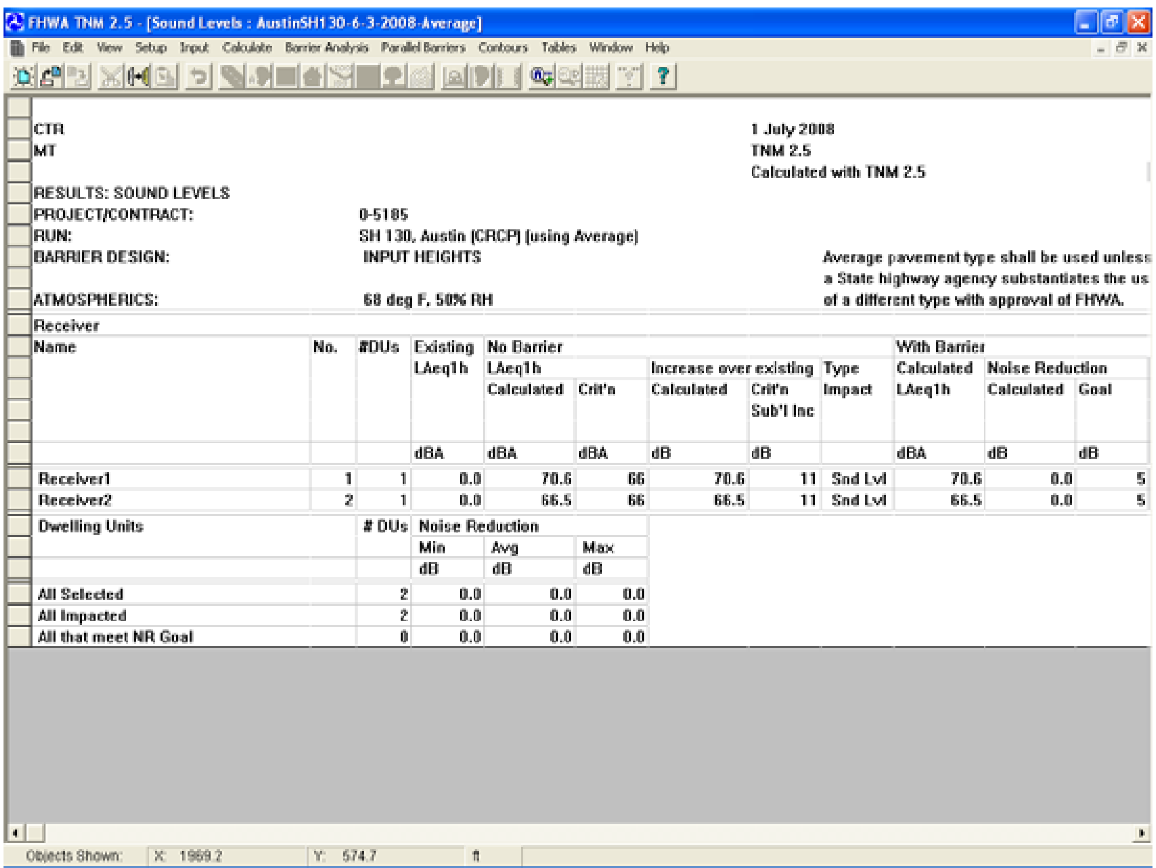
HWY	City	ID	Type	Const_Y	Climate	Binder	Test_YR	Agency	T1	T2	T3	Tavg	L1	L2	L3	Lavg	AVG	Center	TotRain	AvgMaxT	AvgMinT	TFP	MaxT	MinT	Day32	AvgT
IH10	Ykm	WB4	PFC	2006	WN	P	2007.8	CTR	99.7	99.5	99.2	99.4	99.3	99.2	99.0	99.3	99.2	99.3	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	WB5	PFC	2006	WN	P	2007.8	CTR	99.9	0.0	0.0	99.9	98.2	98.6	99.5	98.4	99.2	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	WB5	PFC	2006	WN	P	2007.8	CTR	99.8	99.2	99.8	99.5	99.1	98.8	99.0	99.0	99.3	98.6	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	WB6	PFC	2006	WN	P	2007.8	CTR	99.3	98.9	98.8	99.1	98.5	98.2	98.6	98.4	98.8	99.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	EB1	PFC	2001	WN	P	2008.7	CTP	101.0	100.7	100.9	100.8	99.7	100.5	99.8	100.0	100.4	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	EB2	PFC	2001	WN	P	2008.7	CTP	100.0	97.9	98.8	98.9	99.0	97.4	99.4	98.6	98.8	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	EB3	PFC	2001	WN	P	2008.7	CTP	101.3	101.5	101.3	101.4	100.3	100.8	100.6	100.6	101.0	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	WB1	PFC	2001	WN	P	2008.7	CTR	101.3	101.0	100.8	101.0	99.0	100.5	100.3	99.7	100.4	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	WB2	PFC	2001	WN	P	2008.7	CTR	99.6	99.4	99.2	99.4	98.0	98.9	98.8	98.4	98.9	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH10	Ykm	WB3	PFC	2001	WN	P	2008.7	CTR	100.5	99.4	100.7	100.0	101.3	101.0	99.2	100.5	100.2	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH35	Ykm	10	PFC	2005	DF	P	2007.8	CTR	101.6	101.4	101.2	101.4	100.9	100.9	101.0	100.9	101.2	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH35	Ykm	11	PFC	2005	DF	P	2007.8	CTR	100.4	100.2	100.3	100.3	100.3	99.9	100.3	100.2	100.2	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH35	Ykm	12	PFC	2005	DF	P	2007.8	CTR	99.9	99.8	99.6	99.8	100.1	100.2	99.9	100.1	99.9	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH35	Ykm	13	PFC	2005	DF	P	2007.8	CTP	100.1	100.2	100.0	100.1	100.0	100.1	100.2	100.1	100.1	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH35	Ykm	7	PFC	2005	DF	P	2007.8	CTP	101.1	101.1	101.1	101.1	100.6	100.7	100.5	100.6	100.9	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH35	Ykm	8	PFC	2005	DF	P	2007.8	CTP	101.3	101.1	101.3	101.2	100.8	101.0	100.6	100.8	101.0	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
IH35	Ykm	9	PFC	2005	DF	P	2007.8	CTR	101.4	101.3	101.2	101.3	101.1	100.9	100.9	101.0	101.1	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
US290	Ykm	EB1	PFC	2004	WN	P	2007.8	CTR	99.4	100.4	100.4	99.9	99.6	99.7	100.3	99.9	99.9	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
US290	Ykm	EB2	PFC	2004	WN	P	2007.8	CTR	99.7	99.8	99.8	99.7	98.8	100.2	99.7	99.6	99.6	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
US290	Ykm	EB3	PFC	2004	WN	P	2007.8	CTR	98.5	99.5	98.7	98.9	98.1	98.4	98.4	98.3	98.6	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
US290	Ykm	WB1	PFC	2004	WN	P	2007.8	CTR	99.7	99.7	99.6	99.7	98.5	99.5	99.4	99.0	99.4	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
US290	Ykm	WB2	PFC	2004	WN	P	2007.8	CTP	100.6	100.6	100.6	100.6	100.4	100.5	100.8	100.4	100.5	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4
US290	Ykm	WB3	PFC	2004	WN	P	2007.8	CTP	100.6	99.8	100.2	100.2	100.2	100.1	100.1	100.1	100.1	0.0	53.6	78.3	58.5	0.0	99	21	17	68.4

0 indicates missing values

Appendix B: TNM Results of Special Case Studies

This appendix includes the TNM analyses performed for the Austin SH 130 sections. These CRCP sections were measured on June 3, 2008 and June 12, 2008. The explanation of the tests conducted on these occasions is presented in Chapter 6. The TNM analyses were performed using the two pavement type options that the program includes that are applicable to rigid pavements: "average" and "PCC." In this page, and in each of the subsequent pages, the results of the program for one analysis are displayed, as presented by the program's output screens. The actual roadside measurement that corresponds to each case is shown on top of each TNM analysis.

Date: 6/3/2008
Measurement Period: 1
Actual Roadside Measurement: 72.8 dBA at 7.5 m
TNM Result: 70.6 dBA
Pavement Type Option: Average


FHWA TNM 2.5 - [Sound Levels : AustinSH130-6-3-2008-Average]

CTR 1 July 2008
MT TNM 2.5
Calculated with TNM 2.5

RESULTS: SOUND LEVELS
PROJECT/CONTRACT: 0-5185
RUN: SH 130, Austin (CRCP) (using Average)
BARRIER DESIGN: INPUT HEIGHTS
ATMOSPHERICS: 68 deg F, 50% RH

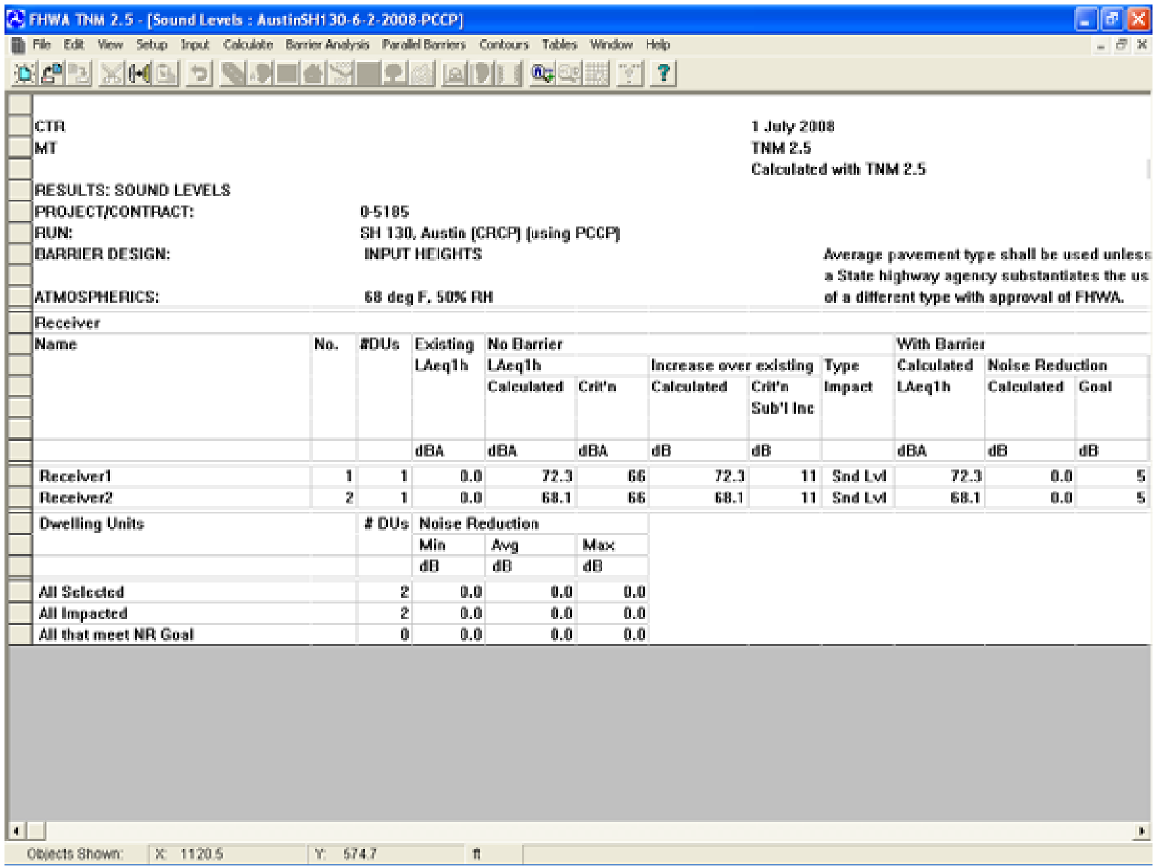
Average pavement type shall be used unless a State highway agency substantiates the us of a different type with approval of FHWA.

Receiver

Name	No.	#DUs	Existing LAeq1h	No Barrier LAeq1h Calculated	No Barrier LAeq1h Crit'n	Increase over existing Calculated	Increase over existing Crit'n Sub'l Inc	Type Impact	With Barrier Calculated LAeq1h	Noise Reduction Calculated	Noise Reduction Goal
			dBA	dBA	dBA	dB	dB		dBA	dB	dB
Receiver1	1	1	0.0	70.6	66	70.6	11	Snd Lvl	70.6	0.0	5
Receiver2	2	1	0.0	66.5	66	66.5	11	Snd Lvl	66.5	0.0	5

Dwelling Units	# DUs	Noise Reduction Min	Noise Reduction Avg	Noise Reduction Max
		dB	dB	dB
All Selected	2	0.0	0.0	0.0
All Impacted	2	0.0	0.0	0.0
All that meet NR Goal	0	0.0	0.0	0.0

6/3/2008
Measurement Period: 1
Actual Roadside Measurement: 72.8 dBA at 7.5 m
TNM Result: 72.3 dBA
Pavement Type Option: PCC



FHWA TNM 2.5 - [Sound Levels : AustinSH130-6-2-2008-PCCP]

File Edit View Setup Input Calculate Barrier Analysis Parallel Barriers Contours Tables Window Help

CTR — 1 July 2008
MT — TNM 2.5
Calculated with TNM 2.5

RESULTS: SOUND LEVELS
PROJECT/CONTRACT: 0-5185
RUN: SH 130, Austin (CRCP) (using PCCP)
BARRIER DESIGN: INPUT HEIGHTS
ATMOSPHERICS: 68 deg F, 50% RH

Average pavement type shall be used unless a State highway agency substantiates the us of a different type with approval of FHWA.

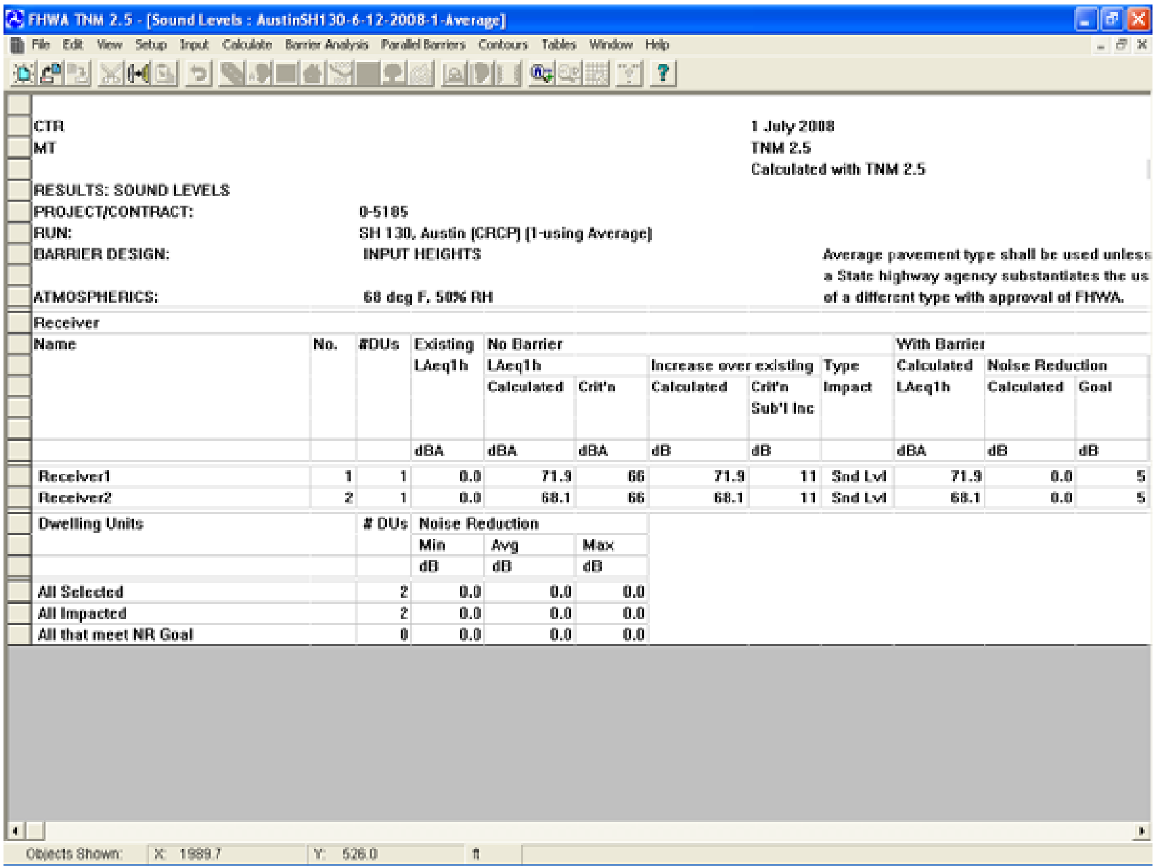
Receiver Name	No.	#DUs	Existing LAeq1h	No Barrier LAeq1h Calculated	No Barrier LAeq1h Crit'n	Increase over existing Calculated	Increase over existing Crit'n Sub'l Inc	Type Impact	With Barrier Calculated LAeq1h	Noise Reduction Calculated	Noise Reduction Goal
			dBA	dBA	dBA	dB	dB		dBA	dB	dB
Receiver1	1	1	0.0	72.3	66	72.3	11	Snd Lvl	72.3	0.0	5
Receiver2	2	1	0.0	68.1	66	68.1	11	Snd Lvl	68.1	0.0	5

Dwelling Units	# DUs	Noise Reduction Min	Noise Reduction Avg	Noise Reduction Max
		dB	dB	dB
All Selected	2	0.0	0.0	0.0
All Impacted	2	0.0	0.0	0.0
All that meet NR Goal	0	0.0	0.0	0.0

Objects Shown: X: 1120.5 Y: 574.7 ft

6/12/2008
Measurement Period: 1
Actual Roadside Measurements: 73.7 dBA at 7.5 m
68.4 dBA at 15 m

TNM Result: 71.9 dBA at 7.5 m
68.1 dBA at 15 m
Pavement Type Option: Average


FHWA TNM 2.5 - [Sound Levels : AustinSH130-6-12-2008-1-Average]

File Edit View Setup Input Calculate Barrier Analysis Parallel Barriers Contours Tables Window Help

CTR 1 July 2008
MT TNM 2.5
Calculated with TNM 2.5

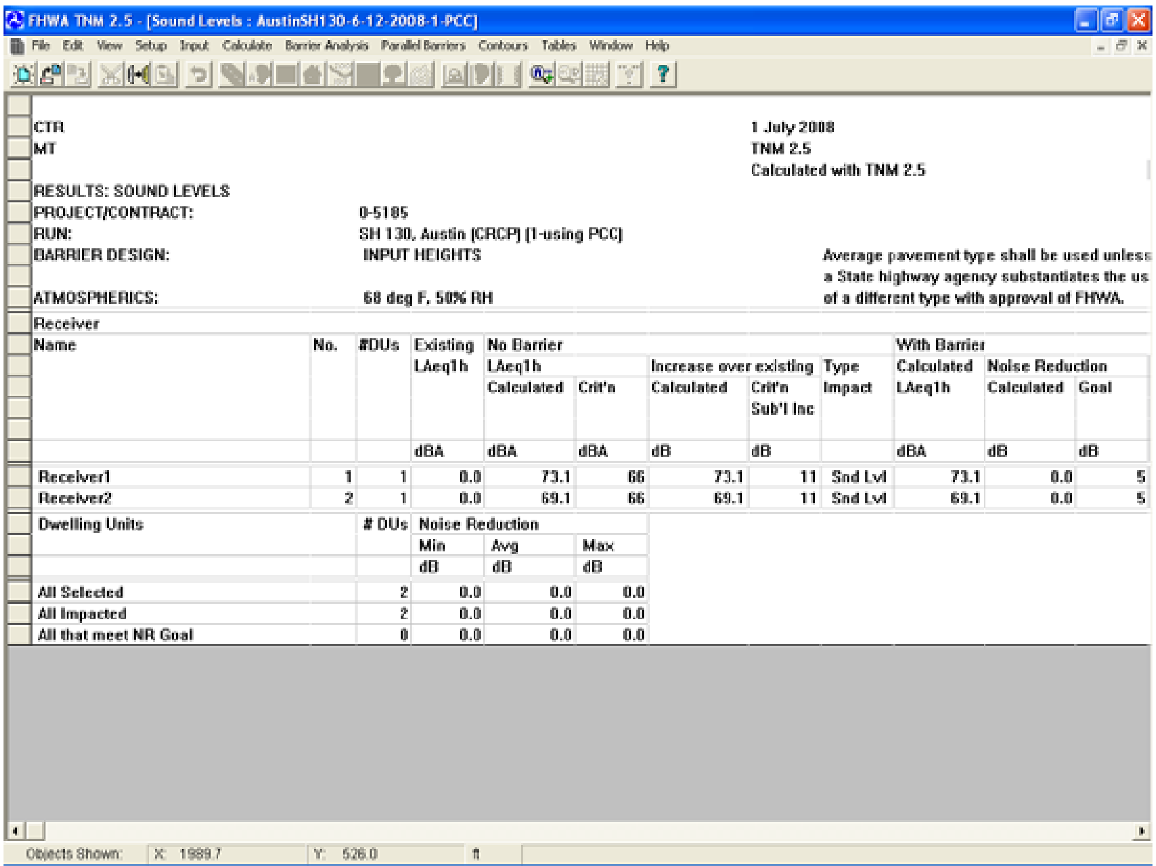
RESULTS: SOUND LEVELS
PROJECT/CONTRACT: 0-5185
RUN: SH 130, Austin (CRCP) (1-using Average)
BARRIER DESIGN: INPUT HEIGHTS
Average pavement type shall be used unless a State highway agency substantiates the us of a different type with approval of FHWA.
ATMOSPHERICS: 68 deg F, 50% RH

Receiver Name	No.	#DUs	Existing LAeq1h	No Barrier LAeq1h Calculated	No Barrier LAeq1h Crit'n	Increase over existing Calculated	Increase over existing Crit'n Sub'l Inc	Type Impact	With Barrier Calculated LAeq1h	Noise Reduction Calculated	Noise Reduction Goal
			dBA	dBA	dBA	dB	dB		dBA	dB	dB
Receiver1	1	1	0.0	71.9	66	71.9	11	Snd Lvl	71.9	0.0	5
Receiver2	2	1	0.0	68.1	66	68.1	11	Snd Lvl	68.1	0.0	5

Dwelling Units	# DUs	Noise Reduction Min	Avg	Max
		dB	dB	dB
All Selected	2	0.0	0.0	0.0
All Impacted	2	0.0	0.0	0.0
All that meet NR Goal	0	0.0	0.0	0.0

Objects Shown: X: 1989.7 Y: 526.0 ft

6/12/2008
Measurement Period: 1
Actual Roadside Measurements: 73.7 dBA at 7.5 m
68.4 dBA at 15 m
TNM Result: 73.1 dBA at 7.5 m
69.1 dBA at 15 m
Pavement Type Option: PCC



CTR
MT

1 July 2008
TNM 2.5
Calculated with TNM 2.5

RESULTS: SOUND LEVELS
PROJECT/CONTRACT: 0-5185
RUN: SH 130, Austin (CRCP) (1-using PCC)
BARRIER DESIGN: INPUT HEIGHTS
ATMOSPHERICS: 68 deg F. 50% RH

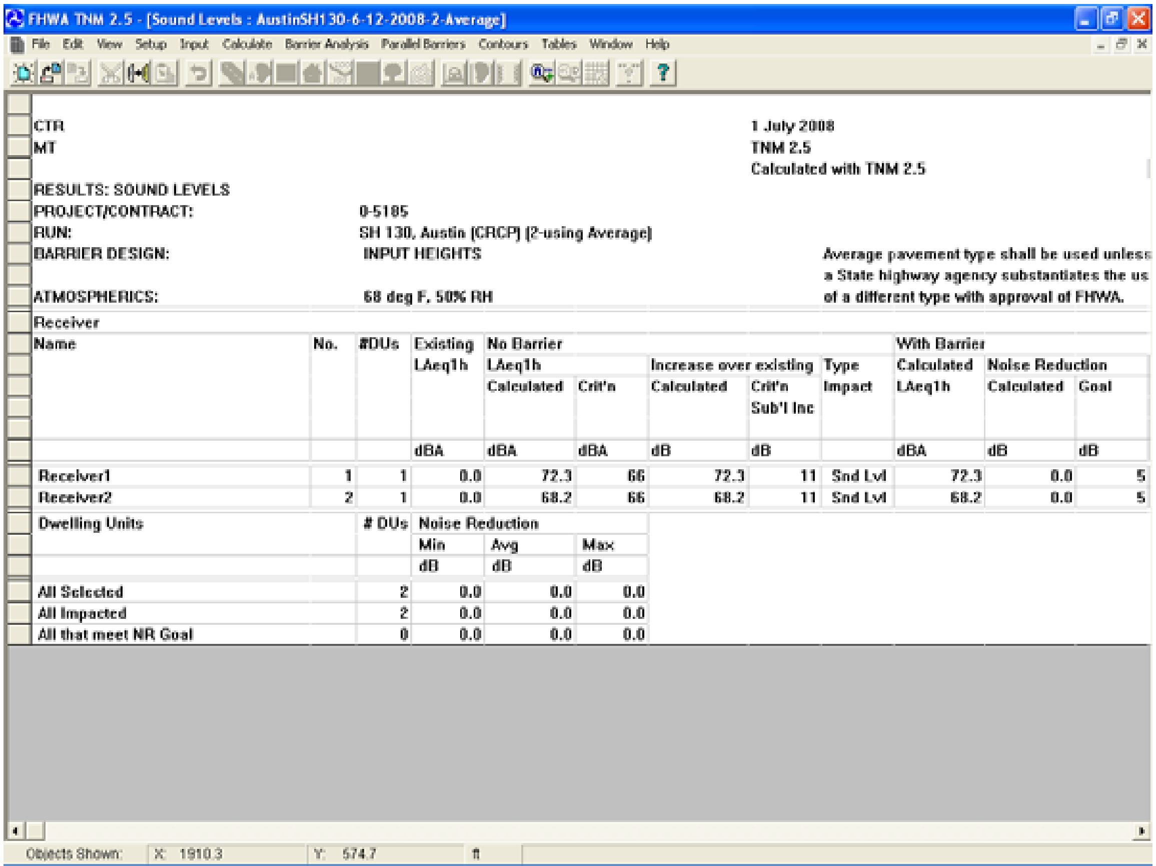
Average pavement type shall be used unless a State highway agency substantiates the us of a different type with approval of FHWA.

Receiver											
Name	No.	#DUs	Existing	No Barrier					With Barrier		
			LAeq1h	LAeq1h		Increase over existing		Type	Calculated	Noise Reduction	
				Calculated	Crit'n	Calculated	Crit'n Sub'l Inc	Impact	LAeq1h	Calculated	Goal
			dBA	dBA	dBA	dB	dB		dBA	dB	dB
Receiver1	1	1	0.0	73.1	66	73.1	11	Snd Lvl	73.1	0.0	5
Receiver2	2	1	0.0	69.1	66	69.1	11	Snd Lvl	69.1	0.0	5

Dwelling Units	# DUs	Noise Reduction		
		Min	Avg	Max
		dB	dB	dB
All Selected	2	0.0	0.0	0.0
All Impacted	2	0.0	0.0	0.0
All that meet NR Goal	0	0.0	0.0	0.0

6/12/2008
Measurement Period: 2
Actual Roadside Measurements: 75.2 dBA at 7.5 m
69.9 dBA at 15 m

TNM Result: 72.3 dBA at 7.5 m
68.2 dBA at 15 m
Pavement Type Option: Average



CTR 1 July 2008
MT TNM 2.5
Calculated with TNM 2.5

RESULTS: SOUND LEVELS
PROJECT/CONTRACT: 0-5185
RUN: SH 130, Austin (CRCP) (2-using Average)
BARRIER DESIGN: INPUT HEIGHTS
ATMOSPHERICS: 68 deg F, 50% RH

Average pavement type shall be used unless a State highway agency substantiates the us of a different type with approval of FHWA.

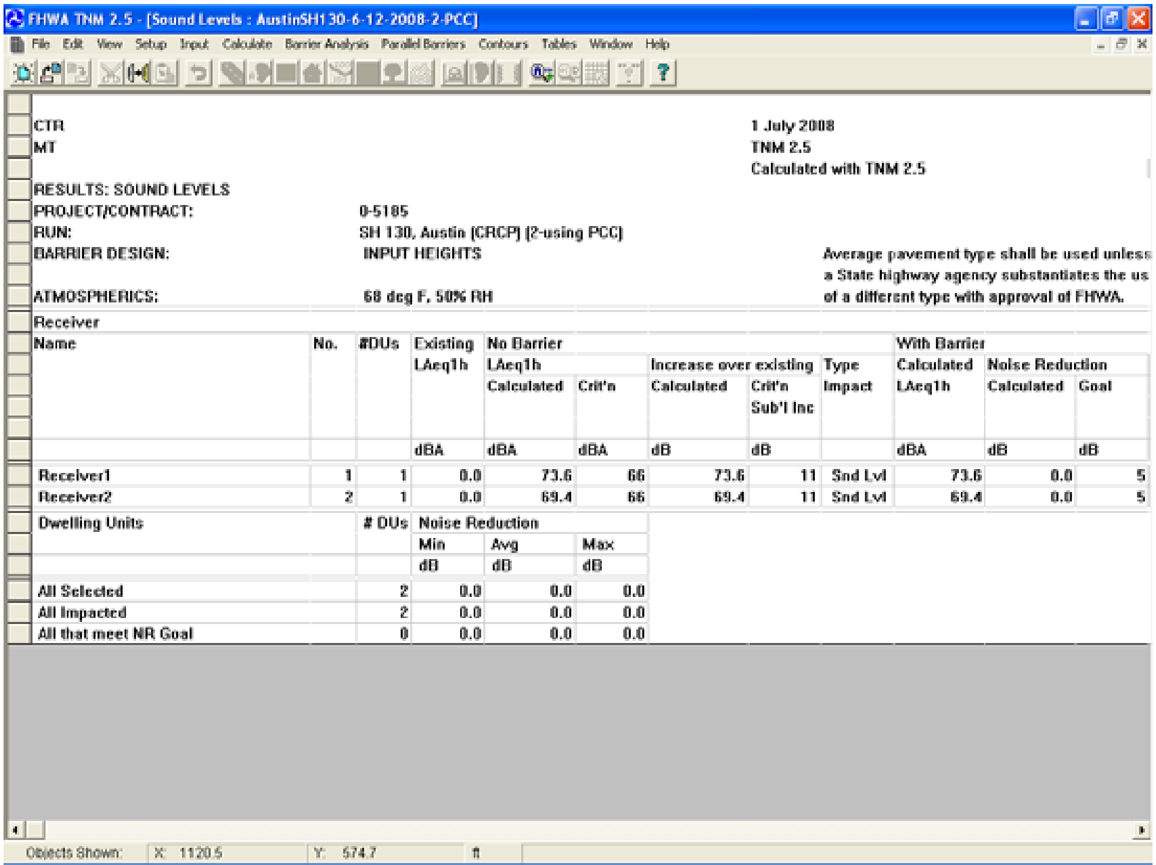
Receiver Name	No.	#DUs	Existing LAeq1h	No Barrier LAeq1h Calculated	No Barrier LAeq1h Crit'n	Increase over existing Calculated	Increase over existing Crit'n Sub'l Inc	Type Impact	With Barrier Calculated LAeq1h	Noise Reduction Calculated	Noise Reduction Goal
			dBA	dBA	dBA	dB	dB		dBA	dB	dB
Receiver1	1	1	0.0	72.3	66	72.3	11	Snd Lvl	72.3	0.0	5
Receiver2	2	1	0.0	68.2	66	68.2	11	Snd Lvl	68.2	0.0	5

Dwelling Units	# DUs	Noise Reduction Min	Noise Reduction Avg	Noise Reduction Max
		dB	dB	dB
All Selected	2	0.0	0.0	0.0
All Impacted	2	0.0	0.0	0.0
All that meet NR Goal	0	0.0	0.0	0.0

6/12/2008
Measurement Period: 2
Actual Roadside Measurements: 75.2 dBA at 7.5 m
69.9 dBA at 15 m

TNM Result: 73.6 dBA at 7.5 m
69.4 dBA at 15 m

Pavement Type Option: PCC


FHWA TNM 2.5 - [Sound Levels : AustinSH130-6-12-2008-2-PCC]

File Edit View Setup Input Calculate Barrier Analysis Parallel Barriers Contours Tables Window Help

CTR | 1 July 2008
MT | TNM 2.5
Calculated with TNM 2.5

RESULTS: SOUND LEVELS
PROJECT/CONTRACT: 0-5185
RUN: SH 130, Austin (CRCP) (2-using PCC)
BARRIER DESIGN: INPUT HEIGHTS
ATMOSPHERICS: 68 deg F, 50% RH

Average pavement type shall be used unless a State highway agency substantiates the us of a different type with approval of FHWA.

Receiver Name	No.	#DUs	Existing LAeq1h	No Barrier LAeq1h Calculated	No Barrier Crit'n	Increase over existing Calculated	Increase over existing Crit'n Sub'l Inc	Type Impact	With Barrier Calculated LAeq1h	Noise Reduction Calculated	Noise Reduction Goal
			dBA	dBA	dBA	dB	dB		dBA	dB	dB
Receiver1	1	1	0.0	73.6	66	73.6	11	Snd Lvl	73.6	0.0	5
Receiver2	2	1	0.0	69.4	66	69.4	11	Snd Lvl	69.4	0.0	5

Dwelling Units	# DUs	Noise Reduction Min	Avg	Max
		dB	dB	dB
All Selected	2	0.0	0.0	0.0
All Impacted	2	0.0	0.0	0.0
All that meet NR Goal	0	0.0	0.0	0.0

Objects Shown: X: 1120.5 Y: 574.7 ft