Evaluating Tire/Pavement Noise Utilizing the On-Board Sound Intensity Method

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ABSTRACT OF THE THESIS

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Mitigating transportation noise is a major concern for Departments of Transportation (DOT) nationwide. From a responsibility standpoint, once a noise source leaves the boundary of the property, the noise control falls under the jurisdiction of the DOT. In the past, mitigation by the DOT was typically accomplished by erecting a sound barrier. If there was more noise or louder noise, a larger wall was used. As construction of these walls is prohibitively expensive, DOTs are increasingly interested in mitigating noise from the source. In order to investigate noise being produced at the source, the on-board sound intensity method was utilized to investigate quiet pavements. The method revealed the acoustical properties of both conventional pavements and quiet pavements. This research also led to the investigation of the effects of vehicle speed, effects of temperature and effects of different consumer tires and the role each plays in the generation of noise at the tire pavement interface.

Acknowledgements

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Chapter 1: Background

INTRODUCTION

Mitigating transportation noise is a major concern for Departments of Transportation (DOT) nationwide (1). From a responsibility standpoint, once a noise source leaves the boundary of the property, the noise control falls under the jurisdiction of the DOT (2). In the past, mitigation by the DOT was typically accomplished by erecting a sound barrier (2). If there was more noise or louder noise, a larger wall was used. As construction of these walls is prohibitively expensive, DOTs are increasingly interested in mitigating noise from the source (3,4). It is known that on highways, the controlling noise generating mechanism is the tire/pavement interface [3]. DOTs nationally have received numerous noise complaints from residents who are located near interstates and state highways throughout the country. To begin to understand how to mitigate noise at the source, the first step is to begin understand the fundamentals relevant to tire/pavement noise.

BASICS OF ACOUSTICS

Sound Versus Noise

Sound is all around us at all times, whether it is the music coming from a speaker, the leaves rustling or a car driving by (3). Sound occurs whenever there is movement. From a technical approach sound is small but fast changes in air pressure that cycle higher and then lower than the air pressure that is all around us (3). It includes everything we can hear and even some things we cannot. Noise is sound, however not all sounds are noise (1,3). Noise is unwanted sound or sound that is found objectionable (2,3). Since this is determined through human perception, noise to one person may not be considered noise by another person (2).

Decibels

In order to quantify the intensity of the pressure differentials created by sound according to the perception of the human auditory system the decibel (dB) is utilized (2). A decibel expresses the ratio of the measured sound pressure level to a standard reference level based on a logarithmic scale (2). The purpose for a logarithmic scale is because the human auditory system is inherently non-linear (1). For example, hearing a sound change from .1 to 10 Pascals is equivalent to the same as a change from 1 to 10 Pascals (2). In addition something heard at 2 Pascals does not sound twice as loud as 1 Pascal (2). The decibel system is a way to describe how loud something is without describing its tonal quality.

Hertz

If the decibel enables the description of the volume of a sound, the next step is to define the tonal quality of a sound. To do this sound is broken down into different frequencies. The frequency of a sound describes how fast the air pressure changes are occurring (3). To describe the frequency or pitch of a sound the unit of hertz (Hz) is utilized. A hertz is the equivalent of cycles per second defined as the frequency of an event in one second of time (5). The event being described for noise is the amount of times the sinusoidal wave of pressure change occurs within one second of time (3). A higher frequency responds to a higher perceived pitch of a sound. The human ear can perceive sounds as low as 20 Hz and as high 20,000 Hz (2,3). Due to this, no frequency outside of this range is considered when doing noise evaluations (2,3). Similarly when reporting results of a study the frequency spectrum being reported is weighted to accommodate human perception (3,6).

The most common weighting scheme used in reporting traffic noise is the A-weighting scheme. This manipulation puts a greater emphasis on frequencies between 1000 Hz and 4000 Hz as people are the most sensitive in this range (2,5). Levels outside of this frequency range are then attenuated. When results are reported that have applied the A-weighting scheme it should be denoted (2,3,6). For example, dB(A) or dBA should be used instead of just dB in order to alleviate any confusion.

By understanding the aforementioned basics of acoustics, sounds can be described in both volume and pitch.

TIRE NOISE GENERATION

Generating Mechanisms

Tire/pavement noise generation can be generally described through two modes, mechanical vibrations of the tire and aerodynamic phenomenon (7). However, technically there is several noise generating mechanisms at work when a tire is rolling across a pavement (4,7). These generating mechanisms work together in unison to make the noise perceived when a vehicle drives past a receiver (5). It is important to understand all the mechanisms working simultaneously to generate the noise that researchers are trying to attenuate.

The first mechanism is the sound generated when the tire actually hits the pavement. While rolling the tread blocks are traveling circumferentially along with the tire, individually impacting the pavement hundreds if not thousands of times a second

(3,4,5,7). This action generates noise in the same way thousands of small rubber mallets impacting the pavement every second would (3). The next generating mechanism causing sound production is the air being pumped by the interaction between the tire and pavement (3,4,5,7). Within the contact patch, where the tire is actually in contact with the pavement, there is significant void space due to the passages and grooves creating a the tread pattern. This void space, which is constantly being distorted and deformed, forces air both outward and inward from the tire while also simultaneously trapping and compressing pockets of air within the contact patch (4,5,7). As the tire loses contact with the pavement on the back end, the air that was trapped is forced out. This action can be equated to clapping where much of the sound that is heard is due to the air being pushed away quickly (3). Similarly, the air being initially forced both inward and outward can be equated to whistling where air is forced out through a small opening (3).

While the tire is in motion considerable horizontal forces are transferred from the tire to the pavement through the interaction of the tread blocks upon the pavement (5). If these imposed horizontal forces exceed the limits of friction the tire tread will briefly slip before re-adhering to the pavement (5). This slipping creates a distinctive noise each time this event occurs, which can be described as the sound of sneakers squeaking on a basketball court throughout a game (3,4,5,7). For a tire however, these slips can occur thousands of times a second, generating a high frequency sound as the tire rolls. The last generating mechanism is the stick-snap mechanism. This sound occurs due to the adhesion that occurs when the tread of a tire interacts with pavements (3,4,5,7). As the tread blocks exits the contact patch the adhesive forces hold the tread block to the pavement (5). It is analogous to the sound of applying and removing a suction cup thousands of times a second (3).

Amplifying Mechanisms

In conjunction with the generating mechanisms there are also several interactions occurring that amplify the sound being generated. The first amplifier is termed the "acoustical horn" (3). The acoustical horn occurs naturally due to the geometry that occurs when a tire interacts with the pavement. This geometry causes a wedge shaped segment of open air in front of the tire (3,4,5,7). Within this wedge the sound is reflected multiple times similar to the bell of a horn. However unlike a horn, the sides of this cone are open space, which leaves the amplification to be focused in the direction parallel to the tire (4,5). The next amplification mechanism that occurs is the Helmholtz Resonance. This amplification effect is best described by equating it to blowing across the top of a bottle (3). Blowing air in itself is typically not that loud, however when you blow across the top of a bottle, the bottle significantly amplifies the sound (5). This same effect occurs closer to the same mouth of the cone of open air used in describing the horn effect. The third amplification mechanism is due to the sips in the tire treads opening and closing while air is transferred through them. This effect is comparable to pipe resonance utilized in an organ (3). As the tire rolls air is forced through the sips of the tire outward and as the sips deform. It is important to note that sounds generated elsewhere during the interaction between the tire and pavement can be funneled through these sips and be amplified as well.

Lastly, while the tire is in motion considerable vibration energy is created and amplified by the response of the cavity resonance of the tire. The sound waves are reflected and amplified within the void space of the tire (3,5). This is equivalent to striking a bass drum in the way that the larger open space reflects and amplifies the sound. Sidewall vibrations within the tire also amplify the smaller noise generating mechanisms underneath the contact patch (5). These vibrations transfer into the sidewall which in turn amplifies them the same way an upside down pie plate would amplify a vibrating cell phone. When combined, all these generation and amplification mechanisms produce a loud and complicated noise source.

Test Method

In order to quantify the effects that different pavements and tires have on noise generation a test method called on-board sound intensity (OBSI) was developed. The OBSI method measures the near-field noise being generated at the tire/pavement interface and is governed by AASHTO TP 76-09 (6). It accomplishes this by utilizing four free field microphones paired into two separate intensity probes. The two microphones in each intensity probe are spaced at the known distance of .63±.04 inches. Each probe is placed 4.0±.25 inches from the sidewall and 3.0±.25 inches from the surface of the pavement, which can be seen in Figure 1. Additionally the two probes are 8.25±.25 inches apart centered about the hub to place each probe at the leading edge and trailing edge of the contact patch. The tire utilized is an ASTM Standard Reference Test Tire (SRTT) (8). These probes and standard tire allow researchers to record and analyze the noise being produced during the tire/pavement interaction.

Testing Procedure

Unless otherwise noted for the purpose of a specific experiment all testing was conducted in the right lane, at 60 mph ± 1mph. The driver was required to keep the right wheels within the standard wheel path within the lane, verify speed control throughout each test, monitor the equipment in the right side mirror, and assess the roadway for anything that could change the noise quality of each test (i.e. A large truck passing by, a sound wall, an overpass etc.). The equipment utilized to measure the tire/pavement noise on the outside of the vehicle as previously described is shown in Figure 1. The technician with the laptop begins each test and watches the test section to make sure the test begins at the same point during each run. The equipment utilized to measure the tire/pavement noise on the inside of the car is shown in Figure 2. The technician running the laptop was required to monitor the coherence of sound pressure between the microphones and PI index during each test to ensure the validity of each measurement. After the test was complete, the technician with the laptop needs to record all pertinent information for that measurement and prepare for the next. Two people were required for testing for all instances. At a minimum of one location along each different material, the ambient air temperature, pavement temperature, tire temperature, wind speed, barometric pressure and the tire pressure are recorded. Before the start of each instance of testing, each microphone is required to undergo standard calibration with a pistophone. The calibration information was recorded no later than one hour before the measurements begun and was repeated after the measurements were completed. If the measurement period length was greater than four hours, microphone calibration was required again at the four hour limit.

Figure 1 Sound Testing Apparatus

Figure 2 Test Setup from Inside the Vehicle

The frequency analysis of the measured sound intensity was performed using one-third octave band resolution. During measurements, the frequency range of 200 to 10,000 Hz (center frequencies of one-third octave bands) was included. One third octave bands with center frequencies of 500 to 5000 Hz consistently provide accurate results. The one-third octave band filters conform to ANSI S1.11. Verification of the microphones was recorded at the beginning and end of each test section, and the data was validated according to AASHTO TP 76-09 (6).

The measurements were recorded as an energy average (linear) over a 5.0 second measurement period. The signals were A-weighted prior to digitization, using an OBSI setup of two intensity probes measuring the leading edge and trailing edge of the tire simultaneously. The sound intensity levels of the two probes were energy averaged for each run. The averages for all runs were then averaged together arithmetically. A minimum of three runs were completed to meet the criteria to meet the coherence, PI index, and run-to-run criteria put forth by AASHTO TP 76-09 (6). The run to run difference in any one-third octave band level with a center frequency between 500 and 5000 Hz shall be no greater than 1 dB, the PI Index for each measurement shall be no less than 5dB in each one-third octave band with a center frequency between 500 and 5000 Hz, and the coherence of sound pressure between the two microphones of the sound intensity probe shall be greater than 0.8 for each one-third octave band with a center frequency between 500 and 5000 Hz. Any runs that did not comply with any of the above listed criteria were disregarded upon analysis.

Site selection was determined on location as a 440 foot test section for each material for which testing was desired. Each area where testing of a material was desired, was assessed by the sound testing crew by completing a dry run over the material to determine appropriate sites to test. A good site had a contiguous section of pavement with no material changes and no bridge decks. Mile marker signs are utilized for site selection as they remain in the same location and are the easiest to find and distinguish between throughout all of the runs. If testing in the area was completed again in the future, measurements can be taken at the same locations by using these markers.

The analysis of the measurements taken was completed in several separate processes using the following methods. Following the test section selection process and the testing procedure set forth by the OBSI method AASHTO TP 76-09 (6), each test section with three or more viable measurements were averaged together to get a representation for the overall material. Typically, following the OBSI method, one 440 foot test section was required to complete a material analysis. The author however suggests that a better material characterization can be created by testing multiple sites on a particular material and averaging all of the results for that particular material. A table and coinciding bar graph of overall material averages was compiled for each material to show the range of differences between all of the materials tested. The benefit of the bar graph is the easy ability to see the variability of all of the materials tested at the tire/pavement interface. Secondly, one-third octave band frequency spectrum graphs are created for each site and then averaged to represent each material. The frequency graphs show the measured sound intensity levels along the one-third octave band spectrum, which is the typical frequency band used to show sound measurements for OBSI. The one-third octave band allows researchers to easily see unique spectral signatures for different materials while avoiding frequency clutter. Different materials can then compared to determine differences in the way the tire generated noise will be perceived by a receiver. The averaged one-third octave band frequency can be viewed as an averaged snapshot of an equalizer showing a sound generated from a tire interacting with a particular pavement. Typically, the higher frequencies shown on one-third octave band frequency spectrums are more irritating to the human ear, and the lower frequencies are more readily ignored by the human ear. A-weighted measurements are shown because it is the weighting scheme which resembles the average human perception of sound (3).

Utilizing the OBSI method and analysis procedure researchers are able to identify and quantify the noise being produced at the tire/pavement interface. This ability raised further questions however. Predominately, does each pavement type, such as a dense graded asphalt (DGA), stone mastic asphalt (SMA) or open graded friction course asphalt (OGFC) have a unique frequency response? Can noise being generated on several pavements with the same tire be evaluated accurately utilizing statistical methods? What effect does vehicle speed have on tire/pavement noise being generated? What effect do different tires have on the noise being generated at the tire/pavement interface? And lastly, how does temperature affect tire/pavement noise?

Chapter 2: Spectral Signatures

INTRODUCTION

The objective of this chapter is to build the case that different asphalt pavement mix designs yield distinct acoustical properties. This chapter works through a method of analysis to decipher the difference between one in-service pavement's distinct acoustical properties against another. Secondly, the method helps to verify that similar mix types exhibit similar acoustical properties. The author conducting this research felt that this was an important endeavor because it provides opportunities to understand how tire/pavement noise changes for a particular pavement over a long period of time while reducing the amount of variability through normalization and statistical measures, with an emphasis maintained on practicality.

DISCUSSION

Data Normalization

Run to run variability

The first step required for each set of data that is taken, is to compile any measurements from each testing location that conform to AASHTO TP 76-09 (6). A minimum of three measurements that are within 0.6 dB(A) is required, but very often more are acquired. An example of this can be seen in Figure 3. If a five mile section is tested, there are roughly twenty measurement sections to compile.

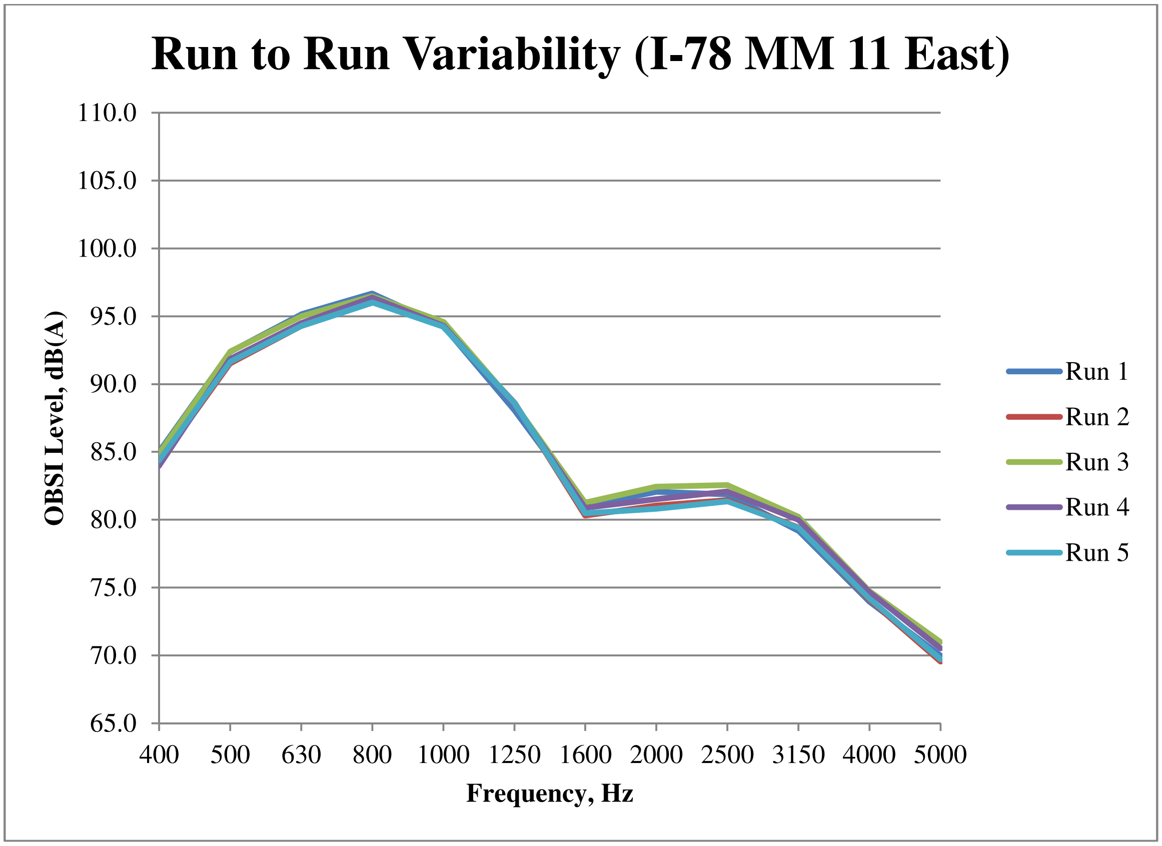

Figure 3 I-78 Run to Run Variability

The graph represents five different runs that all started at Milepost 11.0 East on a fourteen mile test section on I-78 from testing that ensued in March 2010. The ambient temperature for the day was recorded at 92.6 °F. This section was set up to evaluate an Asphalt Rubber Open Graded Friction Course (AROGFC) that was paved in the summer of 2009. This graph shows how close the run to run variability was for that milepost. Each time the test vehicle circled around the fourteen mile test section, the vehicle was positioned well within the wheel path, the laptop technician was able to start the measurement at the same spot every time, and the equipment positioning and stability remained constant throughout.

Moderate roadway variability

The best case and most desirable sampling would consist of even measurements where no variables changed from run to run. Unfortunately, this is not always the case. Even if the environmental factors remain exactly the same for the entire testing period the reality of asphalt pavement is that it is slightly variable over distance. Whether this variability is derived from slight variations in mix from the plant, variations in compaction temperature, variations in compaction densities, and a range of other factors, the more sections that are tested along a single material on the same roadway, the more variability that will be shown through the OBSI measurements. For the example above, every milepost had similar quality of run to run variability, where there was minimal to no change over the course of one testing day. Figure 4 shows the compilation of the testing on I-78 for the same fourteen mile section depicted in Figure 3.

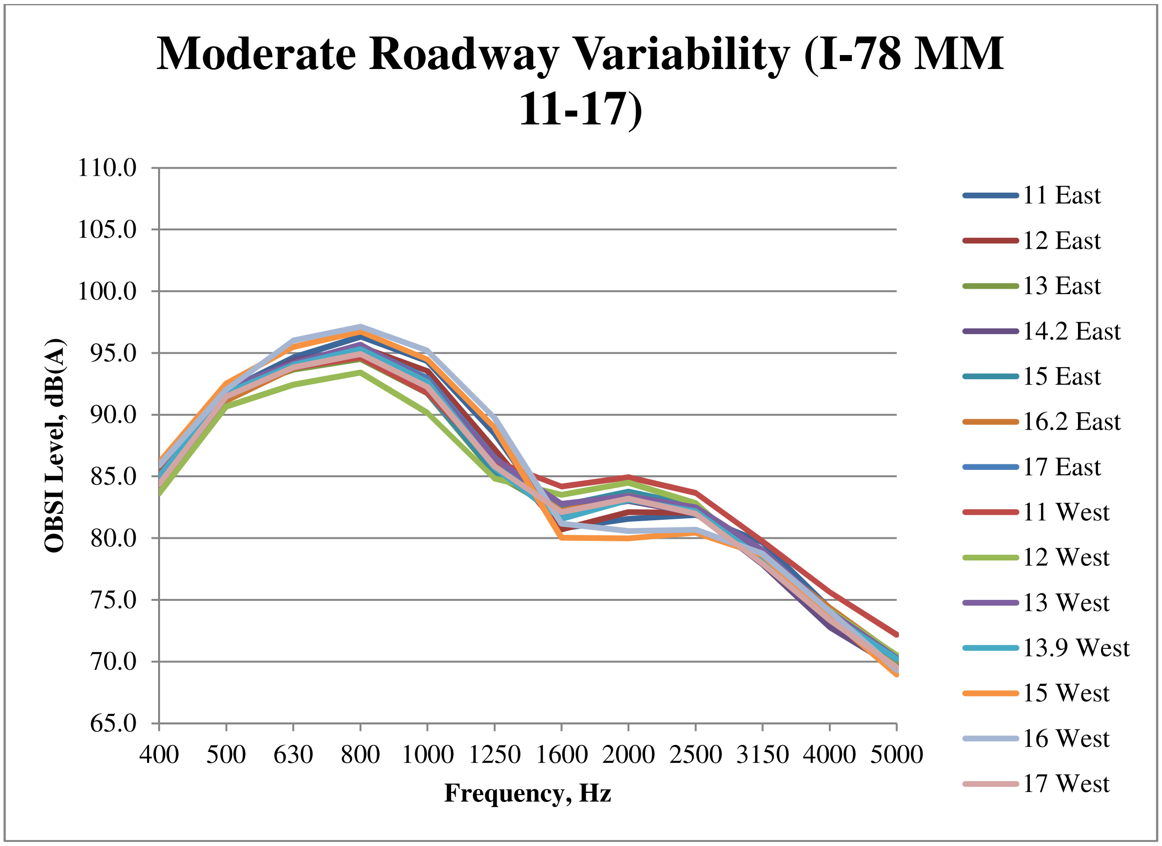

Figure 4 Moderate Roadway Variability

With such a long section, it was no surprise that there was a maximum three decibel difference recognized for the recorded overall levels when all of the mile posts are compared to each other. Looking more closely at Figure 4 though, it is apparent that most of the measurements at each milepost are very similar, with only a few highly variable outliers. All of the mile posts are averaged to create a representative pavement profile for that AROGFC pavement. This average can be seen in Figure 5.

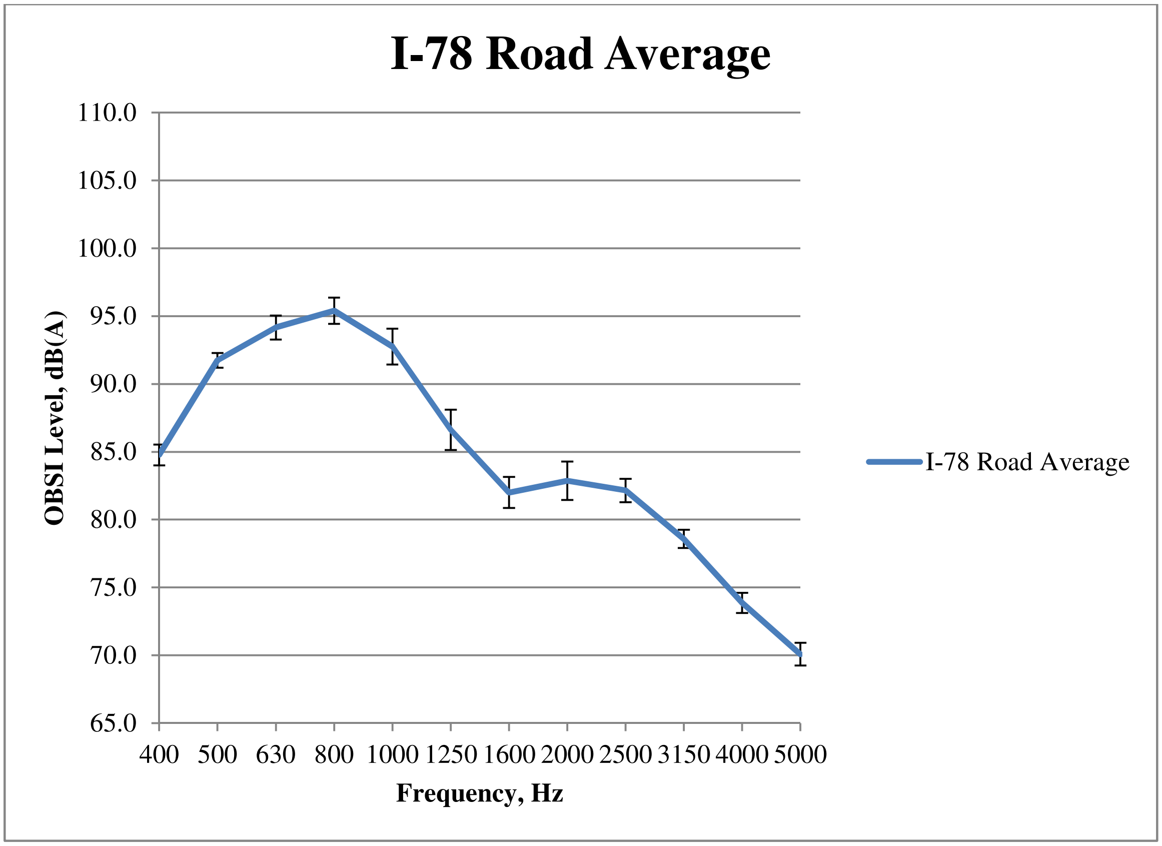

Figure 5 I-78 Road Average

Shown as one line, the shape of the curve still closely represents that which is seen in Figure 4. Added to this average, the 1s standard deviation is graphically depicted to show the variability within the average. The outliers from Figure 4 cause the standard deviation to be higher across the entire frequency spectrum for the average shown in Figure 5, while the plot shows what the typical frequency spectrum looked like on average for that AROGFC pavement on I-78 that day.

Low roadway variability

Another example shows how it is possible for a five mile section to exhibit almost no variation on any stand-alone section or as a compilation of all of the sections. Figure 6 shows a compilation of each mile marker tested on Rt. 202 in April of 2010.

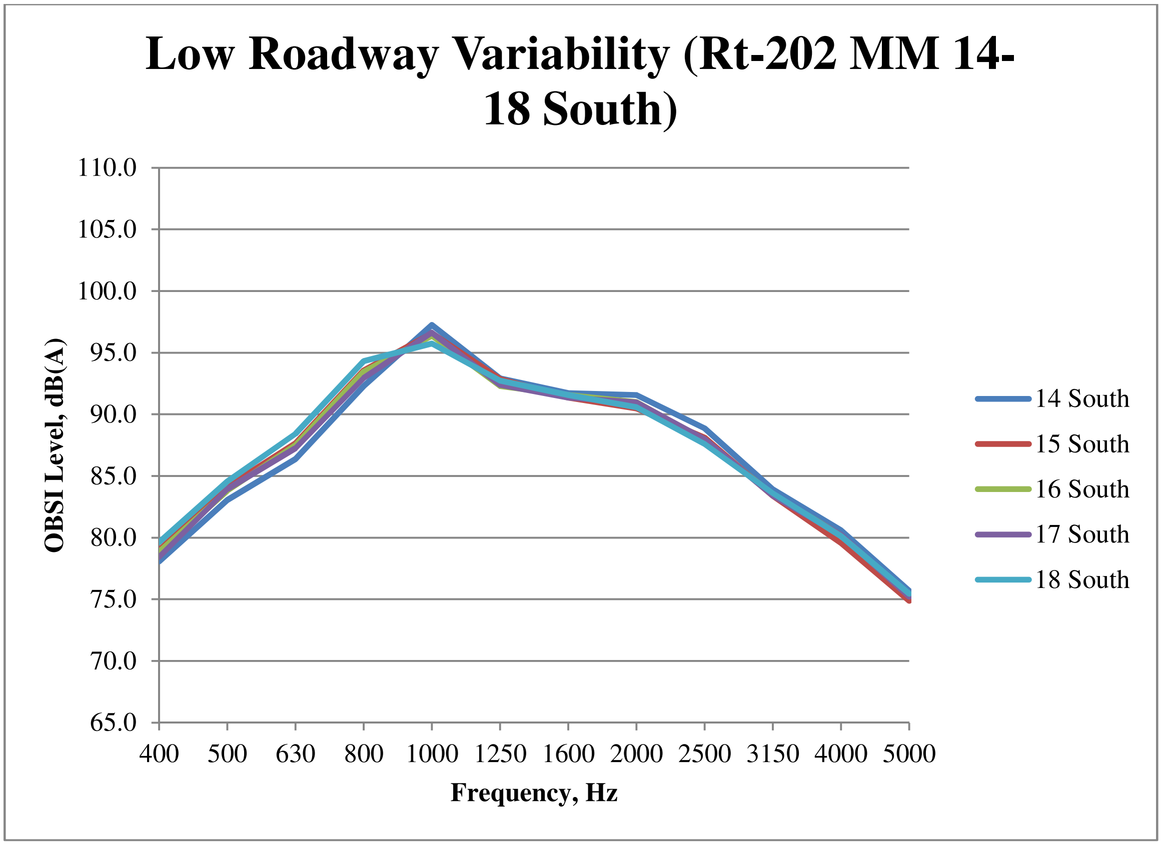

Figure 6 Low Roadway Variability

The ambient temperature on the day of testing was recorded at 83.4 °F. The pavement tested was a 9.5mm Superpave mix with 76-22 grade binder. Figure 6 shows minimal variations across the depicted one-third octave band frequency spectrum. The average of these materials is shown in Figure 7; it very closely resembles what is seen in Figure 6.

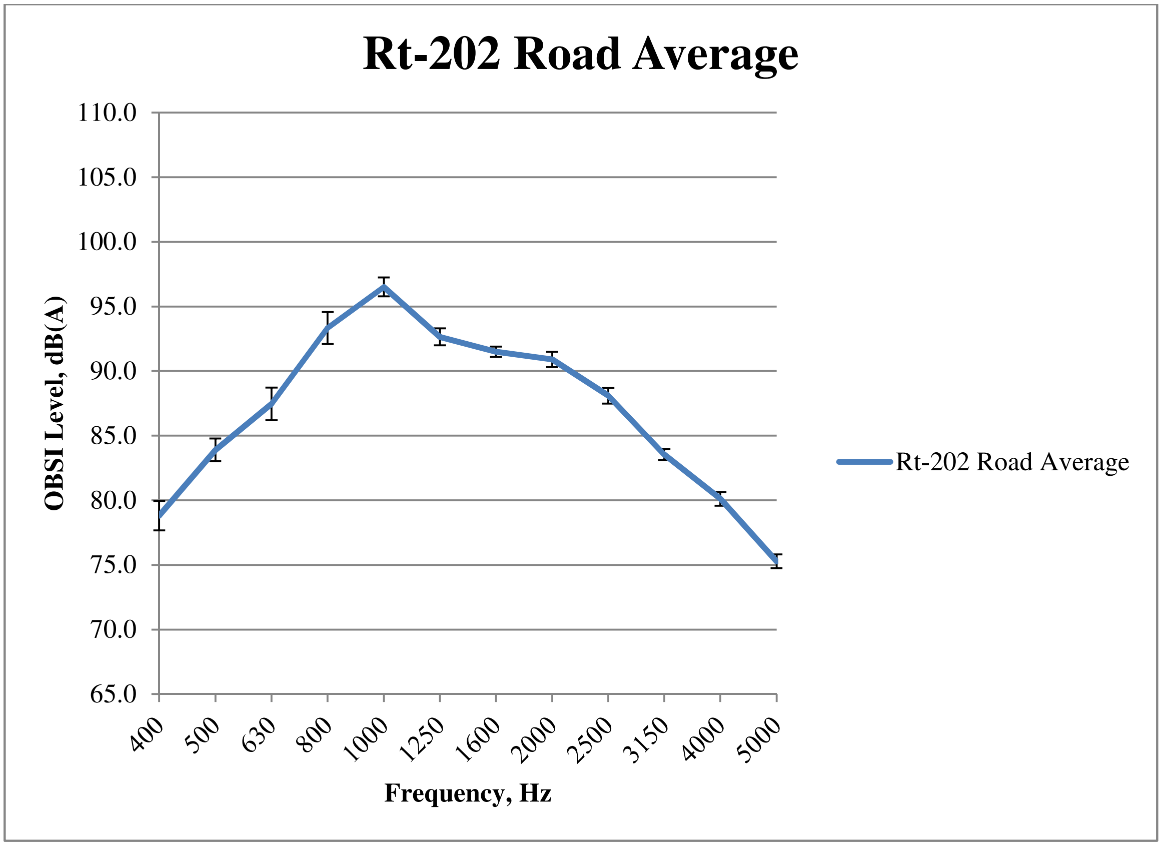

Figure 7 Rt-202 Road Average

Pavement Type Comparisons

Similar pavements

Once each pavement is compiled to an average, it is often interesting to look at how similar pavement types compare to each other from different sections on different roadways. The overall average chart makes it easier to compare the same section with future measurements as well, to determine if the effects of temperature or some other factor changed any noise property generated at the tire/pavement interface. Figure 8 shows three differently aged DGA averages tested during different times of year and with different recorded ambient temperatures.

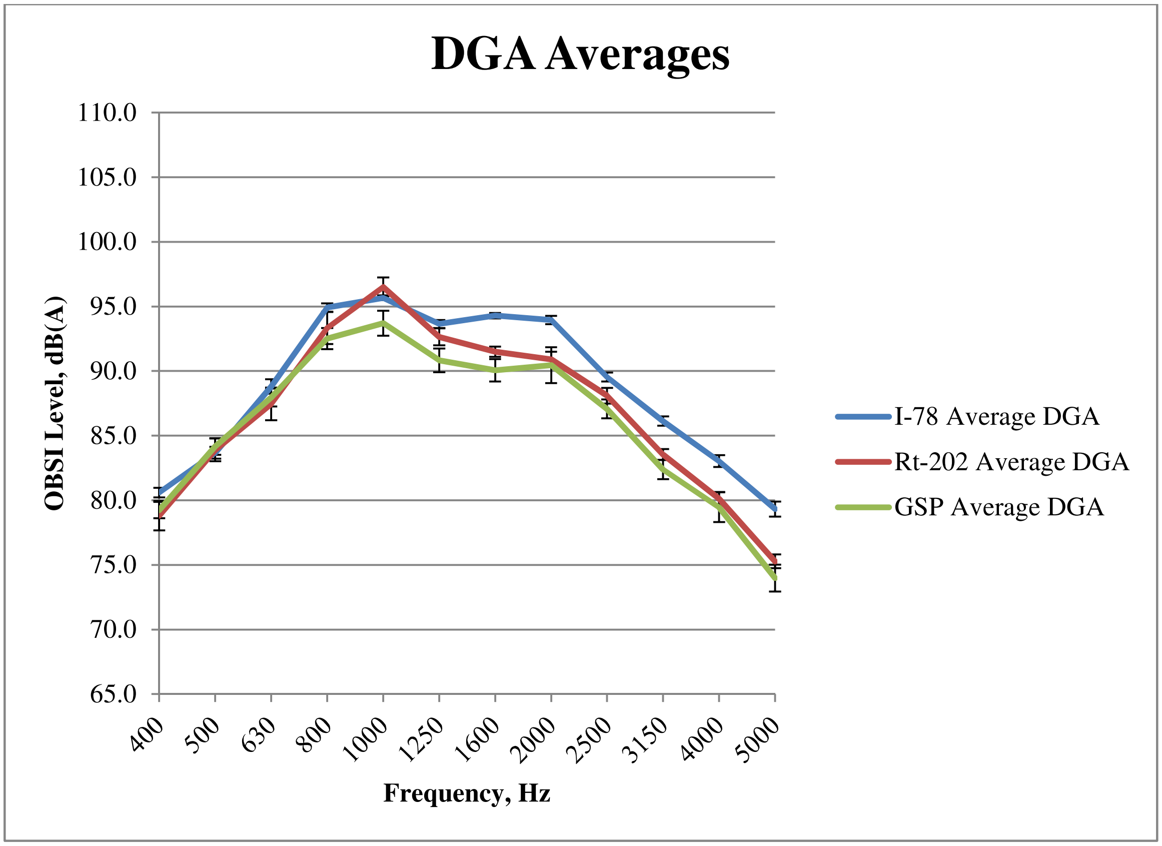

Figure 8 DGA Averages

The three pavements shown are from Rt-202, I-78, and the Garden State Parkway (GSP). The Rt-202 section is the 9.5mm Superpave mix taken from Figure 7. I-78 was a three mile section of Superpave 12.5M76 that was tested in May 2010 at a recorded ambient temperature of 60.5 °F. The third was the GSP Superpave 12.5H76 tested in April 2010 at a recorded ambient temperature of 62.8°F. The relationship that we concluded here was that each DGA has a very similar curve. Even though one is a 9.5mm and one of the 12.5mm mixes was designed for medium loading, the curves still looked the same. For the most part, the standard deviation bars overlap for all of the pavements. This is also a sign that the pavements, from a statistical point of view, are similar.

Since this was a surprising discovery, three OGFC pavements were placed next to each other to determine if they all looked similar to each other. Figure 9 shows three different OGFC pavements side by side.

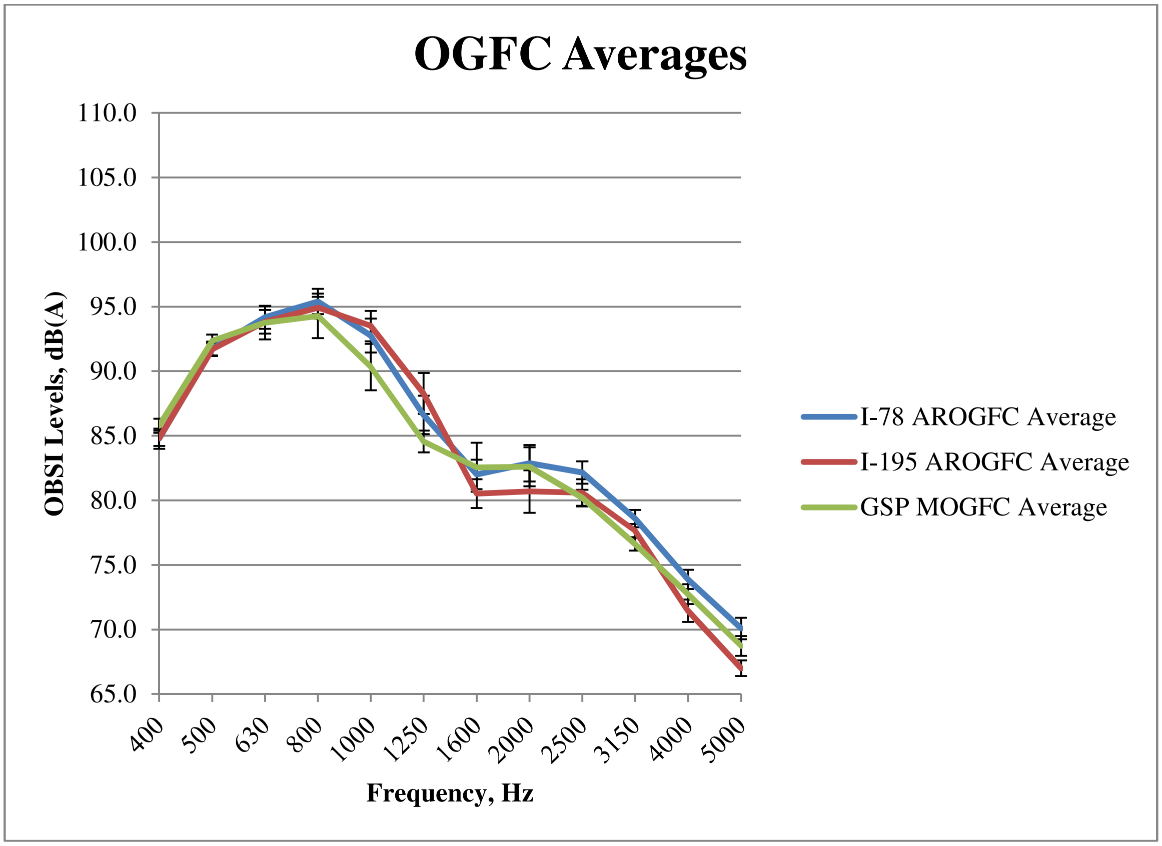

Figure 9 OGFC Averages

The first is the I-78 AROGFC average from Figure 5. The second was an AROGFC that was tested one week after it was paved in October 2010 on I-195. The ambient temperature during testing on I-195 was recorded at 62.2°F. The third pavement is an MOGFC on the GSP that was tested in June 2010. The MOGFC was paved in 2005. The ambient temperature recorded while testing the MOGFC on the GSP was 86.0°F. This spectrum analysis showed us that the OGFC pavements, similar to how the DGAs looked similar to each other, had very similar curves when they were plotted on the one-third octave band spectrum. As with the DGA pavements, the OGFC pavements that are shown in Figure 9 have standard deviation bars that overlap significantly. If the testing location or road information was not known for any of the pavements shown here, one could assume that they were similar.

Different pavements

Since the three examples of different DGA pavements shown in Figure 8 exhibited similarly shaped one-third octave band spectra and separately the three examples of different OGFC pavements shown in Figure 9 exhibited similarly shaped one-third octave band spectra, the next logical step seemed to be to compare a DGA to and OGFC to see how different they looked when they were overlaid. Figure 10 shows how the two mix designs have different acoustical properties because each has statistically different spectra.

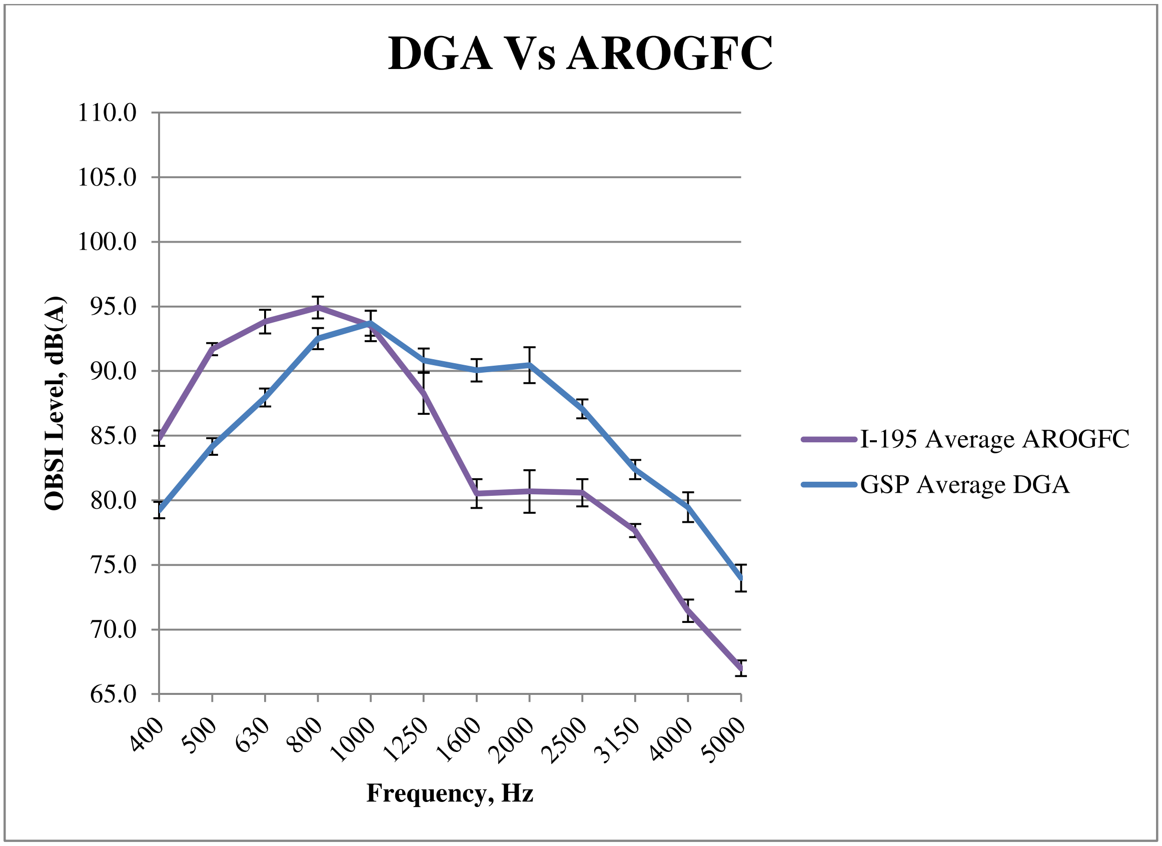

Figure 10 DGA vs. OGFC

The two pavements, shown in Figure 10, demonstrate an obvious visual difference when overlaid on the same chart. Since the analysis method utilized throughout the paper thus far has been capable of differentiating between two different mix types in NJ, verification was necessary. To accomplish this, data from an OBSI study completed in Massachusetts was processed using the same method to compare similar pavement types paved in different regions.

New Jersey vs. Massachusetts

Example 1: DGAs

The first example of the verification, shown in Figure 11, is comparing the NJ DGA from the GSP which was shown in Figure 8 to a DGA tested in MA on I-495.

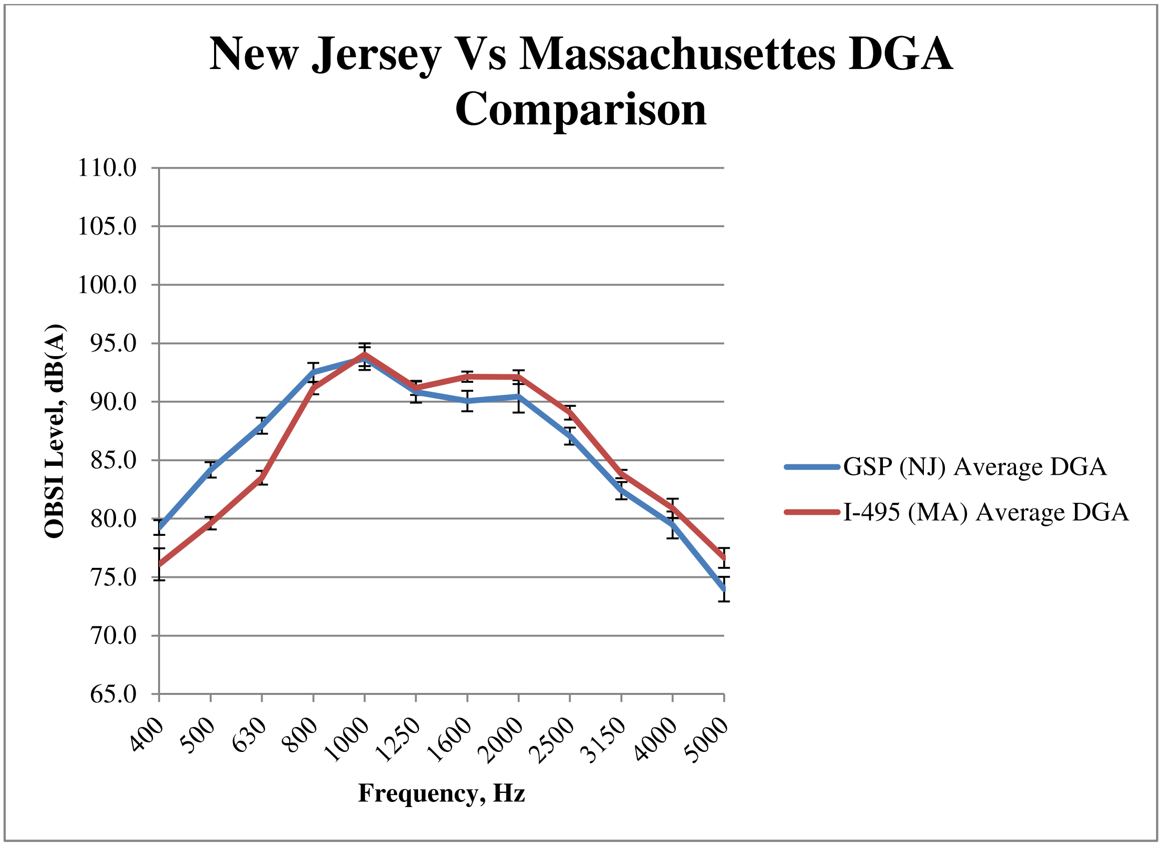

Figure 11 NJ vs. MA DGA Comparison

The Mass DGA was tested in October 2010 and the ambient temperature recorded during testing was 73.3°F. Looking at Figure 11, both pavements seem to have very similar frequency curves and that the MA DGA looks very similar to the other DGA examples utilized throughout the paper.

Example 2: OGFCs

For the final example the NJ I-78 AROGFC shown on Figure 5 and Figure 9 is overlaid by an OGFC that was tested on I-290 in MA. This example is shown in Figure 12.

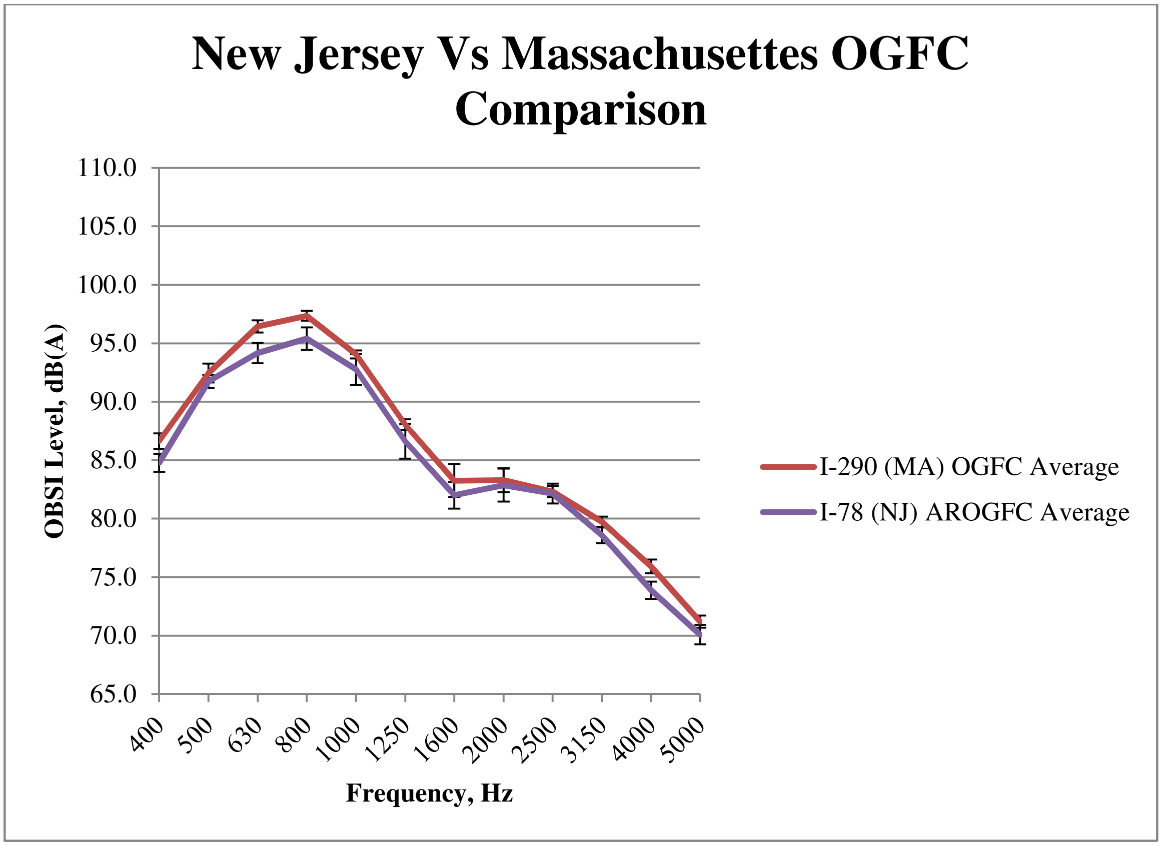

Figure 12 NJ vs. MA OGFC Comparison

The MA I-290 OGFC in Figure 12 was tested in October 2010 with an ambient temperature recorded of 76.2°F. Both curves appear to be very similar and the MA OGFC, as a pavement type, looks very similar to the NJ OGFC examples shown throughout the paper. This regional comparison showed that although pavements have inherent variation, the spectral curves represented by similar pavement types are distinctly unique to that pavement type.

SUMMARY

The OBSI method has been recognized as an effective method for quickly and effectively evaluating tire/pavement interface noise generated on in service pavements (9). The method is designed to standardize tire/pavement interface measurements as much as possible. Throughout two years of data collection and analysis, the author has noticed patterns develop in the on-third octave band spectrum analysis plots for different pavement types.

From a pavement materials perspective, deciphering the patterns that emerged logically became the first step to understand the acoustical properties of different asphalt mixes. It was found that all the pavements tested conform within the range of 65 dB(A) to 110 dB(A) throughout the frequency spectrum of 400 Hz to 5000 Hz, however within that range different pavements types began to display unique signatures. The OGFC pavements, exemplified in Figure 9, exhibited a curve that is most easily resembled by 2 parabolic curves, one between the 400 Hz to 1600 Hz center frequency range and the second between the 1600 Hz to 5000 Hz center frequency range. The maximum within the 400 Hz to 1600 Hz range was about 95 dB(A) between the 630 Hz and the 1000 Hz center frequency. The considerably lower maximum within the 1600 Hz to 5000 Hz range was about 84 dB(A) around the 2000 Hz center frequency. Alternatively, the curve exhibited by the DGA spectra, could most easily be described as a trapezoid. The DGA curve had two peaks which occurred at the 1000 Hz center frequency around 94 dB(A) and at the 2000 Hz center frequency around 92 dB(A) respectively. These signatures reoccurred when different roadways were evaluated which helped to validate the idea that a standard pavement type designed using mechanistic pavement design should yield a standard tire/pavement noise spectral signature. To confirm that this idea was not regionally based only in NJ, results recorded in MA were compared to the findings in NJ. It appears that the patterns discovered were universal as they transcended both regions. This is useful to know because if noise testing is required in a particular area, but the pavement type is not known, it is possible to go out in the field and determine roughly what type of pavement type it is, independent of region, provided a long enough section was measured and an appropriate average was taken. The examples of slight differences between two similar pavement types that were displayed in Figures 8 and 9 stem from any number of unknown environmental factors, pavement age discrepancies, or human induced error during testing. Even with these variations, the same basic spectral signatures were represented for each, just at slightly higher or lower decibel levels respectively.

Because the purpose of this study was to determine a method of analysis to decipher the difference between an in-service pavement's distinct acoustical properties against another, the analysis provided within identified, defined, and verified distinct patterns, which will aid in the ability to discover and track changes over the length of the long term NJDOT pavement resource program study that is being conducted.

Chapter 3: Statistical Comparison

INTRODUCTION

This study was completed for All States Material Group in Massachusetts. The main focus of the All States Massachusetts study is to look at the noise levels that result from the different materials All States has designed and produced over the last ten years. Initially, the goal is to quantify the noise properties of the pavements in Massachusetts. Then a secondary goal after finding the overall noise levels would be to analyze differences in the sound properties due to differences in mix type, mix design, and aging. This information can then be utilized throughout the pavement selection process to allow for noise concerns to be accounted for while retaining the safety and maintenance capabilities necessary in a given locale.

This project encompassed fifteen different pavement surfaces which were located throughout eastern Massachusetts. The measurements were recorded between October 25, 2010 and October 29, 2010. The pavement selection was completed by All States Material Group. Each material section was roughly two miles long, which allowed the CAIT acoustic technicians to choose appropriate testing locations according to the AASHTO TP 76-09 specifications (6).

The first set of materials tested on Monday October 25, 2010, was located on I-295 near the Rhode Island-Massachusetts border. Four different materials were located there: an Asphalt Rubber Gap Graded placed in 2008 (ARGG 2008), Asphalt Rubber Gap Graded with Advera warm mix additive placed in 2008 (ARGG w/Advera WM 2008), Novachip placed in 2008, and a Novachip with asphalt rubber placed in 2008.

The second day of testing, Tuesday October 26, 2010, contained 3 different test sections. On I-95 near Attleboro, MA two different contractors had placed similar Asphalt Rubber Gap Graded mixes in 2009. Both mixes were evaluated to see the variation in the noise characteristics between contractors. The second test section of the day was located on I-495, where two different materials had been placed in 2009 between exits 21-23, which provided an opportunity to look at an Asphalt Rubber Gap Graded and an Open Graded Friction Course. The third test section evaluated that day was on I-290 near Northborough, MA. I-290 provided an OGFC that was placed in 2006.

The third day of testing, Wednesday October 27, 2010 was utilized to export the data recorded the previous days. Rain and wet pavement conditions required that testing would be put on hold and eventually caused a late start on Thursday.

On Thursday October 28, 2010, I-495 and Rt-2 provided two different pavements. On Rt. 2, standard 19mm Superpave dense graded asphalt was tested near Littleton, MA. A two year old OGFC section was provided on the I-495 section. The third test section, tested in the afternoon, was located farther north on I-495, which provided two additional materials: an Asphalt Rubber Gap Graded laid in 2010 and a 9.5mm Superpave + 2% Latex mix which was also laid in 2010.

The last test section was located on I-95 near Amesbury, MA. It was evaluated on Friday October 29, 2010. It provided two pavements that were each paved a year apart, an OGFC placed in 2003 and an OGFC placed in 2002. These were the oldest test sections evaluated in Massachusetts.

TESTING METHOD

The testing procedure followed the method described thoroughly in Chapter 1 according to AASHTO TP 76-09 (6). After the overall table, bar graphs, and spectrum graphs were generated, the variance in test runs for each pavement surface was determined using the f-test for two-sample variance analysis. If the variances were statistically similar, t-tests for two-samples assuming equal variance analysis were completed. If the variances for each material were statistically not similar, t-tests for two-samples assuming unequal variances were completed. The resultant data was compiled into a statistical matrix which helped to determine which materials exhibited statistically similar loudness using the A-weighted decibel values. Based on the results, pavement surfaces determined to be statistically similar were then graphed side by side to show where the similarities and differences occurred. Ideally, if two different materials can provide equal loudness while remaining fundamentally different in terms of safety, maintenance, and longevity in a particular region, it would allow pavement engineers to make better pavement selections. Similarly, if certain materials are known to remain quieter for longer in a given region, the information can be utilized during pavement selection and pavement rehabilitation.

RESULTS

The overall values shown in Table 1 indicate the average overall levels recorded on each of the different materials tested in Massachusetts for All States Materials Group. The overall values represent the loudness of the noise that would be heard at the tire pavement interface.

Table 1 Overall Noise Levels

Road	Material	dB(A) Overall	StDev (1s)
I-495 S	9.5mm superpave + 2% Latex	100.0	0.4
I-495 N	ARGG 2009	100.5	0.7
I-95 S	ARGG 2009	100.5	0.2
I-95 N	ARGG 2009	100.5	0.2
I-295 N	ARGG 2008	100.8	1.2
I-495 N	ARGG 2010	100.8	0.2
I-95 S	7 year old OGFC	101.2	0.6
I-95 S	Lynch AR-GG 2009	101.2	0.2
I-95 N	Lynch AR-GG 2009	101.3	0.2
I-495 S	OGFC 2008	101.3	0.7
I-295 N	ARGG w/advera warm mix 2008	101.4	0.3
I-95 N	8 year old OGFC	101.7	0.7
I-495 S	OGFC 2009	101.8	0.4
I-495 N	OGFC 2008	102.0	0.2
I-290 E	OGFC 2006	102.9	1.2
I-290 W	OGFC 2006	102.9	1.2
Rt-2 E	19 mm superpave	103.1	0.6
Rt-2 W	19mm superpave	103.1	0.6
I-295 S	Novachip w/asphalt rubber 2008	104.5	0.2
I-295 S	Novachip 2008	105.1	0.2

The overview of materials below in Figure 13 shows the average overall noise level recorded for each material. The loudest material, the I-295 Novachip that was placed in 2008 was 5 dB(A) louder than the quietest material, the I-495 9.5mm Superpave mix, which is a noticeable difference. When looking at overall sound levels, it is important to remember that the decibel scale is logarithmic. When the noise levels compared are related to the same type of noise, a one to three decibel change is considered “just perceptible” to the human ear. A five decibel change is considered “noticeable.” A ten decibel change is “twice” as loud.

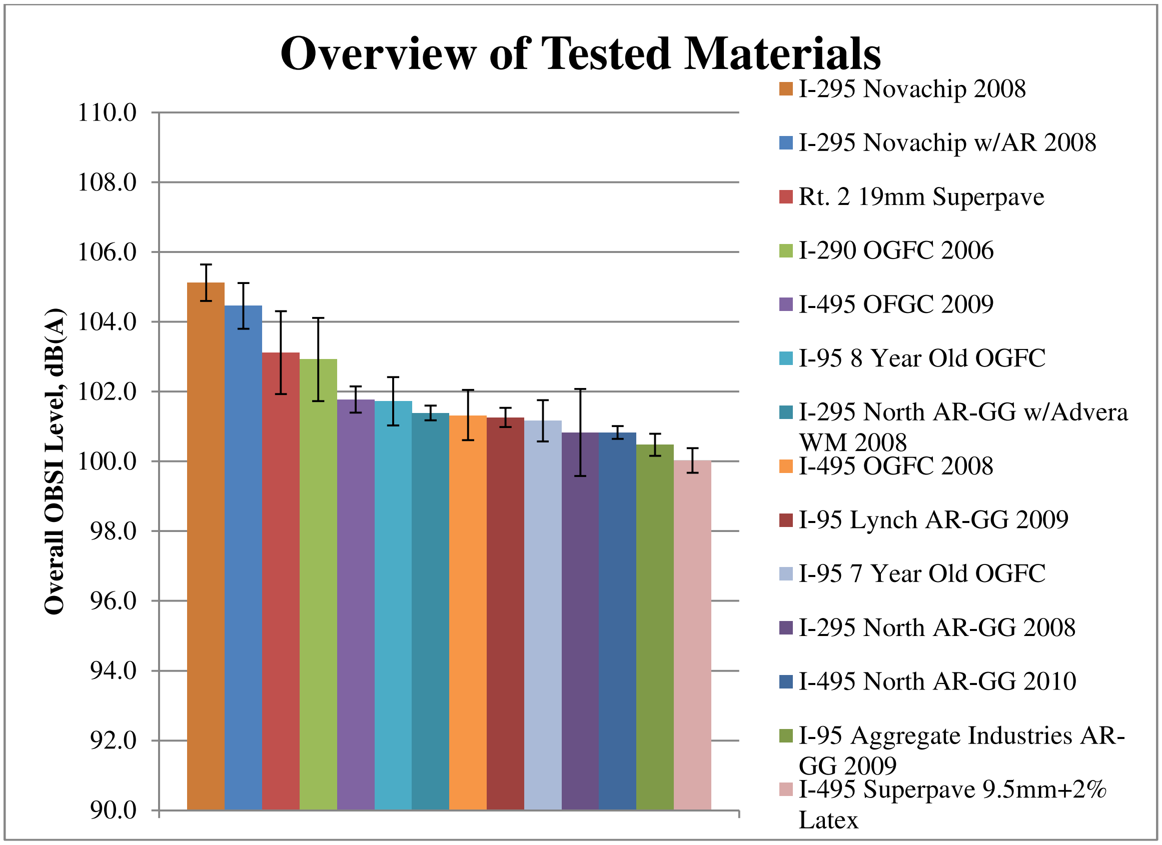

Figure 13 Average overall levels for the materials tested in MA

Measuring overall noise is a useful tool to begin to understand the loudness of noise propagating from the tire/pavement interface, but it does not describe the quality of the noise itself. To begin to understand the quality of the sound, spectrum graphs that range from 400 Hz to 5000 Hz represented along a one-third octave band are used, where higher frequencies relate to higher pitched noise. Since the measurements are A-weighted, the frequencies are already represented along an equal sound power to what an average human would perceive. Higher frequencies are perceived as "more annoying" to the human ear, as opposed to lower frequency noise. Therefore, pavement surfaces that generate noise more towards the higher frequency ranges are less desirable than pavement surfaces that generate noise at the lower frequency range, even when the average A-weighted decibel values are identical.

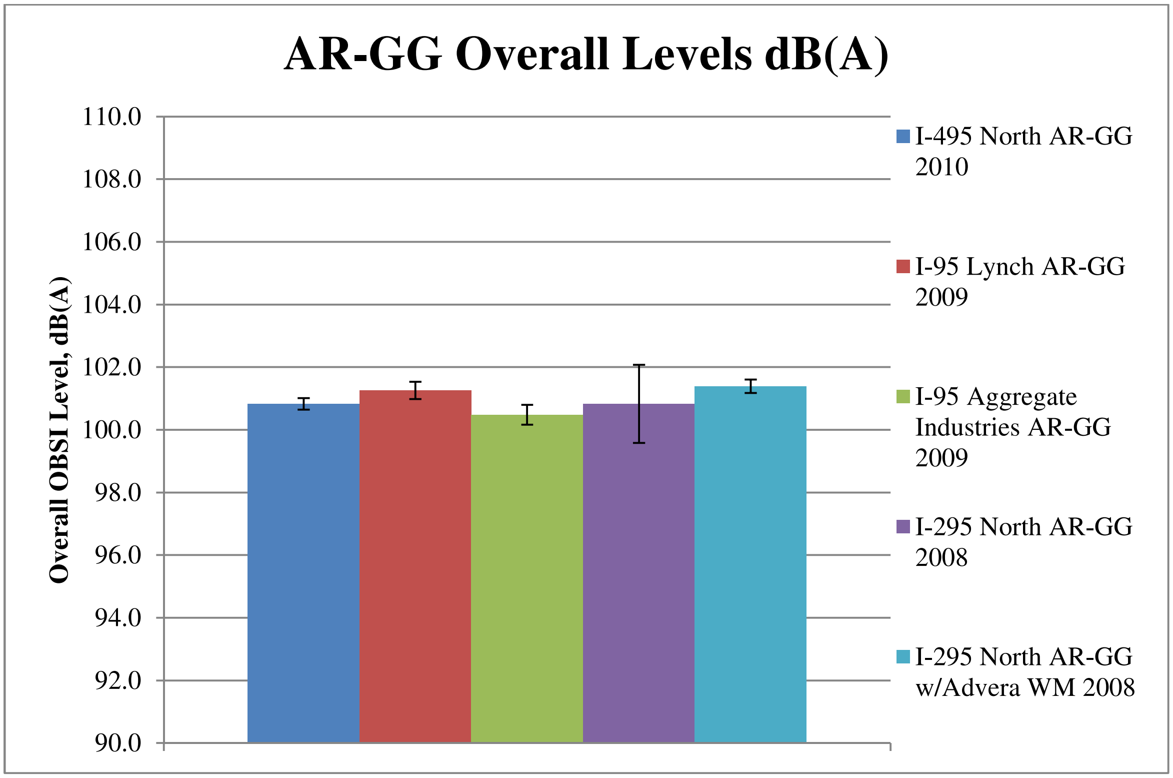

Figure 14 ARGG overall levels, dB(A)

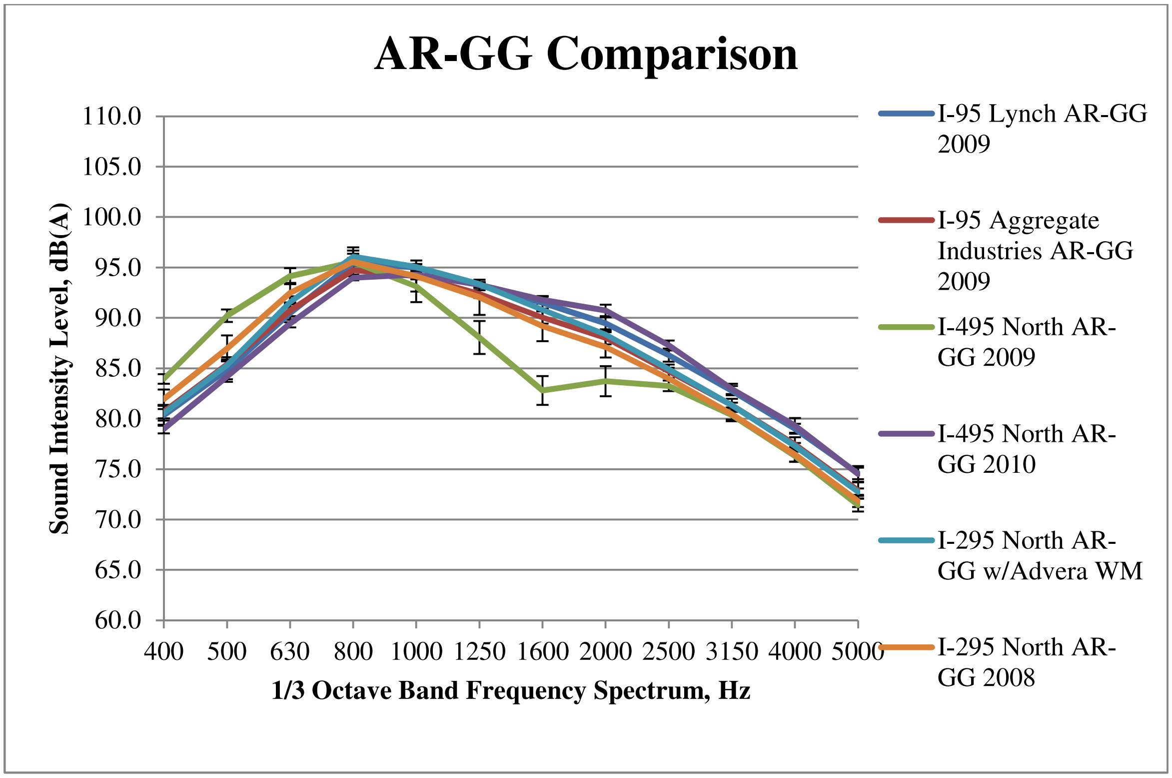

Figure 15 ARGG Spectrum Comparison

The asphalt rubber gap graded mixes, shown in Figure 14, appear to be similar on the overall levels, but when looking at the spectrum graph (Figure 15), it appears that the I-495 North ARGG that was placed in 2009 has perceptible differences in sound quality. Figures 16 through 18 show three examples of the ARGG pavements tested in MA. The more open pavement surface shown in Figure 16 is most likely the cause of the reduced noise level for the I-495 N ARGG pavement between 1000 Hz to 2000 Hz frequency range. The other two ARGG pavements shown below (Figures 17 and 18), have more binder filling the void spaces in between the aggregate.

Figure 16 I-495 N ARGG 2009

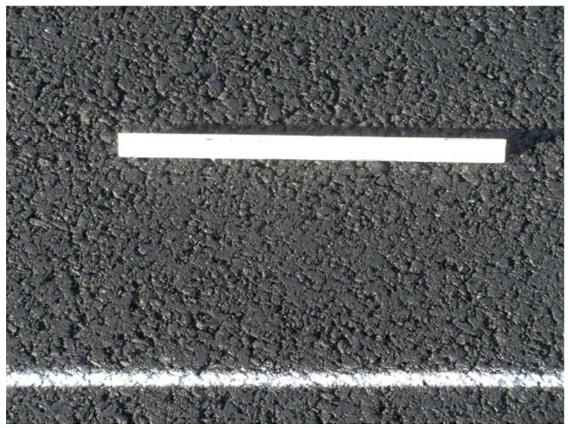

Figure 17 I-495 S ARGG 2010

Figure 18 I-95 N ARGG Lynch 2009

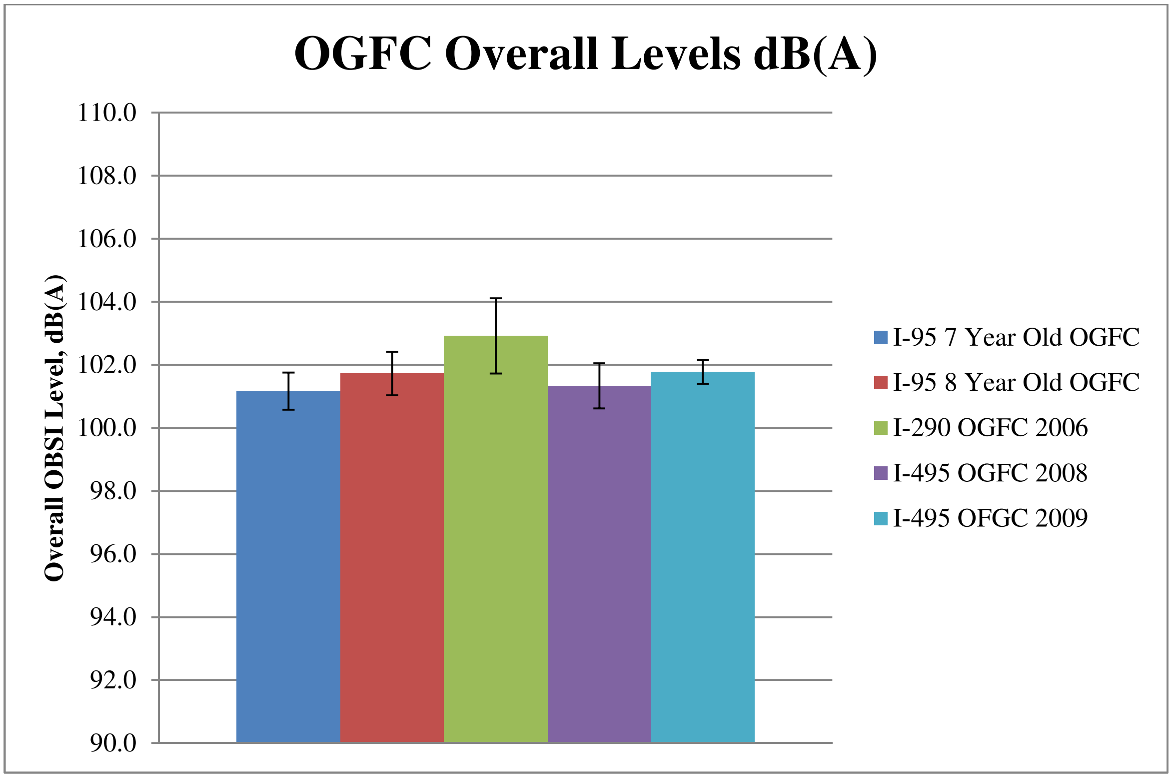

Figure 19 OGFC overall levels, dB(A)

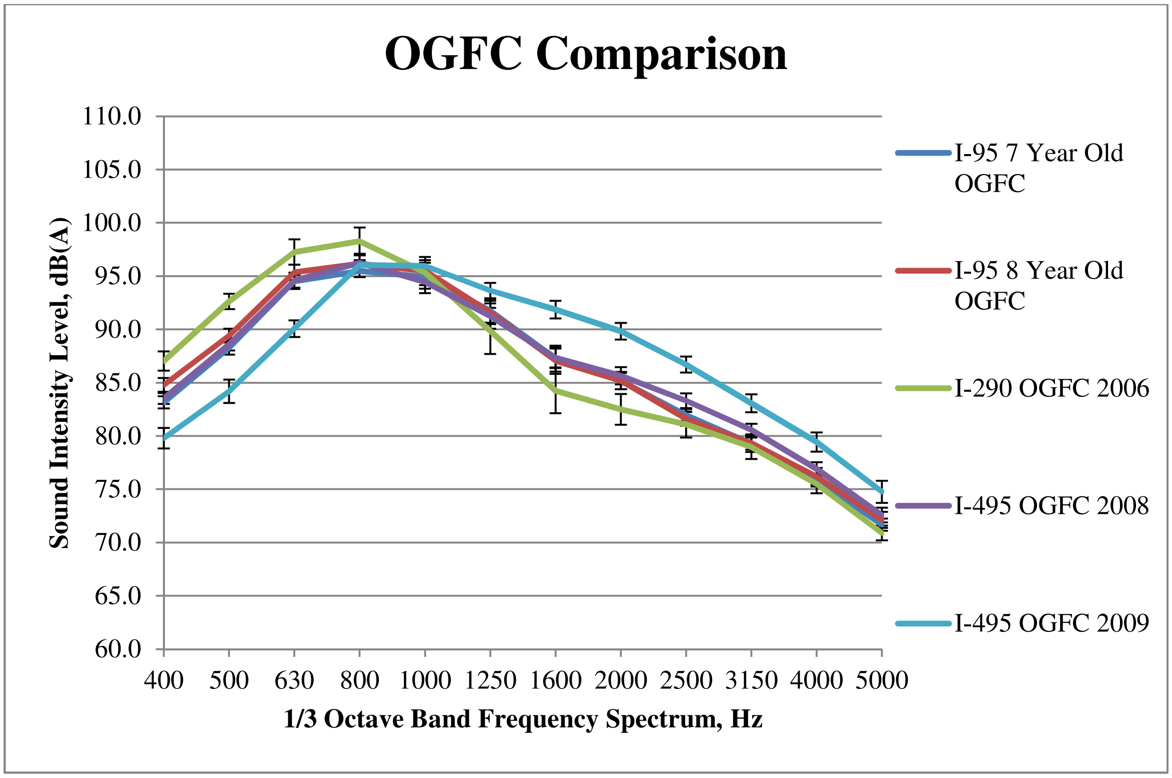

Figure 20 OGFC Spectrum Comparison

The OGFC surfaces, shown in Figures 19 and 20, were surprisingly loud, with overall levels between 101 and 103 dB(A), where we would normally consider OGFC surfaces to be quiet pavements with levels under 100 dB(A). Figure 19 definitively shows that the OGFC materials tested in MA did not show a perceptible change in noise level over time. The eight year old OGFC tested was on I-95 was roughly the same overall loudness as the newest OGFC from 2009. In Figure 20, of the five OGFC materials evaluated, only the I-495 OGFC that was placed in 2009 did not follow the standard trend of open-graded materials. Typically in open-graded materials, the lower density causes the sound intensity level for the frequencies between 1250 hz to 5000 hz to usually be lower, which is evident in all but the 2009 I-495 OGFC. This can be more easily seen in the OGFC vs DGA (Figures 27 and 28) or OGFC vs ARGG (Figures 31 and 32) charts shown later. At this time, it is not evident as to the reasoning for the differences in the frequency spectrum of the I-495 OGFC pavement surface. Figures 21 and 22 show examples of the OGFC pavements surfaces evaluated in MA. The I-95 OGFC pavement from 2002 (Figure 22) shows significantly more wear than the I-495 S OGFC 2009 pavement (Figure 21).

Figure 21 I-495 S OGFC 2009

Figure 22 I-95 N OGFC 2002

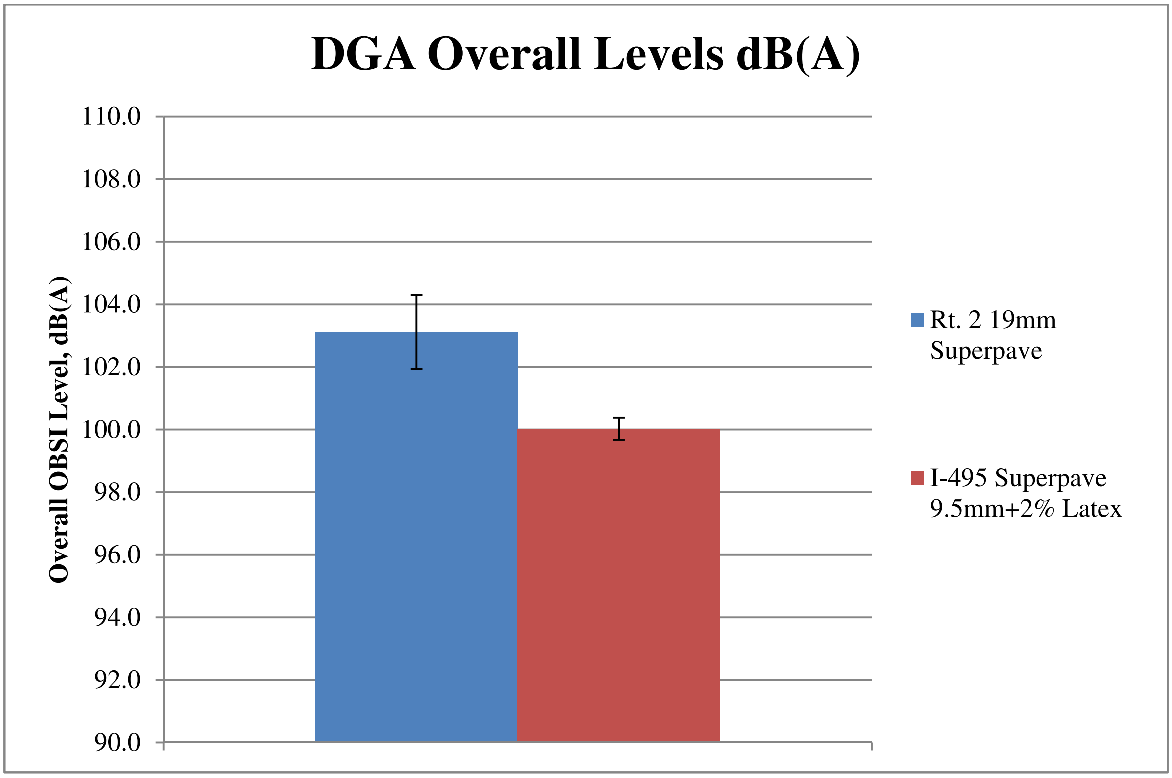

Figure 23 DGA Overall Levels dB(A)

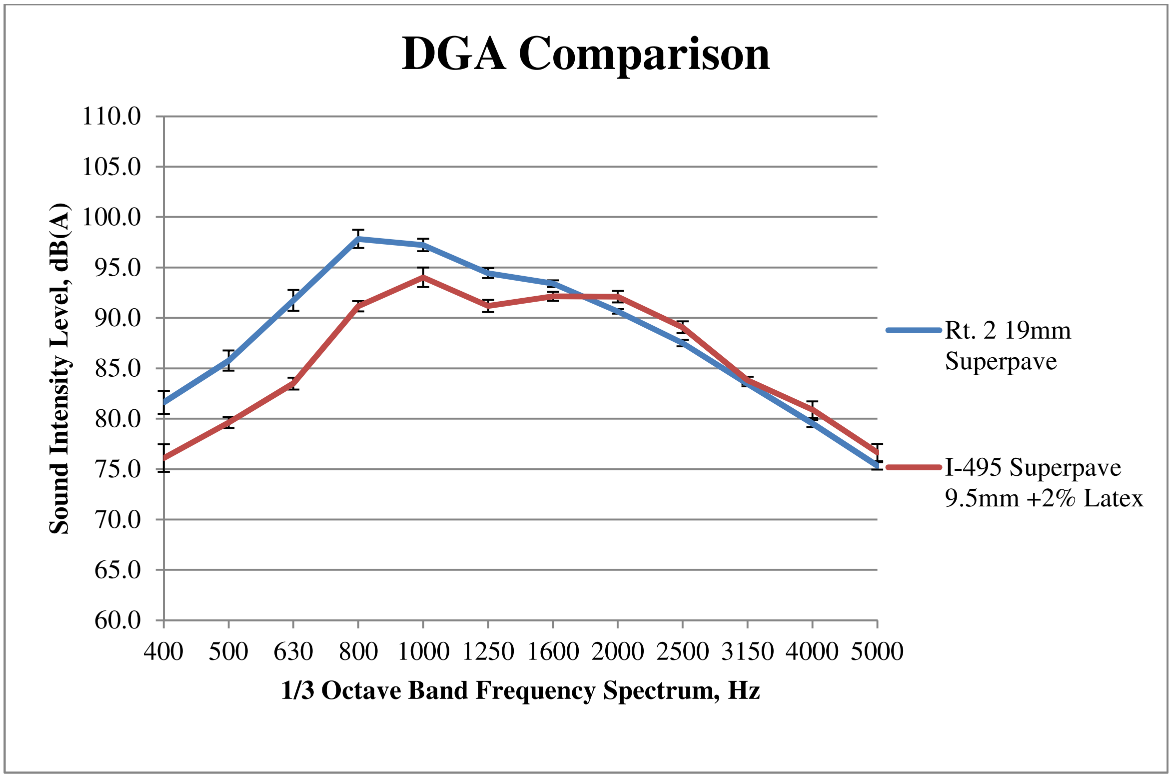

Figure 24 DGA Spectrum Comparison

The dense graded asphalts, as shown in Figure 23, range from 103.1 dB(A) to 100.0 dB(A). The sound profiles shown in Figure 24 are a good example of how aggregate size influences noise levels. The larger the aggregate the louder the surface, especially in the lower frequency range. The same can be said for texture; the rougher the material, especially those with positive texture, the louder the surface, which is typically seen in the low end of the frequency spectrum. This is also easy to see in Figures 25 and 26, which show examples of the two dense graded asphalt materials tested. As expected, the 19mm mix is significantly rougher than the 9.5mm mix, which led to the direct increase in noise seen in Figure 23.

Figure 25 Rt. 2 19mm Superpave

Figure 26 I-495 S 9.5mm Superpave + 2% latex

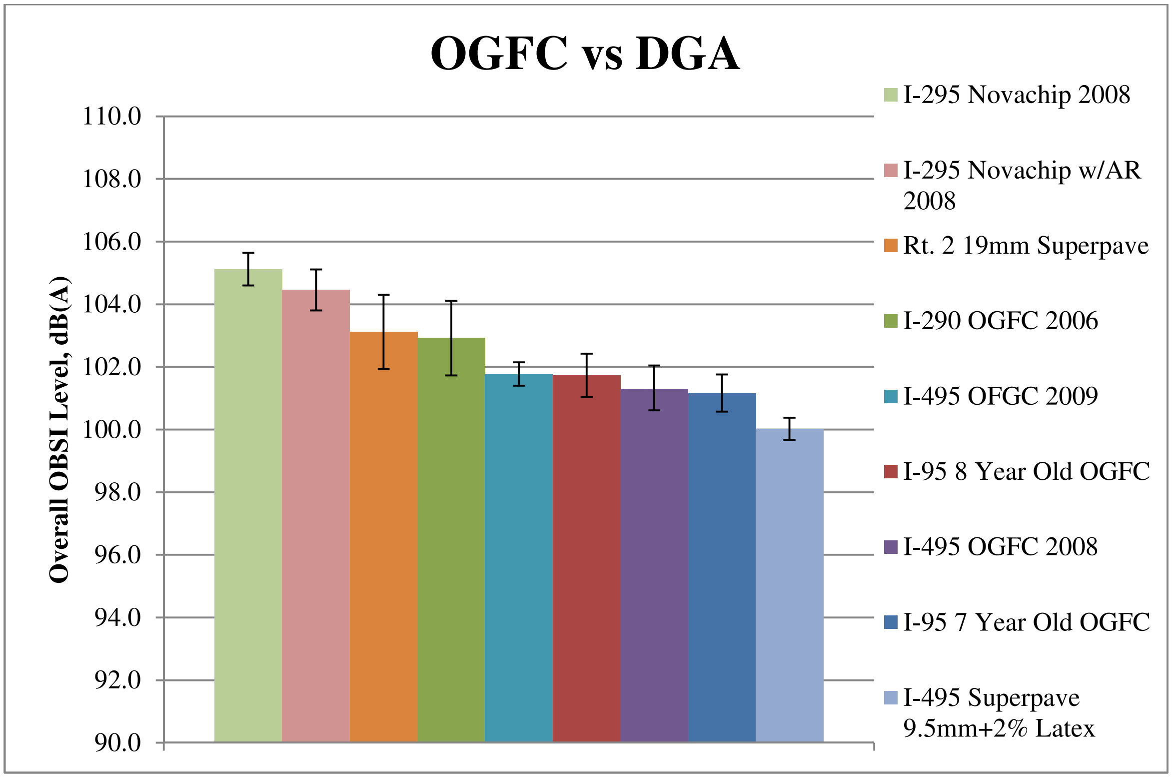

Figure 27 OGFC vs DGA Overall Levels, dB(A)

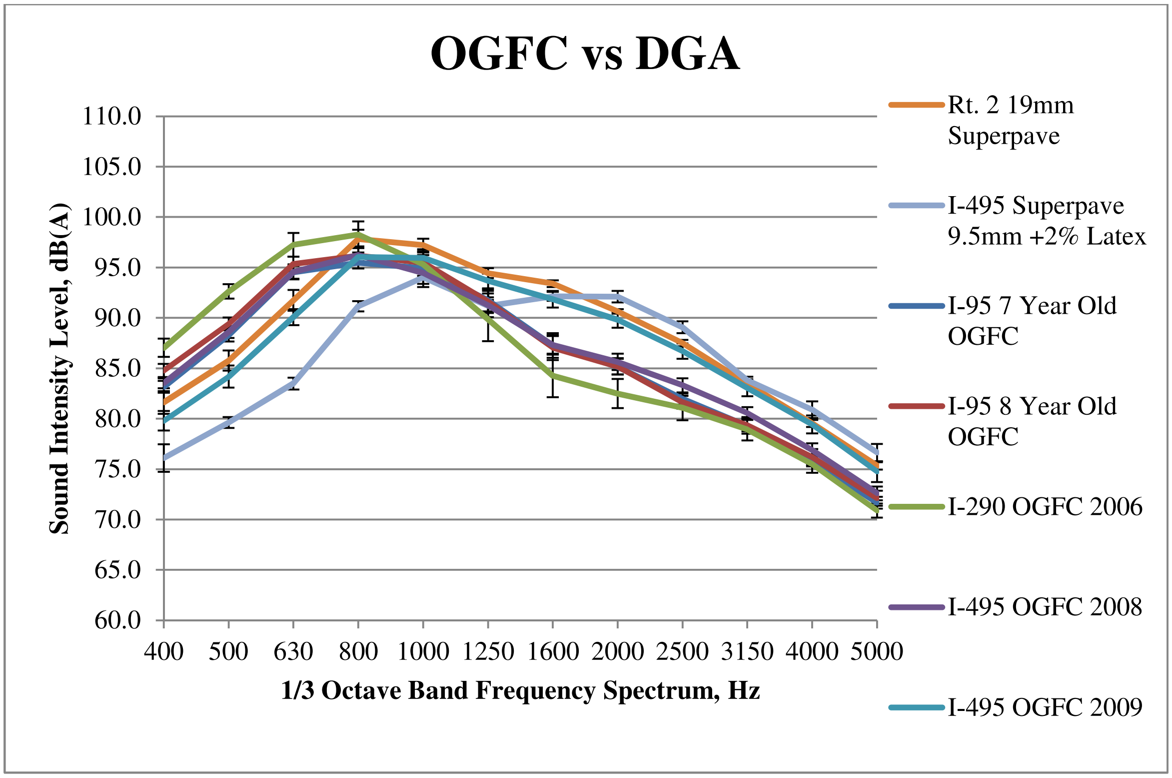

Figure 28 OGFC vs DGA Spectrum Comparison

Since OGFC pavements are typically considered 'quiet pavements' they were compared to the DGA pavements tested in Massachusetts to compare differences between the pavement surfaces. Both the overall bar chart (Figure 27) and the spectrum graph (Figure 28) show that even though the OGFC and DGA pavements in Massachusetts were loud, the OGFC pavements still did a better job in reducing the noise levels in the 1250 hz to 5000 hz range. The higher frequencies relate to higher pitched whines which can be more annoying to the human ear than the lower frequencies. For instance, the I-495 OGFC 2008 is 5 dB(A) quieter at 2000 hz than the 19mm superpave material. The most interesting comparison is the Rt. 2 19mm superpave material was only .5 dB(A) higher than the I-495 2009 OGFC. Figure 29 shows the I-290 OGFC 2006 pavement, which although paved in 2006, exhibits a more plesant sound quality (shown on Figure 28) than

I-495 2009 OGFC pavement. Figure 30 shows the I-495 N 2008 OGFC pavement, which also outperforms the I-495 2009 OGFC. In Figure 29, the larger aggregate exposed on the pavement surfaces most likely accounts for the major difference between the I-290 OGFC 2006 pavement and the I-495 OGFC 2008 pavement.

Figure 29 I-290 OGFC 2006

Figure 30 I-495 N OGFC 2008

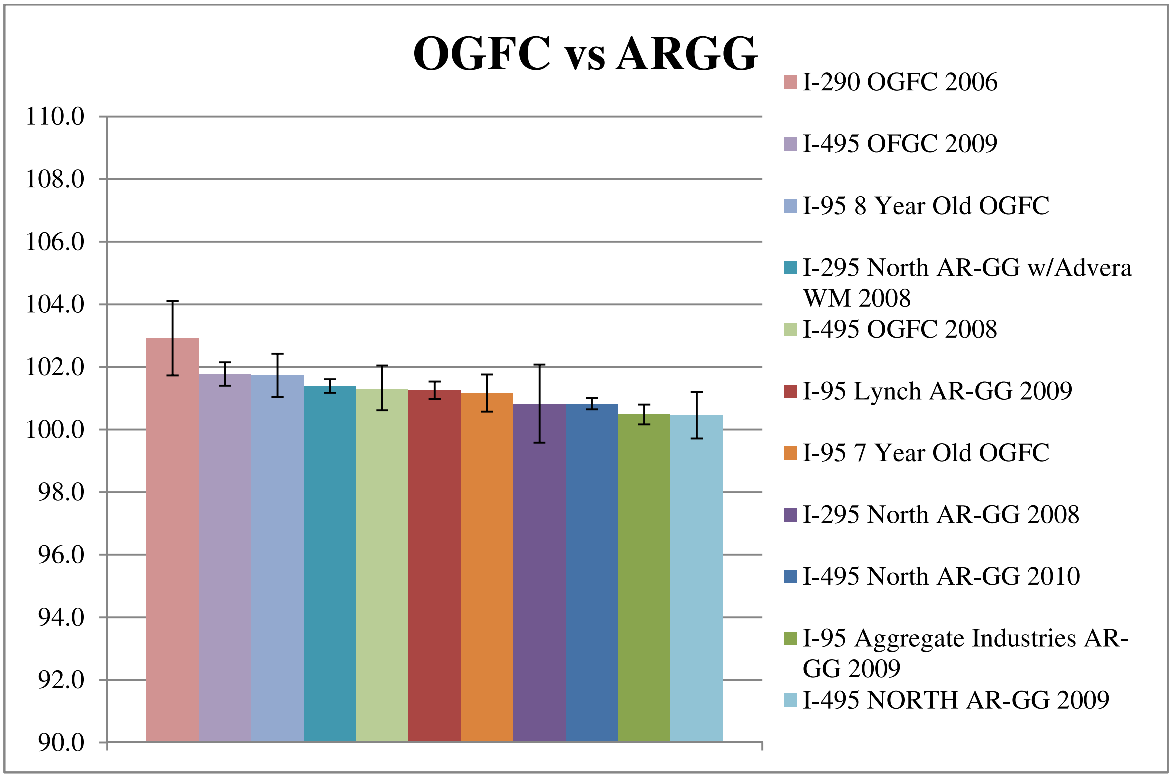

Figure 31 OGFC vs ARGG Overall Levels, dB(A)

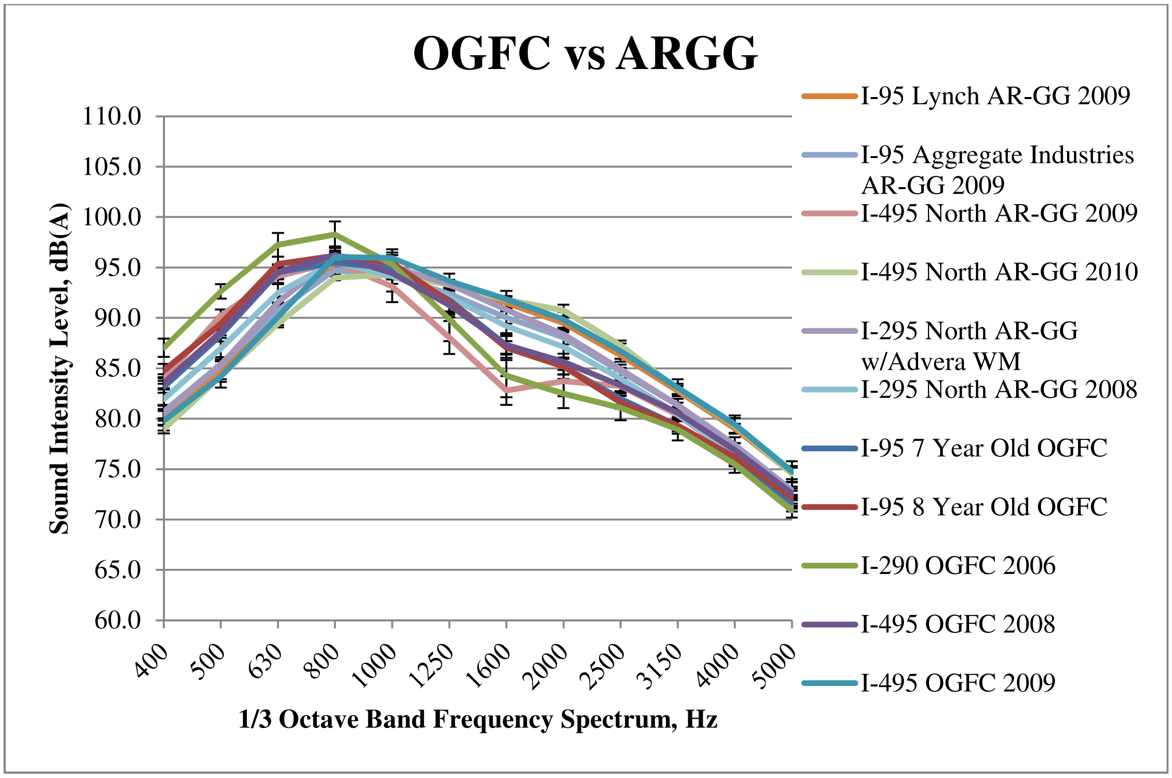

Figure 32 OGFC vs ARGG Spectrum Comparison

Several of the asphalt rubber gap graded mixes had similar overall levels (Figure 31) to the open graded friction course levels found in Massachusetts. The spectrum graph (Figure 32) showing the comparison of ARGG pavements to OGFC pavements shows that with only a few outlying materials, most of the gap graded mixes noise values fell in between the open graded mixes especially between the 1000 Hz to 5000 Hz range. Typically as pavements get older, especially open graded pavements, the noise gets louder. Regarding the pavements tested in Massachusetts, some of the newer OGFC pavements were louder than the older pavement sections. Unfortunately, no ARGG pavements older than two years were evaluated to see the longevity of the noise properties. The differences between ARGG and OGFC pavements will be discussed more when comparing the statistically similar pavement data. Figure 33 shows the I-295 N

ARGG from 2008 that was compacted using warm mix technology and Figure 34 shows the same material, an identical mix that was laid opposite the warm mix on I-295 N with the standard compaction procedures. The warm mix pavement was .5 dB(A) louder than the standard mix pavement. The 7 year old OGFC, I-95 N OGFC 2003 (Figure 35) was similar to the ARGG mixes, which can be seen in both Figure 31 and Figure 32.

Figure 33 I-295 N ARGG w/advera WM 2008

Figure 34 I-295 N ARGG 2008

Figure 35 I-95 N OGFC 2003

STATISTICAL COMPARISONS

Disclaimer

The process followed to create the following comparisons uses only the calculated A-weighted overall values as the population. This method is useful to determine if any of the materials exhibit the same overall loudness, but does not relate to the quality of sound or how it would be perceived (i.e. – noise levels along the frequency spectrum). The graphical representations of the different pavements related below are representative of particular materials which were determined to be either statistically significant or not significant, based on the average overall average of each material tested. The graphical representations of each pavement's spectral signature is shown as an aid to understand the quality of sound, not to suggest that equal loudness is equal perception.

Overview

The purpose of completing the statistical matrix was in the interest of trying to determine if any materials of the pavement surfaces had the same overall noise levels. If different materials have similar overall noise levels, possibly they could be substituted for other materials to fulfill design criteria. The variance between each overall level for each material was determined using the f-test for two-sample variance analysis. If the variances were statistically similar, t-tests for two-samples assuming equal variance analysis was completed. If the variances for each material were statistically not similar, t-tests for two-samples assuming unequal variances was completed. A 95% confidence interval was used to determine the statistical significance. The resultant data was compiled into a statistical matrix (Figure 36) which helped to determine which materials exhibited statistically similar loudness. The statistical matrix results lead to three relevant discoveries; the two novachip pavements were statistically not similar, not all of the OGFC pavements were similar to each other, and there were several ARGG pavements that were statistically similar to certain OGFC pavements. The results for the statistical analysis are shown in this section.

Statistical Matrix

	[illegible]	[illegible]	ARGG 2009 I-95 Lynch S	ARGG 2009 I-95 Lynch N	ARGG 2009 I-95 Aggregate Industries S	ARGG 2009 I-95 Aggregate Industries N	Novachip w/AR 2008 I-295 S	ARGG 2008 I-295 N	Novachip 2008 I-295 S	ARGG 2008 I-295 N w/advera WM	OGFC [illegible] I-29[illegible]	[illegible]	[illegible]mm DGA [illegible]. 2 W	19mm DGA Rt. 2 E	ARGG 2010 I-495 N	9.5mm DGA I-495 S	ARGG-2009 I-495 N	OGFC 2009 I-495 S	OGFC 2008 I-495 N	OGFC 2008 I-495 S
[illegible]		[illegible]	N	N	Y	Y	N	Y	N	Y	N	[illegible]	N	N	N	N	N	N	N	N
[illegible]			N	N	N	N	N	N	N	N	N	[illegible]	N	N	N	N	Y	N	Y	N
[illegible]				Y	N	N	N	N	N	Y	N	[illegible]	N	N	N	N	N	N	N	N
[illegible]					N	N	N	N	N	Y	N	[illegible]	N	N	N	N	N	N	N	N
[illegible]						Y	N	N	N	N	N	[illegible]	N	N	N	N	N	Y	N	Y
[illegible]							N	N	N	N	N	[illegible]	N	N	N	N	N	Y	N	Y
[illegible]								N	N	N	N	[illegible]	N	N	N	N	N	N	N	N
[illegible]									N	N	N	[illegible]	N	N	Y	N	N	N	N	Y
[illegible]										N	N	[illegible]	N	N	N	N	N	N	N	N
[illegible]											N	[illegible]	N	N	N	N	N	N	N	N
[illegible]												[illegible]	N	N	N	N	N	N	N	N
[illegible]													N	N	N	N	N	N	Y	N
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[illegible]																N	N	N	N	Y
[illegible]																	N	N	N	N
[illegible]																		N	Y	N
[illegible]																			N	Y
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Figure 36 Statistical Matrix

The two different novachip pavements shown in Figures 37 and 38 were interesting to separate out because they were shown to be statistically not similar, although they are only .5 dB(A) different on the overall level. Using OBSI measurements, it is generally recommended to make conclusions based on measured differences of over 1 dB(A). Although with sound intensity measurements it is possible to measure small pressure differences accurately under one decibel. Since a sound intensity measurement technique is utilized, the pavement temperatures recorded for these two pavements were similar, the measurements were done on the same day with the same environmental and procedural controls, it was determined that the two novachip pavements were not statistically similar with the Novachip AR being quieter. The A-weighted average overall chart shown in Figure 37 shows how close the two materials were in terms of loudness, while the spectrum analysis shown in Figure 38 shows how similar the sound was between the two different materials.

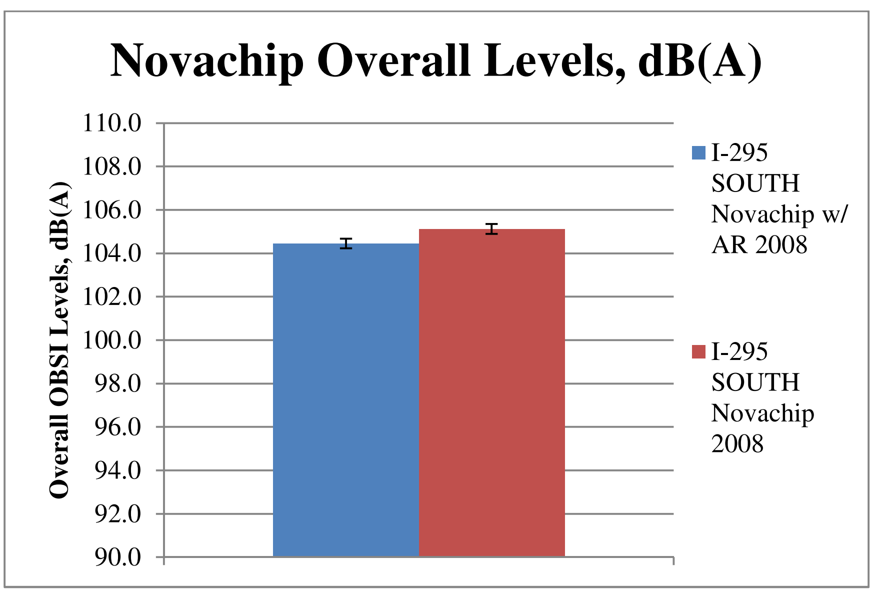

Figure 37 Novachip Overall Levels, dB(A)

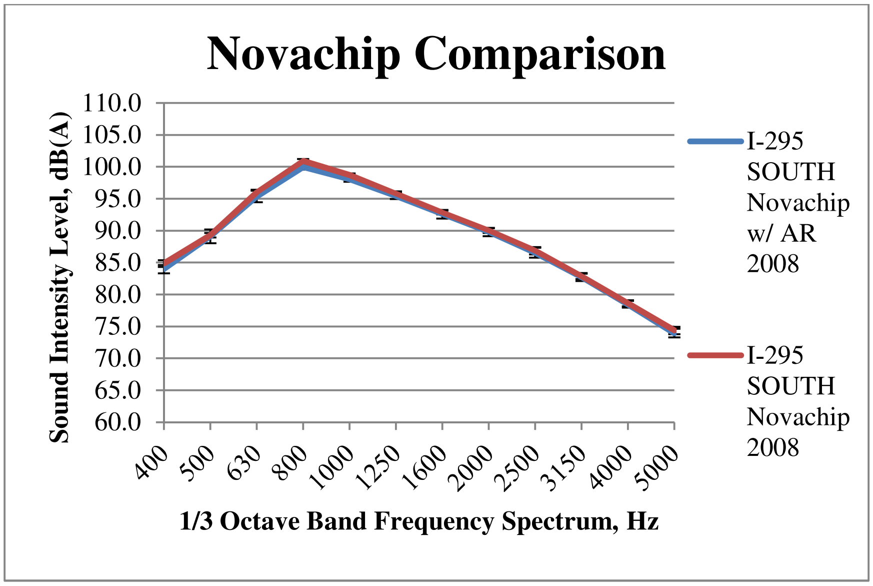

Figure 38 Novachip Comparison

ARGG 2008 I-295 N vs Statistically Similar OGFCs

The material measured on I-295 N, an asphalt rubber gap graded mix, was shown to be statistically similar to two different open graded friction course materials, the OGFC on I-95 S that was placed in 2003 and the OGFC on I-495 S that was placed in 2008. The overall level chart (Figure 39) shows that the overall noise level for the three pavements are within .5 dB(A) of each other. The spectrum chart (Figure 40) shows how the pavements are relatively similar along the entire spectrum. It is important to notice on the spectrum graph that the OGFC from 2003 is more than one decibel quieter than the OGFC from 2008 in the 2000 hz to 3150 hz frequencies. Since the pavements are so similar on both the frequency spectrum and the overall level, it is safe to say that this particular ARGG mix could be used as a substitute for an OGFC pavement for noise reduction purposes. It would be adventageous to look further into the noise properties of ARGG materials over their expected lifespan in Massachusetts.

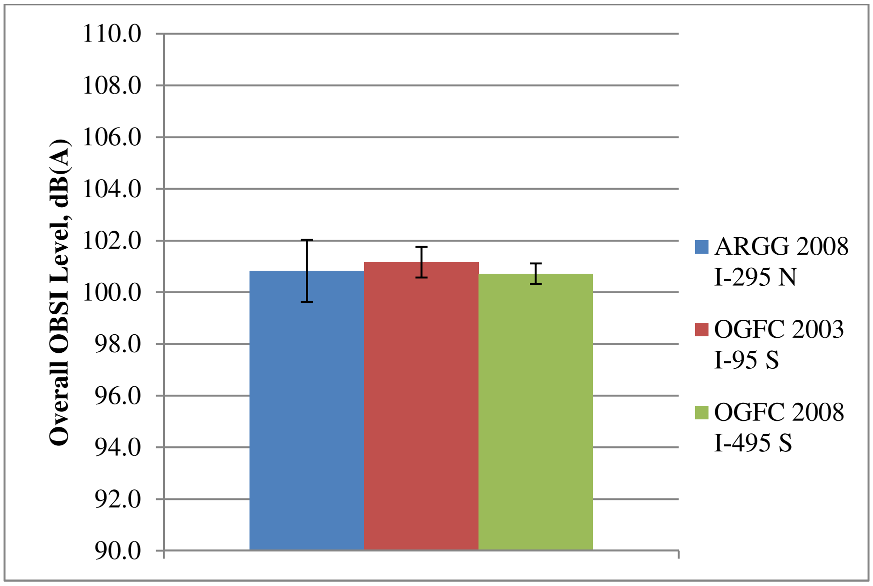

Figure 39 ARGG 2008 I-295 N vs Statistically Similar OGFCs (Overall, dBA)

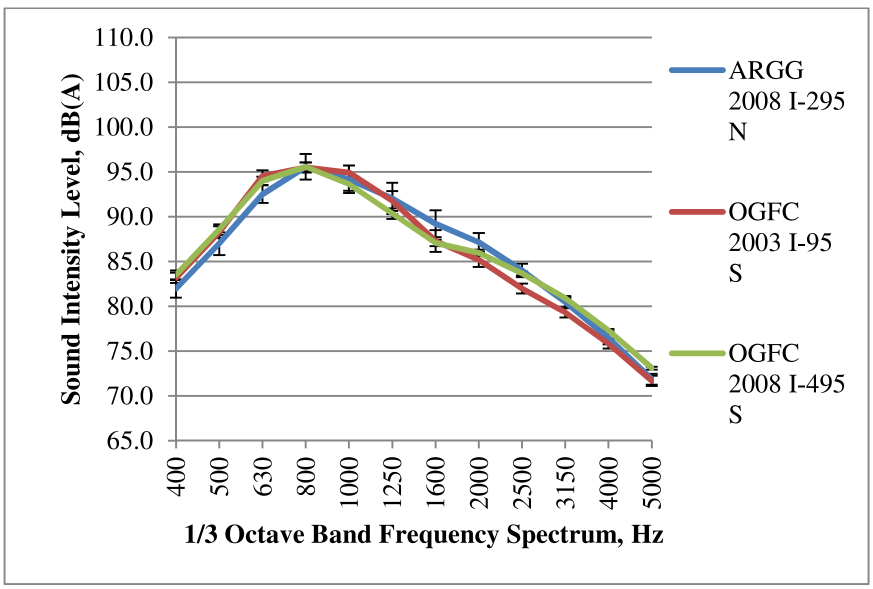

Figure 40 ARGG 2008 I-295 N vs Statistically Similar OGFCs (Spectrum)

ARGG 2008 I-295 N w/advera WM vs Statistically Similar OGFC

The ARGG from I-295 N w/advera Warm Mix was calculated to be statistically similar to the OGFC on I-95 S that was laid in 2003. The comparisons can be seen on Figures 41 and 42. As seen in Figure 42, the I-95 2003 OGFC has at least a 2 dB(A) quieter profile between the 1250 hz to the 3150 hz range. Since this range is considered to be more annoying to the average person, if it is taken into consideration that the OGFC has lasted for seven years already and still has a reasonably good sound profile, it seems that this OGFC mix would be better to use for sound quality than the ARGG warm mix.

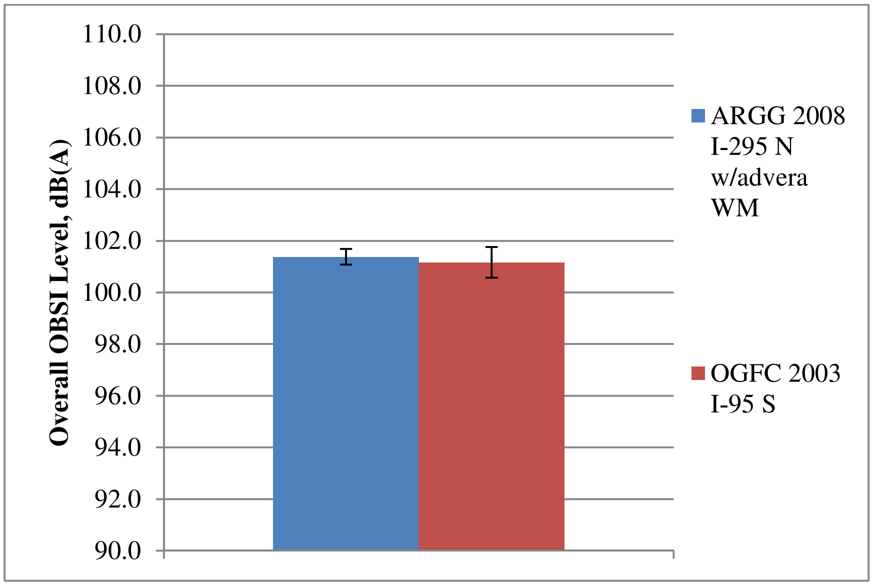

Figure 41 ARGG I-295 N w/Advera WM vs Statistically Similar OGFC

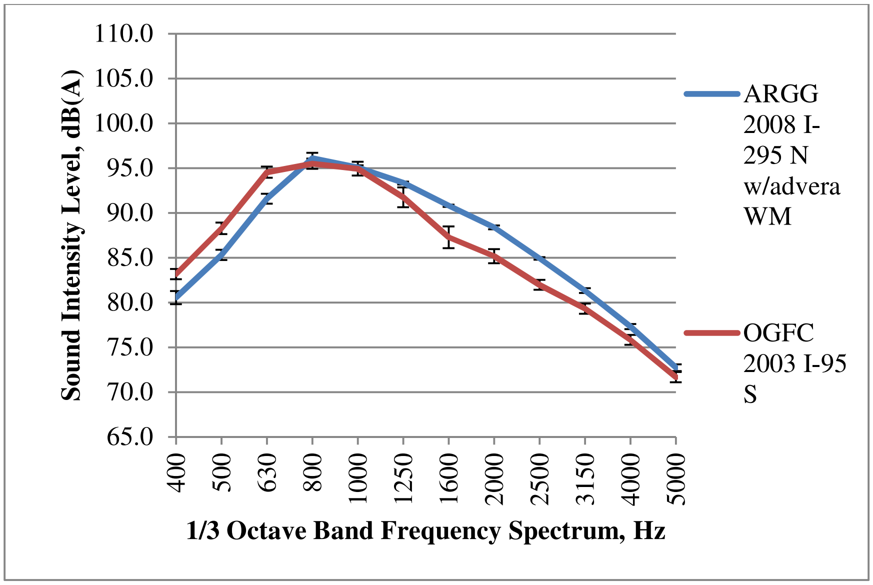

Figure 42 ARGG I-295 N w/advera WM vs Statistically Similar OGFC (Spectrum)

ARGG 2009 I-95 Aggregate Industries vs Statistically Similar OGFCs

The ARGG 2009 I-95 placed by Aggregate Industries was calculated to be statistically significant to OGFC 2003 I-95 S, OGFC 2008 I-495 S, and OGFC 2009 I-295 S. This can be seen in Figures 43 and 44. The spectrum comparison in Figure 44 graphically explains why each of the pavements were determined to be statistically equal, where the ARGG 2009 I-95 Aggregate Industries material is positioned directly in the middle of the other pavements.

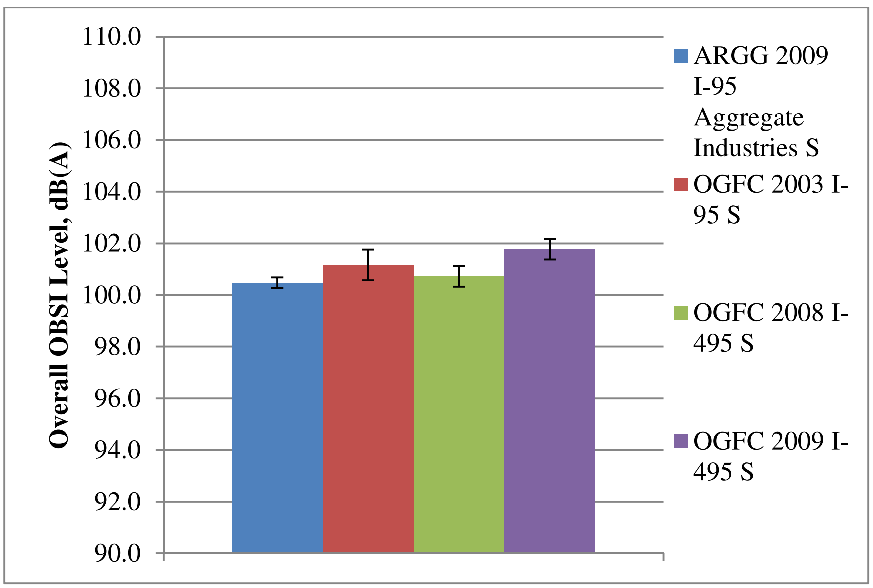

Figure 43 ARGG 2009 I-95 Aggregate Industries vs Statistically Similar OGFCs

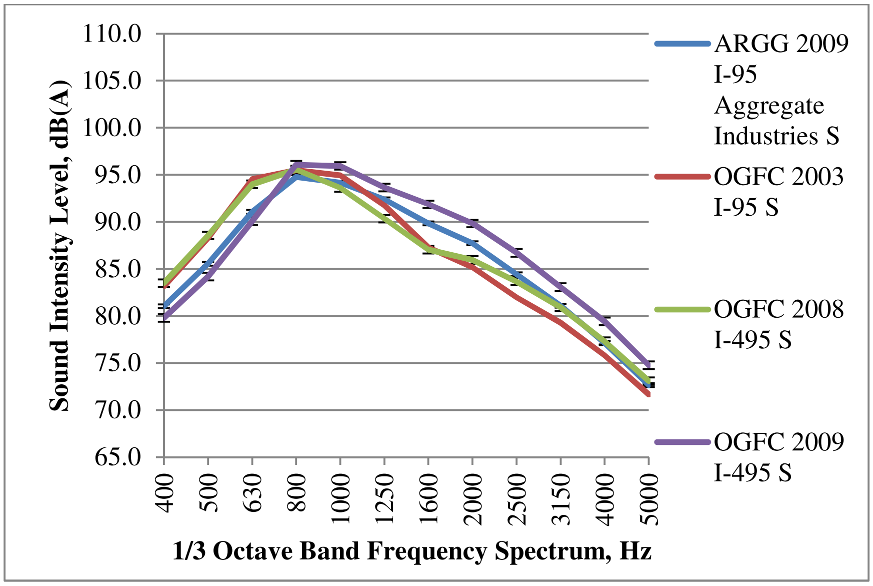

Figure 44 ARGG 2009 I-95 Aggregate Industries vs Statistically Similar OGFCs (Spectrum)

ARGG 2009 I-495 N vs Statistically Significant OGFC

The ARGG 2009 I-495 N material was calculated to be statistically equal to the OGFC 2002 I-95 N and OGFC 2008 I-495 N materials. This can be seen in Figures 45 and 46. Figure 46 shows that the ARGG 2009 I-495 N material and the OGFC 2008 I-495 N materials were similar in the lower end of the frequency spectrum, diverged from 800 hz to 2000 hz, and was similar in the higher end of the spectrum.

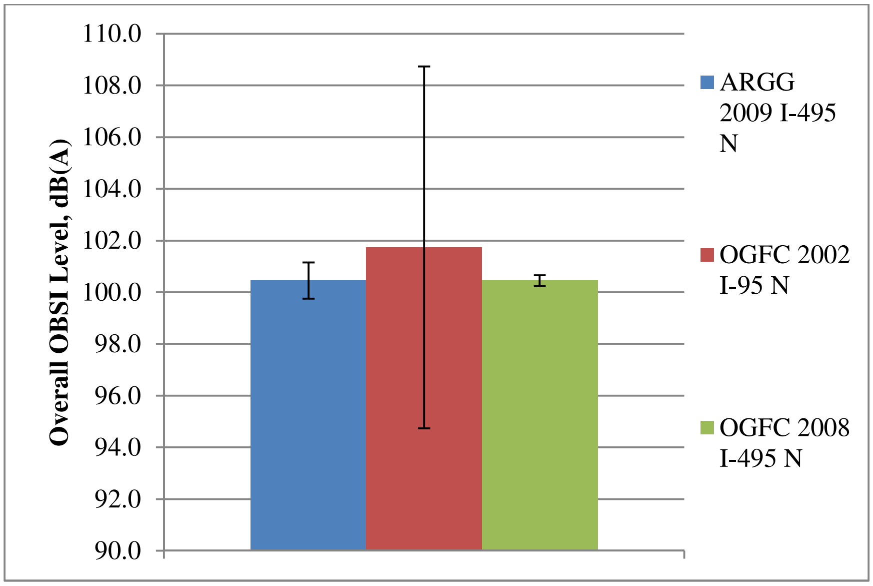

Figure 45 ARGG 2009 I-495 N vs Statistically Significant OGFC (Overall, dBA)

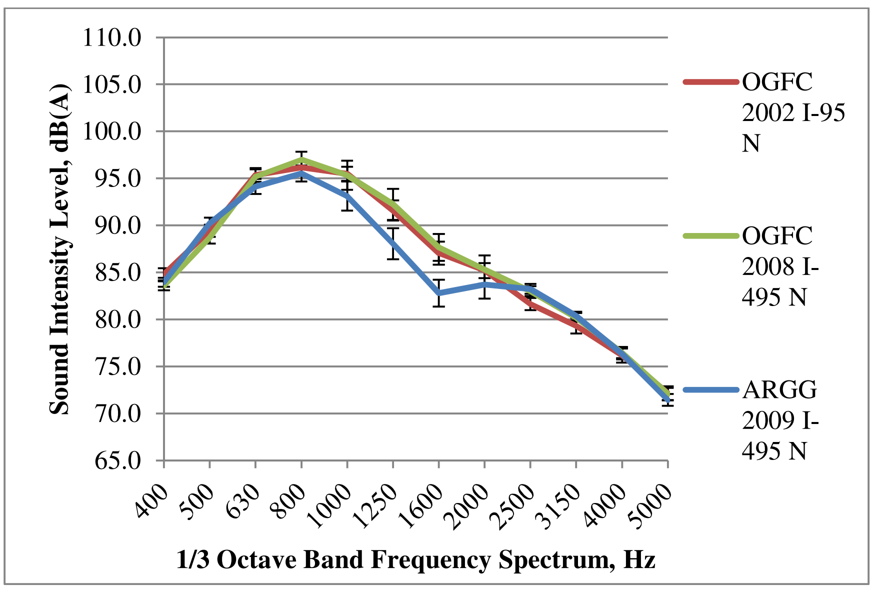

Figure 46 ARGG 2009 I-495 N vs Statistically Significant OGFC (Spectrum)

ARGG 2010 I-495 N vs Statistically Significant OGFC

The ARGG 2010 I-495 N was calculated to be statistically similar to the OGFC 2008 I-495 S materials. This is shown in Figures 48 and 49. The overall values compared were very close to each other, at 100.7 dB(A) for the OGFC 2008 I-495 S and 100.8 dB(A) for the ARGG 2010 I-495 N materials, which suggests that the two materials have equal loudness. However, as shown in Figure 49, both materials have severely different spectral signatures. This is the main reason why the statistical approach taken throughout this chapter should be observed with caution. Driving on either material would create an entirely different experience, just as standing on the side of the road would create an entirely different experience, even though the loudness of both materials is essentially the same. Based on the assumption that greater decibel levels at higher frequencies are more annoying to the human ear, the I-495 S OGFC mixture would be considered a better option for noise mitigation than the ARGG I-495 N pavement surface.

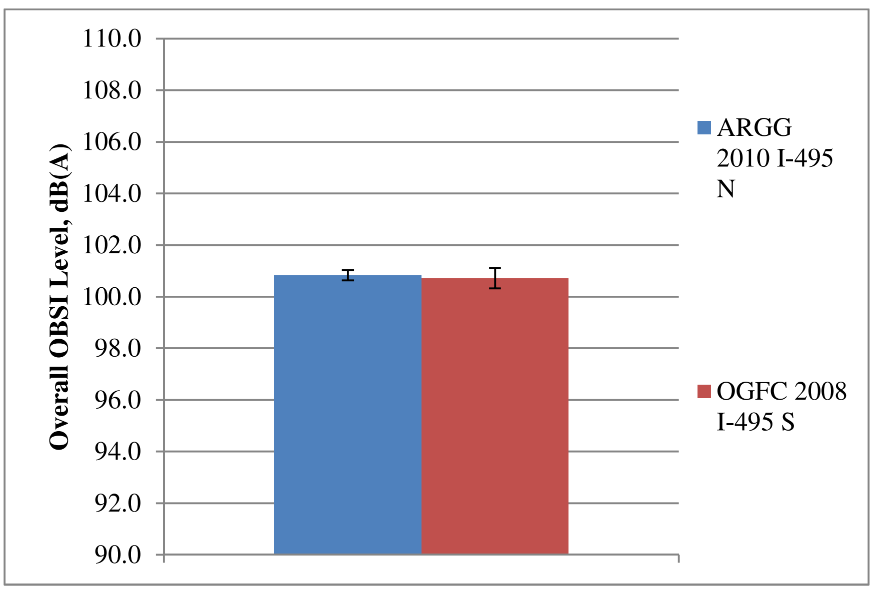

Figure 47 ARGG 2010 I-495 N vs Statistically Significant OGFC (Overall, dBA)

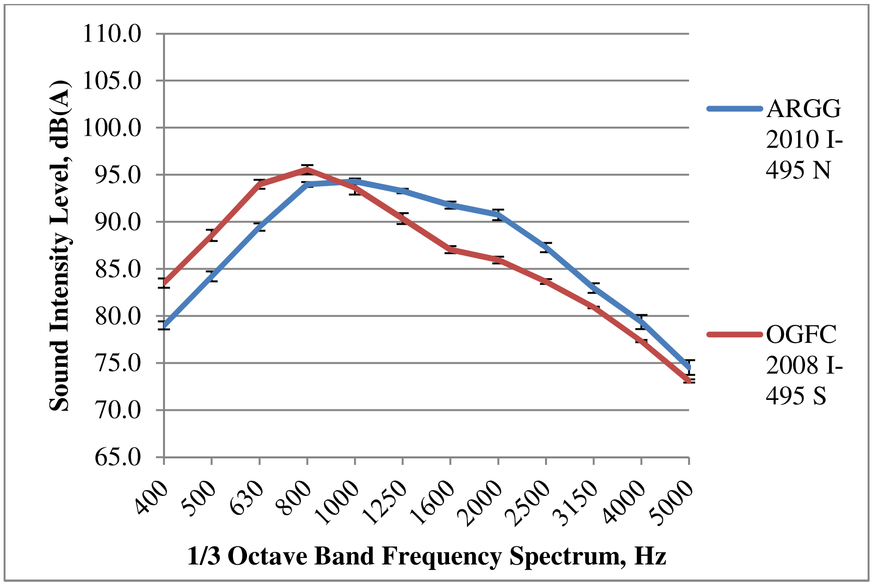

Figure 48 ARGG 2010 I-495 N vs Statistically Significant OGFC

CONCLUSIONS

The main focus of the All States Massachusetts study was to look at the noise levels that resulted from different materials All States has designed and produced over the last ten years. Initially, the goal was to quantify the noise properties of the pavements in Massachusetts, find the differences in the sound properties due to differences in mix type, mix design, and aging, and make recommendations for future pavement selection based on the overall loudness of each different material. This project encompassed fifteen different materials which were all located throughout eastern Massachusetts. The measurements were recorded between October 25, 2010 and October 29, 2010. The material selection was completed by All States Material Group. Each material section was roughly two miles long, which allowed the author to choose appropriate testing locations according to the AASHTO TP 76-09 specifications (6).

The materials selected by All States Materials Group provided a wide array of materials that ranged in age from less than one year to eight years old. The overall loudness varied just over 5 dB(A), with the lowest pavement noise recorded at 100.0 dB(A) for a 9.5mm Superpave+2% Latex mixture, and the highest pavement noise recorded was 105.1 dB(A) for a Novachip material. After quantifying the overall levels, spectrum graphs were created for each material, and comparisons were initially drawn between each type of material. The ARGG materials tested had overall levels between 100.5 dB(A) and 101.4 dB(A), the OGFC materials tested had overall levels between 101.2 dB(A) and 102.9 dB(A), the DGA materials tested had overall levels between 100.0 dB(A) and 103.1 dB(A), and the Novachip materials tested had between 104.5 dB(A) and 105.1 dB(A).

The effects of age were not as apparent as expected. Some of the pavements, such as the I-495 OGFC that was placed in 2009 were louder than some of the oldest pavements tested, such as the I-95 OGFC that was paved in 2002. The ARGG pavements tested only varied in age by a maximum of two years and no correlation between age was found. The effect of asphalt rubber in Novachip was not found to be beneficial from a noise perspective, since it only reduced the noise level by .5 dB(A).

A statistical analysis was completed comparing each material to each other. The resulting information provided several pavements that could potentially be exchanged during material selection for rehabilitation projects. The comparisons were completed off of the overall levels, so the materials that were determined to be similar would exhibit an equal loudness. In the statistical comparison section, it is discussed that although the statistically similar pavements would exhibit equal loudness the sound generated from each different material would be different. It is advised to be careful when choosing alternative pavements, to consider the noise quality of the different pavements to ensure that the most benefit is received by the producers, users, residents, and the general public.

Chapter 4: Effects of Vehicle Speed

INTRODUCTION

With all the benefits discussed in Chapter 1 that the OBSI method provides, the author had found a fatal shortcoming, the ability to compare results taken at different speeds. This inability to compare pavements tested at different vehicle speeds significantly inhibits researchers from not only being able to compare their results with other researchers, but also sometimes with comparing their own work. This problem became apparent when the author was asked to perform a noise study in Massachusetts on a 35 mph (≈56.3 kph) road. Now although 35 mph (≈56.3 kph) is an accepted testing speed in AASHTO TP 76-09, the author would have no other data collected at that speed to compare it to then (6). This became exceedingly frustrating because a plethora of data had been acquired prior, but mostly at 60 mph (≈96.6 kph) with minimal data collected also at 45 mph (≈72.4 kph). This forced the author to test the road in Massachusetts at 45mph (≈72.4 kph) in order to have results to compare to. Prior research has been conducted to determine a correlation factor between vehicle speed and overall OBSI levels, however the range examined was notably narrow (10,11). This narrow range was applicable to minor corrections needed for small run-to-run variations, but as explained later in this paper should not be globally applied to larger speed variations.

OBJECTIVES

Although AASHTO TP 76-09 allows for testing at a multitude of speeds, there has been no way to compare results taken at different speeds (6). This is why a research study was deployed in December 2011 to determine a correlation factor between vehicle speed and overall OBSI levels. A study was conducted where a single 440 ft (≈134.1 m) test section was analyzed using the OBSI method according to AASHTO TP 76-09 with the exception of varied vehicle speeds. The speed range investigated was from 20 mph ± 1 mph (≈32.2 kph ± 1.6 kph) to 50 mph ± 1 mph (≈80.5 kph ± 1.6 kph) at every 5 mph (≈8.05 kph) interval equaling seven total testing speeds. The data collection time was adjusted at each speed in order to enable data collection over the entire 440 ft (≈134.1 m) test section. The test section was located outside of 93 Road One, Piscataway, NJ. The section was comprised of a homogenous Dense Graded Asphalt (DGA) with no obstructions such as joints. Start and end points of the 440 ft (≈134.1 m) test section were marked with both road paint and safety cones. This ensured that the test operators could start the measurement at the correct location and also verify a proper end time. The overall test section can be seen in Figure 49 with the designated start and stop locations, as well a close up of the start location marking in Figure 50.

Figure 49 Overall Test Section

Figure 50 Designated Start Point Close Up

DISCUSSION

Once all testing was completed, results were prepared as described earlier. Table 2 shows each speed with its corresponding standard deviation. Also compiled with the same data is Figure 51, visually describing the overall OBSI levels for each speed. Thirdly the frequency chart, in Figure 52, can also be seen. Each graph includes corresponding error bars when applicable representing one standard deviation for each point respectively.

Table 2 Reference Data

Speed (mph)	Reference OBSI Level (dB(A))
5	67.9
10	78.2
15	84.2
20	88.4
25	91.7
30	94.8
35	97.0
40	98.9
45	100.6
50	101.9
55	103.5
60	104.8
65	106.0
70	107.1
75	108.2
80	109.1
85	110.0
90	110.9
95	111.7
100	112.4

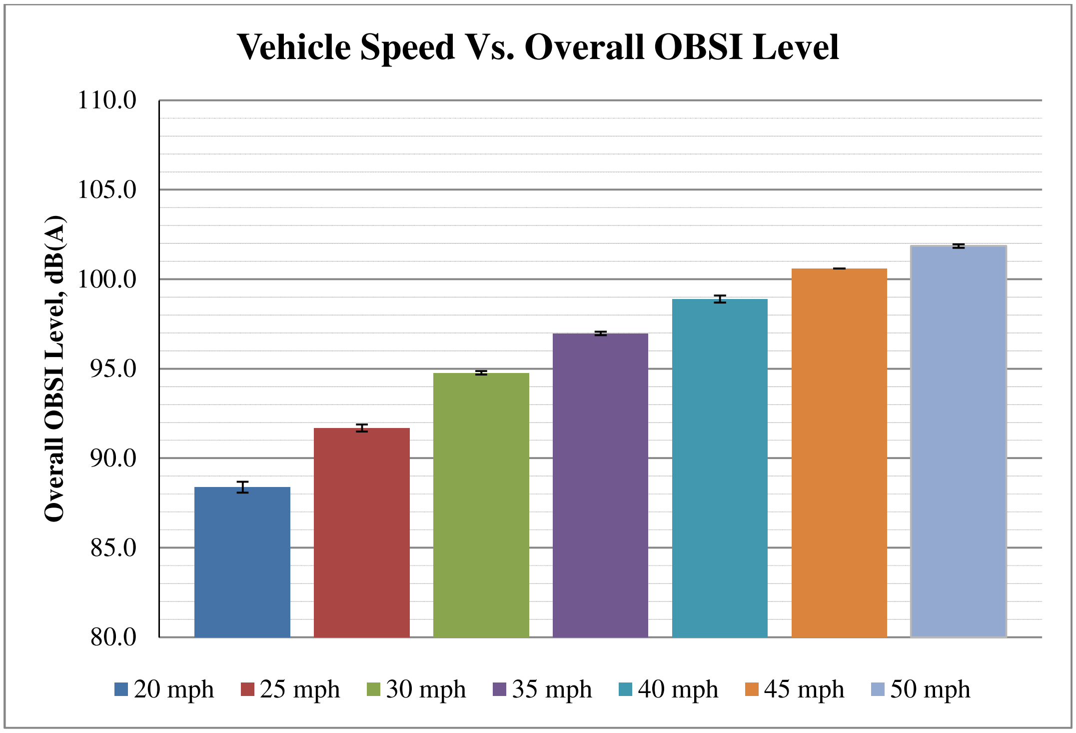

Figure 51 Overall OBSI levels bar chart

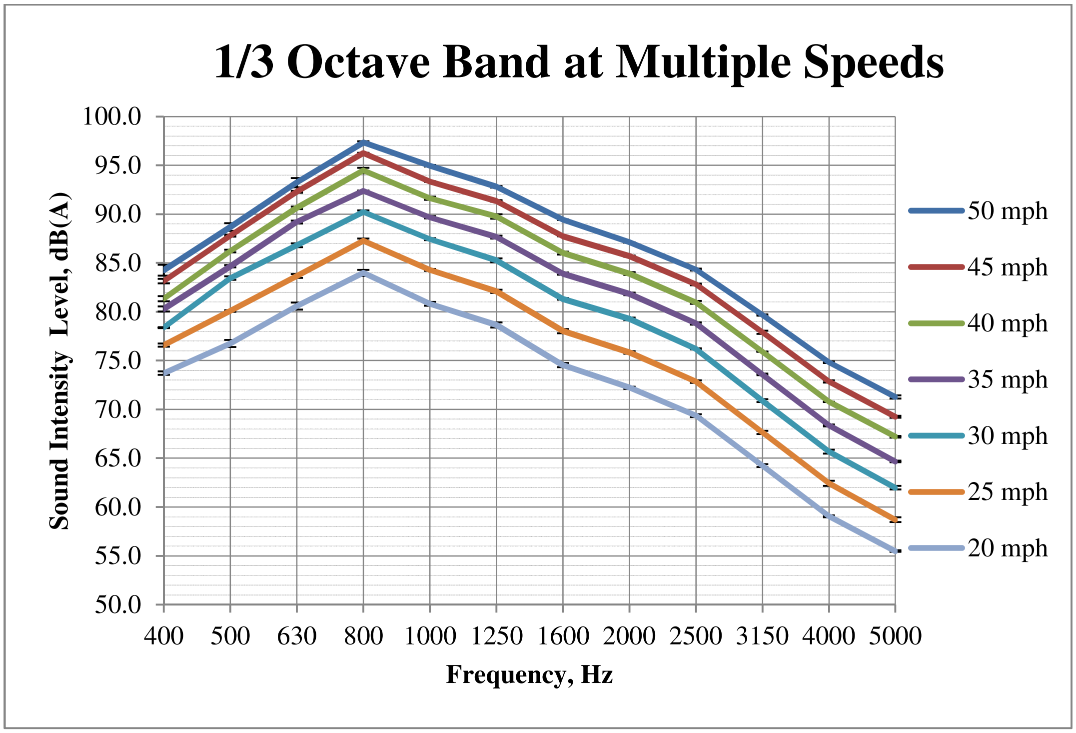

Figure 52 Spectral Analysis

Figure 52 clearly demonstrates that the frequency response is independent of speed. Meaning that with an increase in vehicle speed the acoustical signature remains the same along the one-third octave band. This is important because it shows that the tire/pavement noise being produced only changes in amplitude and does not change in tonal quality. This discovery is what then enabled the author to go on and investigate a global correction factor for speed. The reason this step was critical to proceed was because the author has found that though tire/pavement noise can have identical overall OBSI levels they can also have completely different spectral signatures as discussed earlier. Metaphorically, this means that just because the volume of a piano is the same, the notes being played can be significantly different.

After finding that the spectral signatures stayed constant, an investigation for a global correction factor was conducted. Each valid measurement was then plotted on an x-y scatter plot, and it was determined through trial and error that a logarithmic regression was appropriate. This is shown in Figure 53. The logarithmic regression fitted to the results clearly exemplified that the relationship between overall OBSI levels and vehicle speed, is a logarithmic relationship. The r-squared value, displayed in Figure 53, was .9979. This means that 99.79% of the total variation in the overall OBSI levels can be explained by the change in vehicle speed.

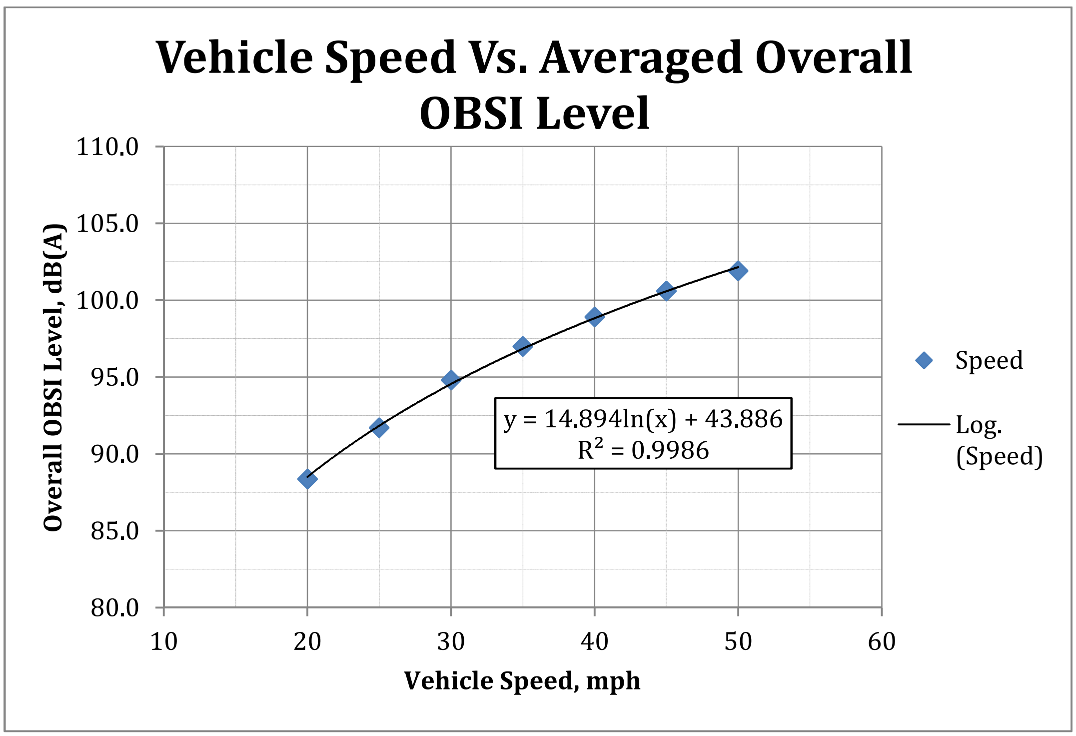

Figure 53 Logarithmic Regression

From finding the aforementioned relationship, CAIT acousticians have developed an expression to now normalize overall OBSI levels to any speed desired. In order to describe the global correction factor determined, data from this study will from now on be referred to as the 'reference data' for the remainder of this paper and will be necessary for corrections of other roads. With all other influential factors equal, the equation for the global correction factor is as follows:

Corrected OBSI level$=14.879\ln(S_D)+43.919+$*(Reference OBSI level-Recorded OBSI level)*

Where 'S_D' is the desired speed to be normalized to, 'Reference OBSI level' is the overall OBSI level from Table 1 at the speed the measurement to be normalized was taken at and 'Recorded OBSI level' is the overall OBSI level that was collected in the field. By using this equation, researchers can now shift the relationship to align with the overall OBSI level recorded in the field to the appropriate level, and then it can be used to interpolate what the overall OBSI level would be at any speed for the pavement tested as exemplified in Figure 54.

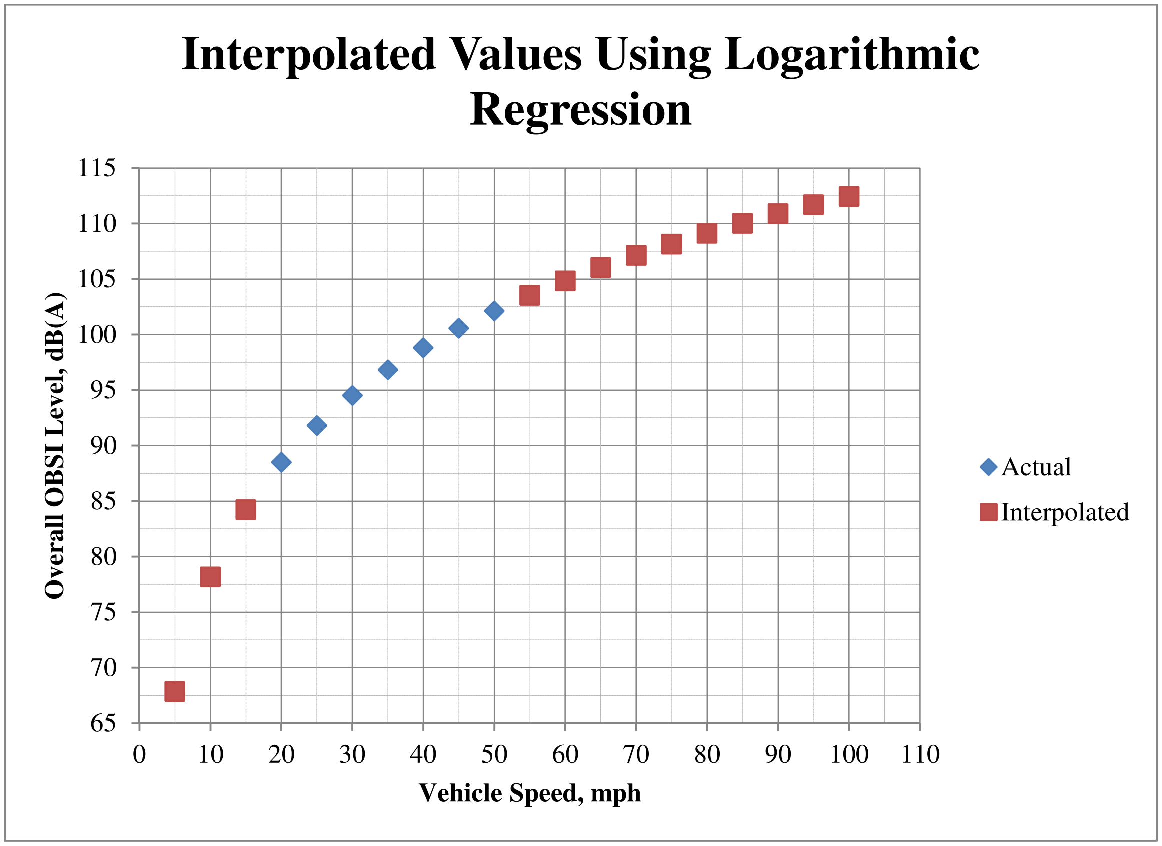

Figure 54 Interpolated Values

CONCLUSIONS

The need for a correction factor was evident to compare both data collected by the author and also to compare to data collected by other engineers. This is because comparing OBSI results at different speeds, until now, was not possible. To attempt to solve this problem, a research study was conducted to set out to find a correction factor that could be globally applied in a multistep process. The first thing that needed to be verified was that the spectral signature remained constant with an increase in vehicle speed. This was found to be true and at that point the relationship between vehicle speed and tire/pavement noise was investigated. To attempt to find the relationship, all the overall OBSI levels were plotted on an x-y scatter plot. From there, through trial and error it was determined that a logarithmic regression was the best fit yielding an r-square value of .9979. Once that relationship was found, the normalization equation was developed making the data collected for this paper 'reference data' which then allows the relationship to be properly fitted to any data collected in the field and normalized to any speed desired. Verification was performed, by looking at prior research performed by Donovan and Lodico (11).

Though Donovan and Lodico determined the relationship between vehicle speed and tire/pavement noise was a linear relationship, their research was not proven to be necessarily incorrect (11). For their study they looked at a very acute speed range of 5 mph (≈8.05 kph) centered around 60 mph (≈95.6 kph) with the main focus being a precision and bias statement. Therefor it was not surprising that when they processed their data that the relationship would look linear. To ensure the validity of both research efforts, Donovan and Lodico's relationship was applied to the aforementioned results and when looked at in such a small range, the results were very similar. However if you were to expand Donovan and Lodico's research to encompass a large speed range, similar to this study, the trend would not hold to be true.

It should be noted however that even with such strong correlation and verification from previous Federal Highway research efforts more research needs to be conducted. This section does identify a global correction factor, but at this time the correction factor should solely be applied to DGA pavements. It is unsure at the time of submission of this paper whether this correction factor is applicable to other pavement surface courses, such as Open Graded Friction Courses and Stone Matrix Asphalt. It is also unsure at the time of submission if this relationship remains true under different temperature conditions.

However if all data is normalized for temperature under current AASHTO TP 76-11 specifications then this effect should be negligible, however it is recommended that more research should be performed on these effects.

Chapter 5: Effect of Tires

INTRODUCTION

Recently tire manufacturers have been advertising "quiet" tires as additions to their line of "green" tires. These claims have not only attained the attention of consumers but also researchers who have been investigating highway noise at the source. To quantify how loud or quiet these "quiet" tires are at the tire pavement interface, a small but comprehensive study was initiated utilizing the On-Board Sound Intensity (OBSI) method. By designing a controlled experiment with three different test pavements and four different tires, researchers were able to measure the noise generated at the tire/pavement interface for each of the tires and determine the discrete differences between each of the consumer tires. Each tire was related to a Standard Reference Test Tire (SRTT) to show the relative noise levels for each pavement.

METHODOLOGY

A comprehensive testing plan was developed to isolate the discrete differences in the tires themselves. The OBSI testing performed throughout this study adhered to the AASHTO TP 76-11 (6) specification when possible and exceeded it in such instances as the addition of taking tire tread depth measurements and an increased number of durometer hardness measurements on the tire. Testing utilizing tires other than the SRTT and testing performed at tire inflation pressures other the specified 30 ±1psi (206.7 ± 6.89 kPa) (6) were the two main deviations from the test specification but were deemed acceptable to fit the scope of the study. The rear passenger wheel of the test vehicle was slightly heavier than the specified recommended weight, but consistency was maintained throughout the experiment at approximately 900 pounds (410 kg).

Pavements

The layout of the OBSI testing sections consisted of three different test sections that provided three distinctly different pavement surfaces. The first section was a Portland cement concrete pavement (PCC) on I-287 near Wanaque, NJ. The elevation on the I-287 section ranged between 260 - 320 feet above sea level. The average annual daily traffic (AADT) measured in this section was 67,187 in 2008. The second section was an Open Graded Friction Course (OGFC) functional asphalt overlay on I-78 near Basking Ridge, NJ. The elevation on the I-78 section ranged between 230 - 400 feet above sea level. The AADT near the I-78 section was recorded at 41,268 in 2008. Finally, the third section was a Dense Graded Asphalt (DGA) located on I-80 near Hope, NJ. The elevation on I-80 ranged between 480 – 500 feet above sea level. The AADT near the I-80 section was 46,532 in 2009. Each of these sections provided as many constants as could be provided within NJ test sections, while still providing three distinct wearing courses, with similar elevation and similar local traffic loading.

Tires

Four different tires were utilized for this tire study. The Standard Reference Test Tire (SRTT) typically used in the OBSI method was chosen as a general control for testing since it is the standard tire used in AASHTO TP-76 11 (*1*). The first tire chosen for investigation was the Bridgestone Ecopia™ which the manufacturer purported to be a "quiet" tire (1*2*). The second tire chosen, due to general consumer interest to save money on fuel and reduce their carbon footprint was the Continental ProContact™, which is purported by the manufacturer to be a low rolling resistance, low CO_2, and high mileage tire (1*3*). Finally, to investigate a more aggressive tread pattern, the fourth tire chosen was the Firestone Winterforce™ which similarly is purported by the manufacturer to be quiet while still affording extra traction in winter conditions due to its aggressive tread pattern (14). In order to enable equal comparisons between all four tires, a single size of P225 60R16 was used since it is the size of the SRTT (8). The same model 16 inch (406.4 mm) rim manufactured by American Racing was utilized to mount each tire. Each tire was professionally mounted and balanced at a local third party tire service center. The four tires can be seen below in Figure 55; from left to right are the Firestone Winterforce™, Bridgestone Ecopia™, SRTT, and the Continental ProContact™. The serial numbers and build dates for each tire can be found in Table 3 below.

Figure 55 A Visual Tread Comparison of Each Tire

Table 3 Tire Manfucacturer Data

Tire Name	Serial Number	Build Date (Week)	Build Date (Year)
SRTT	ANX0EVUU	15th	2009
CONTINENTAL	P5X33X5	33rd	2011
FIRESTONE	VNX3WW68	48th	2011
BRIDGESTONE	OBX0E26	7th	2012

Before the tires were used, the hardness of each tire was determined following the ASTM D-2240-05 specification (15), which required a minimum of 5 hardness measurements per tire per test. For the purposes of this study, each tread pattern was measured at a minimum of 5 standard locations across the tread pattern and repeated radially around the tire at 5 equally spaced intervals. A minimum of 25 measurements per tire were recorded, well in abundance of the specification. In addition to hardness, tread depth was measured by following the ASTM F421-07 specification (16). Fifty or more tread depth measurements were recorded for each tire at discrete tread block locations. Before the tires were used for OBSI testing, a 300 mile (483 km) loop was followed with each tire to condition each tire evenly. Finally after OBSI field-testing was completed on each tire, the hardness and tread depth measurements were repeated to record any change.

OBSI Methodology

On each roadway tested, a minimum of six and maximum of ten 440’ (134.2 m) sections were utilized to ascertain a respectable average for each pavement type. One discrete 440’ (134.2 m) control test section was utilized on each pavement to provide additional field data throughout testing including ambient temperature. A minimum of three measurements were taken at each 440’ (134.2 m) test section although often up to six measurements were collected for better representations of each section and tire. The weight of the vehicle was measured on site before the commencement of each test period to determine the passenger rear tire weight. Although the newer recommended weight for the right rear tire was exceeded slightly, the weight was kept as standardized as possible and the same combination of noise technicians was used throughout the experimental period. Table 2 below shows the weights collected over the course of testing.

Table 4 Tire Loads Prior to Each Test (lbs.)

Date	Road	Driver Front	Passenger Front	Driver Rear	Passenger Rear
6/11/2012	I-287	1265	1225	903	902
6/11/2012	I-287	1269	1201	964	944
6/13/2012	I-287	1260	1207	905	897
6/14/2012	I-287	1259	1194	892	915
6/14/2012	I-287	1256	1244	895	892
6/15/2012	I-78	1251	1231	848	937
6/15/2012	I-78	1242	1219	909	880
6/15/2012	I-78	1237	1229	899	913
6/18/2012	I-78	1276	1205	814	919
6/18/2012	I-78	1225	1239	890	909
6/19/2012	I-78	1226	1251	880	912
6/19/2012	I-78	1247	1222	903	901
6/20/2012	I-80	1242	1225	905	902
6/20/2012	I-80	1210	1263	904	890
6/20/2012	I-80	1197	1263	897	891
6/21/2012	I-80	1236	1249	874	904
6/21/2012	I-80	1230	1257	879	903
6/26/2012	I-80	1222	1270	869	902
6/26/2012	I-80	1222	1255	877	907

Tire Impressions

To help evaluate the differences between the tires, tire impressions were made using a tactile pressure film. The film, distributed and analyzed by Sensor Products Inc., was Fujifilm Prescale® Ultra Low pressure film which is capable of measuring contact pressures from 28-85psi (172-586 kPa). The measurements taken on the pressure film were conducted with the driver and testing technician in the car with all of the equipment installed as it would be to collect OBSI measurements. The measurement time, date, exposure time, ambient temperature, humidity, inflation pressure, tire name, tire serial number position, and tread direction in relation to the sheet were recorded. The exposure time and relative humidity were important for the Topaq® analysis, which is a computer analysis provided by Sensor Products Inc. The Topaq® analysis was conducted as part of a package purchased with the pressure film. It provided the average contact pressure, the contact area, the total area of the tire patch, and the force exerted. Figure 56 below illustrates the visual pressure grid provided along with the Topaq® analysis. The SRTT is located at the top center of the figure. For the remainder of the figure, the left column of images are the imprints taken with the tire inflated to 30 psi (207 kPa) and the right column of images are the impressions taken at the tire inflation pressure of 44 psi (303 kPa). Following the SRTT in top down order is the Continental ProContact™, Firestone Winterforce™, and finally the Bridgestone Ecopia™. Impressions for both 30 and 44 psi (207 and 303 kPa) were taken because testing was conducted at both inflation pressures for all tires but the SRTT. This is because AASHTO TP 76-09 calls for the testing tire to be inflated to 30 psi ± 1 psi (207 ± 6.89 kPa). However the recommended inflation pressure for each consumer tire was 44 psi (303 kPa). Thus, to thoroughly investigate the noise quality of each of the tires, both the AASHTO TP 76-09 testing pressure and the manufacturers designed inflation pressures were utilized.

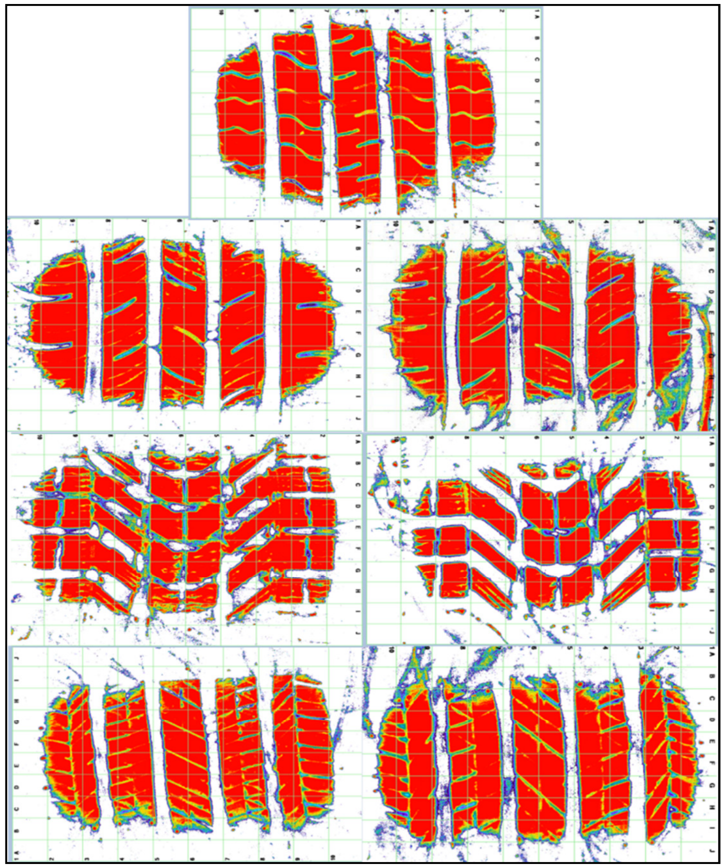

Figure 56 A Visual Representation of Each Tire Pressure Impression

RESULTS

Tire Changes

The changes in hardness from before and after testing are shown below in Table 5. As seen in Table 4 the Bridgestone had the largest change in hardness measurements followed by the Continental. The minimal changes in the SRTT and Firestone can be deemed as negligible since the scale of the actual durometer is only measured out to whole number deviations. It is also interesting to note the SRTT was consistently the hardest tire, which is most likely attributed to oxidative aging since the SRTT had a significantly earlier build date.

Table 5 Durometer Hardness Measurements

Tire	Before	After	Change
SRTT	67.7	67.1	-0.6
Continental Eco-Plus ProContact™	63.6	62.0	-1.6
Firestone Winterforce™	59.7	59.4	-0.3
Bridgestone Ecopia™	59.2	57.1	-2.1

The before and after tread depth measurements are shown below in Table 6. The Continental ProContact™ experienced the most tread wear at the completion of the OBSI testing. The technician that inspected the tires also noted that the Continental exhibited more wear and did not appear to be in as stable of a condition as the other tires.

Table 6 Tread Depth Measurements (inches)

Tire	Before	After	Change
SRTT	0.300	0.293	-0.006
Continental ProContact™	0.311	0.300	-0.011
Firestone Winterforce™	0.411	0.404	-0.007
Bridgestone Ecopia™	0.292	0.290	-0.002

OBSI Results

The average overall OBSI levels were significantly different between the tires. Figure 57 below, shows the recorded average overall OBSI levels for all four tires on each pavement. Regardless of pavement surface, the tires consistently showed results in order of loudest to quietest with the Firestone Winterforce™ always being the loudest, followed by the SRTT, Bridgestone and finally the Continental respectively. The Firestone had the highest average overall OBSI level recorded throughout the entire study by at least 2 dB(A) at 106.6 dB(A) on the PCC pavement surface. The Continental offered the lowest average overall OBSI level recorded throughout the study on the OGFC with an average overall OBSI level of 98.6 dB(A).

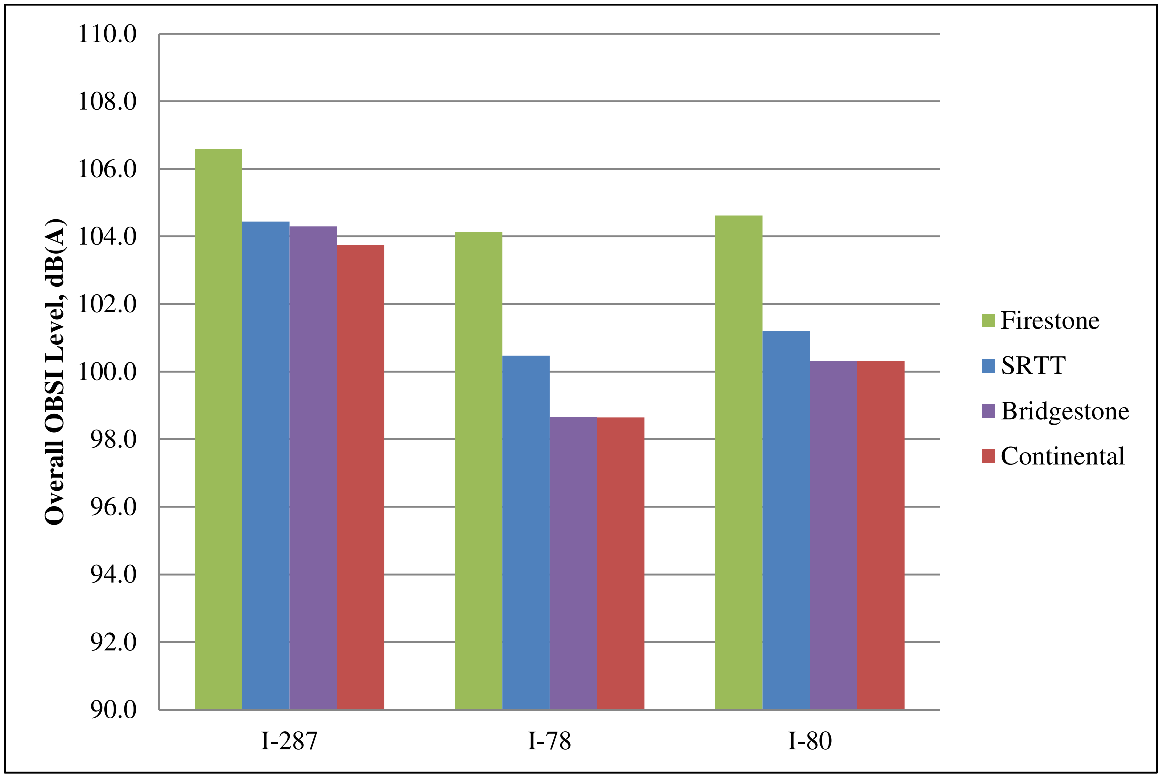

Figure 57 The Compiled Results of the Average Overall OBSI levels

Figures 58 through 60 below show how each tired responded spectrally when tested on each surface type utilizing the 30 psi (207 kPa) inflation pressure. It can be seen that all of the tires with the exception of the Firestone responded similarly on the PCC. The Firestone however, appears to have a significant peak between the 630 Hz center frequency and the 1000 Hz center frequency. This peak is the dominating factor explaining the higher average overall OBSI levels for the Firestone. The comparison of the tires on the OGFC also shows the same features with the exception that the SRTT also slightly peaks in the same frequency range as the Firestone but with less amplitude. The differentiation between all the tires in this specified range reveals where the tire's tread design and rubber hardness start to dominate noise generation at the source.

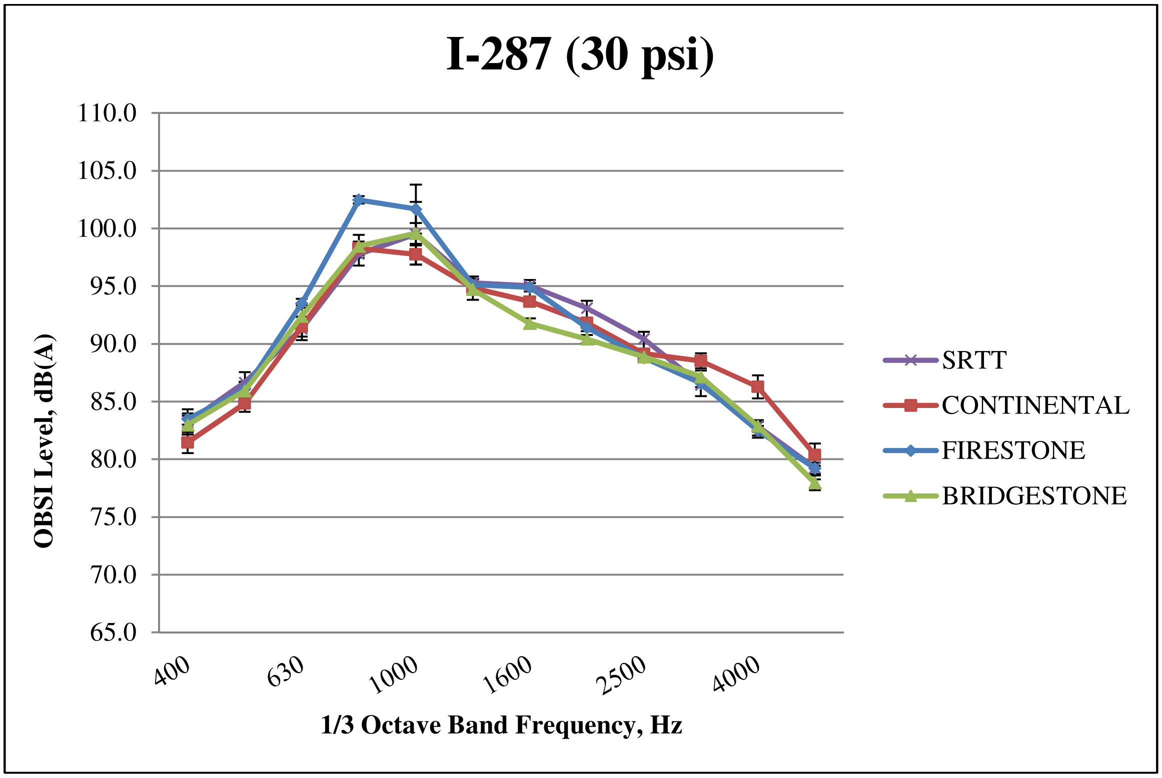

Figure 58 The I-287 Spectral Responses for Each Tire at 30 psi

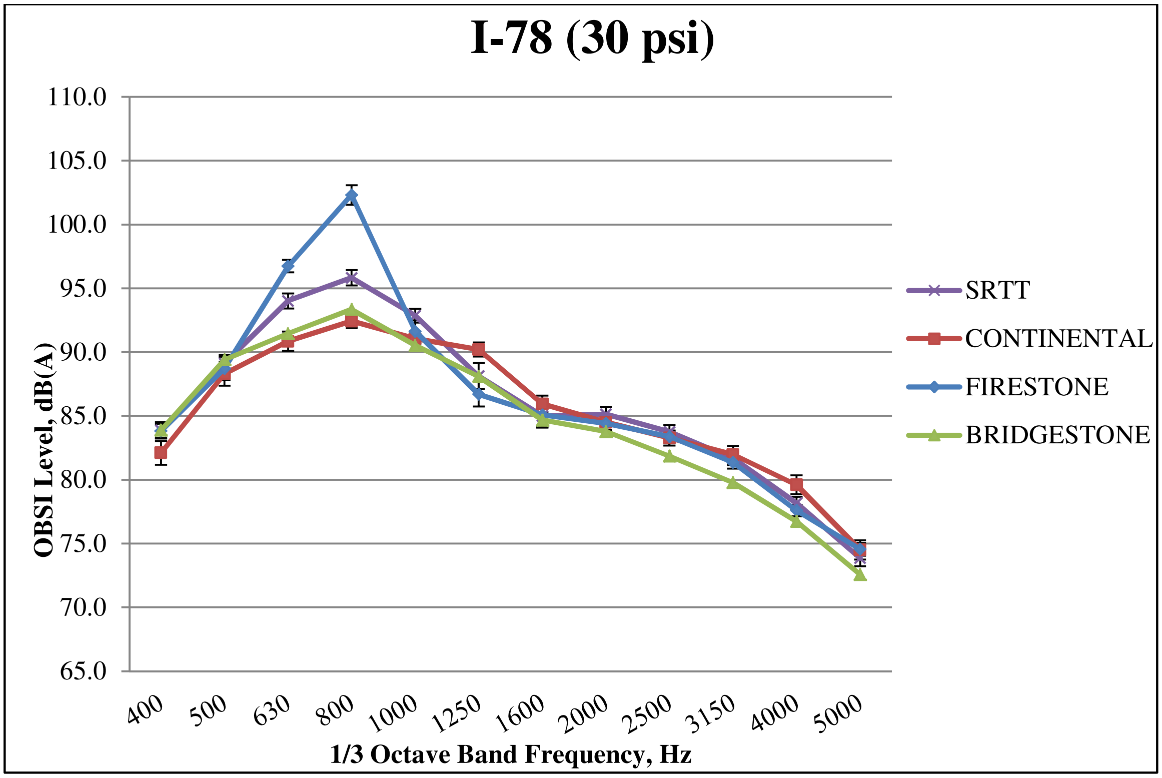

Figure 59 The I-78 Spectral Responses for Each Tire at 30 psi

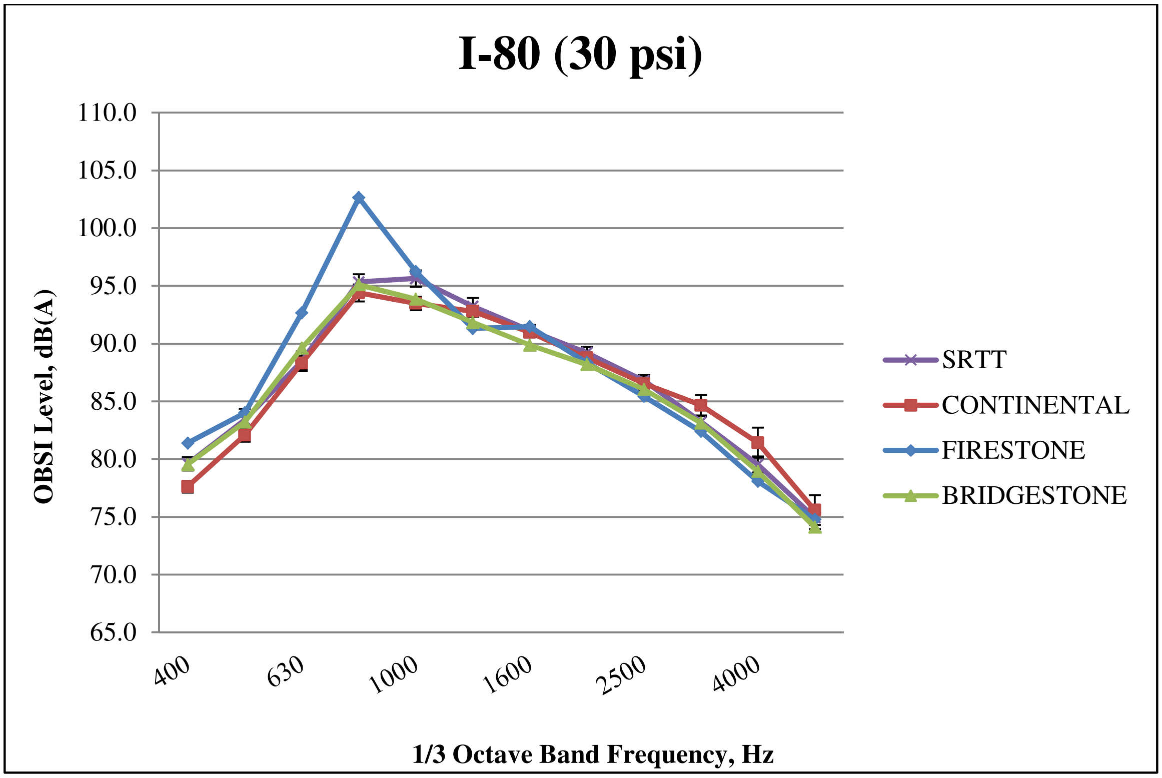

Figure 60 The I-80 Spectral Responses for Each Tire at 30 psi

Figures 61 through 63 below show how each tire responded spectrally when testing using a tire pressure of 44 psi (303 kPa) on the different pavement surfaces. These figures omit the SRTT because no testing was performed using the SRTT at 44 psi (303 kPa) for this study. Similar spectral responses from each tire occurred for an inflation pressure of 44 psi (303 kPa) as previously seen for 30 psi (207 kPa) on the different pavement surfaces. However it is interesting to note that the Bridgestone and Continental both seemed to peak at the 1000 Hz center frequency similar to the Firestone due to the change in tire pressure on the PCC. This peak for the Bridgestone and Continental was not as noticeable on the asphalt pavements potentially due to the smoothness and air voids associated with the asphalt pavements tested.

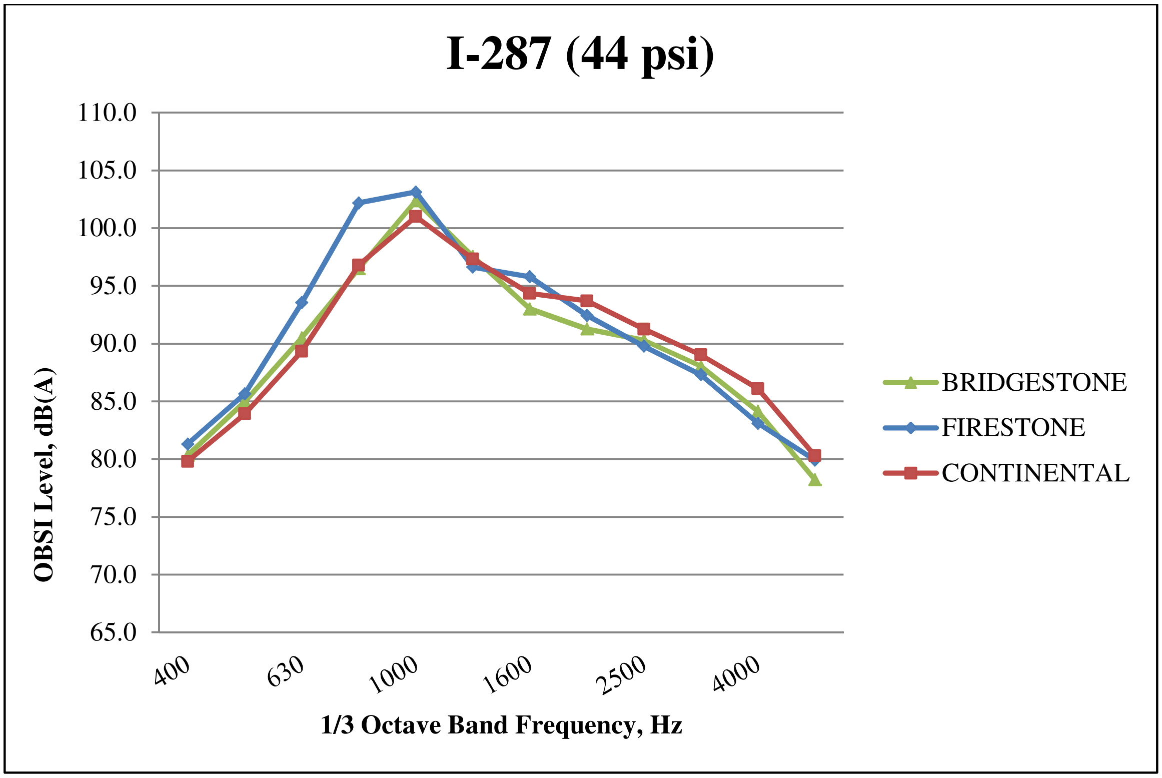

Figure 61 The I-287 Spectral Responses for Each Tire at 44 psi

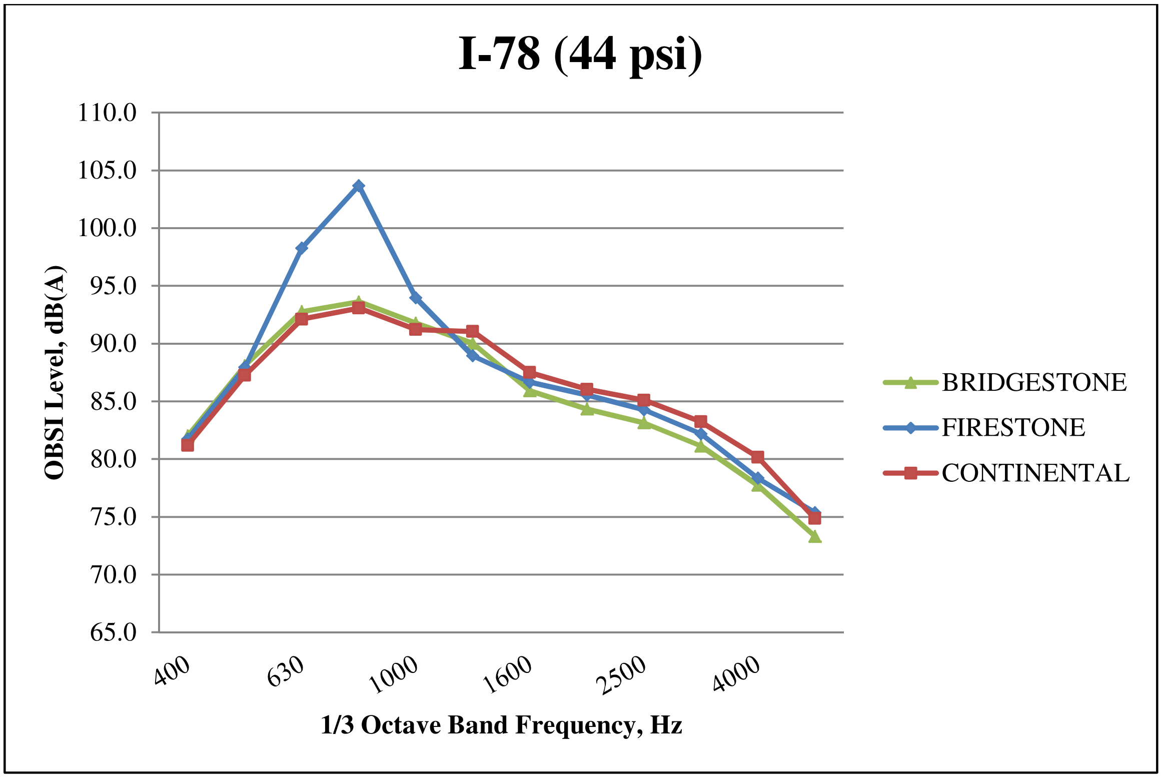

Figure 62 The I-78 Spectral Responses for Each Tire at 44 psi

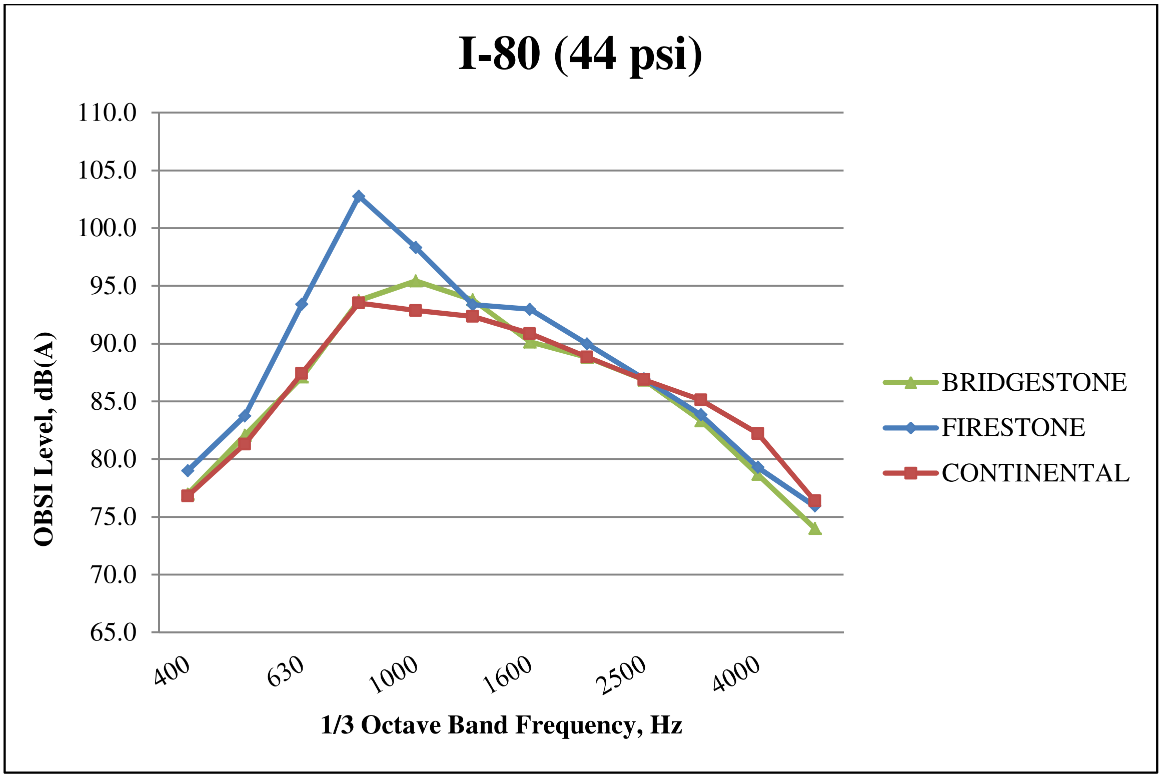

Figure 63 The I-80 Spectral Responses for Each Tire at 44 psi

To investigate the Firestone further all measurements taken for each inflation pressure on each pavement surface were overlaid with each other in Figure 64 below. Figure 64 clearly demonstrates that regardless of inflation pressure or pavement surface the Firestone consistently peaked at the 800 Hz center frequency to a nearly identical dB(A) level. This clearly demonstrates that this spike can be attributed as mechanism of the tire itself, most likely the distinct aggressive tread design.

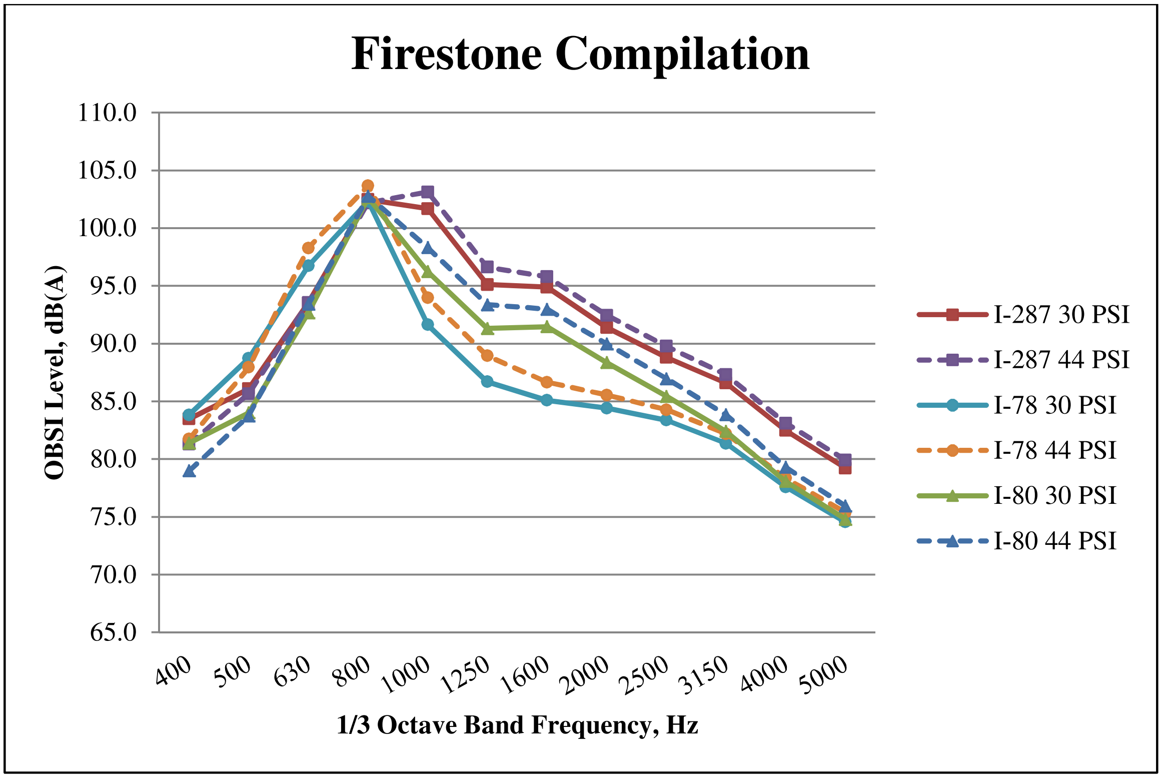

Figure 64 The Compiled Firestone Spectral Responses

Figures 65 and 66 below show how the spectral response changed due to inflation pressure changes for both the Continental and Bridgestone respectively. For each tire tested the average overall OBSI levels increased with an increase in inflation pressure. This can be explained with the Topaq® analysis due to higher pressures exerted at the tire/pavement interface.

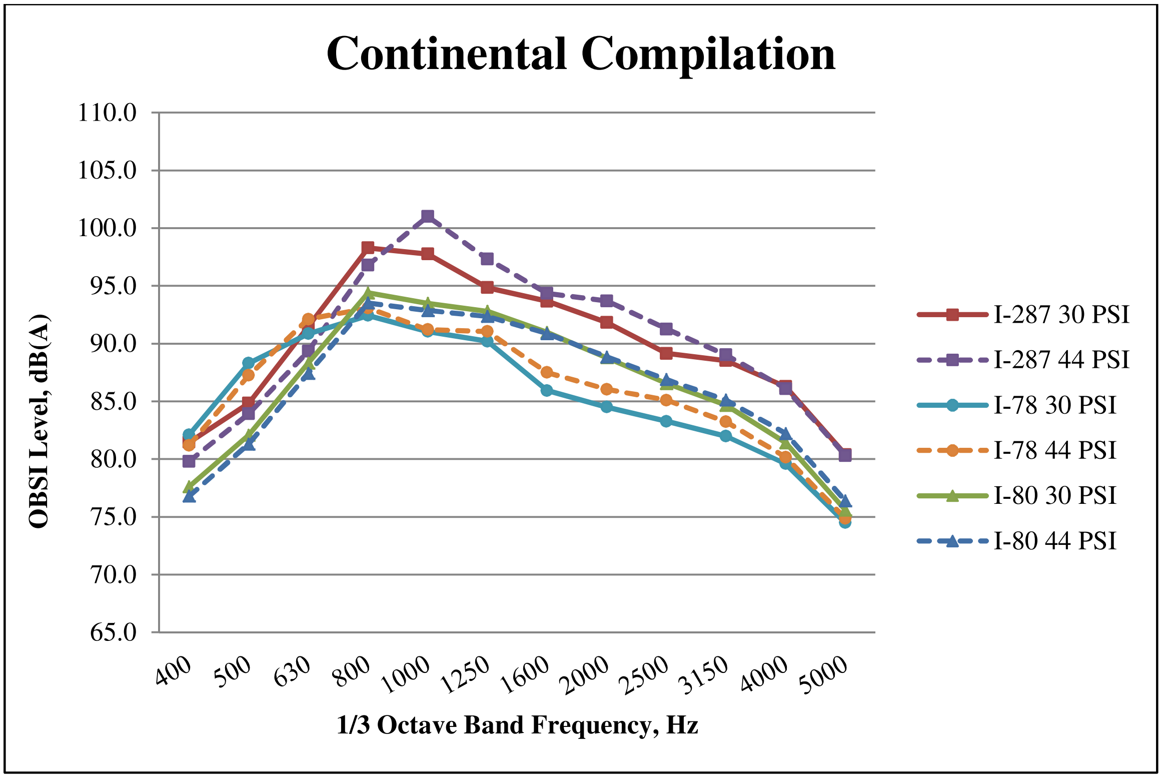

Figure 65 The Compiled Continental Spectral Responses

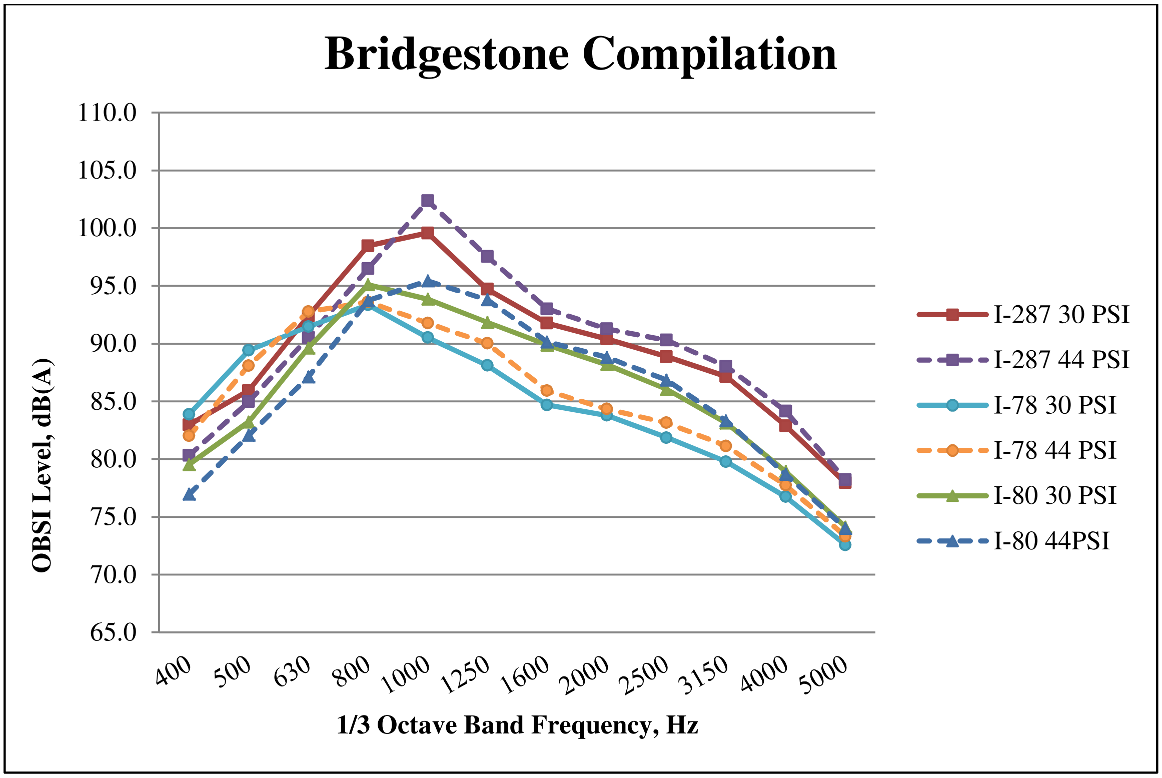

Figure 66 The Compiled Bridgestone Spectral Responses

CONCLUSIONS

In conclusion, the purpose of the study was to quantify the effective differences in specifically chosen modern consumer tires. Three tires were selected due to their manufacturer's advertised properties. A purported quiet tire, a "green" low-rolling resistance tire and a "quiet" winter tire were ultimately selected for testing. Three distinctly different pavement types were selected to investigate how the different tires would react on different surfaces to help prevent any bias. During the study, hardness and tread depth measurements were taken before and after testing to record any physical changes in the tires, tire impressions to understand the force distribution of the tire and vehicle weights prior to all OBSI testing sessions to ensure similar testing conditions for a fair comparison.

The Continental, although marketed as a low rolling resistance tire (13), was found to be the quietest tire overall. On the PCC the Continental was quieter by a minimum of .6 dB(A) when compared to any of the other tires. It was quieter on the OGFC by a minimum of .1 dB(A) when compared with any of the other tires tested. Lastly the Continental was found to be equal in overall OBSI level to the Bridgestone on the DGA with average levels of 100.3 dB(A). It should be noted however that the Continental did show the greatest tread-wear out of all of the tires, with almost double the amount of wear of the SRTT. As stated earlier the technician that inspected the tires after testing was completed also stated concern about the structural integrity of the tire.

The Bridgestone, the purported "quiet" tire (12), was ranked as the second quietest in average overall OBSI level out of the consumer tires tested. The Bridgestone was found to be 0.1 dB(A) quieter than the SRTT on the PCC section, 0.9 dB(A) quieter than the SRTT on the DGA pavement and 1.8 dB(A) quieter then the SRTT on the OGFC section.

The Firestone Winterforce proved to be the loudest tire of the consumer tires tested in this study. This was expected due to the aggressive tread pattern design. The Firestone proved to be minimally 2.2 dB(A) louder in average overall OBSI level on the PCC than any other tire tested. It performed similarly as the loudest tire on the DGA section with minimum average overall OBSI level of 3.4 dB(A) higher than any other tire. Finally on the OGFC section the largest difference average overall OBSI level was 3.6 dB(A) greater than any other tire tested. When analyzing the data the researchers also noticed a reoccurrence of a large spike in intensity level at the 800 Hz center frequency for the Firestone. This feature maintained similar intensity despite varying pavements, pressures and overall values which led the authors to believe that it is a design property of the tire itself.

Other than the Firestone, the tires all followed the same general trends in generated noise response. The Firestone had higher intensity levels between the 500 Hz center frequency and 1000 Hz center frequency range, which led to its higher measured average overall OBSI levels. It was also shown that regardless of the tire being tested, increased inflation pressure led to increased overall loudness. This can be potentially explained by the Topaq® analysis which showed the increased reaction pressures in Figure 56. In conclusion, the final comparison of the tires tested leaves the Continental as the quietest tested tire overall, the Bridgestone as the second quietest, the SRTT as the third quietest and finally the Firestone being loudest.

Chapter 6: Effects of Temperature

INTRODUCTION

Most recently, issues faced by researchers have been focused around how to account for temperature variations throughout testing. This is important for both long term pavement studies performed across multiple seasons and the ability to normalize data to a specific temperature in order for researchers from different regions to compare results.

Preliminary research has focused solely on the relationship between ambient temperature and OBSI overall levels (11). This ideology has gained support throughout the OBSI community due to the ease of application in the field. It is in the opinion of the author though, that this method becomes inaccurate when applied on a global scale. This is due to the fact that both the pavement being tested and the tire being utilized during experimentation are viscoelastic materials (17,18). This means their moduli are constantly changing due to environmental influences such as temperature and loading frequency. This section will go on to further explain why these properties appear to be the controlling factors in regards to the temperature correction of OBSI measurements.

Pavement temperature fluctuates due to environmental constraints both daily and seasonally. This fact creates an inherent issue when trying to analyze the effects of different pavements on pavement noise especially over long periods of time. Pavement temperature has been shown to primarily be a function of ambient temperature throughout the day (19). In conjunction with the ambient temperature, other factors influence testing and should be taken into account. Those factors include the following: solar radiation, wind speed and direction, cloud coverage, precipitation, moisture content, and several other factors that make it difficult to conclusively determine the temperature of a pavement during the testing process (19). To further complicate the issue, Portland cement concrete pavements (PCC) and asphalt pavements react to temperature fluctuations differently due to the viscoelastic nature of asphalt.

Similarly, when conducting tire/pavement noise measurements the operating conditions of the tire, mainly the temperature, become an integral part of the noise influences as well. The tire's rubber behaves in a viscoelastic manner and as such, changes with time and temperature over the length of any given testing period (17). Tire temperature behavior is different than pavement temperature because it is dependent on the interaction of the tire hitting the pavement, the frequency of that interaction, the tire inflation pressure, tread depth, and tread design (17).

Understanding that often researchers are dealing with multiple viscoelastic materials that are experiencing variations in temperature during OBSI testing is critical. The moduli of both the tire and pavement are constantly changing in the duration of any given test period. This is why the author found it to be critical to investigate how both materials are reacting and similarly how their interactions affect OBSI measurements. For the purposes of this paper only temperature will be investigated and all other parameters will be kept as constant as possible.

METHODOLOGY

To analyze the multitude of differences between the tire and pavement temperature interactions, each of the different components need to be studied separately. To maximize the benefit of a single study, multiple smaller tests were run in conjunction with OBSI testing. OBSI testing primarily followed the AASHTO TP 76-09 specification (6). The same set of test sections and tire combinations were utilized from the same study described in Chapter 5.

Temperature

Temperature was measured using two Micro-Epsilon thermoMETER CT™ infrared temperature probes mounted alongside the standard OBSI mounting rig. The probe positioning can be seen in Figure 1. Two probes were aimed at the tire near the wheel well while the third was on the aft end of the OBSI rig aimed towards the pavement, all highlighted with yellow tape.

Figure 67 OBSI Rig with Temperature Probes

The Micro-Epsilon temperature probes measured continuously throughout each OBSI test and were set to record in intervals of one second in length. Through post-processing, five temperature measurements were collected on each temperature probe simultaneously to an OBSI measurement and were averaged to provide a representative temperature for both the tire and pavement throughout each measurement.

Tire Conditioning

Prior to any OBSI testing a 300 mile (482.8 km) “break in” period was performed on each tire in order to condition it. The same route was followed for each tire under similar environmental conditions. Also during the conditioning period a small study was performed to determine amount of time it takes each tire to reach a consistent operating temperature. In order to achieve this, a 30 mile (48.3 km) homogeneous DGA subsection was isolated for testing. This test section provided not only continuous pavement surface but also a wide shoulder to safely install the “cold” tire along with the OBSI rig and temperature probes. Each tire was installed at the same location and the temperature was monitored for a half hour after the tire was mounted and the vehicle reached a constant speed of 60 mph (96.5 km/h). It was determined that each tire reached a consistent operating temperature within 5 to 8 minutes. This was important for researchers to know because before each OBSI test was performed the tire must be warmed up to its consistent operational temperature. After determining the “warm up” times, the author chose to “warm up” each tire for a minimum of 10 minutes at 60 mph (96.5 km/h) prior to OBSI testing to ensure equilibrium had been achieved.

Complex Shear Modulus Determination

Complex shear modulus was chosen as the property to analyze because both tire rubber and pavements could be measured using an identical method on a dynamic shear rheometer (DSR), using a solids fixture. An ulterior incentive for utilizing shear as a metric to studying tires is that a significant portion of the tire/pavement interaction is related to shear stress. By measuring the pavement and tire on the same machine ensures an equivalent comparison. An example of a pavement sample loaded into the DSR can be seen in Figure 68.

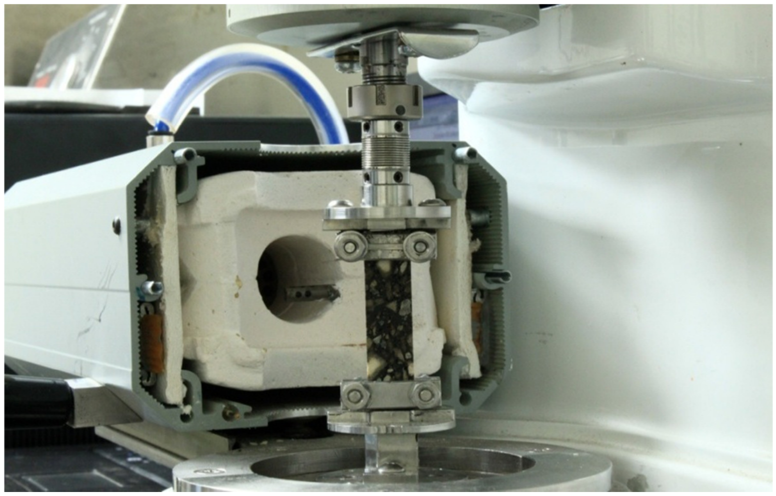

Figure 68 Asphalt in DSR

The pavement samples used for this study were representative samples of the pavement types measured with OBSI in the field. The aggregate sources, nominal aggregate size, and binder choice were similar. To test the pavements with the dynamic shear rheometer, the ASTM specification D7552 – 09 was utilized (*20*). Five samples of each material were tested at seven temperatures ranging from 39.2°F (4 C) to 140°F (60C) over a frequency range from 0.1 to 80 Hz. The test was performed as a stress control test following general asphalt testing protocol to reduce sample damage by remaining in the linear viscoelastic region. To ensure this testing was performed from the coldest to the hottest temperatures and by starting at the highest and ending with the lowest frequencies.

The tire samples were cut directly from the tire tread blocks after the necessary OBSI testing was completed to achieve three samples from each tire. The ASTM method

D5992 – 96 was followed and merged with D7552 to ensure an overlap of the testing frequencies and temperatures (20,21). Testing the tires in this way enabled identical comparisons of the viscoelastic properties of the rubber and the asphalt.

RESULTS

After all the raw temperature, OBSI and DSR measurements were taken, post processing was required in order to compile and analyze the results in a concise format. In order to do this initially, Isotherms were created to determine the how the complex shear modulus changes due to different temperatures at discrete frequencies for both the asphalts and tires. An example of this can be seen in Figure 69 which was created for the OGFC.

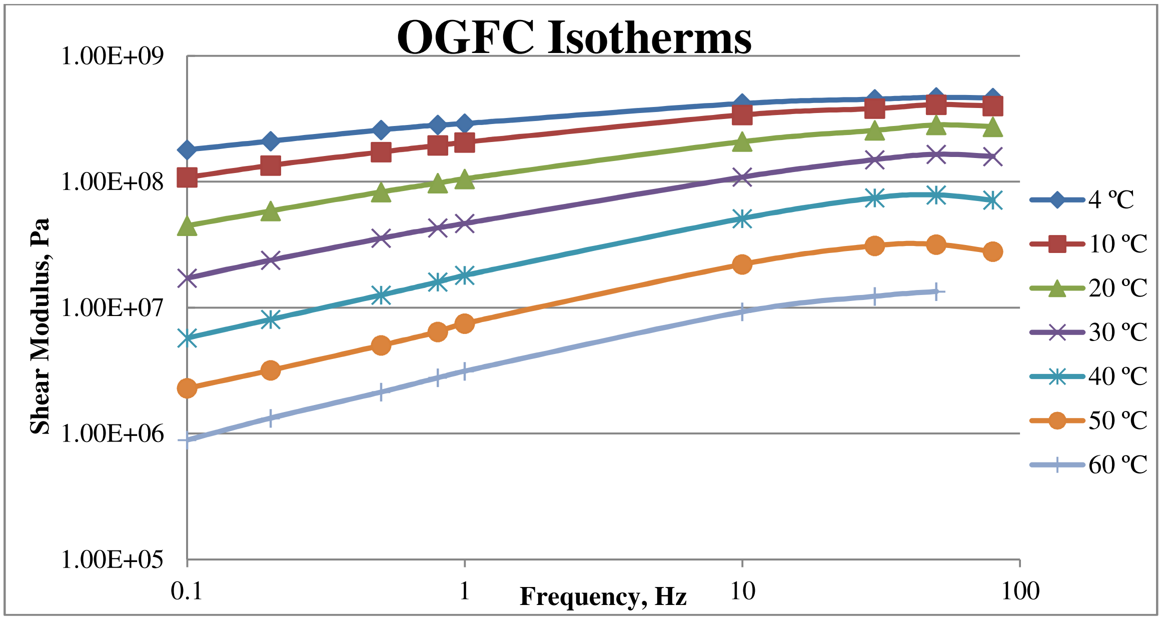

Figure 69 OGFC Isotherms

The data was then condensed to represent the complex shear modulus normalized to 12.63 Hz across multiple temperatures. The frequency 12.63 Hz was utilized because it is the calculated frequency that a single transverse line on a tire sized P225 60R16 contacts the pavement when the testing vehicle is moving at 60mph (96.5kp/h). The relationships between temperature and complex shear modulus isolated at 12.63 Hz is shown in Figure 70 for all of the tires.

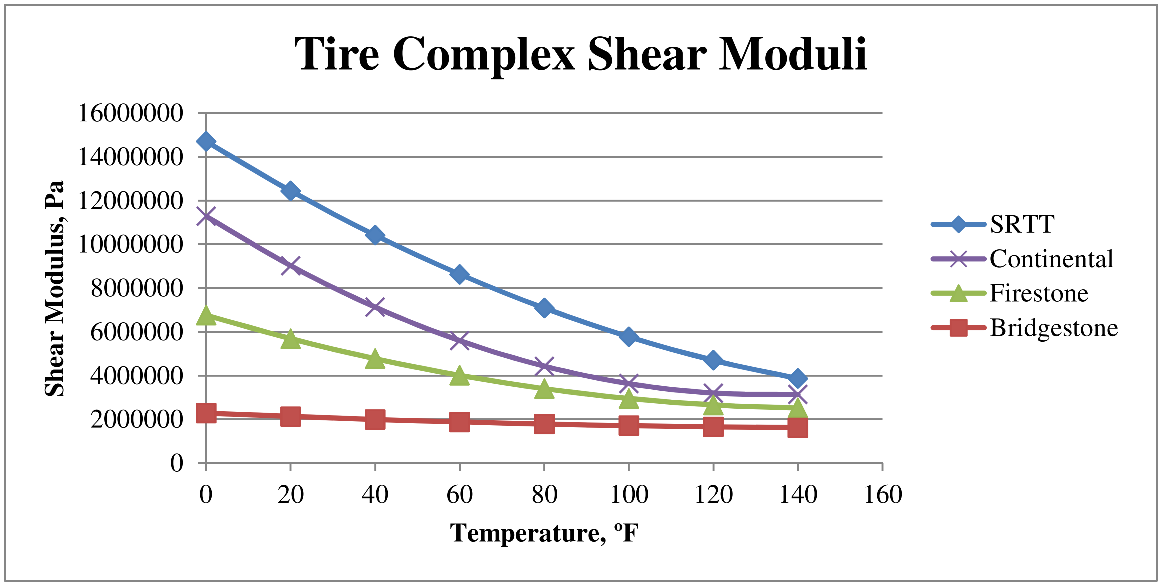

Figure 70 Tire Complex Shear Moduli

It is important to note at this point, that for the analysis portion regarding data relevant to PCC a constant elastic modulus of 1.32 GPa was utilized based off of data provided with the concrete. The relationships between temperature and complex shear modulus isolated at 12.63 Hz is shown in Figure 71 for each of the pavements. Each pavement and tire moduli, normalized to 12.63 Hz, had a corresponding equation that could be used to interpolate the exact complex shear modulus at specific temperatures. This enabled the determination of the moduli for both the tire and pavement at the exact instance of OBSI testing.

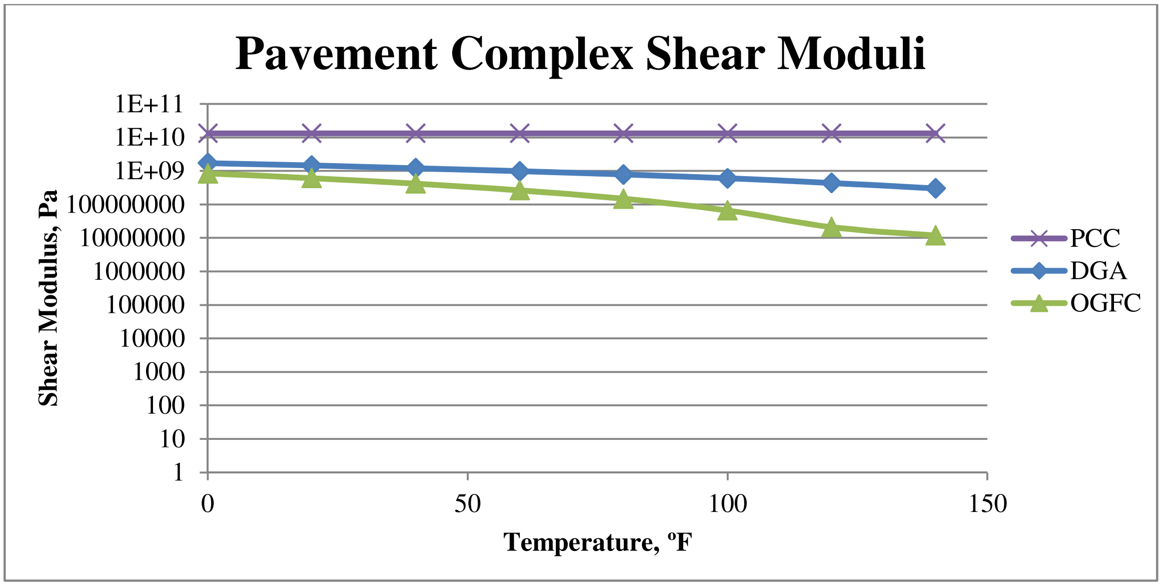

Figure 71 Pavement Complex Shear Moduli

For the final analysis, all of the data collected throughout the noise testing was combined with the testing results from the DSR. The average temperature recorded during each noise measurement for both the tire and pavement was utilized to determine what the complex shear moduli of both materials were at the exact time of each OBSI measurement. The ratio of the pavement's complex shear modulus and the tire's complex shear modulus was then determined. Lastly, plots were created showing the OBSI level of each measurement against the ratio of the pavement and tire's complex shear moduli as shown below in Figures 72-75.

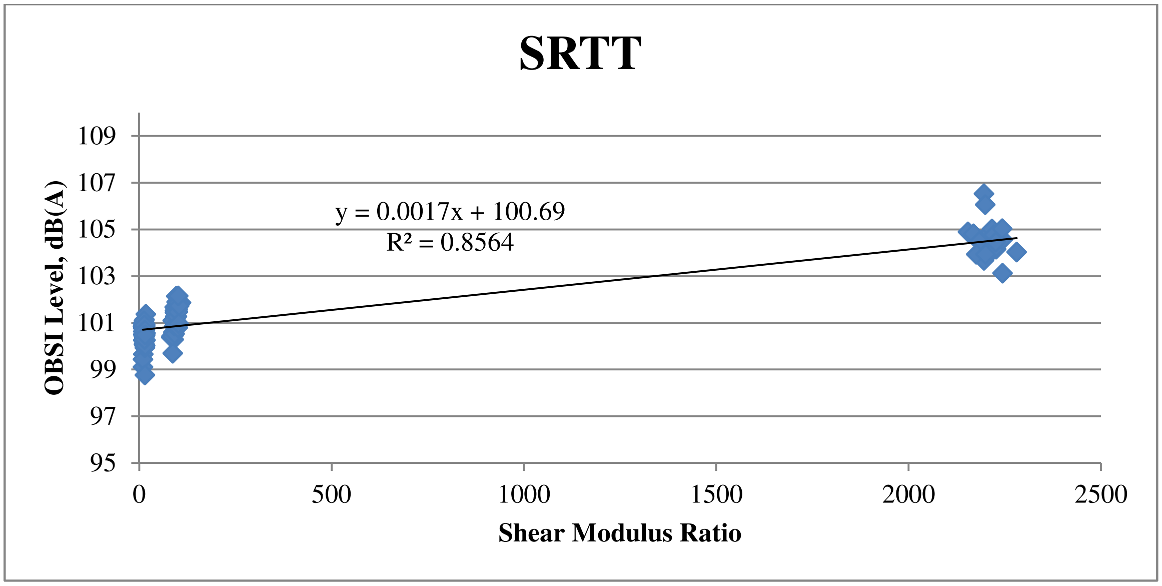

Figure 72 Compilation of Complex Shear Modulus Ratios vs. OBSI Levels for SRTT

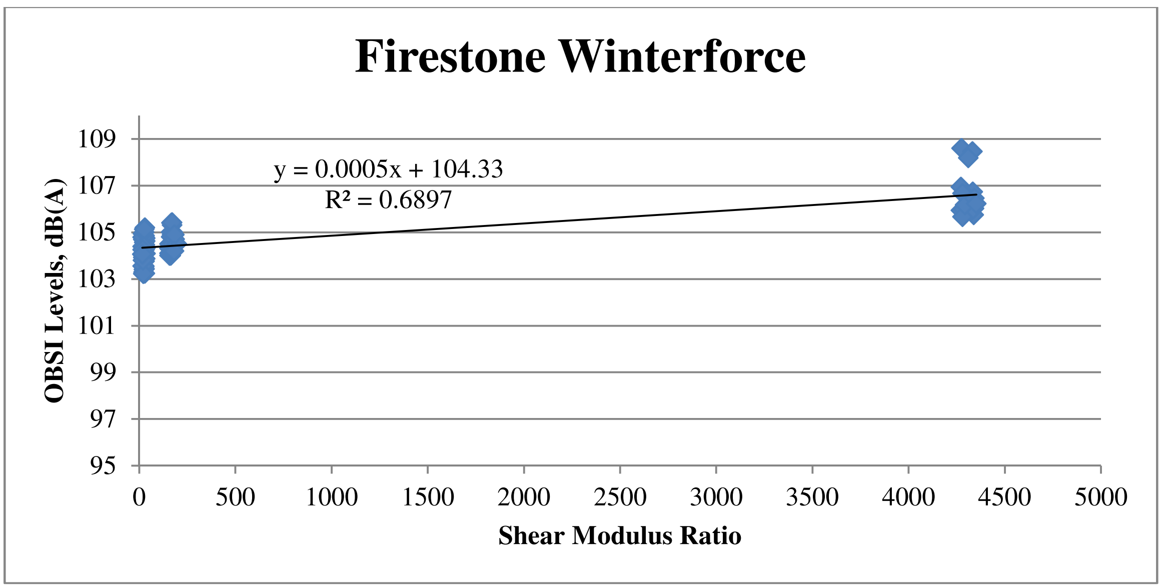

Figure 73 Compilation of Complex Shear Modulus Ratios vs. OBSI Levels for Firestone Winterforce

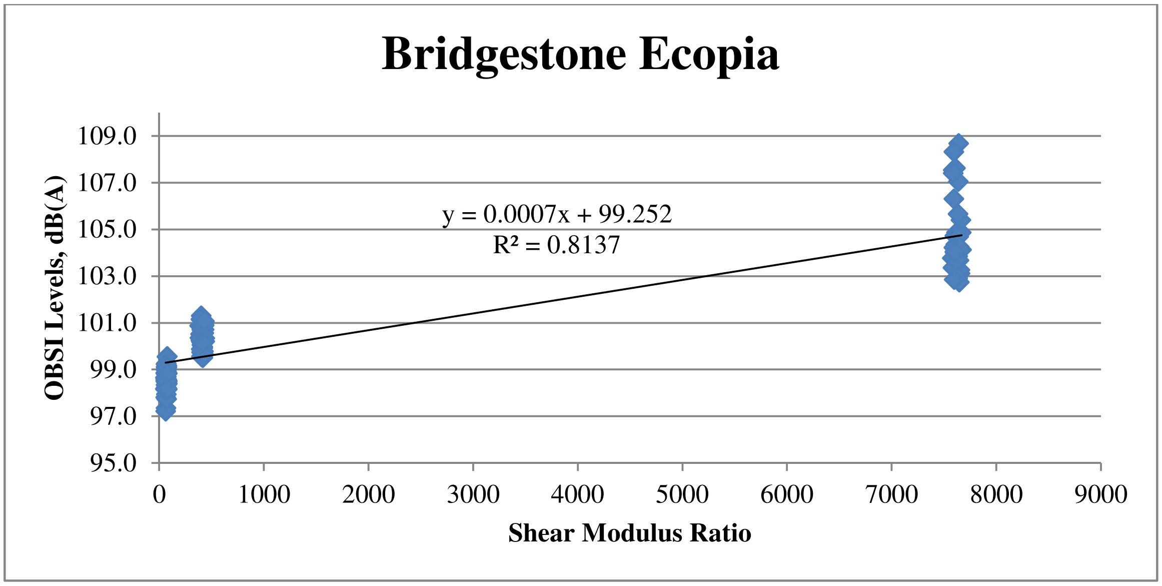

Figure 74 Compilation of Complex Shear Modulus Ratios vs. OBSI Levels for Bridgestone Ecopia

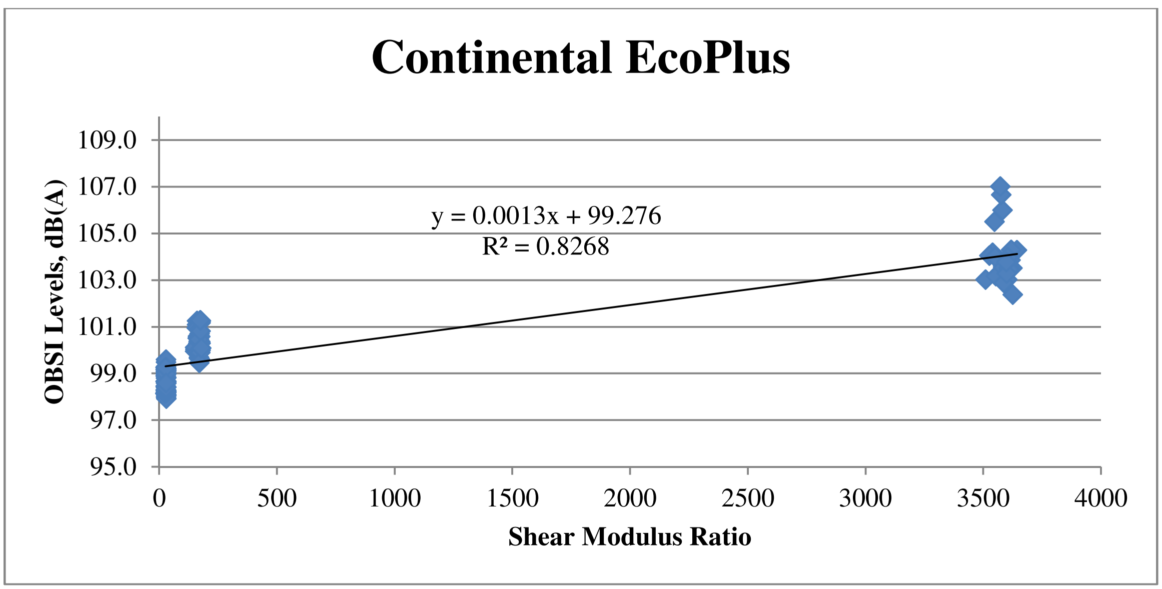

Figure 75 Compilation of Complex Shear Modulus Ratios vs. OBSI Levels for Continental EcoPlus

Each plot above represents all the complex shear moduli and Overall OBSI Level data taken for each tire. It can be clearly seen in each plot that there are three distinct clusters of data points. For each plot the left most cluster of points represents the OGFC tested on I-78, the right most cluster represents the PCC test on I-287 and the middle cluster represents all the measurements taken on the DGA located on I-80.

CONCLUSIONS

Preliminary results from this method appear to be extremely promising. Trend lines added onto Figures 72-75 clearly show a relationship with R^2 values above .8 with the exception of the Firestone. This is understandable due to the aggressive nature of the tread pattern potentially distorting the Overall OBSI Level results with a dominating emphasis in the low frequency range. The other three "typical" tires however conformed much more readily. It should also be noted at this point that when looking at the ratios between the tires and pavements complex shear moduli, the pavement's modulus almost completely dominates due to it being orders of magnitude larger than the tire's. This does not in any way mean that the complex shear modulus of the tire should be disregarded. The tire's complex shear modulus should always continue to be considered in order to maintain a universal comparison. It is important to point out that although each tire has a considerably different tread pattern as shown in Figure 55, they all conformed to the general complex shear modulus ratio and OBSI level trends.

This research also explains prior research initiatives that demonstrate the decrease of OBSI level measurements as temperatures increase. This conforms to the trend found by the authors of this paper because as temperature increases the complex shear modulus of both the tire and pavement decrease which would lead to a lower ratio meaning lower OBSI level measurements as discussed prior.

The author of this paper acknowledge that this was a small preliminary study and much larger sample sizes need to be studied across various temperature ranges throughout the annual seasons before a more definitive conclusion can be reached. Future research is being planned to focus on the topic of this paper which include much larger sample sizes at larger temperature variances. However the early results of this method are proving to be very promising and conform to previous findings made in this respective field of research.

Chapter 7: Final Conclusions

The OBSI method has been recognized as an effective method for quickly and accurately evaluating tire/pavement interface noise generated on in service pavements (9). The method is designed to standardize tire/pavement interface measurements as much as possible. The method, even in its young age, has proven to be quickly implementable on in service pavements for easy noise evaluations on isolated pavement services. It enables discrete comparisons between different wearing courses to determine the noise qualities in a uniform and equal fashion.

Throughout two years of data collection and analysis, patterns began to develop in the on-third octave band spectrum analyses for different pavement types. From a pavement materials perspective, deciphering the patterns that emerged became the first step to understand the acoustical properties of different asphalt mixes. It was found that all the pavements tested conform within the range of 65 dB(A) to 110 dB(A) throughout the frequency spectrum of 400 Hz to 5000 Hz, however within that range different pavements types began to display unique signatures. The OGFC pavements exhibited a curve that is most easily resembled by 2 parabolic curves with a distinctive drop around 1600 Hz. The spectral analysis exhibited by the DGA pavement, could most easily be described as a trapezoid. The DGA curve had two peaks which occurred at the 1000 Hz center frequency and at the 2000 Hz center frequency. These signatures reoccurred when different roadways were evaluated which helped to validate the idea that a standard pavement type designed using mechanistic pavement design should yield a standard tire/pavement noise spectral signature. To confirm that this idea was not regionally based only in NJ, results recorded in MA were compared to the findings in NJ. The pavements from MA readily conformed to the previously discussed trends. This is useful to know because if noise testing is required in a particular area, but the pavement type is not known, it is possible to go out in the field and determine roughly what type of pavement type it is, independent of region, provided a long enough section was measured and an appropriate average was taken. Because the purpose of this particular study was to determine a method of analysis to decipher the difference between an in-service pavement's distinct acoustical properties against another, the analysis provided within identified, defined, and verified distinct patterns.

The main focus of the second study for the All States Massachusetts group was to look at the noise levels that resulted from different materials All States has designed and produced over the last ten years. Initially, the goal was to quantify the noise properties of the pavements in Massachusetts, find the differences in the sound properties due to differences in mix type, mix design, and aging, and make recommendations for future pavement selection based on the overall loudness of each different material. This project encompassed fifteen different materials which were all located throughout eastern Massachusetts.

The materials selected by All States Materials Group provided a wide array of materials that ranged in age from less than one year to eight years old. The overall loudness varied just over 5 dB(A), with the lowest pavement noise recorded at 100.0 dB(A) for a 9.5mm Superpave+2% Latex mixture, and the highest pavement noise recorded was 105.1 dB(A) for a Novachip material. After quantifying the overall levels, spectrum graphs were created for each material, and comparisons were initially drawn between each type of material. The ARGG materials tested had overall levels between 100.5 dB(A) and 101.4

dB(A), the OGFC materials tested had overall levels between 101.2 dB(A) and 102.9 dB(A), the DGA materials tested had overall levels between 100.0 dB(A) and 103.1 dB(A), and the Novachip materials tested had between 104.5 dB(A) and 105.1 dB(A).

The effects of age were not as apparent as expected. Some of the pavements, such as the I-495 OGFC that was placed in 2009 were louder than some of the oldest pavements tested, such as the I-95 OGFC that was paved in 2002. The ARGG pavements tested only varied in age by a maximum of two years and no correlation between on age was determined. The effect of asphalt rubber in the Novachip mix was not found to be beneficial from a noise perspective, since it only reduced the noise level by .5 dB(A).

A statistical analysis was completed comparing each material to each other. The resulting information provided several pavements that could potentially be exchanged during material selection for rehabilitation projects. The comparisons were completed off of the overall levels, so the materials that were determined to be similar would exhibit an equal loudness. In the statistical comparison section, it was discussed that although the statistically similar pavements would exhibit equal loudness the sound generated from each different material would be different. It is advised to be careful when choosing alternative pavements, to consider the noise quality of the different pavements to ensure that the most benefit is received by the producers, users, residents, and the general public.

After the determination that spectral signatures of different pavements existed and that statistics could be readily applied it was pertinent to investigate the influence that vehicle speed contributed to tire/pavement noise generation. The need for a correction factor was evident to the author to enable the comparison of both data collected by the author and also to compare to data collected by other researchers. This is because comparing OBSI results at different speeds, was not possible. To attempt to solve this problem, a research study was conducted to set out to find a correction factor that could be globally applied in a multistep process. The first thing that needed to be verified was that the spectral signature remained constant with an increase in vehicle speed. This was found to be true and at that point the relationship between vehicle speed and tire/pavement noise was investigated. To attempt to find the relationship, all the overall OBSI levels were plotted on an x-y scatter plot and a series of regression was performed determining the best fit was a logarithmic function. Once that relationship was found, the normalization equation was developed making the data collected for this paper ‘reference data’ which then allows the relationship to be properly fitted to any data collected in the field and normalized to any speed desired. Verification was performed, by looking at prior research performed by Donovan and Lodico (11). It should be noted however that even with such strong correlation and verification from previous Federal Highway research efforts more research needs to be conducted.

After investigating the effect that vehicle speed has on OBSI results, it was decided to investigate how different consumer tires effect the generation of tire/pavement noise. In order to achieve this goal, three tires were selected due to their manufacturer’s advertised properties. A purported quiet tire, a “green” low-rolling resistance tire and a “quiet” winter tire were ultimately selected for testing. Three distinctly different pavement types were selected to investigate how the different tires would react on different surfaces to help prevent any bias.

The Continental, although marketed as a low rolling resistance tire (13), was found to be the quietest tire overall. It should be noted however that the Continental did show the greatest tread-wear out of all of the tires, with almost double the amount of wear of the SRTT. The Bridgestone, the purported “quiet” tire (12), was ranked as the second quietest in average overall OBSI level out of the consumer tires tested. The Firestone Winterforce proved to be the loudest tire of the consumer tires tested in this study. This was expected due to the aggressive tread pattern design. When analyzing the data the researchers also noticed a reoccurrence of a large spike in intensity level at the 800 Hz center frequency for the Firestone. This feature maintained similar intensity despite varying pavements, pressures and overall values which led the authors to believe that it is a design property of the tire itself.

Other than the Firestone, the tires all followed the same general trends in generated noise response. The Firestone had higher intensity levels between the 500 Hz center frequency and 1000 Hz center frequency range, which led to its higher measured average overall OBSI levels. It was also shown that regardless of the tire being tested, increased inflation pressure led to increased overall loudness. This can be potentially explained by the Topaq® analysis which showed the increased reaction pressures in Figure 56. In conclusion, the final comparison of the tires tested leaves the Continental as the quietest tested tire overall, the Bridgestone as the second quietest, the SRTT as the third quietest and finally the Firestone being loudest. The last experiment performed after determining the role that tires have on influencing tire/pavement noise generation was to identify the effect temperature has on OBSI measurements.

Preliminary results from this experiment appear to be extremely promising. Regression lines added onto Figures 72-75 clearly demonstrate a strong relationship with R^2 values above .8 with the exception of the Firestone. This is understandable due to the aggressive nature of the tread pattern potentially distorting the Overall OBSI Level results with a dominating emphasis in the low frequency range. The other three "typical" tires however conformed much more readily. It is important to also point out that although each tire has a considerably different tread pattern as shown in Figure 55, they all conformed to the general complex shear modulus ratio and OBSI level trends.

This research also conformed to prior research initiatives that demonstrated the decrease of OBSI level measurements as temperatures increased. This coincides with the conclusions of the author of this paper because as temperature increases the complex shear modulus of both the tire and pavement would decrease which would lead to a lower ratio meaning lower OBSI level measurements.

The author of this paper acknowledges that this was a small preliminary study and much larger sample sizes need to be studied across various temperature ranges throughout the annual seasons before a more definitive conclusion can be reached. Future research is being planned to focus on the topic of this paper which include much larger sample sizes at larger temperature variances. However the early results of this method are proving to be very promising and conform to previous findings made in this respective field of research.

In conclusions it has been determined that each different pavement type generates a unique spectral signature. The OBSI method can be easily deployed to evaluate in service pavements and later generate statistical comparisons between pavements to help inform DOTs nationally with pavement selections in regard to acoustical contributions in the surrounding locale. Not only can mix type selection help alleviate noise emissions from the source but also choosing an appropriate speed limit that can satisfy both safety and noise generation goals also can be utilized. Tire selection also showed to influence the amount of noise being generated at the tire/pavement interface with clearly louder and quieter tires. Finally the most promising advancement for the field which still requires significant research is the effect temperature has on tire pavement noise. The current ideal of using ambient air temperature may help further this research but it is the opinion of the author that utilizing the materials properties is the proper procedure to follow.

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