Eight Year Evaluation of the Noise Performance of the Caltrans Asphalt Research Pavements on LA 138

Prepared for

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CHAPTER 1

INTRODUCTION

In 2001, Caltrans began designing and planning for the construction of five asphalt concrete (AC) pavements along State Route 138 in Los Angeles County (LA 138). The purpose of these sections was to provide acoustic performance data on several quieter pavement constructions. Three of the selected pavements were of an open graded design, two thicknesses of AC and one of rubberized AC. The performance of these quieter pavements was to be compared to a single section of new dense graded AC. A section of bonded wearing course was also constructed as the fifth section. The intention was to evaluate these pavements over a period of five or more years to assess their initial acoustic performance and their acoustic longevity. The initial test plan called for repeated statistical passby (SPB) measurements[1,2] over this time period. This particular two-lane section of LA 138 was well suited to this type of measurement due to the relative flatness of the terrain and its low traffic volumes.

At the time of the construction of the LA 138 test sections, Caltrans was in the process of implementing a new approach for measuring the acoustic performance of the pavements. This technique was based on the on-board measurement of tire/pavement sound intensity that has been previously used in the automobile industry in test track applications[3,4]. Early in 2002, Caltrans supported the adaptation of this methodology to the measurement of the noise performance of in-service highways[5]. One of the first applications of the On-Board Sound Intensity (OBSI) methodology was the LA 138 sections. Measurements were conducted on the five AC research test sections of LA 138, between October 2002 and October 2008 in an effort to document the tire/pavement noise levels of these pavements as they age. Measurements were made primarily during the fall (October) and spring (March to May) time frames, although some summer (June and July) and winter (January) measurements were also made. Tested pavements included a Dense Grade Asphalt Concrete (DGAC), two overlay sections of Open Graded Asphalt Concrete (OGAC) (75-mm in thickness and 30-mm in thickness), a Rubberized Asphalt Concrete (RAC) open graded (Type (O) pavement), and a Bonded Wearing Course (BWC). The pre-overlay pavement, which was a DGAC leveling course, was measured in March 2002.

In addition to the measurement and documentation of the pavement sections over time, these test sites were also used for the further development of the OBSI procedure. This included parameter testing, comparison of test tires, comparison of equipment configurations, and comparison of test vehicles, as well as other novel methods of characterizing AC pavement performance. This report summarizes the acoustical performance of the five LA 138 pavement sections, utilizing on-board tire/pavement noise source measurements over a six-year period and discusses the results of the testing conducted in conjunction with this study. Appendices also provide information on tests and evaluations that were completed in conjunction with this research including sound propagation measurement for ground level sources (Appendix A), tests results for multiple tire designs (Appendix B), evaluations of the ASTM Standard Reference Test Tire (Appendix C), and a comparison of close proximity sound pressure level measurements to other test methods used in this research (Appendix D).

CHAPTER 2

TEST PAVEMENTS AND MEASUREMENT SITES

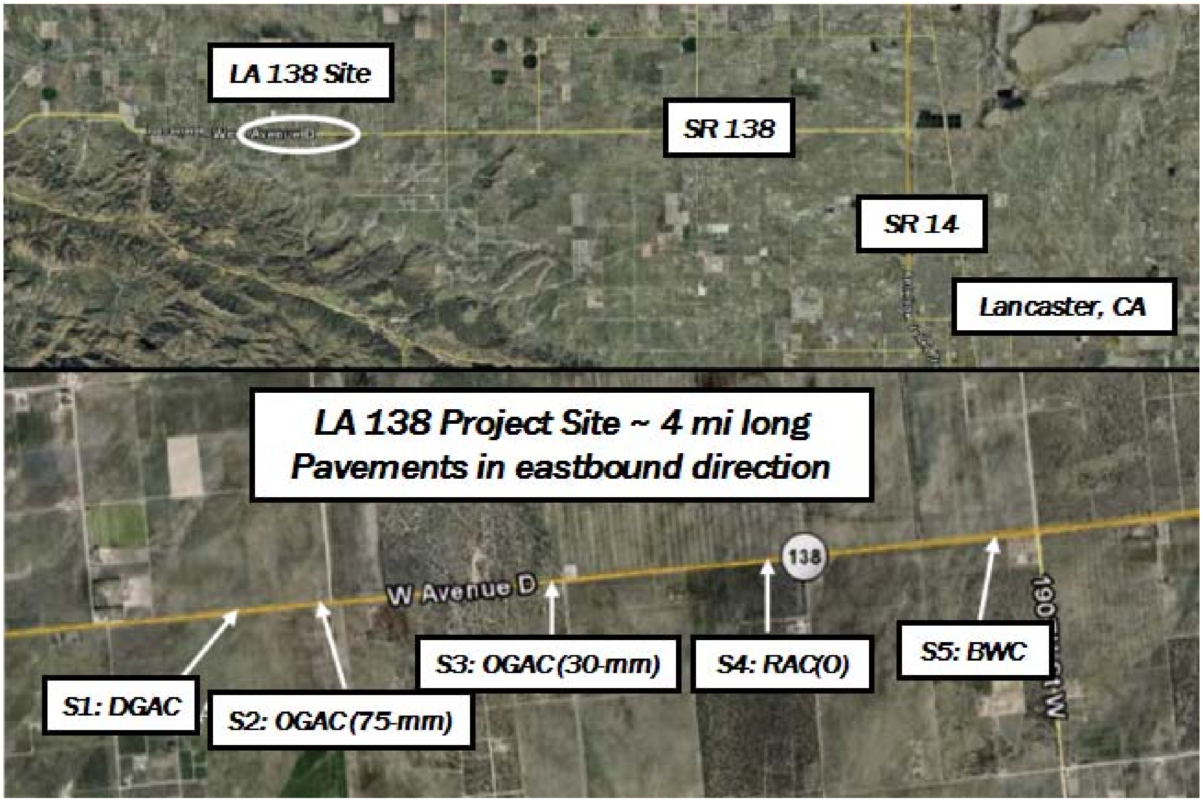
Five Test Sections along LA 138

Noise measurements, durability, permeability, and friction performance were evaluated by Caltrans in partnership with the University of California Pavement Research Center at UC Davis and Berkeley between September 2005 and January 2006[6]. In this study, the aggregate gradations of the test sections were measured and compared to the operating ranges of the standard specifications. Eastbound and westbound directions were measured for the OGAC (75-mm), OGAC (30-mm), RAC(O), and BWC sections; only the westbound direction was measured for the DGAC test pavement. According to their findings, all segments indicated gradations finer than the standard specifications. The nominal maximum aggregate size (NMAS) for all measurements was 12.5-mm, with the exception of OGAC (75-mm) measuring 9.5-mm[6].

The UC Pavement Research Center also examined air-void content, as well as other surface condition measurements between September 2005 and January 2006[6]. According to their study, the air-void content (CoreLok method) of the open-graded surfaces were between 9% and 13%. In general, UCPRC found air-void content ranging from 10% to 18% for open-graded mixtures around the state highlighting the variability in the OGAC pavement surfaces. In contrast, their study found the dense-graded surfaces to have air-void content ranging from about 4% to 7%. Along the LA 138 sections that were tested, they found the westbound direction had a lower air-void content, as well as lower permeability compared to the eastbound. They attributed the lower sound intensity levels measured in the open-graded mixtures to the higher air-void content.

LA 138 Test Measurement Site

The test sections were constructed over a four-mile section of LA 138 near the community of Neenach (shown in Figure 2.1a). Traveling from west to east, the sections were numbered sequentially as indicated in Figure 2.1a, which also shows the overall landscape surrounding the test pavements. The photograph in Figure 2.1b illustrates the terrain and shoulder configuration at the beginning of Section #2; the terrain for each section is similar to that shown for Section #2. Prior to initial measurements of the overlays in October 2002, the OBSI levels of a new DGAC leveling course were measured at each passby test site in March 2002. The test sites, corresponding to each of the five research pavements, are defined by pre-determined passby measurement microphone "lines" perpendicular to the roadway. The OBSI measurements were made at distances beginning at +220 feet through –220 feet relative to these microphone lines. Photographs of the five test pavements and the initial DGAC leveling course, as tested in 2002 are shown in Figure 2.2.



(a) Project Site and Measurement Locations

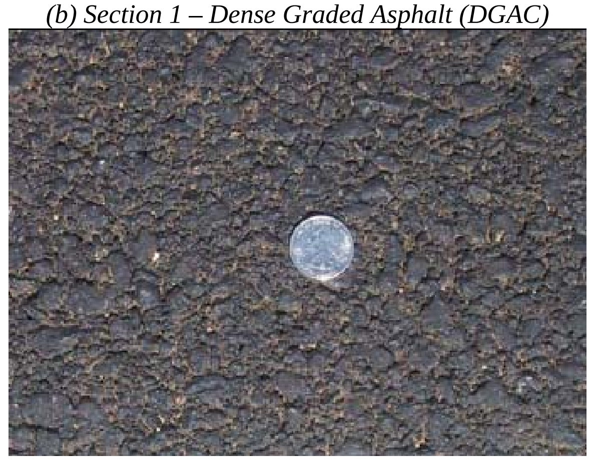
(b) Terrain & Shoulder Configuration at the Beginning of Section #2

Figure 2.1. Testing Sites along LA 138

(a) Pre-Overlay – Dense Graded Asphalt (DGA)

(b) Section 1 – Dense Graded Asphalt (DGAC)

(c) Section 2 – Open Graded Asphalt Concrete (OGAC-1), 75-mm Thick Overlay



(d) Section 3 – Open Graded Asphalt Concrete (OGAC-2), 30-mm Thick Overlay

(e) Section 4 – Rubberized Asphalt Concrete (RAC(O))

(f) Section 5 – Bonded Wearing Course (BWC)

Figure 2.2. Photographs of Pavement Surfaces

CHAPTER 3

TIRE/PAVEMENT NOISE MEASUREMENTS

OBSI Test Procedure

Under the CA-OBSI procedure, the sound intensity fixture and associated microphones are attached to and supported by the test vehicle in unenclosed space as indicated in Figure 3.1, to allow for measurement positions that are very close to the leading or trailing edge of the tire contact patch. Use of the dual-probe sound intensity fixture beginning in May 2007[7], following comparison testing between the configurations in April and October 2006, allowed the leading and trailing edge positions to be measured simultaneously.

(a) Single Probe Configuration (leading edge) *(b) Dual Probe Configuration*

Figure 3.1. OBSI Equipment Installed on the Test Vehicle

Each probe consisted of two ½" G.R.A.S. phase-matched condenser microphones, installed on ½" G.R.A.S. 26AK microphone preamplifiers, attached to a plastic probe holder at a spacing of 0.63-inches (16-mm) in a side-by-side configuration and fitted with a spherical windscreen. The probe was positioned 3-inches (75-mm) from the pavement surface and 4-inches (100-mm) from the face of the tire, at locations opposite the leading and trailing contact patch of the tire, and oriented so that the sensitive axis was toward the tire. For the single probe configuration, data from the leading and trailing edge positions are acquired separately for the same section of pavement and then averaged together during post-analysis to determine the intensity of the sound propagating away from the tire/pavement interface toward the "wayside" or community. For the dual probe configuration, the leading and trailing edge data taken simultaneously was summed on an energy basis to form a tire average for each pass. Three or more passes were made for each test section, which were averaged together during post-analysis. Five pavement sections were measured for the eastbound direction of travel along LA 138. During some of the measurement periods, westbound sections were also measured.

Testing was conducted at a test speed of 60 mph (97 km/h) with a "cold" tire inflation pressure of 30 psi. For the single probe measurement procedure, the microphone signals were input to a Larson Davis 2900 dual channel real-time analyzer and analyzed into one-third octave band levels in real time using a 5-second averaging time corresponding to 440 ft of vehicle travel. The signals were also recorded on a Sony DAT recorder for later analysis. For the dual probe, the microphone signals were acquired with the Brüel & Kjaer PULSE System in real-time third octave band levels and in narrow band fast Fourier Transforms (FFT) using a 5-second averaging time. Under both procedures, the microphones were calibrated using a Larson Davis Model CAL200 acoustic calibrator set for 94 dB at the beginning and end of each measurement period. The actual time signals of the four microphones were viewed during data acquisition and, for the single probe, the signals were also monitored audibly. OBSI quality metrics of coherence between the two microphones comprising each probed and the difference between sound pressure and sound intensity level were monitored during data acquisition for the dual probe method and viewed during post-processing under the single probe procedure.

The sound intensity measurements were conducted on a Subaru Outback test vehicle with the single probe fixture from March 2002 through October 2006 and on a Chevrolet Malibu with the dual probe fixture beginning in May 2007 and thereafter. Comparison testing between the two configurations and equipment components was conducted in April and October 2006 and is discussed later in this report. Testing throughout this study was conducted using a Goodyear Aquatred 3 (Aquatred) P205/50R15 test tire with a load consisting of two people and the CA-OBSI instrumentation. Additional tires were tested during some of the measurement periods for comparison purposes (see Table 3.1). Through 2006, a secondary tire test was the Uniroyal Tiger Paw AWP, which is also a P205/50R15 tire. This tire has also been tested in Europe as part of the "NITE" study[8] and typically produces levels about 2 dB lower than the Aquatred. In 2005, the Aquatred was no longer commercially available. In an effort to transition to a more available tire, testing with the ATSM P225/60R16 Standard Reference Test Tire (SRTT)[9] began in 2006. This tire is similar in appearance to the AWP and is labeled as a Uniroyal Tiger Paw tire. Photographs of the Aquatred, the Tiger Paw AWP, and the SRTT are shown in Figure 3.2.

(a) Aquatred 3 *(b) Uniroyal Tiger Paw AWP* *(c) SRTT*

Figure 3.2. Photograph of Each Test Tire

Field Parameters

OBSI measurements were conducted over 16 measurement periods between March 2002 and October 2008. The test matrix is shown in Table 3.1. As part of the continuing development and

Table 3.1. Test Matrix for OBSI Measurements Conducted on LA 138

Testing Period	Measurement Configuration	Tires	Parameters	Additional Testing
March 2002	Subaru, Single Probe	Aquatred	Testing of pre-overlay pavement	Interior, Passby
October 2002	Subaru, Single Probe	Aquatred, Tiger Paw, Firestone, Glacier Grip, RainForce	Testing of new pavement sections, comparison of tires	Interior, Passby, CPX
March 2003	Subaru, Single Probe	Aquatred, Tiger Paw	Pavement aging, comparison of tires	Interior, Propagation, Dynamic Stiffness
July 2003	Subaru, Single Probe	Aquatred	Pavement aging	Interior
October 2003	Subaru, Single Probe	Aquatred	Pavement aging	Passby, Propagation
April 2004	Subaru, Single Probe	Aquatred, Tiger Paw	Pavement aging, comparison of tires	
January 2005	Subaru, Single Probe	Aquatred	Pavement aging	
April 2005	Subaru, Single Probe	Aquatred	Pavement aging, temperature effects	
June 2005	Subaru, Single Probe	Aquatred	Pavement aging	
October 2005	Subaru, Single Probe	Aquatred	Pavement aging	
April 2006	Subaru, Single/Dual Probe	Aquatred, Tiger Paw, SRTT	Pavement aging, single vs. dual probe, comparison of tires	
October 2006	Subaru/Malibu, Single/Dual Probe	Aquatred, 2 SRTT	Pavement aging, single vs. dual probe, comparison of test cars, comparison of tires	Passby
May 2007	Subaru/Malibu, Dual Probe	Aquatred, 6 SRTT, Blank, Ribbed	Pavement aging, comparison of test cars, comparison of tires, effect of tire wear	Passby
October 2007	Malibu, Dual Probe	Aquatred, SRTT	Pavement aging, comparison of tires	
April 2008	Malibu, Dual Probe	Aquatred, SRTT	Pavement aging, comparison of tires	
October 2008	Subaru/Malibu, Dual Probe	Aquatred, 3 SRTT, Blank, Ribbed	Pavement aging, comparison of test cars, comparison of tires	

demonstration of the sound intensity technique, Controlled Passby (Passby) tests were also conducted periodically for the duration of the testing cycle. Additionally, Close Proximity (CPX), Vehicle Interior Noise (Interior), Sound Propagation (Propagation), and Dynamic Stiffness testing were also conducted in conjunction with OBSI testing. Table 3.1 illustrates the testing parameters for each of the 16 periods.

CHAPTER 4

INITIAL MEASUREMENTS AND RESULTS

Tire/pavement noise measurements were taken along LA 138 at each of the five sections in the eastbound and westbound directions. The noise levels are used to compare different pavement compounds under varying environmental conditions and to study the effects of aging. The primary technique used to quantify noise generated on the test pavements was sound intensity, as described above.

Leveling Course, March 2002

Sound intensity measurements were taken in March 2002 for the initial DGAC Leveling Course prior to the overlay application. The Subaru test vehicle with a Goodyear Aquatred 3 tire was used for the March 2002 testing. Data was collected in the eastbound and westbound directions, but the results shown in this report represent the eastbound direction only. Figure 4.1 illustrates the overall A-weighted OBSI levels measured at each of the five test sites in the eastbound direction. The average of overall levels for all test sections was 99.2 dB(A) with a standard deviation of 0.3 dB .

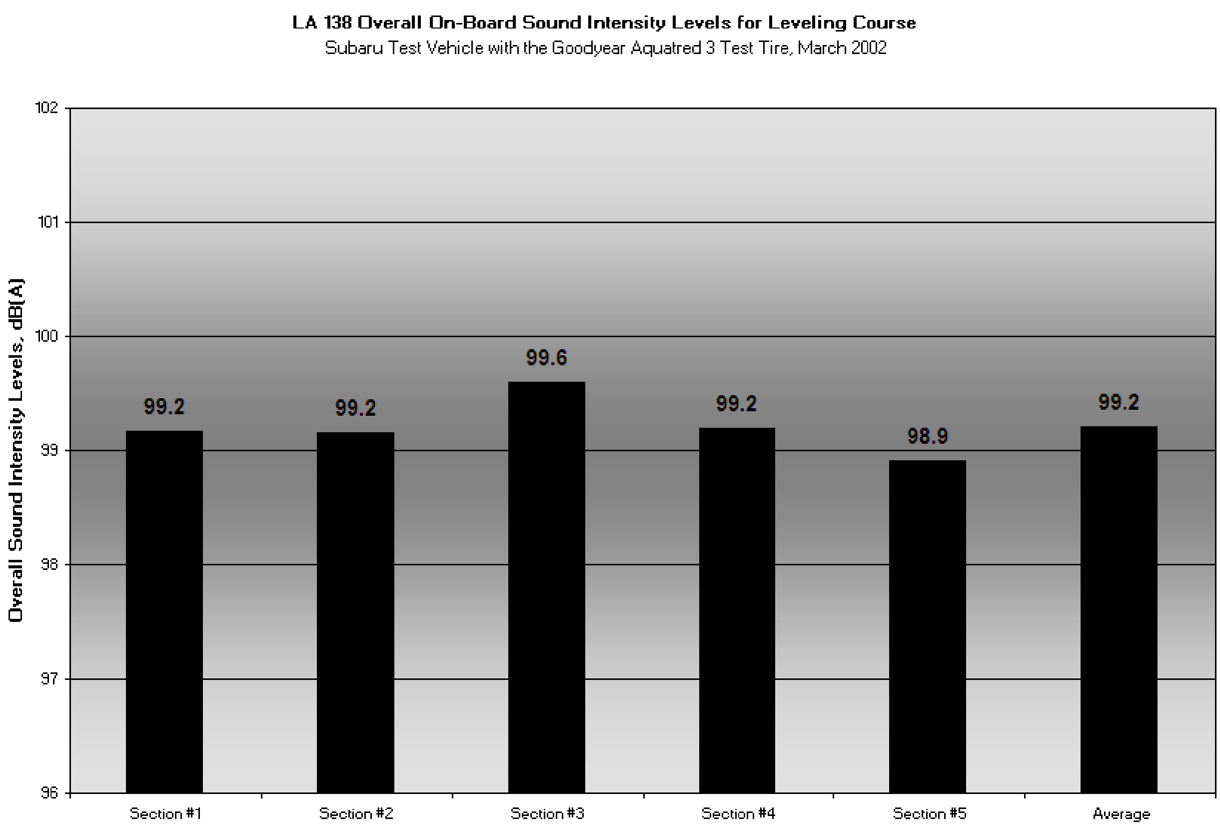


Figure 4.1. Overall A-Weighted OBSI Levels for the DGAC Leveling Course (Pre-Overlay), March 2002

Overlays, October 2002

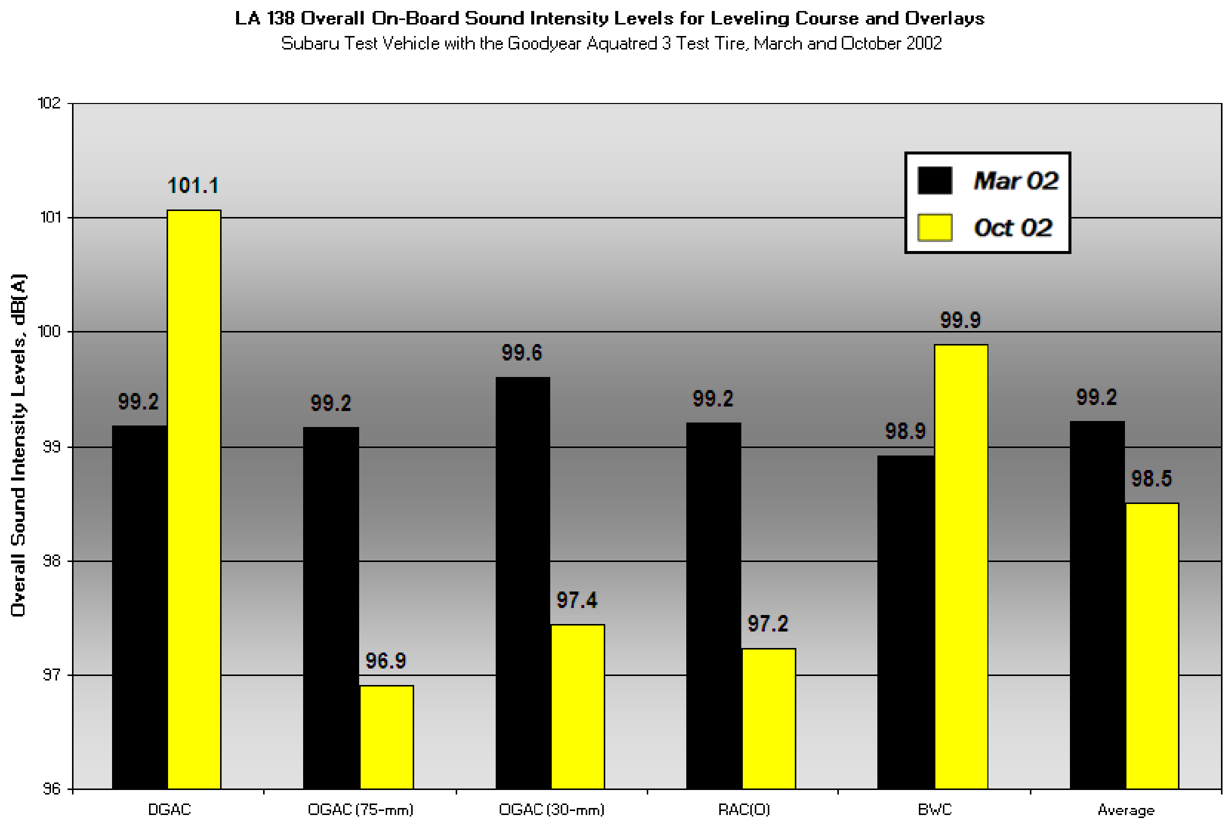
Two months following the overlay application in October 2002, multiple testing methods were used to characterize the sound abatement achieved by each overlay: 1) on-board sound intensity (OBSI) described previously; 2) controlled passby (passby) at distances of 25-ft and 50-ft from the roadway; and 3) interior sound (interior) measured in the passenger cab of the vehicle. Other testing, such as sound propagation, was also considered for the LA 138 test pavements; the results for which are discussed in Appendix A of this report. For all measurements taken in October 2002, the Subaru test vehicle was used. For comparison of the pavement overlays and testing methods, the results in the following sections are limited to data collected with the Goodyear Aquatred 3 test tire; however, other tires were used in October 2002, and the results can be found in Appendix B of this report.

On-Board Sound Intensity Testing

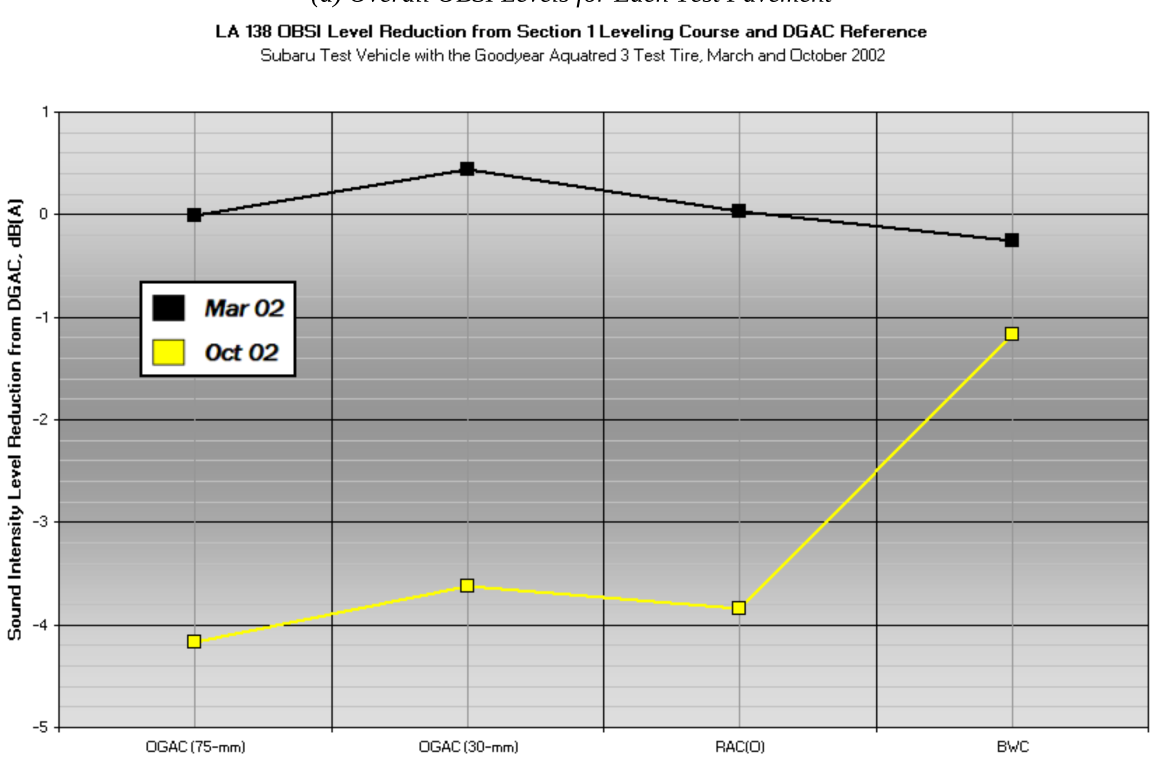
Figure 4.2 shows the overall A-weighted OBSI levels measured for each test pavement in October 2002 compared to the overall levels for the leveling course in March 2002. The overall decibel level reduction from the reference DGAC pavement in Section #1 for the other test sections is also shown in Figure 4.2. The reference DGAC test pavement in Section #1 and the BWC pavement in Section #5 resulted in overall levels that were higher than the leveling course by 1 dB to 2 dB, while both OGAC and RAC(O) pavements measured an average of 2.1 dB lower than the leveling course.

From the overall OBSI levels measured in October 2002, the test pavements were rank ordered with the DGAC reference pavement yielding the loudest levels, and OGAC (75-mm) having the lowest levels. The RAC(O) and OGAC (30-mm) showed similar sound abatement levels as the OGAC (75-mm) test pavement with differences of 0.3 dB and 0.5 dB, respectively. Each of these overlays achieved reductions from the DGAC reference pavement of approximately 4 dB, while the level reduction for the BWC test pavement from DGAC was about 1 dB.

The one-third octave band spectrum for each test pavement in October 2002 is shown in Figure 4.3. For the frequency bands less than 800 Hz, the OGAC (30-mm) and RAC(O) test pavements resulted in the lowest sound intensity amplitudes with the OGAC (75-mm) having levels less than 2 dB higher. BWC measured the highest sound intensity amplitudes at the lower frequency bands, being approximately 1.6 dB higher than the reference DGAC pavement. The peak sound intensity amplitude for each test pavement occurred at the 800 Hz frequency band. Here, the reference DGAC test pavement measured approximately 96.2 dB(A) with slightly over a 1 dB difference with the BWC pavement. The OGAC and RAC(O) pavements were an average of 4.3 dB lower than the DGAC pavement at 800 Hz, which was a significant reduction. For frequency bands above 800 Hz, the rank order indicated by the spectra in Figure 4.3 was consistent with the rank order found with the overall A-weighted levels in Figure 4.2. At the higher frequency bands, the reference DGAC pavement, which resulted in the highest levels, measured an average of 4.5 ± 0.7 dB higher than the OGAC (75-mm) test pavement, which resulted in the lowest sound intensity levels.



(a) Overall OBSI Levels for Each Test Pavement



(b) Reduction of OBSI Levels for Each Test Pavement from DGAC Test Pavement

Figure 4.2. Overall A-Weighted OBSI Levels for Each Test Pavement, March and October 2002

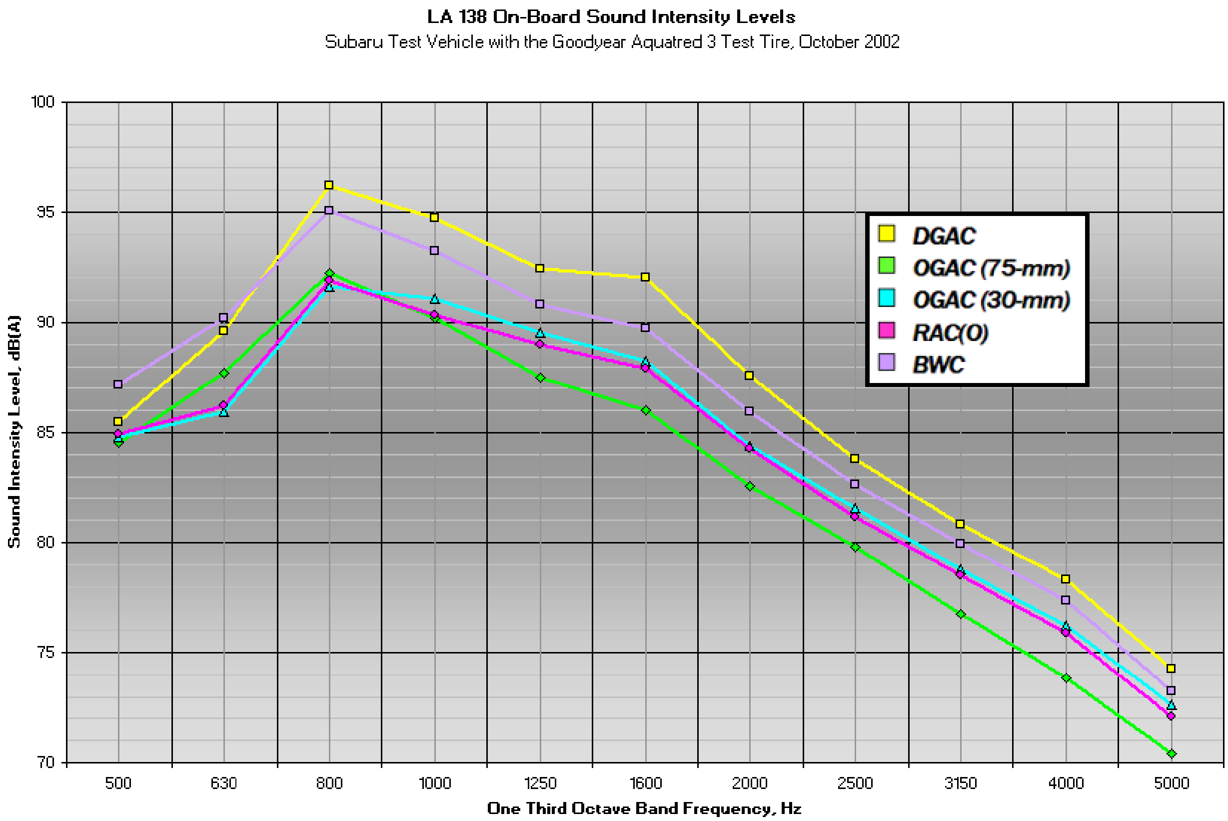


Figure 4.3. One-Third Octave Band Levels for Each Test Pavement, October 2002

In addition to the tire/pavement study for California SR 138, OBSI data for pavements of varying age on other roadways in California (I-280, I-5, I-40, 58 Bypass, I-70, I-80, SR 85, and SR 14) and Arizona (I-10 and SR 202) were also available for comparison. For all OBSI testing, the Goodyear Aquatred 3 test tire was used, and a constant driving speed of 60 mph was maintained. The overall A-weighted OBSI level comparison between the SR 138 test pavements and these other test sections is shown in Figure 4.4. The results shown in the figure were collected during spring, summer, and fall months.

In Figure 4.4, the SR 138 test pavements are identified by the associated colors defined in the October 2002 OBSI spectra results above. For all other roadways, the OGAC and RAC test pavements are shown as a collective group in Figure 4.4 indicated by blue bars. Likewise, the DGAC and PCC pavement types are indicated by green and black, respectively. The average OBSI level for the OGAC/RAC pavement types, not including the SR 138 data, was approximately 99.2 dB(A) with a standard deviation of 1.8 dB, while the average of both of the new OGAC and RAC(O) pavements along SR 138 was 97.2 dB(A) ± 0.3 dB. The average level difference between the SR 138 data and the other similar pavements could be due to factors such as weather conditions and/or possible aging effects, both of which are discussed in Chapter 5 of this report. As shown in Figure 4.4, the average levels for the OGAC/RAC pavements were lower than the average for the DGAC and PCC groups. The group of DGAC pavement types, not including the SR 138 results, measured an average 99.8 dB(A) with a standard deviation of 0.8 dB. In this case, the average for the DGAC reference and BWC pavements along SR 138 was slightly higher, measuring 100.5 dB(A) ± 1.5 dB. However, the difference between the

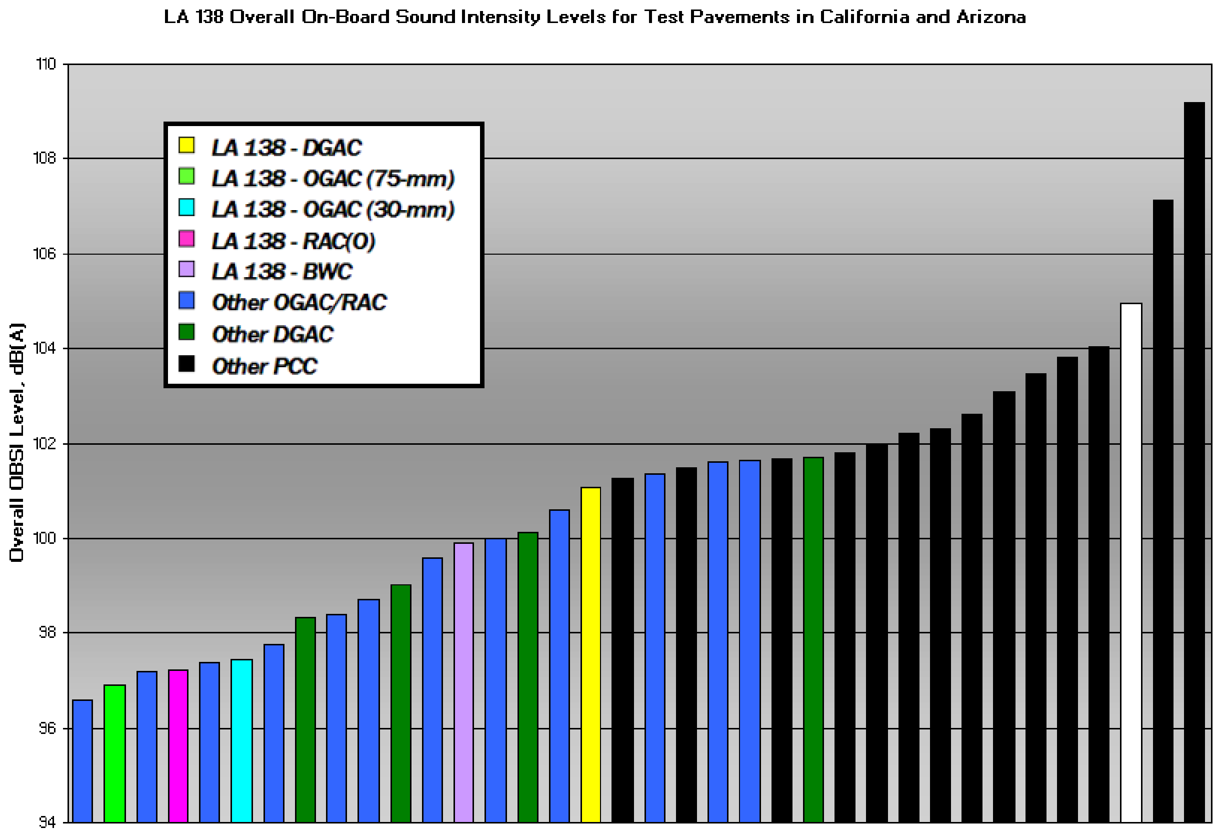


Figure 4.4. Overall A-Weighted OBSI Levels for Each Test Pavement on SR 138 and Other Roadway Test Sections in California and Arizona

DGAC pavement types along SR 138 and the other testing sites was less than 1 dB. The PCC pavement types measured an average overall OBSI of 103.3 dB(A) ± 2.3 dB, which was approximately 3 dB higher than the DGAC pavement types and 4 dB to 6 dB higher than the OGAC/RAC pavement types.

Controlled Passby Testing

In addition to OBSI testing, controlled vehicle passby tests were performed in October 2002 as well. The Subaru test vehicle used for the OBSI testing was also used for the passby testing, and the vehicle speed was also consistent at 60 mph. Two sets of four test tires were used: the Goodyear Aquatred 3 test tire and the Michelin RainForce. This section is limited to the results measured with the Aquatred test tire. The results for the RainForce test tire shown in Appendix B of this report. The passby data was acquired at microphone distances of 25-ft and 50-feet from the centerline of the vehicle path. The 25-ft distance has traditionally been used in Europe, per ISO standards[1]; the 50-ft distance has typically been used in the US. The microphone height was positioned 5-ft above the ground, and testing conditions included a steady cruise mode for all five sections and a coast mode for the DGAC reference only. Previous controlled passby noise testing has shown the cruise condition to be approximately 0.5 dB louder than the coast condition. For the purpose of comparing the passby results to OBSI levels, the discussion in this report is limited to the cruise condition. Figure 4.5 shows the overall A-weighted sound pressure levels (SPL) measured during the controlled passby tests at distances of 25-ft and 50-ft.

The test pavement ranking order indicated in Figure 4.5 by the overall A-weighted passby SPLs show the DGAC and BWC pavements to have the highest levels, while both OGAC pavements and the RAC(O) pavement resulted in the lowest levels. At both microphone distances, the reference DGAC pavement was slightly higher than the BWC pavement by less than 1 dB. The OGAC and RAC(O) pavements had levels within 2 dB of each other at both 25-ft and 50-ft. For all test pavements, the level offset between the passby data at both microphone distances was an average 7.3 dB with a standard deviation of 0.5 dB.

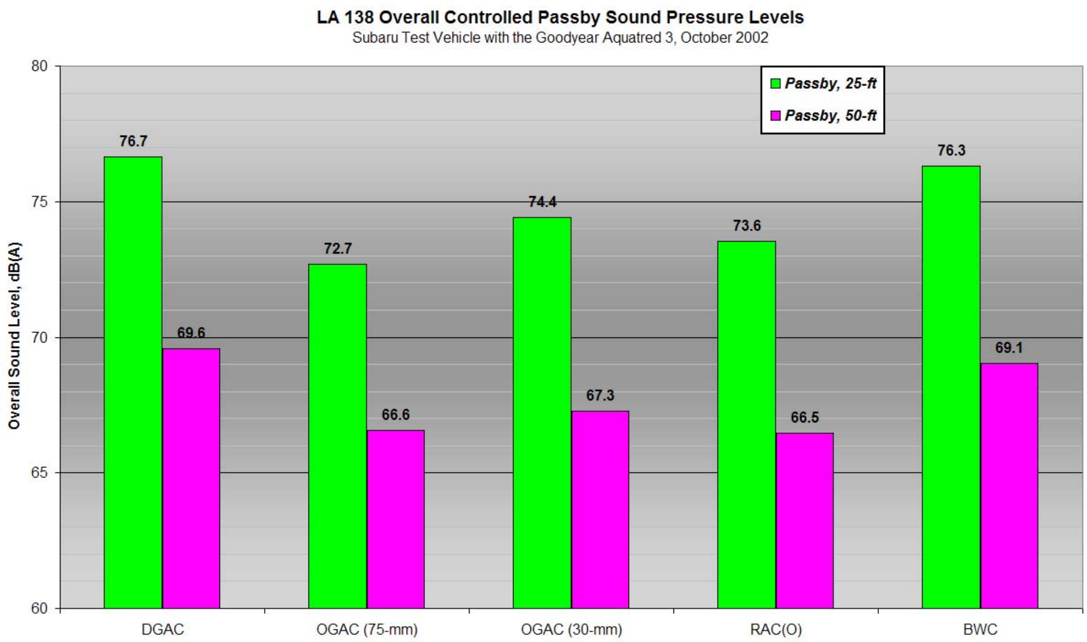
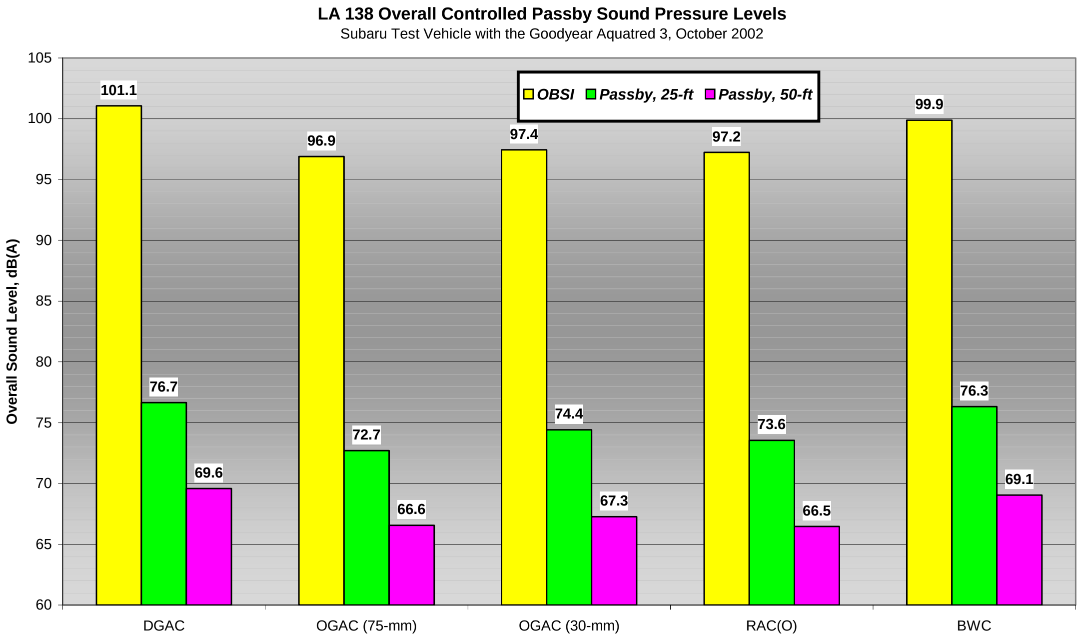


Figure 4.5. Overall A-Weighted Controlled Passby SPLs for Each Test Pavement, October 2002

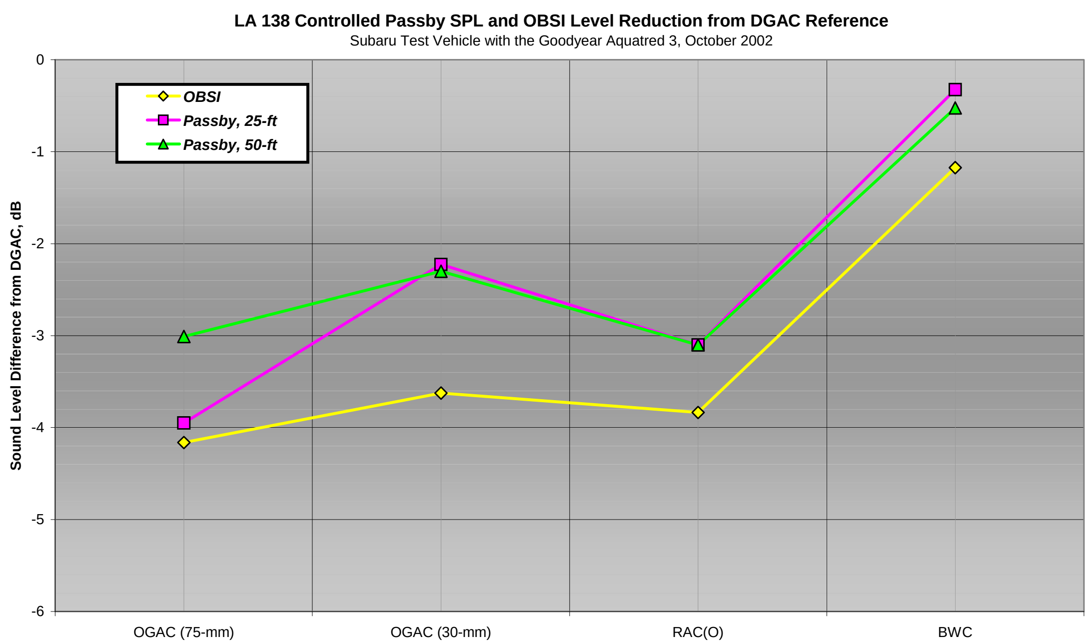
Comparison of Controlled Passby and OBSI Results

The main purpose of the passby tests was correlation to the sound intensity levels, and as such, the overall levels discussed above for both microphone distances are compared in Figure 4.6 to the OBSI data measured in October 2002. Visual inspection of the data of Figure 4.6a indicates that the rank of pavements is similar regardless of the type of test used. In all cases the open graded pavements were lower than the DGAC and BWC by at least 2 dB. In Figure 4.6b, the overall level comparison for each test pavement relative to the reference DGAC is shown. In general, the differences for the passby data are less than that measured with OBSI relative to the DGAC. With the exception of the 25-ft passby level measured on the 75-mm OGAC, the rank ordering of the pavements is retained with all three measurements.

The cross plots in Figure 4.7 compare the overall A-weighted passby levels with the overall A-weighted OBSI levels, showing the best one-to-one linear fit for each data set. The offsets measured between the overall OBSI levels and the passby levels was approximately 23.8 dB with a standard deviation (σ =) of 0.6 at the 25-ft distance and 30.7 (σ = 0.5) at 50-ft.



(a) Overall Controlled Passby SPLs and OBSI Levels for Each Pavement



(b) Reduction of SPLs and OBSI Levels from DGAC Reference for Each Test Pavement

Figure 4.6. Comparison of Overall A-Weighted Controlled Passby SPLs and OBSI Levels for Each Test Pavement, October 2002

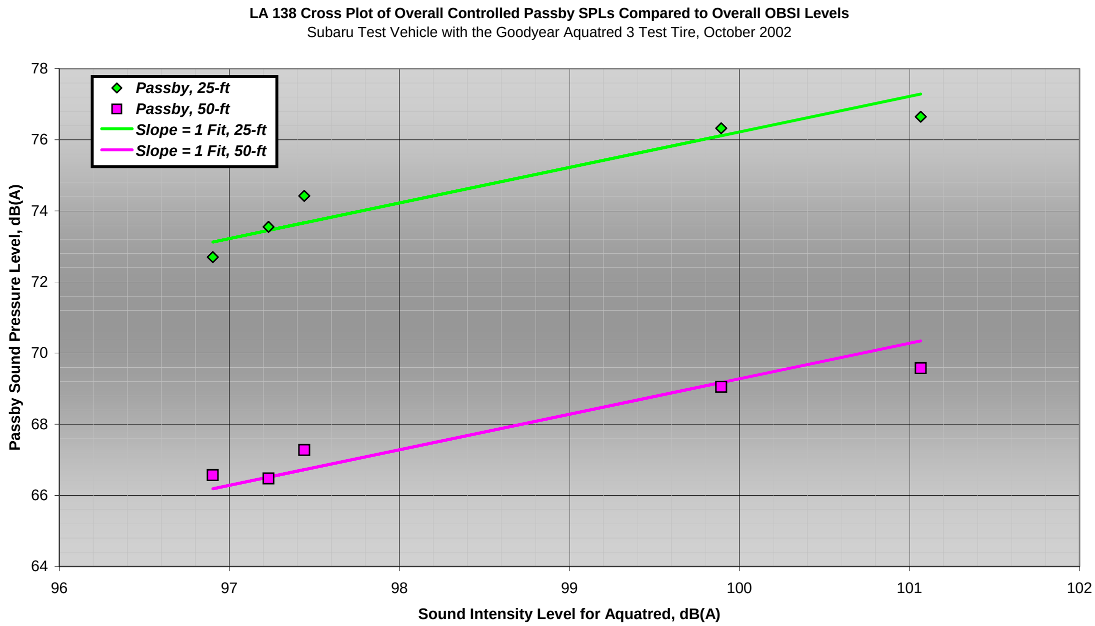
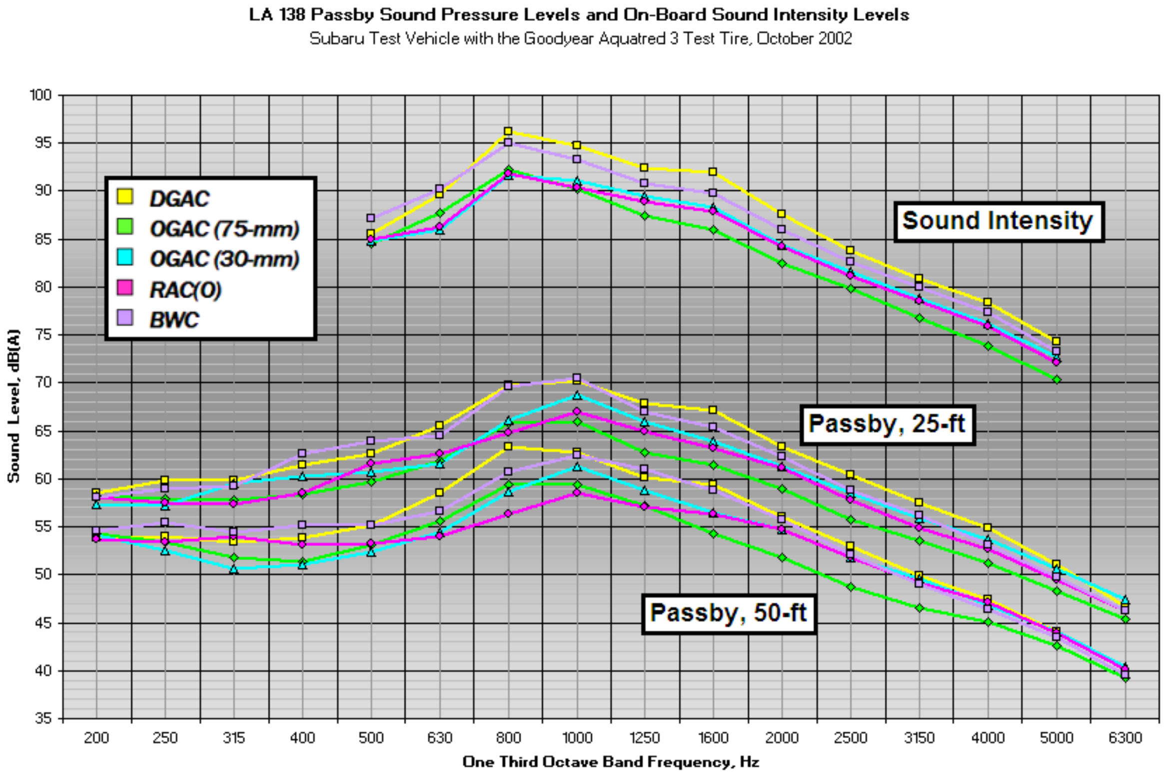


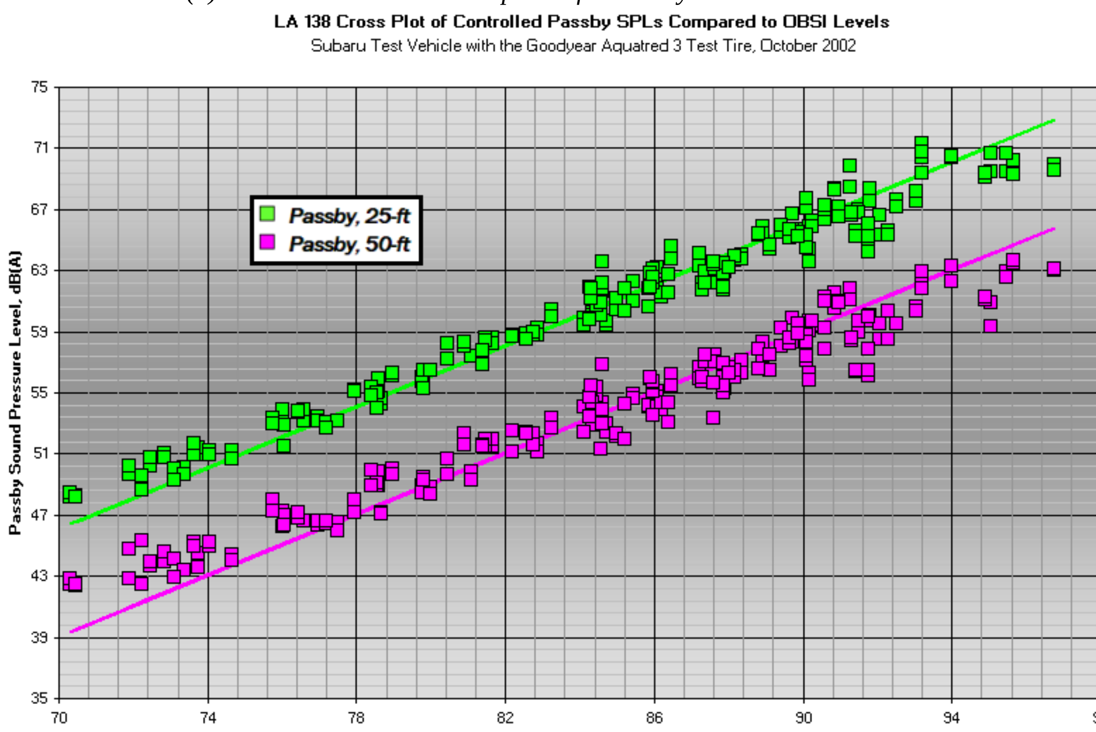
Figure 4.7. Cross Plot of Overall A-Weighted Controlled Passby SPLs Compared to OBSI Levels, October 2002

The one-third octave band spectra for the two passby microphone distances are compared to the OBSI spectra in Figure 4.8a. Careful examination of these data indicated spectral differences were similar for all three data sets. Some subtle differences, however, did exist. While the peak level amplitude observed for the OBSI spectra occurred at 800 Hz, the peak amplitude for both passby data sets occurred in the frequency band range from 800 Hz to 1000 Hz. The differences between the 25-ft and 50-ft passby data sets were as significant as the differences occurring between the OBSI data and the passby data.

In Figure 4.8b, the data sets for the one-third octave band spectra in Figure 4.8a are shown in a cross plot compared with the one-third octave band data for OBSI. This provides a more quantitative evaluation of the difference between the OBSI and passby data on a frequency-by-frequency basis. Using the best one-to-one linear fit for each data set, the offsets between OBSI and the passby levels were determined for the one-third octave band spectra, which is similar to the calculations made above for the overall levels. The 25-ft offset for the spectra cross plot was approximately 23.9 dB (σ = 1.2). Consistent with the literature[3,4,5], the average overall offset was found to be 23.8 dB (σ = 0.6), which is essentially identical to the one-third octave band offset. While the overall offset measured above for the 50-ft microphone distance was 30.7 dB (σ = 0.6), the one-third octave band spectra offset shown in Figure 4.8b was calculated to be 30.9 dB (σ = 1.6). The cross plot for the one-third octave band spectra indicated a large concentration of data points from the OBSI levels of 84 dB(A) to 92 dB(A), which corresponds to the SPL range from 59 dB(A) to 69 dB(A) for the 25-ft distance and 53 dB(A) to 61 dB(A) for the 50-ft distance. This behavior correlates to the one-third octave band frequency range from 500 Hz to 1600 Hz where higher sound level amplitudes were observed.



(a) One-Third Octave Band Spectra for Passby SPLs and OBSI Levels



(b) Cross Plot of One-Third Octave Band Spectra for Passby SPLs Compared to OBSI Levels

Figure 4.8. One-Third Octave Band Spectra for Controlled Passby SPLs and OBSI Levels and the Associated Cross Plot, October 2002

Recall in a previous section of this report, the overall OBSI levels calculated in October 2002 were compared to the overall OBSI levels calculated for multiple roadways containing similar test pavements. Controlled passby and OBSI testing was also conducted on other pavements including the California State Route 58 Bypass around Mojave, Arizona SR 202 in Mesa, and the Caltrans test track in Sacramento. These included in the both the Aquatred and Michelin tires as well as a set of American Silver Premium Edition P205/70R15 tires. Test speeds ranged from 45 to 60 mph. The cross plot in Figure 4.9 shows the passby SPLs for these additional pavements and those from LA 138 compared to the OBSI levels. The offsets measured from the cross plots were approximately 23.6 dB, $\sigma = 0.8$ dB for the levels at 25-ft and 30.4 dB, $\sigma = 0.8$ dB at 50-ft. These offsets are slightly lower than those of LA 138 alone, which may be due to sites differences as some of these had propagation to the microphone positions exclusively over pavement unlike the LA 138 sites.

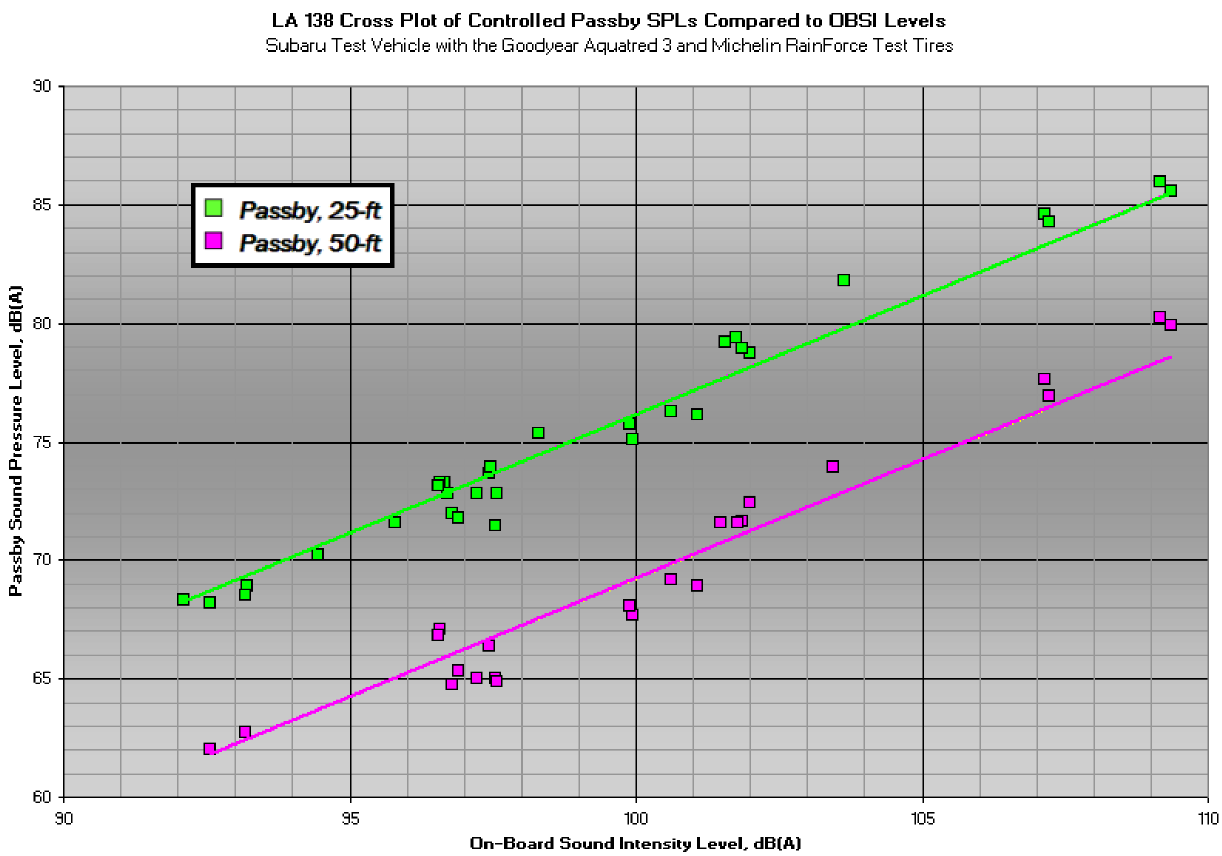


Figure 4.9. Cross Plot of Controlled Passby SPLs Compared to OBSI Levels for Each Test Pavement on SR 138 and Other Roadway Test Sections in California and Arizona

Interior Sound Testing

Interior noise levels were measured at the right rear passenger seat of the Subaru test vehicle with the Goodyear Aquatred 3 test tire in October 2002. The microphone was suspended 24-inches above the seat cushion and positioned in the center to capture the sound levels where a typical occupant's head would be. Similar to the OBSI and passby measurements, the data was obtained at a speed of 60 mph. The data was processed into one-third octave band spectra and overall A-weighted sound levels.

Unlike the passby noise, interior noise was comprised of two components: airborne and structure-borne. The airborne component is equivalent to the sound intensity and passby measurements and is transmitted into the vehicle interior by an airborne path in which the exterior tire/pavement noise is transmitted acoustically through body panels, door components, glass, etc. The structure-borne component arises from vibrations, which are generated at the tire/pavement interface and transmitted mechanically through the tire/wheel assembly, suspension, and body structure. The transmitted vibrational energy excites body panels, such as the floor pan, glass surfaces, and roof, which in turn radiate acoustical energy into the vehicle passenger cab. Typically, the airborne and structure-borne components are separated in frequency with structure-borne dominating in the lower frequencies (below ~400 Hz) and the airborne dominating the higher frequencies (above ~500 Hz). Since the tire is not an efficient radiator of sound at lower frequencies compared to structurally excited body panels, the overall interior A-weighted sound levels are typically governed more by the structure-borne than the airborne path. As a result, there may or may not be a clear correlation between the exterior and interior noise. However, as the driver's and passenger's perception of the "noise" of a pavement can be influenced by what they hear on the inside of a vehicle, this dimension of tire/pavement noise is significant to characterize.

Figure 4.10 shows the overall A-weighted interior sound levels for the frequency range of 500 Hz to 5000 Hz. Based on the overall interior sound data shown in Figure 4.8, the DGAC and BWC

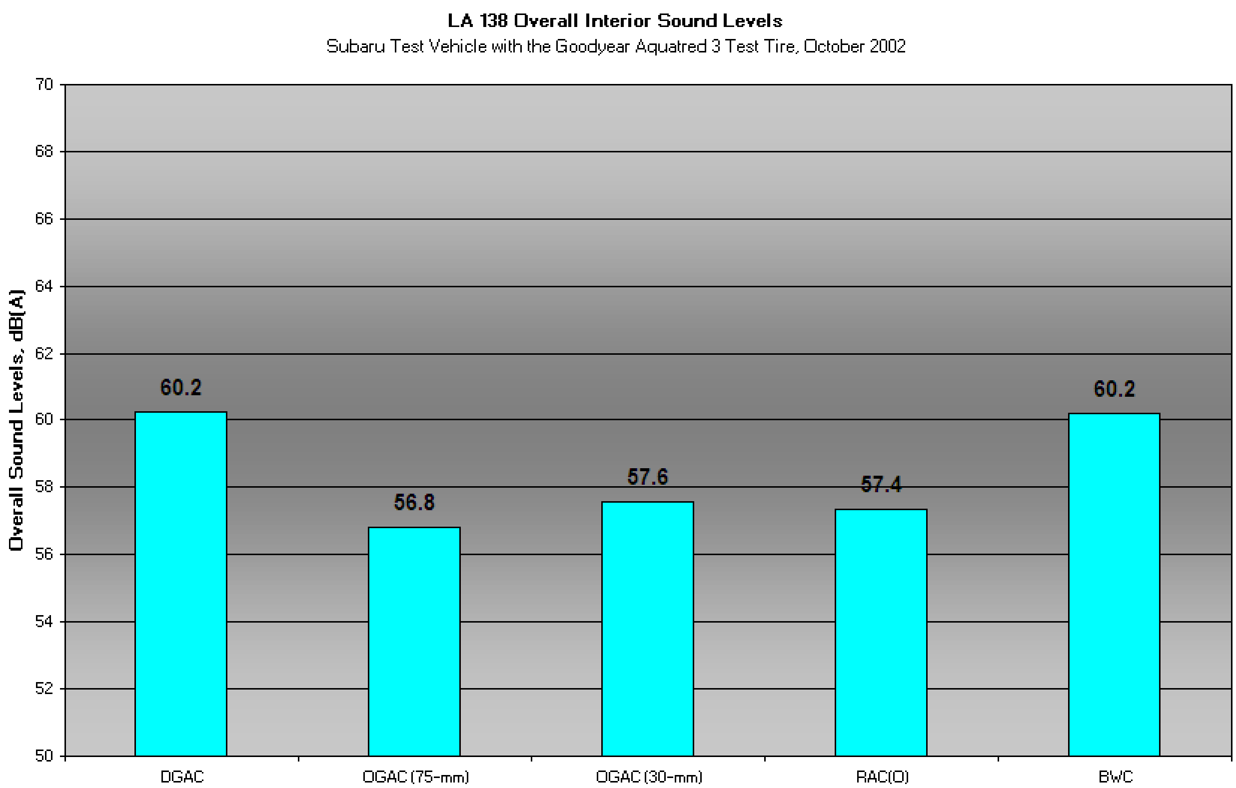


Figure 4.10. Overall A-Weighted Interior Sound Levels for Each Test Pavement, October 2002

pavements had the highest levels, which measured an average of 3 dB greater than both OGAC and RAC(O) pavements. While the OGAC (75-mm) pavement indicated the lowest overall level, the OGAC (30-mm) and RAC(O) levels were within 1 dB.

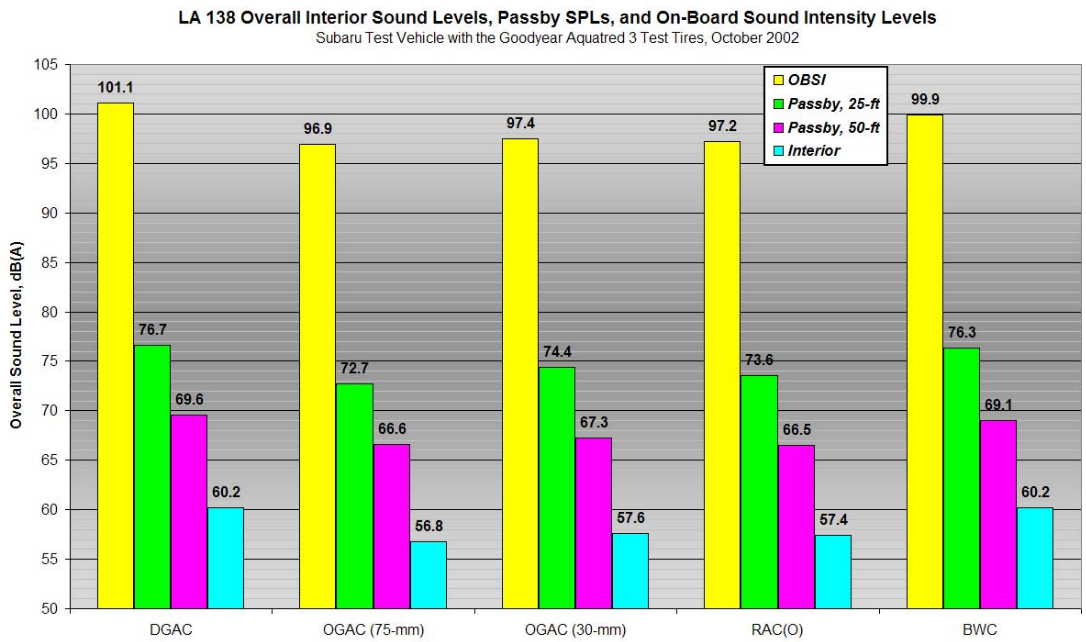
Comparison of Interior Sound Testing, Controlled Passby, and OBSI Testing

The overall levels discussed from Figure 4.10 are compared to the OBSI and passby data measured in October 2002 (Figure 4.11). From the overall interior sound data, the calculated offset from the OBSI data was found to be 40.1 dB ($\sigma = 0.5$). Likewise, the overall interior sound data measured an average 15.6 dB ($\sigma = 0.4$) offset from the passby data at 25-ft and 8.3 dB ($\sigma = 0.5$) offset from the 50-ft passby data.

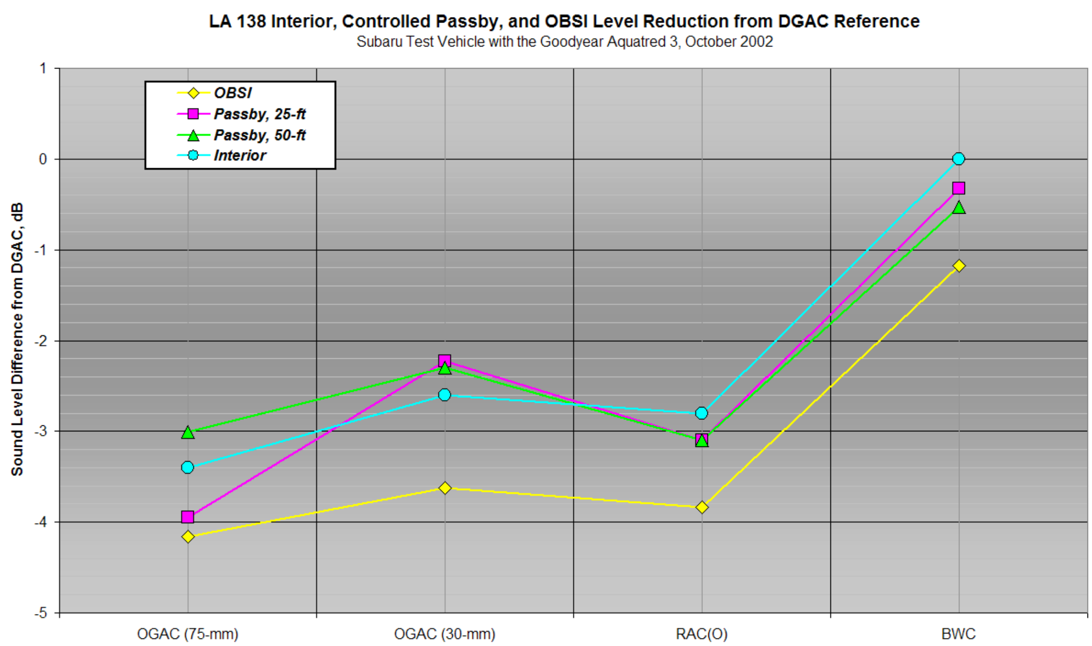
The overall interior sound level comparison for each test pavement relative to the reference DGAC was greatest for the OGAC (75-mm) pavement and smallest for the BWC pavement similar to the OBSI and passby data. From Figure 4.11b, the differences for the interior sound level and 50-ft passby microphone are almost identical as is the 25-ft microphone except for the 75-mm OGAC. As noted previously, OBSI differences relative to the passby data are typically about 1 dB greater and show a very consistent, similar offset from the interior results.

Figure 4.12 shows the interior sound spectra for the airborne region compared to the OBSI spectra (in Figure 4.12a) and the full spectra for interior sound (Figure 4.12b) measured in October 2002. The OBSI data discussed above showed higher levels from 800 Hz to 1600 Hz, with the greatest sound intensity amplitude occurring at 800 Hz; in the cropped frequency band in Figure 4.12a, elevated interior sound levels were apparent from 500 Hz to 1000 Hz. The ranking order for the test pavements based on the airborne region of the interior sound spectra was similar to the OBSI and passby data discussed previously, with the OGAC and RAC(O) pavements having the lowest levels and DGAC and BWC having the highest.

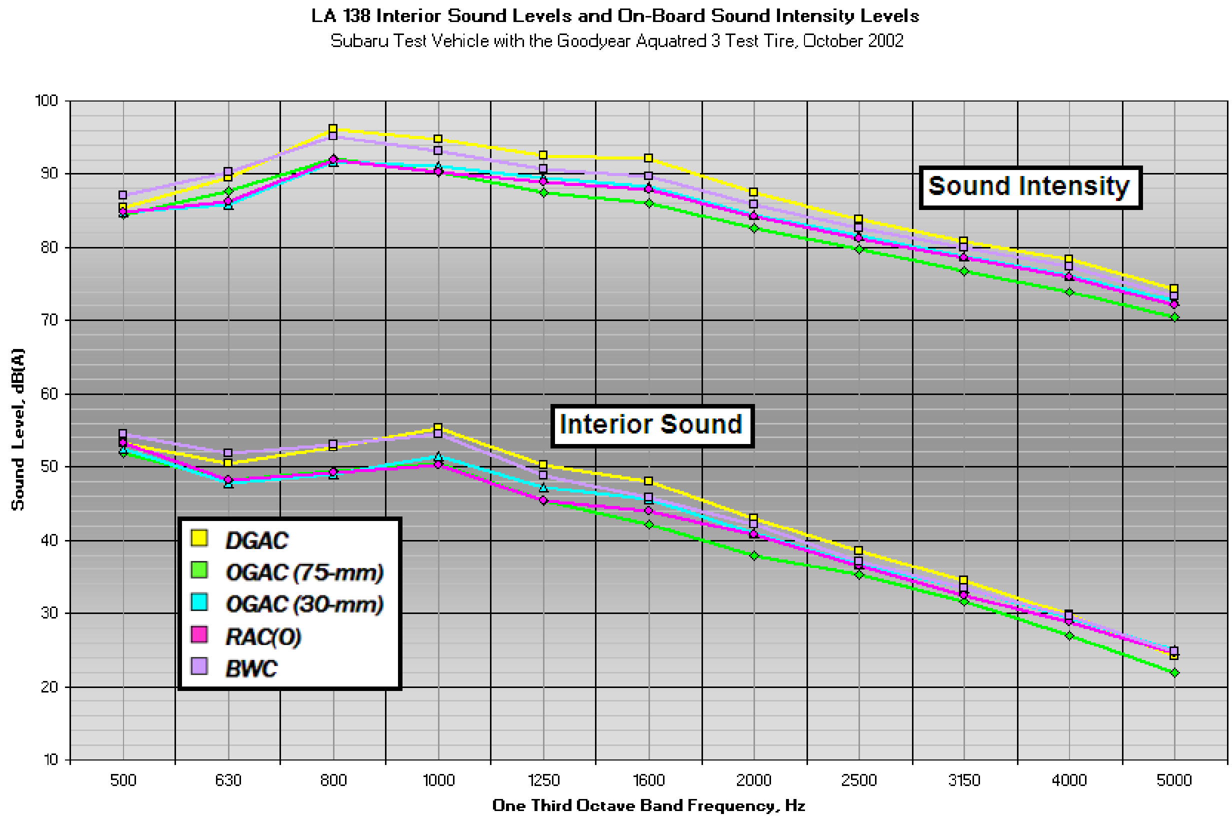
In the structure-borne region below 500 Hz, the ranking order for the test pavements was not apparent. While the BWC pavement resulted in the highest levels for nearly the entire structure-borne region, the other test pavements did not indicate an apparent overall trend, and there was little distinction found between the DGAC, both OGAC, and RAC(O) pavements in this region. These results may signify the little effect the test pavement overlays have on structure-borne noise measured from the interior of the vehicle. This is not too surprising as the aggregate sizes are similar and not particularly large for all five pavements. In these low frequencies, differences in the sections may be more influenced by larger scale (mega-texture) roughness in the surfaces.



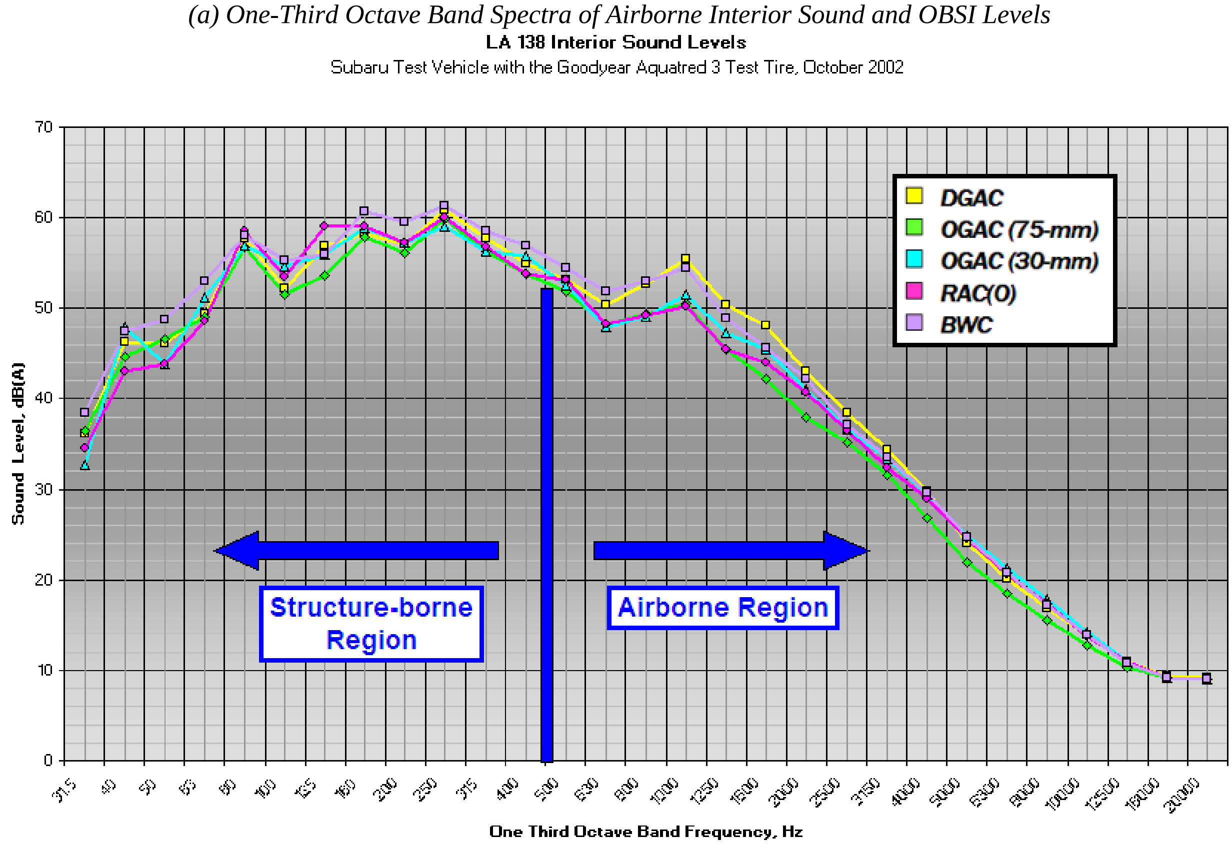
(a) Overall Sound Interior Levels, Passby SPLs, and OBSI Levels for Each Test Pavement



(b) Reduction of Interior, Passby, and OBSI Levels from the DGAC Test Pavement
Figure 4.11. Overall A-Weighted OBSI Levels for Each Test Pavement, October 2002



(a) One-Third Octave Band Spectra of Airborne Interior Sound and OBSI Levels



(b) One-Third Octave Band Spectra of Structure-borne and Airborne Interior Sound Levels

Figure 4.12. One-Third Octave Band Spectra, October 2002

CHAPTER 5

MEASUREMENTS AND RESULTS THROUGH OCTOBER 2008

From the time of the initial overlay measurements in October 2002, OBSI levels for the LA 138 test sections have been measured on a somewhat regular basis as indicated in Table 3.1. In addition to some variation in the month and the year that data was collected, there was some measurements made with different secondary test tires. The most consistent data set over time has been obtained using the Goodyear Aquatred 3 tire. In the first years of the study, the Uniroyal Tiger Paw AWP was used as a secondary tire. Beginning in October 2006, the secondary tire became the ASTM SRTT tire that was tested through the final measurements in October 2008. Switch over to the SRTT was driven by the lack of availability of Aquatred 3 as their production ended in the 2005-2006 time period. Although this did not immediately effect the Caltrans work, there was movement of the OBSI user community to adopt the SRTT as the standard tire test due to its supposed long term availability. To accommodate the larger SRTT tire (P215/60R16), the test vehicle used for the LA 138 measurements changed from a Subaru Outback to a Chevrolet Malibu beginning in 2007. Also in this time period, the data acquisition changed from the single probe system to a dual probe system. To assure comparability of the measurements, the effects of these changes were documented as part of the on-going LA 138 research.

Effects of Pavement Aging

The primary objective of the LA 138 study was to examine the effect of aging on the noise levels of the different AC pavements. In particular, the investigation of the quieter pavements continual production of lower levels of tire/pavement noise was integral. Although the primary method of conducting this research was with the use of OBSI, limited controlled passby data was also obtained.

Goodyear Aquatred 3

The overall A-weighted sound intensity levels for the fall and spring measurements using the Aquatred test tire are shown in Figure 5.1. For all of the test sections except the DGAC reference, there was a clear upward trend in the results over time. For the quieter pavements (i.e., both OGAC pavements and RAC(O)), the increase was about 0.3 dB per year. For the DGAC reference pavement, the increase was less than 0.1 dB per year and was about 0.2 dB per year for the BWC pavement. Some scatter occurred in the data, and the upward trend was not uniform. Initially, some of scatter was thought to be due to seasonal/temperature effects between the spring and fall measurement times, however, in comparing the spring and fall measurements of the same year, no consistent trend was apparent. Because of the smaller increase in level over time for the DGAC pavement, it can be seen from Figure 5.1 that the difference between the DGAC reference pavement and the quieter pavements has declined over time from approximately 4 dB to slightly over 2 dB for both the OGAC (75-mm) and RAC(O) pavements to less than 2 dB for the OGAC (30-mm) pavement. However, the relative rank ordering of the pavements has remained similar through 2008.

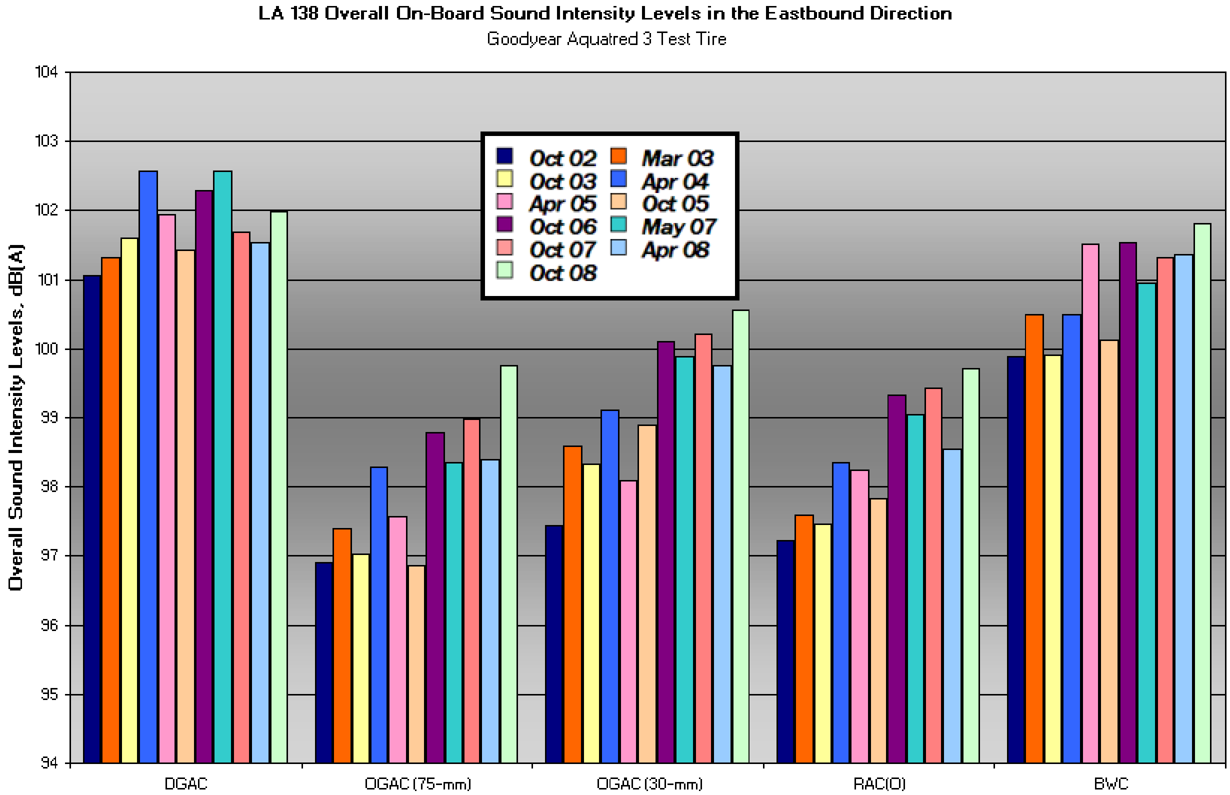


Figure 5.1. Overall A-Weighted OBSI Levels for Each Test Pavement from October 2002 through October 2008

As noted with regard to Figure 5.1, the DGAC reference pavement showed least of amount of change in level between 2002 and 2008. The one-third octave band changes are, however, somewhat more complex (Figure 5.2). In comparison to the appearance of the surface in Figure 2.2, the photographs from 2005 and 2008 (Figure 5.3) show an increasing amount of aggregate exposure. However, the spectra acoustically indicate little change in roughness as in the lower frequencies, below 1000 Hz, there was virtually no change spectra. In the frequencies from 2000 to 3150 Hz, levels are shown to increase somewhat uniformly with pavement age. This may be related to the somewhat polished effect of the aggregate. Adding surface micro-texture through Skidabrader processing of an older DGAC on I-505 in Yolo County produced just the opposite effect shown in Figure 5.2[7]. In the reverse process here over an extended period of time, the more polished aggregate may be responsible for this increase in the higher frequencies. In the middle frequencies, the behavior did not show a consistent tendency with aging; although, these had a level range of almost 3 dB. The BWC surface spectra showed a somewhat similar effect with aging as the DGAC (Figure 5.4). The behaviors above 1600 Hz and below 1000 Hz were very similar between the two pavements and the spectra for October 2008 were remarkably similar (Figure 5.5). Examination of the 2005 and 2008 photographs of the BWC (Figure 5.6) reveal similar changes in appearance between the two pavements. By 2008, the two pavements are visually quite close.

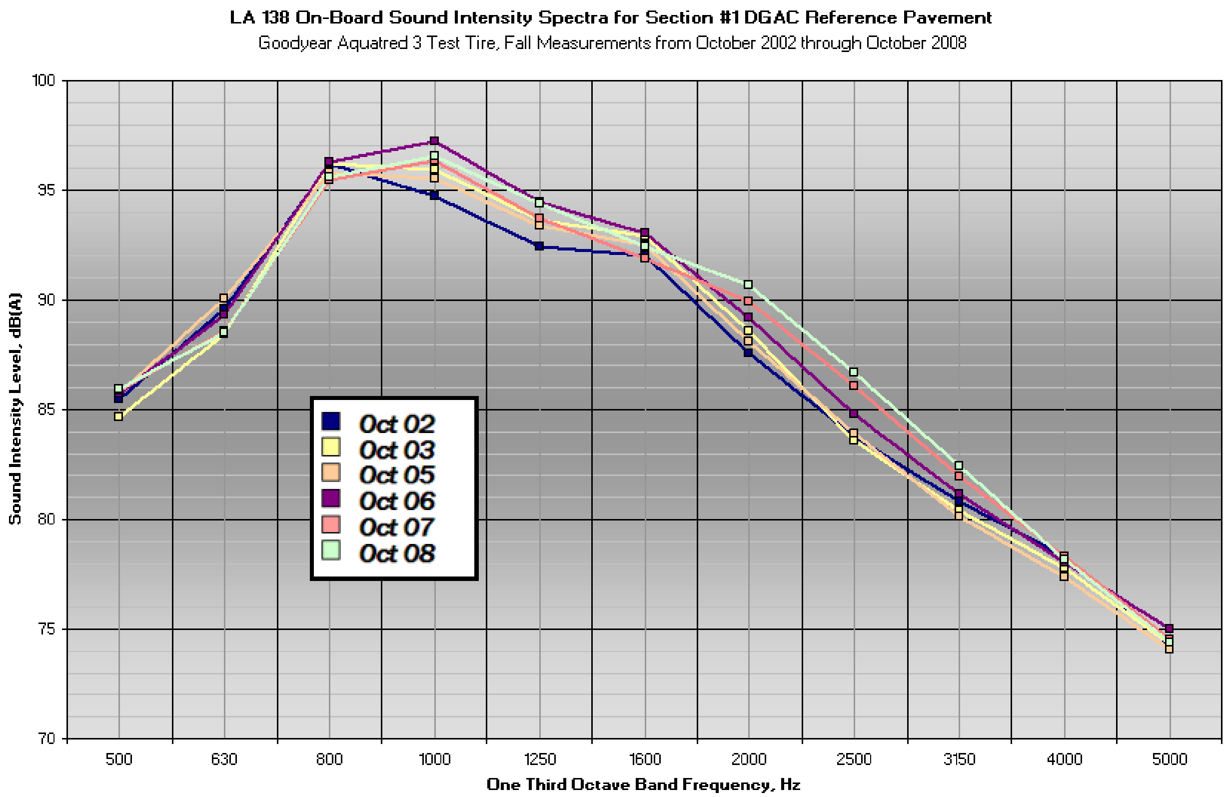


Figure 5.2. One-Third Octave Band Levels for Section #1 DGAC Test Pavement during the Fall Measurements from October 2002 through October 2008

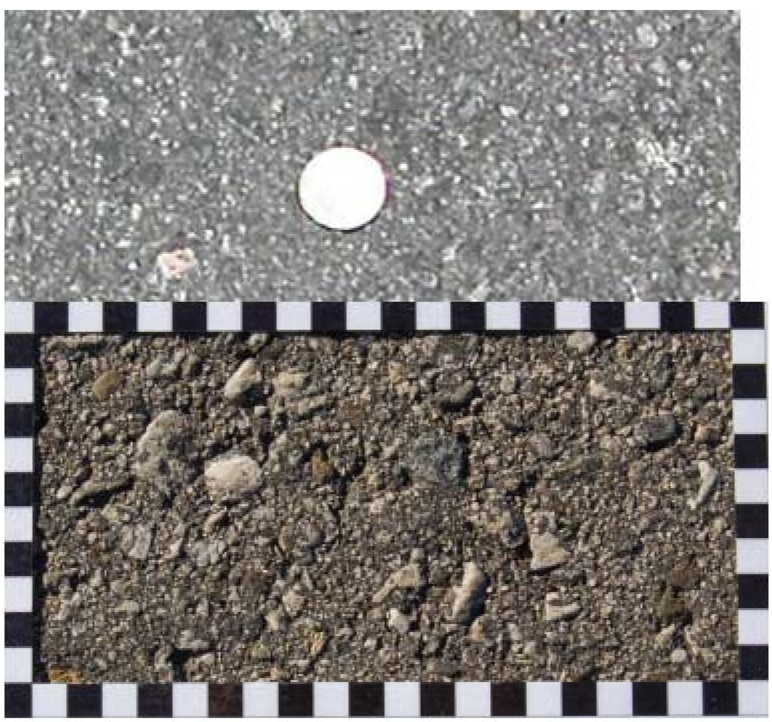


Figure 5.3. Photographs of DGAC Pavement Surfaces (2005 upper, 2008 lower)

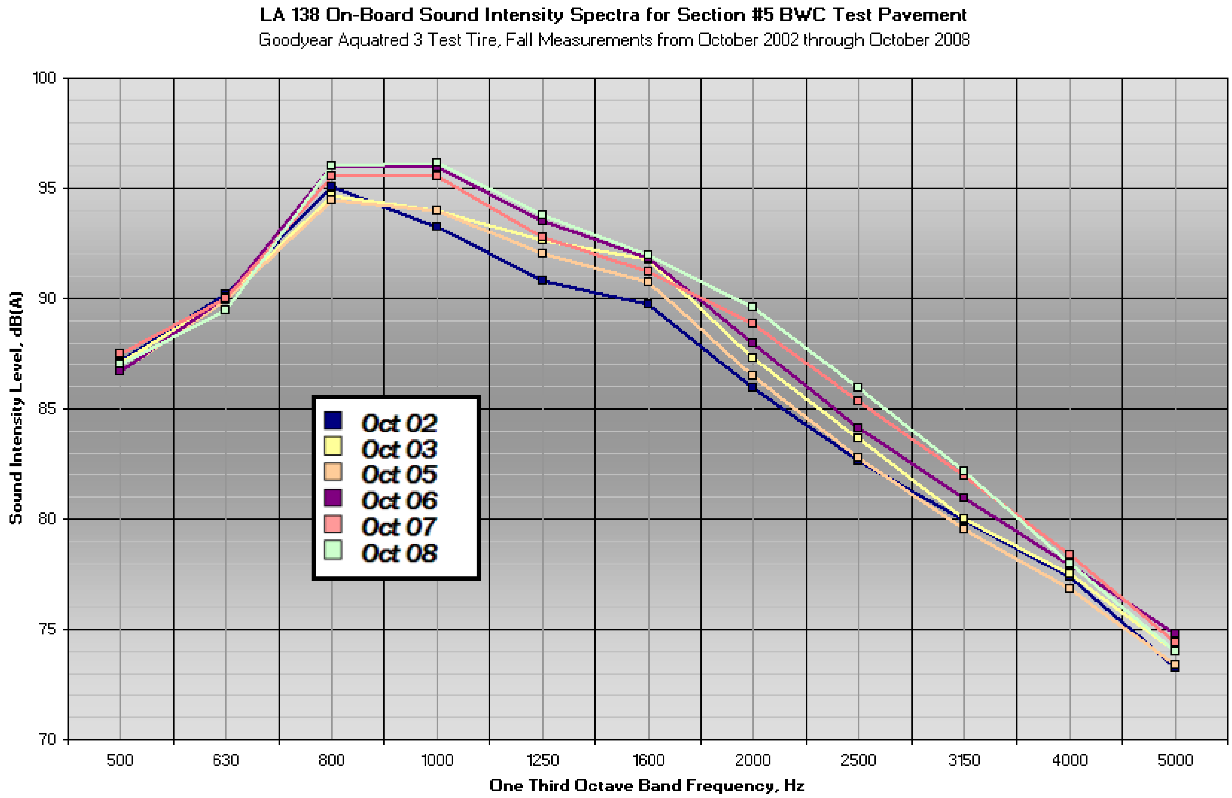


Figure 5.4. One-Third Octave Band Levels for Section #5 BWC Test Pavement during the Fall Measurements from October 2002 through October 2008

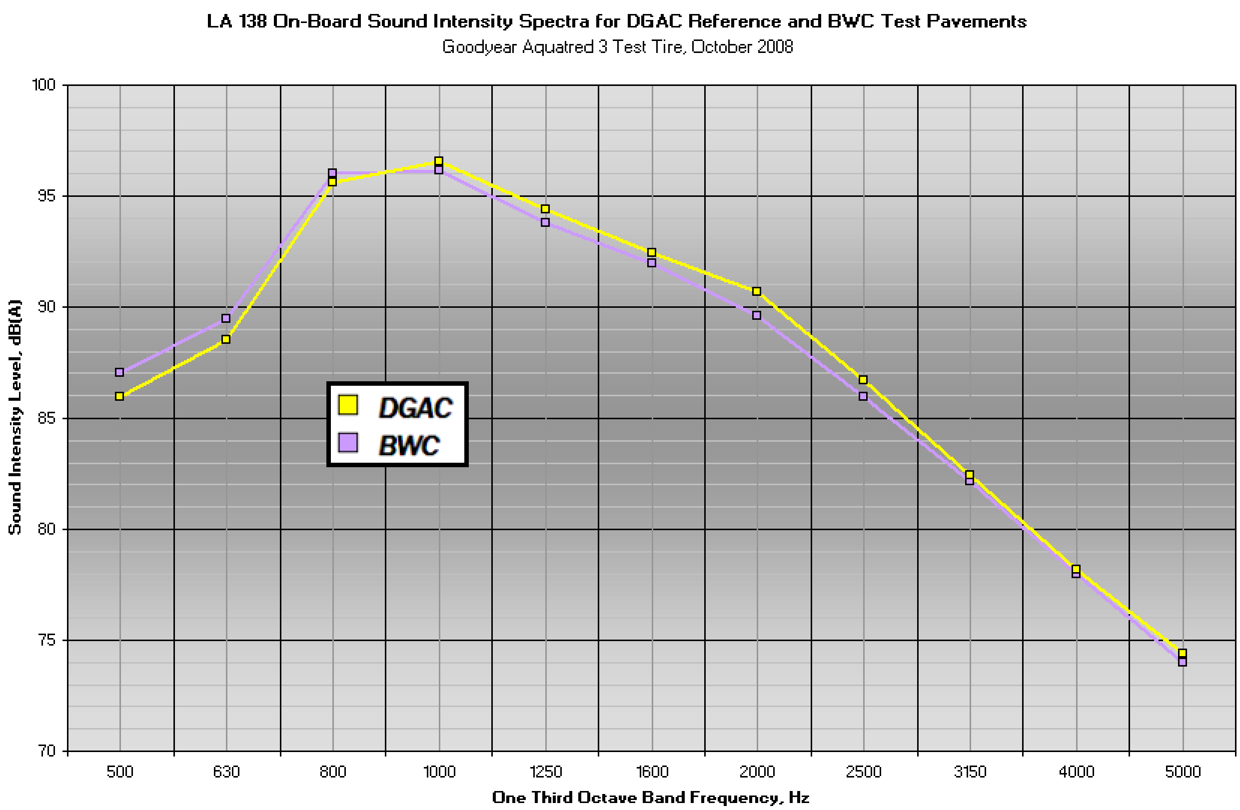


Figure 5.5. One-Third Octave Band Levels for DGAC and BWC Test Pavements, October 2008

Figure 5.6. Photographs of BWC Pavement Surfaces (2005 upper, 2008 lower)

The spectra for the three open graded sections show similar trends with aging. In each case, the largest differences with age occur in the one-third octave bands above 800 Hz (Figures 5.7 through 5.9). In these frequencies, the increases track with the increasing age. For 800 Hz and below, the differences were not as great (2 dB to 3 dB), and a trend upward with pavement age was not so apparent. For the frequencies of 2000 Hz and above, some (~ 2 dB) of the increase noted particularly between 2005 and 2006 can be attributed to data acquisition system and Aquatred tire changes (see Figure 5.17). However, the increase beyond 2006 and also in the frequency range from 1000 Hz to 1600 Hz was not related to this change. Throughout the study period, the 30-mm OGAC had consistently been about 1 dB higher in level than the 75-mm OGAC and the RAC(O) pavements. Comparing the spectral directly in Figure 5.10, the higher levels for the 30-mm OGAC results from a constant 1 dB upward offset in the spectra above 800 Hz. Photographs of these surfaces from October 2008 provide little understanding of the noise performance in these mid- to higher frequencies (Figure 5.11). Similar to the DGAC and BWC, these open graded pavements also show increased exposed and polishing of the aggregate relative the photographs from 2002.

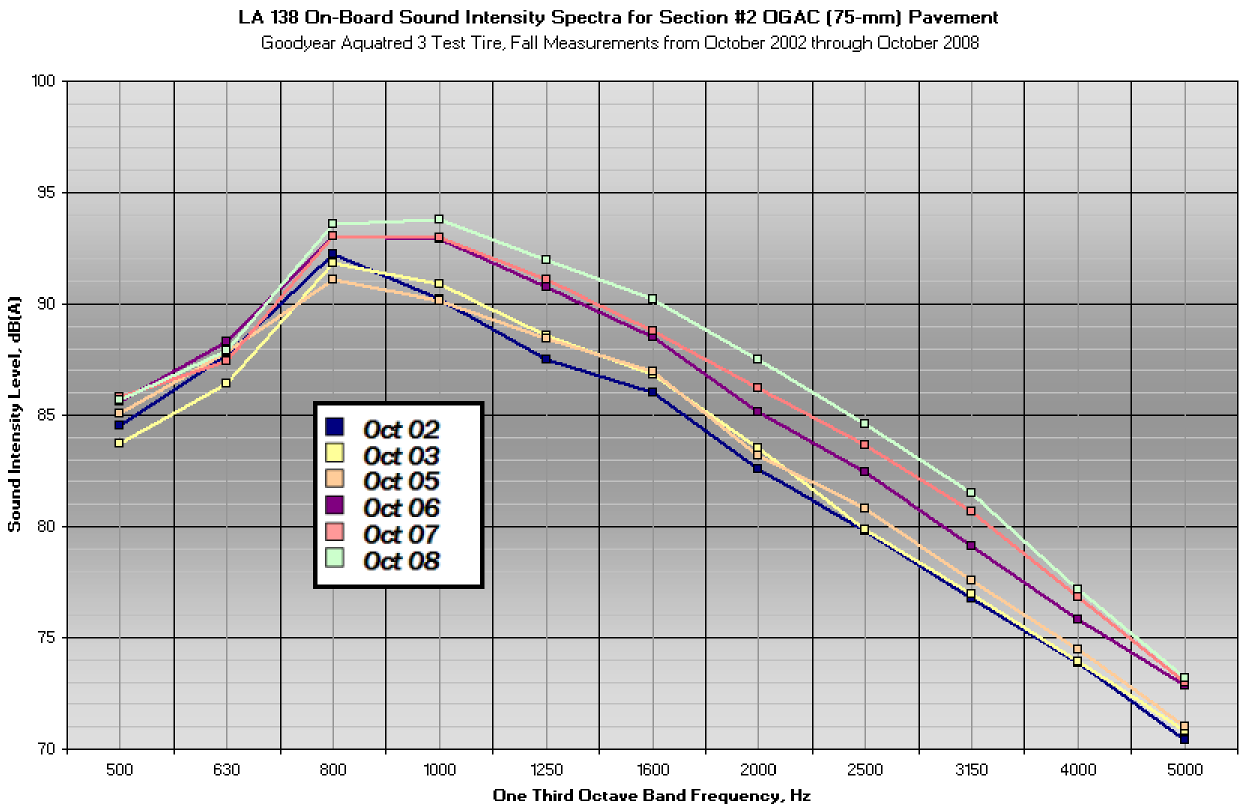


Figure 5.7. One-Third Octave Band Levels for Section #2 OGAC (75-mm) Test Pavement during the Fall Measurements from October 2002 through October 2008

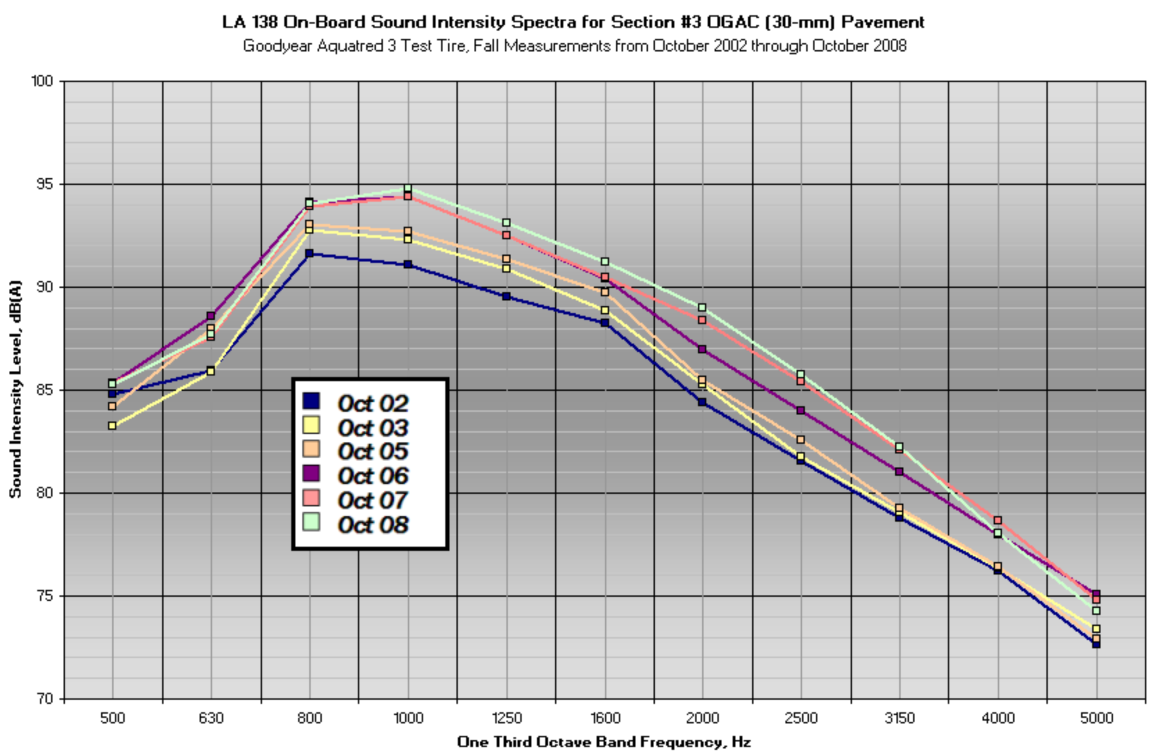


Figure 5.8. One-Third Octave Band Levels for Section #3 OGAC (30-mm) Test Pavement during the Fall Measurements from October 2002 through October 2008

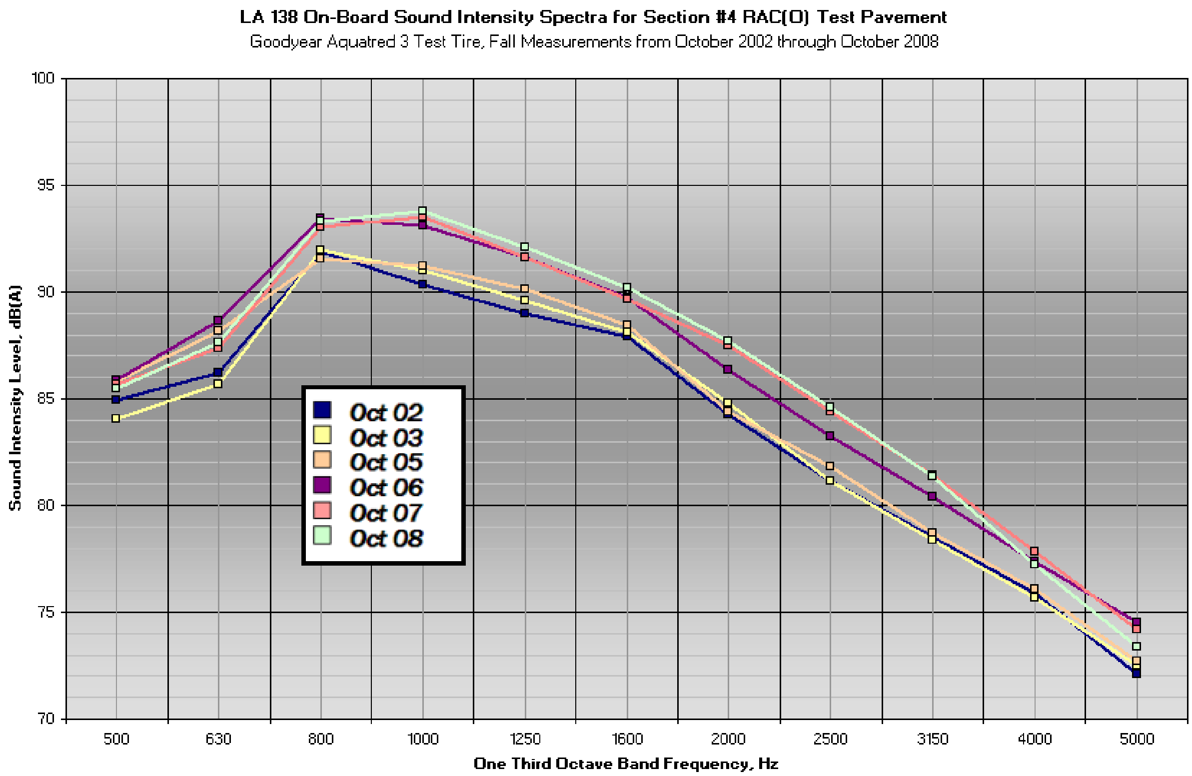


Figure 5.9. One-Third Octave Band Levels for Section #4 RAC(O) Test Pavement during the Fall Measurements from October 2002 through October 2008

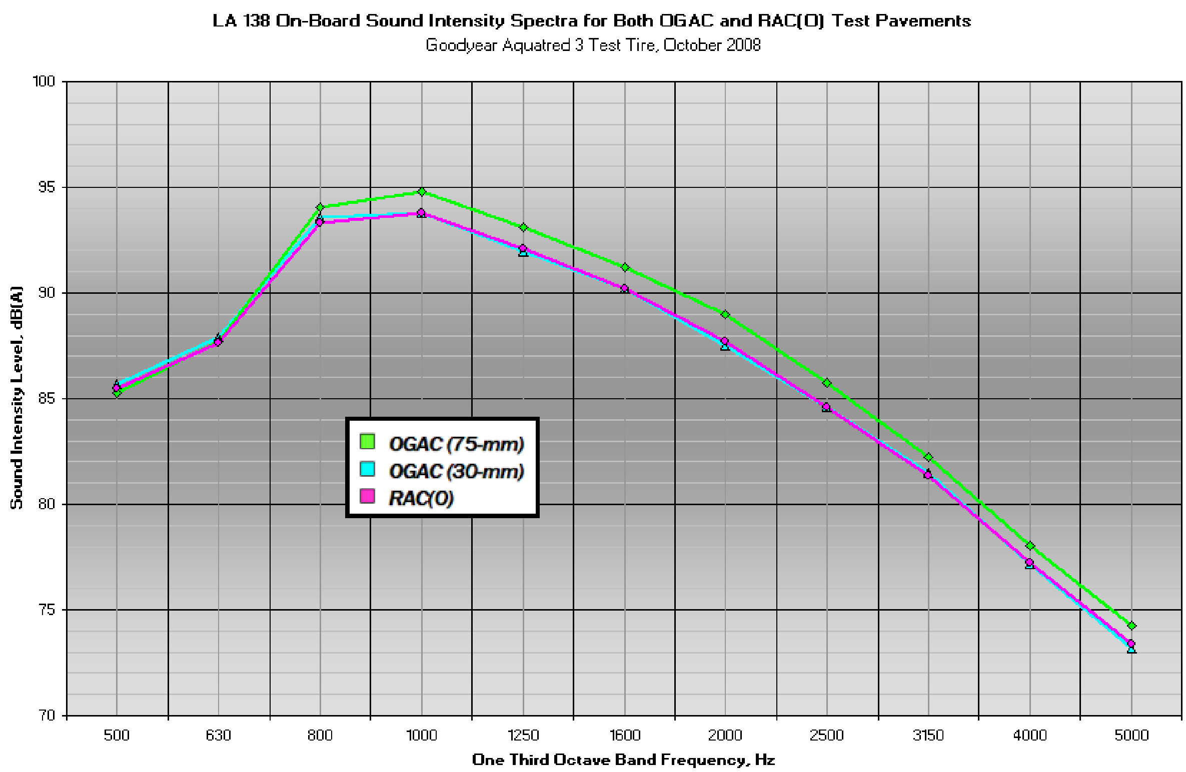


Figure 5.10. One-Third Octave Band Levels for Both OGAC and RAC(O) Test Pavements, October 2008

(a) Open Graded Asphalt Concrete (75-mm) Overlay

(b) Open Graded Asphalt Concrete (30-mm) Overlay

(c) Rubberized Asphalt Concrete Open Graded

Figure 5.11. Photographs of Open Graded Surfaces

Uniroyal Tiger Paw AWP

OBSI measurements were made with the P205/70R15 Tiger Paw tire on the Subaru in October 2002, March 2003, and again in April 2004. From and this other testing, the Uniroyal tire was found to produce tire/pavement noise levels typically about 1.5 dB lower than the Aquatred. Its tread design was somewhat less aggressive than the Goodyear tire and as a result, the Tiger Paw was used as a secondary tire when time allowed. It was also used in this manner for survey of tire/pavement noise OBSI levels conducted in Europe in 2004[8]. The overall A-weighted levels for this tire on five sections as tested on the three occasions is presented in Figure 5.12 along with the corresponding results for the Aquatred tire. From the testing done in Europe and the LA 138 resutls (see Appendix B), the Uniroyal tire rank ordered the pavements the same as the Goodyear Aquatred and other test tires evaluated in 2002. The increase between 2002 and 2004 was also similar for the two tires although the absolute levels were different.

SRTT

OBSI measurements were made with the SRTT test tire on the Malibu test car from October 2006 through October 2008. For these measurements, the level difference between the tires was about 1 dB, with the Aquatred being louder. The SRTT tread design was similar to the Uniroyal Tiger Paw AWP design but produces slightly higher tire noise levels. The OBSI levels measured for the October testing are presented in Figure 5.13, along with the corresponding Aquatred data. As in the case of the Tiger Paw tire, the rank ordering of the pavements was same as that for other test tires. The trends between the two tires were similar to the function of age: for the open graded pavements, the levels showed an increase with time, while for the DGAC and BWC, no increase was indicated within the certainty of the results.

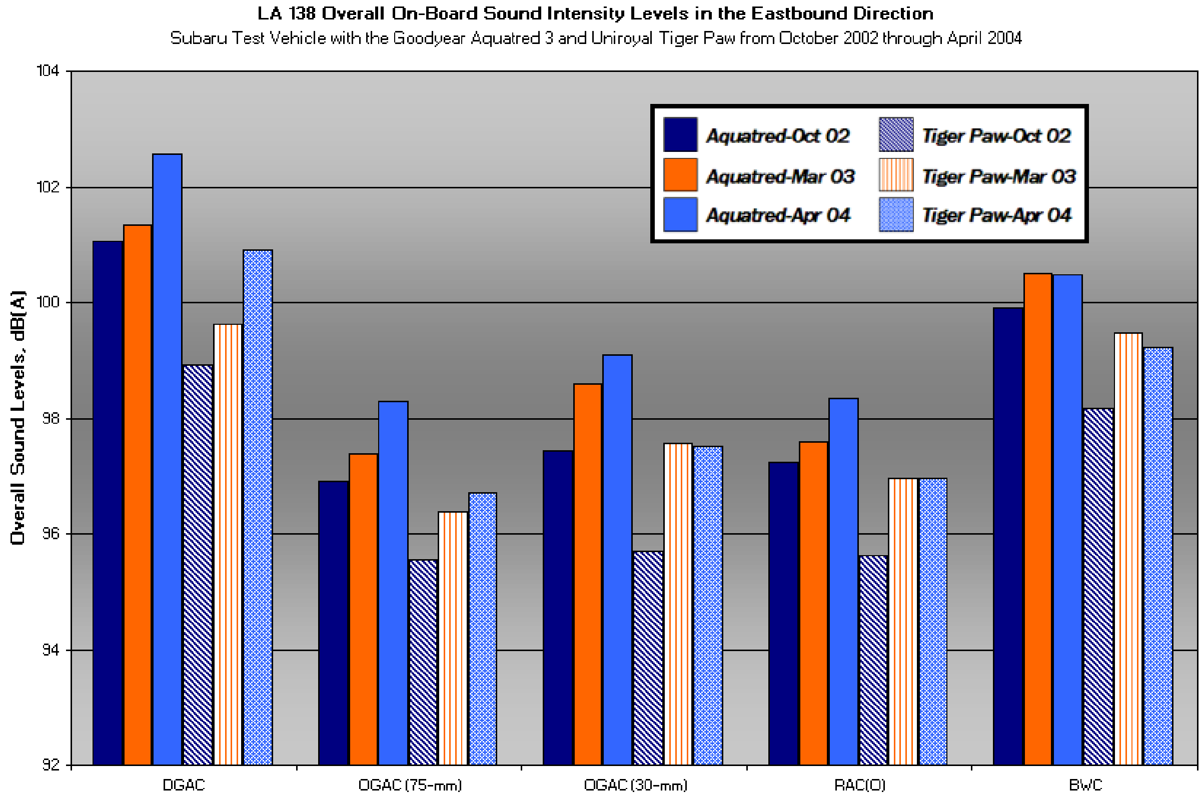


Figure 5.12. Overall A-Weighted OBSI Levels for the Goodyear Aquatred 3 and Uniroyal Tiger Paw test tires along Each Test Pavement from October 2002 through April 2004

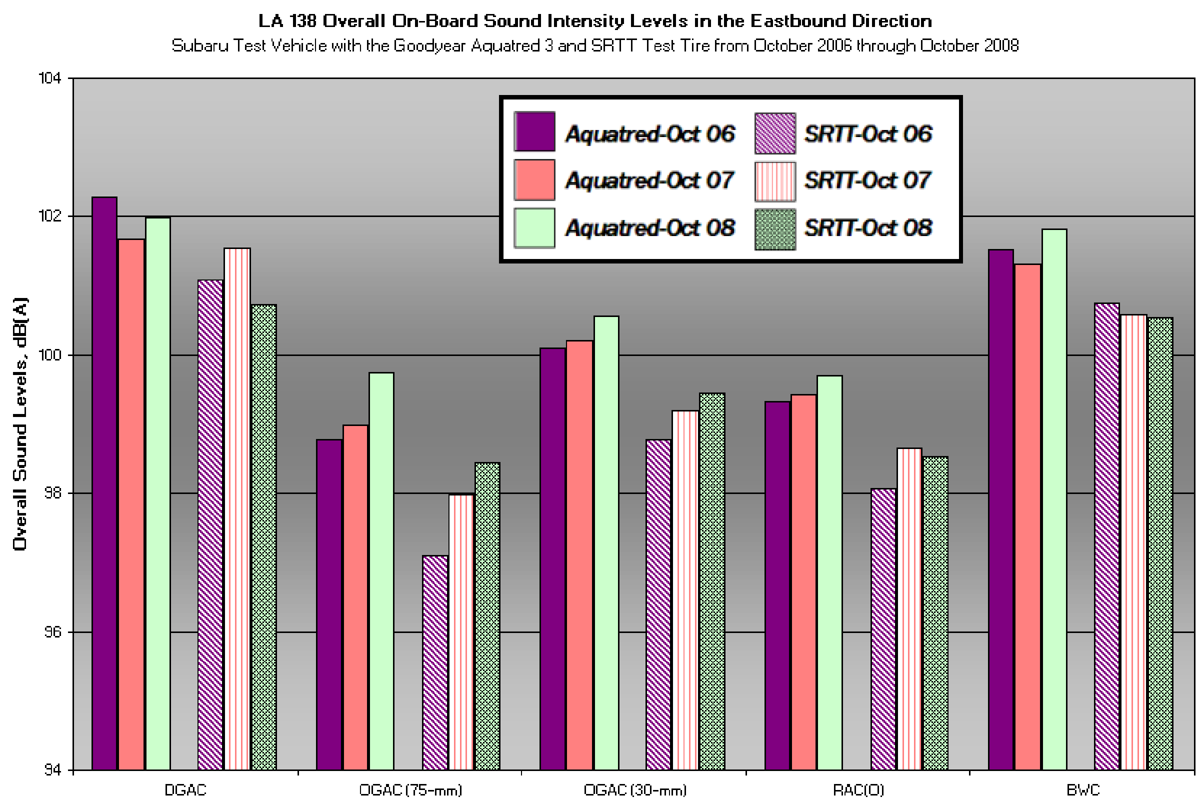


Figure 5.13. Overall A-Weighted OBSI Levels for the Goodyear Aquatred 3 and SRTT test tires along Each Test Pavement from October 2006 through October 2008

Controlled Passby Tests

Controlled passby tests were conducted on four occasions throughout the period from 2002 to 2008. These were all done using the Subaru test vehicle with the same set of four Aquatred tires. The measurements were made at all five pavement sites and at distances of 25-ft and 50-ft from the centerline of the eastbound (closest to the microphones) lane. As indicated in Figure 5.14, these measurements were conducted in October of 2002, 2003, and 2006 and in May of 2007. The trends of these data followed those of the OBSI data; the pavements showed the same rank ordering and levels increase with aging especially for the 25-ft data. At 50-ft, this trend was not as pronounced and some scatter in the difference between the 25-ft and 50-ft was apparent. In general, the aging effect was less pronounced in the passby data than the OBSI. The average increase for all five sections was about 1½ dB for the OBSI data (~0.3 dB per year), and about 1 dB for 25-ft passby results (~0.2 dB per year). For the 50-ft data, the average increase was only about ½ dB, which may be due in part to increased scatter in these data.

The difference in scatter between the two microphone distances was even more apparent when considering the cross plot comparison with the OBSI data, as shown in Figure 5.15. For the 25-ft microphone position, this plot showed that the average offset in the CPB and OBSI was 24.0 dB with a standard deviation of 0.7 dB compared to the 23.8 dB offset and $\sigma = 0.6$ found for the October 2002 data alone. For the 50-ft data, the standard deviation was greater to that indicated previously, 1.1 dB versus 0.5 dB, as was the average offset at 31.5 dB compared to 30.7 dB previously. In the latter two measurements events, it was found that difference between 25-ft and 50-ft microphones had increased an average of 0.8 dB compared to the first two events (2002 and 2003). It is suspected that this may be due in part to changes that occurred in the sites themselves. As illustrated by the photographs in Figure 5.16, in the time between the 2002 and 2007 measurements, the brush along the microphone lines grew sufficiently so that it may have provided some additional attenuation at the 50-ft microphone locations as indicated in the data. For the October 2006 tests, the wind conditions were marginal, typically 8 to 12 mph with the direction of the wind parallel to the roadway. For this measurement set the standard deviation of the individual passby levels at the 50-ft microphone position was typically 0.5 dB compared to 0.2 dB for previous passby data and the data at the 25-ft position.

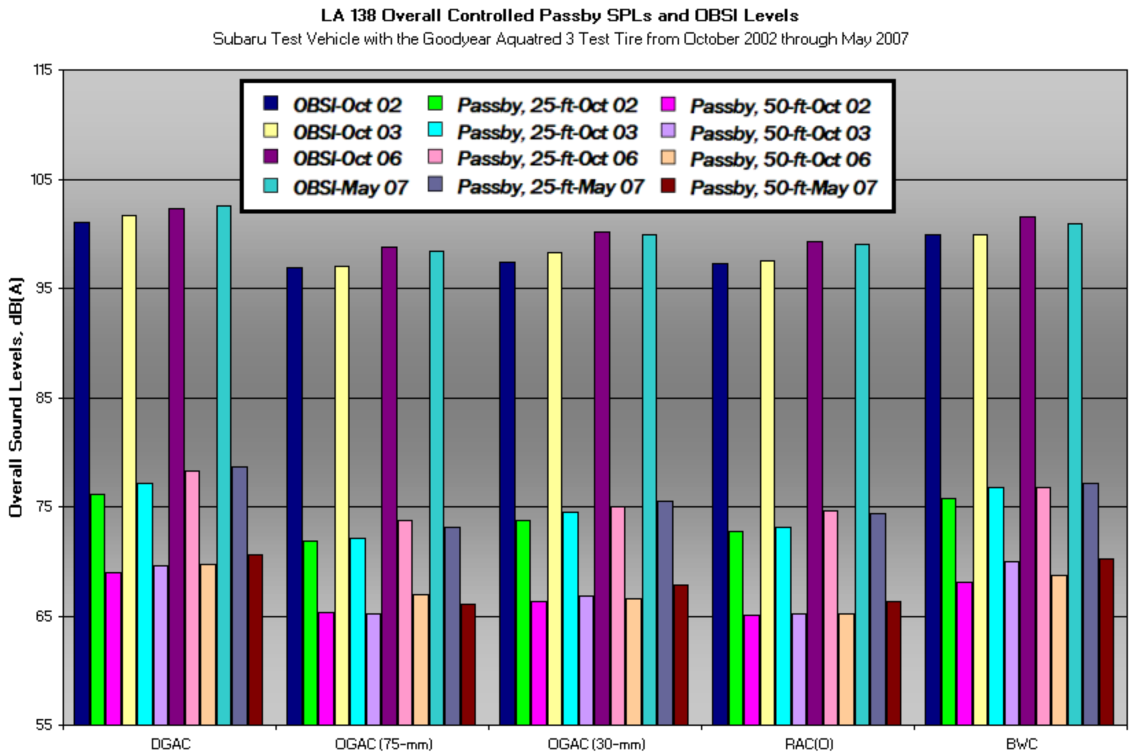


Figure 5.14. Overall A-Weighted Controlled Passby Sound Pressure Levels and OBSI Levels for Each Test Pavement from October 2002 through May 2007

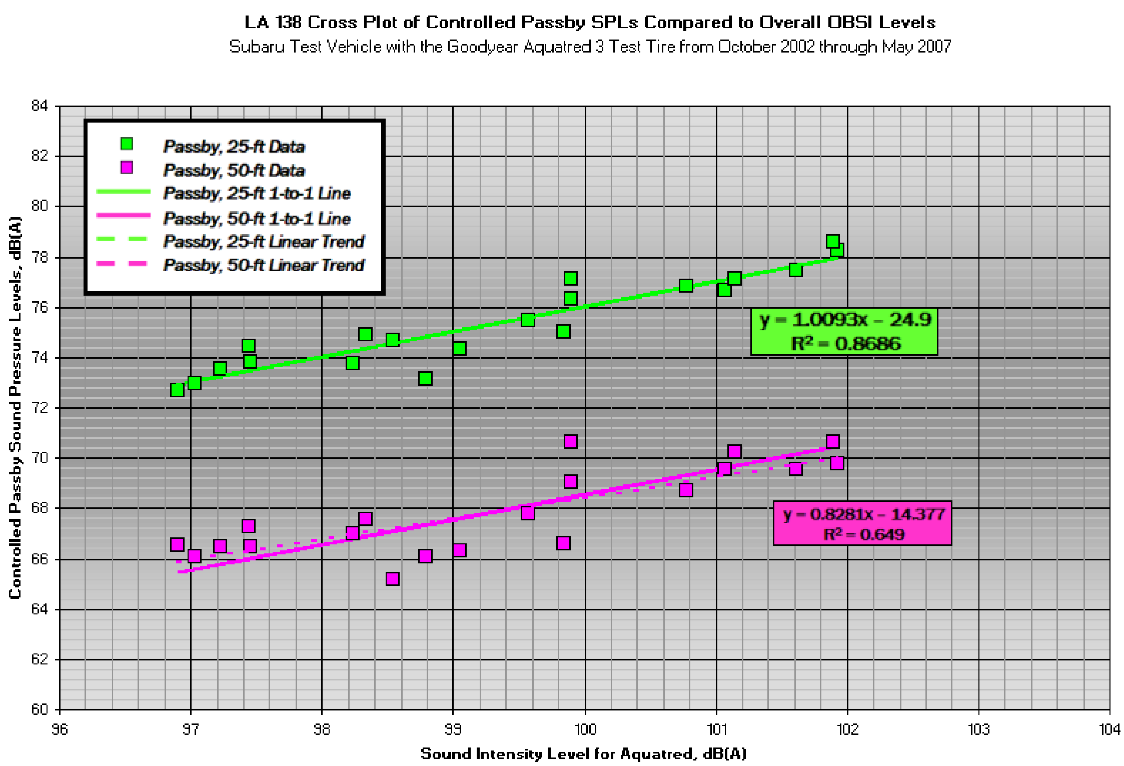


Figure 5.15. Cross Plot of Overall A-Weighted Controlled Passby SPLs Compared to OBSI Levels from October 2002 through May 2007

Figure 5.16. Passby Measurement Conditions at Site 3 in Oct 2002 (Left) and May 2007 (Right)

Transition of Test Tire and Instrumentation

After the May 2007 testing, all of the OBSI measurements were made using a dual probe fixture and a new Aquatred 3 test tire. The testing in October 2006 included measurements to document any OBSI changes that may have resulted from this transition. As part of the development and validation of the two-probe system, it has been determined that changing the probe configuration alone (i.e. same test tire/car and instrumentation) produced differences no greater than run-to-run variation[10]. For the October 2006 testing, three configurations were evaluated. These included the Aquatred tire on the Subaru as measured by the single probe and LD 3000 analyzer; the (same) Aquatred on the Subaru as measured by the dual probe and B&K Pulse analyzer; and the new Aquatred on the Malibu as measured by the dual probe and Pulse. The first and last configuration represented the net transition between the two overall configurations and instrumentation. Prior to field testing, sound intensity measured by the B&K Pulse was compared to that from the LD3000 in a bench-top test. A G.R.A.S. sound intensity calibrator was used to generate a repeatable sound intensity field that could be measured by both systems using the same microphones and pre-amplifiers. This indicated a constant 0.3 dB offset between the two analyzers with the B&K instrument producing the lower levels. The cause of this difference could not be determined; however, it was determined to be within the specified accuracy of the two systems. On-road measurements were taken with the same tire on the Subaru, both analyzers, and the two different corresponding probe configurations, and a constant offset averaging 0.6 dB was found, with the B&K/dual probe system again producing the lower levels (Figure 5.17). Measurements were then made with the Malibu, the two-probe configuration, Pulse, and the new test tire. This produced essentially no difference compared to baseline configuration of the Subaru and the single probe system (Figure 5.17).

Examination of the spectral differences for these three cases indicated consistent trends across all of the LA 138 test sections. An example is shown in Figure 5.18 for the 75-mm OGAC test pavement in the eastbound direction. From these comparisons, it was found that differences between tire/vehicle configuration resulted in increased levels for the new Aquatred on the Malibu of about 1dB to 2 dB at frequencies of 2000 Hz and above. In the frequency range that controls the overall A-weighted level (800 Hz to 1250 Hz), the differences between the analyzers/probe configuration apparently compensates for differences between the tire/vehicle combination. This resulted in essentially no overall A-weighted level change between the

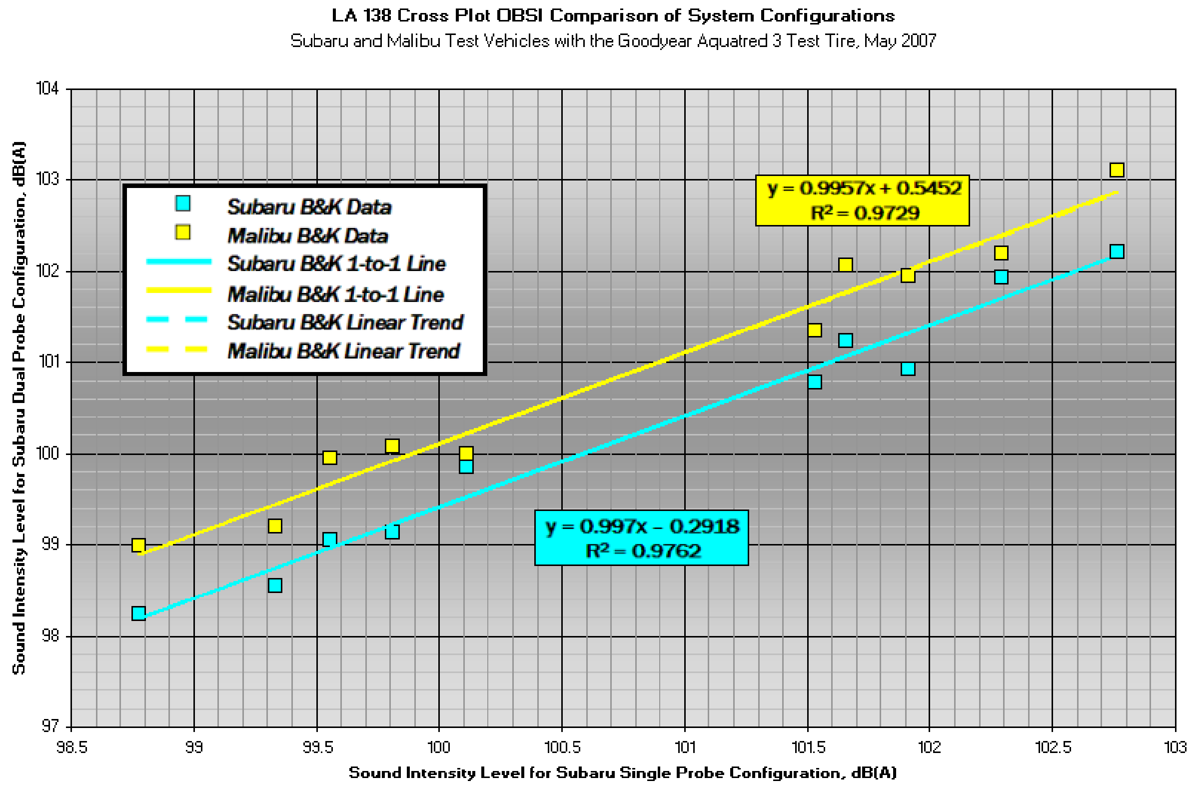


Figure 5.17. Cross Plot of Overall A-Weighted OBSI Levels Comparing the Subaru and Malibu Test Vehicles with the B&K Configuration, May 2007

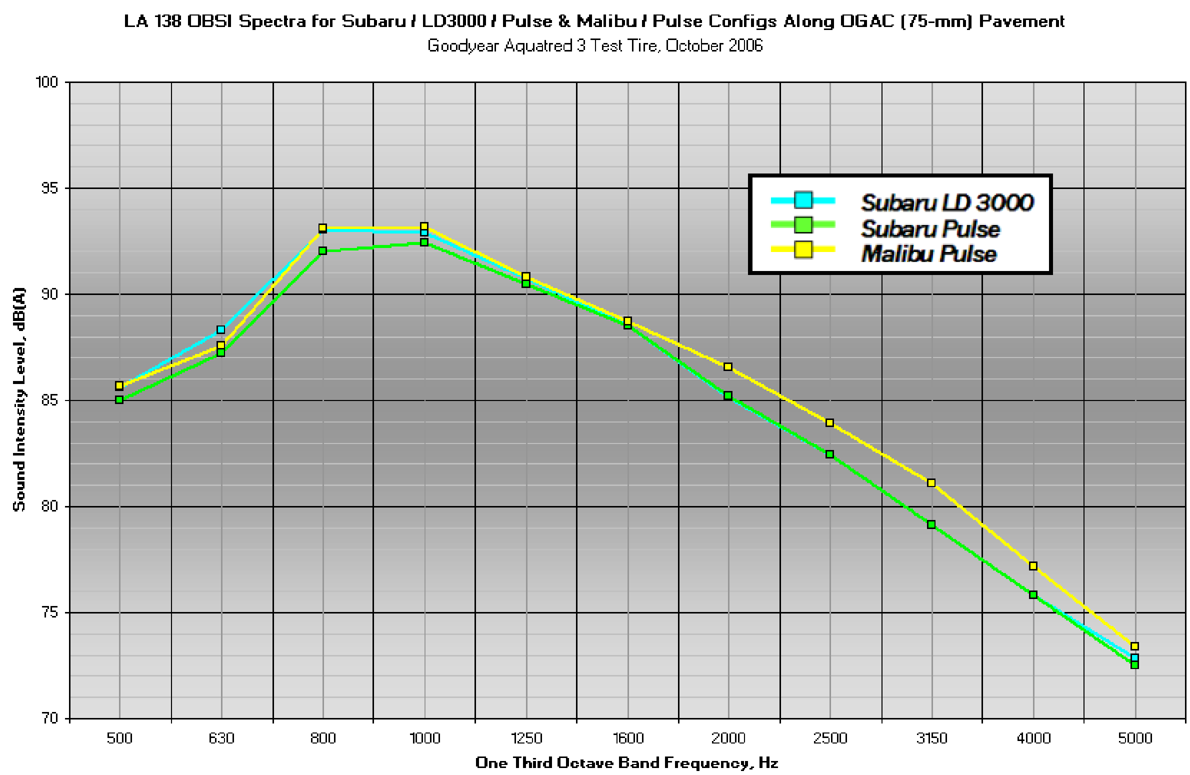


Figure 5.18. One-Third Octave Band Levels for the Subaru Single Probe and Malibu Dual Probe Configurations along the OGAC (75-mm) Test Pavement, May 2007

Subaru/single probe/LD3000 configuration and Malibu/dual probe/B&K Pulse. Although this was a fortuitous circumstance for making overall level comparisons, it also needs to be noted that some spectral shape differences can be expected between data taken with new and old systems.

Comparison LA 138 Test Sections to Other Pavements

Since 2002, the OBSI data available to compare with that of the LA 138 test sections has increased substantially. This has included additional pavements from California and Arizona, as well as some from Nevada[11]. Pavements of different age were also made available for comparison to the recent LA 138 data. Results for DGAC and other AC pavements are shown in Figure 5.19 along with the average of PCC pavements in California, Arizona, and Nevada. It should be noted that for these averages, California data was made exclusively of longitudinally tine and ground PCC while the Arizona and Nevada averages were transversely tined PCC more common in those states. Figure 5.19 also shows the DGAC and BWC pavements from LA 138 as initially measured in 2002 and in October 2008. As would be expected from Figure 4.4, the DGAC performance spans a wide range from quieter to levels approaching the CA average PCC. In this plot, a very rough texture chip seal pavement from SM 84 was also shown and though not a DGAC, its level approached the transverse tined PCC textures of AZ & NV. As noted previously, the LA 138 DGAC showed little increase over the six years of testing. It was initially on the higher end of the DGAC pavements and remains there. The BWC did show some increase and the current levels were the same as the 2008 LA 138 DGAC.

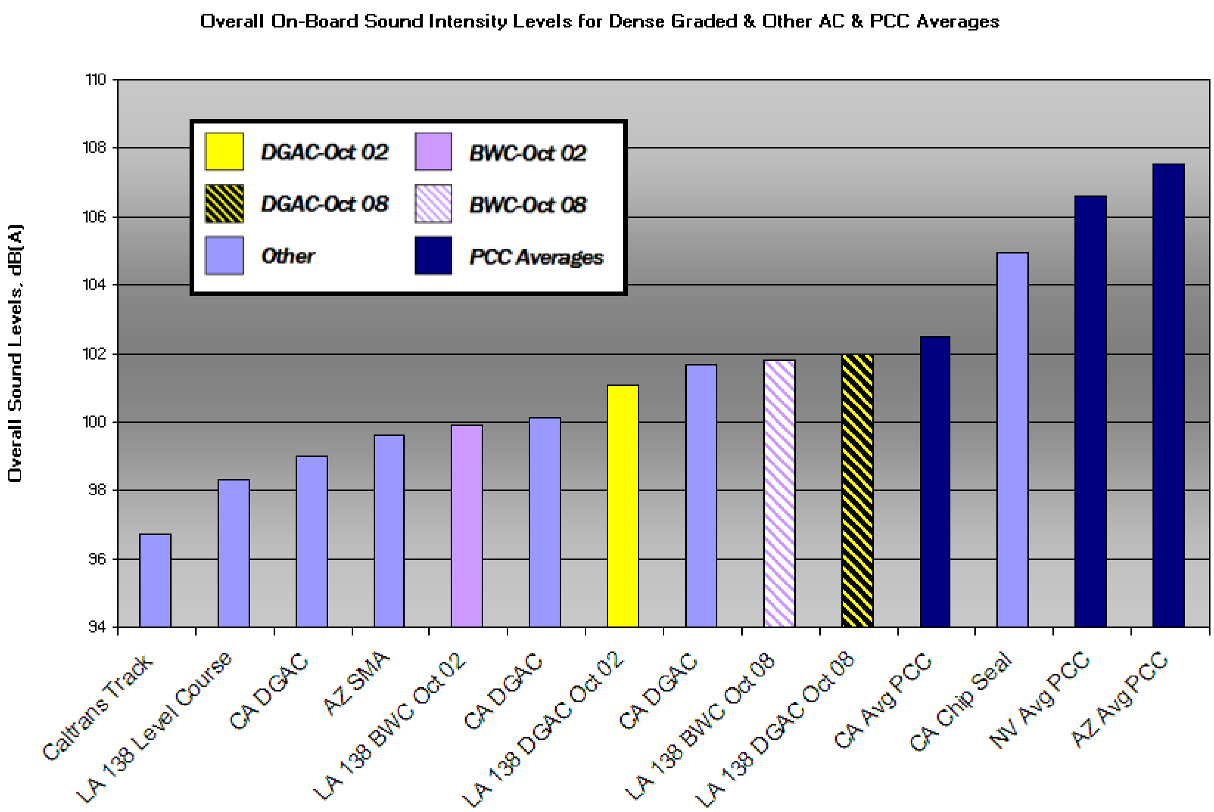


Figure 5.19. Overall A-Weighted OBSI Levels for Dense Graded and Other AC Pavements, as well as PCC Averages

Comparisons of the LA 138 OGAC pavements to other OGAC pavements of varying age are provided in Figure 5.20. In this case, the new LA 138 pavements were noticeably lower than the other OGAC pavements. However, as the pavements have aged, the levels have become more typical of other OGAC pavements. Even as these levels have increased, they still remain 2 dB or more lower than that the CA PCC average. It should also be realized that within the OGAC category, there were actually two other groupings, porous and non-porous. Porous pavements are typically considered to have air avoid ratios of 20% or more. Acoustically, these porous pavements are distinguishable by a "dip" in the spectrum at 1600 Hz, as shown for the three OGAC pavements identified as porous in Figure 5.21. The OGAC from LA 138, as well as that from SM I-280 (on the shoulder), did not reveal such a dip, and the levels decreased more uniformly as the frequency increased. Below 800 Hz, the porous pavements had higher levels than the non-porous due the larger aggregate size, which tends to increase the porosity.

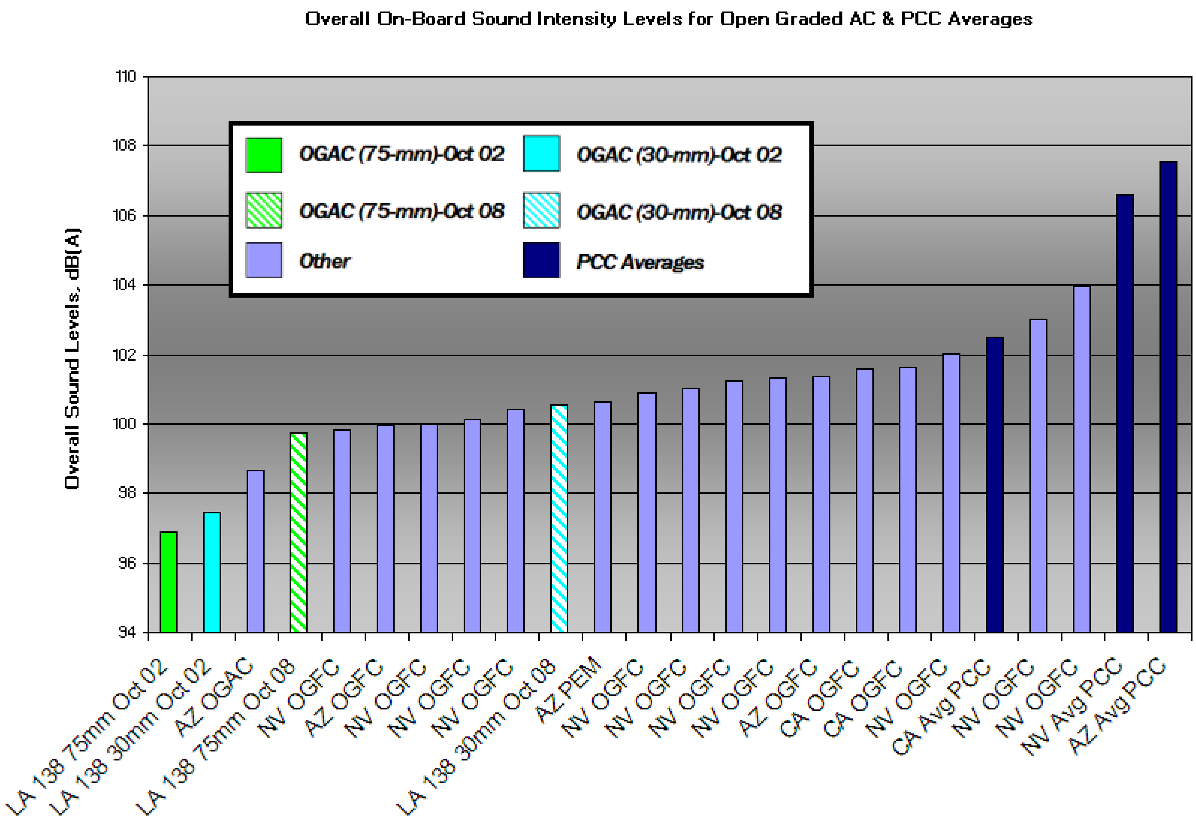


Figure 5.20. Overall A-Weighted OBSI Levels for Open Graded AC and PCC Averages

Comparisons of the LA 138 RAC(O) pavements to other rubberized asphalt pavements are provided in Figure 5.22. As a group, these pavements tend to be quieter than the OGAC pavements even though they also cover a wide range of age, with the oldest being an AZ ARFC constructed in 1990 at 97.5 dB(A). For the LA 138 section, when new, this was only just in the range of other rubberized AC pavements. By 2008, it was more toward the higher end of the RAC(O) pavements though still almost 3 dB lower than the CA PCC average. As was the case with the OGAC pavements, the RAC(O) pavements could also be divided into porous and non-porous classifications. This was again apparent in the spectra (Figure 5.23), which also show a dip at 1600 Hz. Furthermore, the porous RAC(O) pavements showed elevated levels for frequencies below 800 Hz relative to the non-porous, similar to the OGAC pavements. The SM

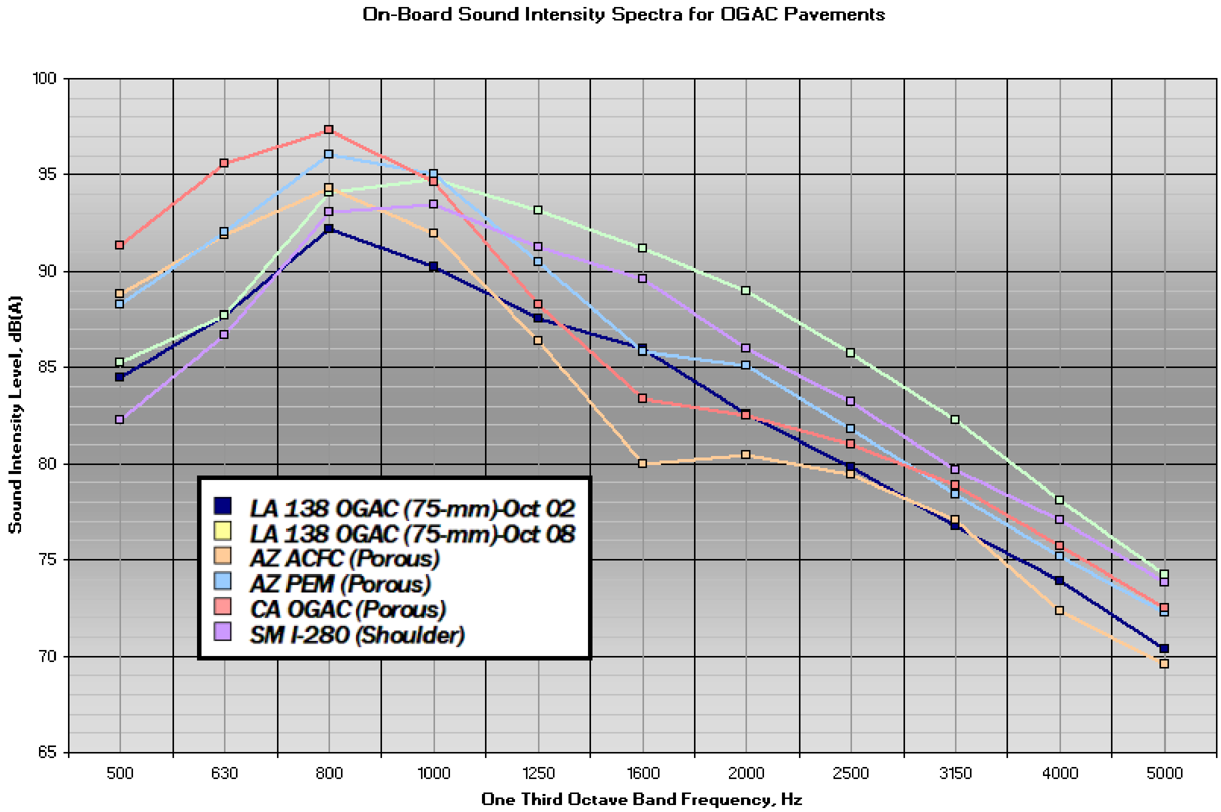


Figure 5.21. One-Third Octave Band Levels for Open Graded AC

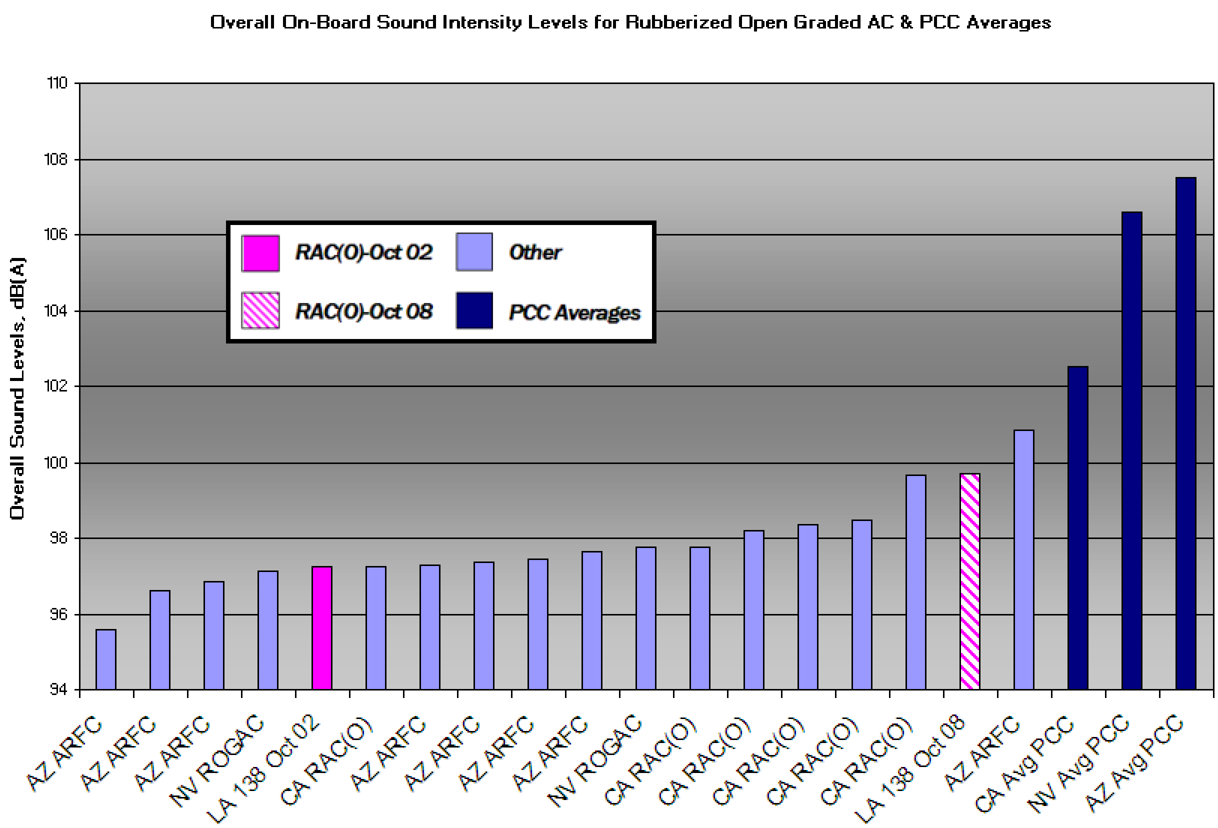


Figure 5.22. Overall A-Weighted OBSI Levels for Rubberized Open Graded AC and PCC Averages

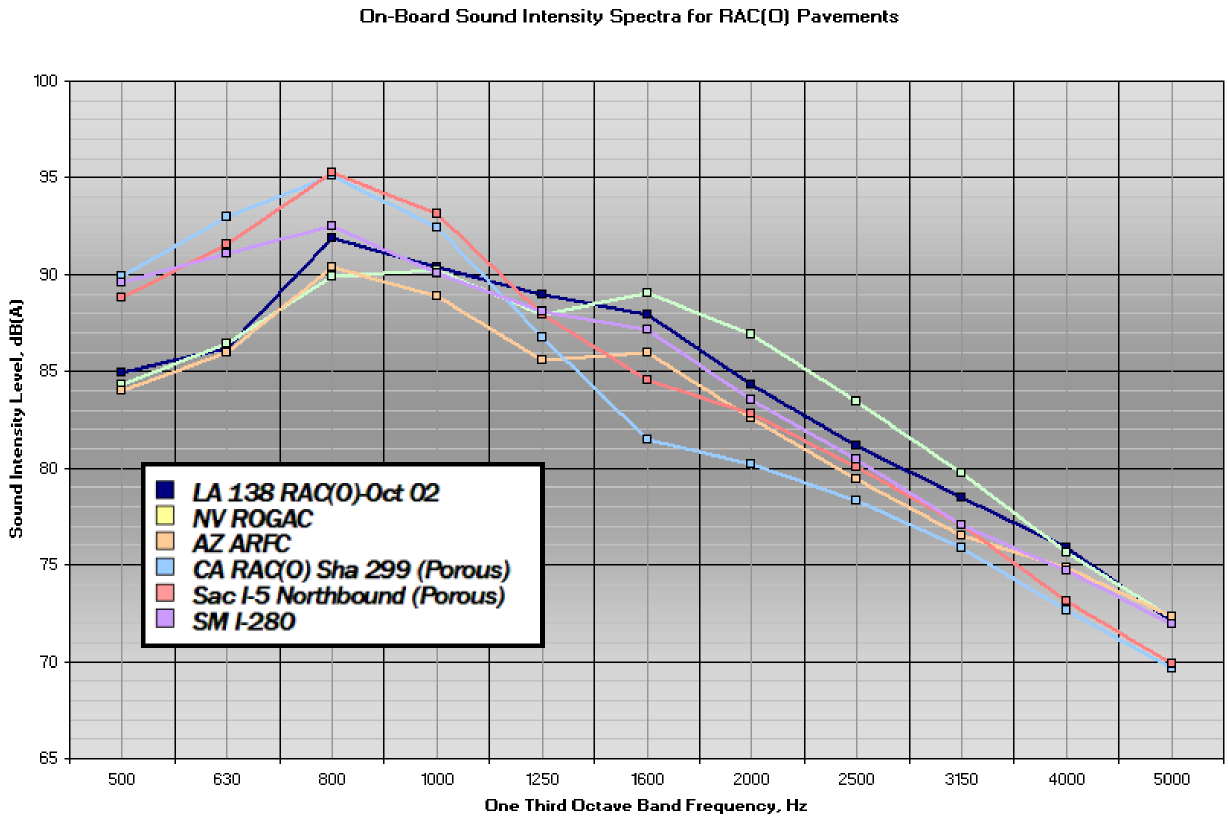


Figure 5.23. One-Third Octave Band Levels for Rubberized Open Graded AC

I-280 RAC(O) pavement, however, indicated an exception to this observation. Although the LA 138 results did not suggest this, it appeared that as a category, lower noise performance was achieved with the rubberized AC even with aging.

Temperature Effects

Air temperatures during OBSI measurements were recorded in January 2005 and every subsequent testing period. As the OBSI measurement technique became more developed, the environmental effects on the measurement results began to be a concern. Weather conditions were available from the National Weather Service beginning in October 2003. Based on review of recorded air temperatures monitored during the measurement periods and reports available from the National Weather Service, an air temperature was assigned to each OBSI measurement under the baseline measurement condition (i.e., with the Aquatred test tire at 60 mph as discussed in the previous sections). Based on the available information, air temperatures ranged from 50 ^{o}F to 95 °F for the twelve baseline measurements where data was available. The relationship between the overall A-weighted OBSI levels and air temperature for the five pavement sections is plotted in Figure 5.24 for the Aquatred test tire.

No clear correlation between air temperature and OBSI level was indicated by the data. Considerable scatter was present in the data set, with r^2 values ranging from 0.003 to 0.262 as the data also include the effect of aging. Even with this confounding factor, the data do indicate a decrease in level with increasing temperature consistent with that observed in many previously

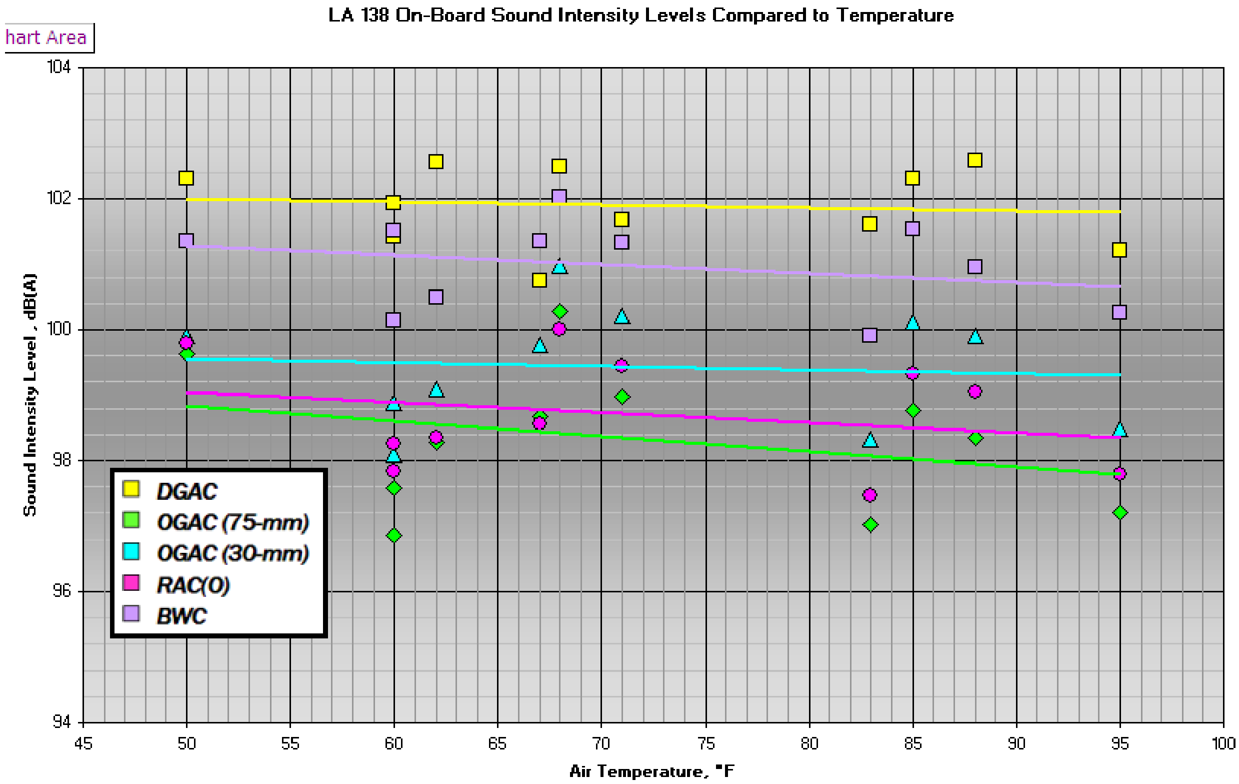


Figure 5.24. Overall A-Weighted OBSI Levels Compared to Air Temperature Along Each Test Pavement with the Subaru Test Vehicle and the Goodyear Aquatred 3 Test Tire, October 2003

published results[12,13,14,15]. However, given the uncertainties due aging effects, no specific OBSI/temperature relationship can be cited from these data.

CHAPTER 6

MEASUREMENTS AND RESULTS FOR OCTOBER 2009 AND 2010

Description of Testing

In October 2009 and 2010, further OBSI measurements were conducted to document the acoustic longevity of the LA 138 test sections through 8 years since their construction. On October 16, 2009, measurements were made with the Aquatred 3 test tire consistent with the data from the beginning of the project in 2002. Measurements were also conducted with an SRTT (#1) which had been used for testing since 2006. During the testing, the air temperature ranged from 78 to 83ºF. On October 14, 2010, measurements were conducted again with both tires with the air temperature ranging from 86 to 75ºF. All measurements were conducted using the two-probe system and the Chevrolet Malibu test vehicle (Figure 3.1b).

In between the time of the 2007 and 2010 measurements, the pavements show only minimal effects of aging based photographs of the surfaces as documented in April 2008 and October 2010 (Figures 6.1 through 6.5). For Sections 1 through 4, it appears as if some additional fines

Figure 6.1: Photographs of DGAC pavement at Section 1 in 2008 (left) and 2010 (right)

Figure 6.2: Photographs of 75mm OGAC pavement at Section 2 in 2008 (left) and 2010 (right)

in the surface have been lost possibly producing slightly more texture as some aggregate becomes more exposed. It is also likely that some more polishing of the aggregate has occurred in the 2½ years, however, this is difficult to detect from the photographs. For Section 5, the bonded wearing course, the surface appears unchanged.

Figure 6.3: Photographs of 30mm OGAC pavement at Section 3 in 2008 (left) and 2010 (right)

Figure 6.4: Photographs of RAC(O) pavement at Section 4 in 2008 (left) and 2010 (right)

Figure 6.5: Photographs of BWC pavement at Section 5 in 2008 (left) and 2010 (right)

Results for Goodyear Aquatred 3

The overall A-weighted OBSI levels for the five test pavements as measured in 2009 and 2010 are shown in Figure 6.6 along with the October data from 2002 through 2008. Through 2010, the rank ordering of the pavements has remained approximately the same although the performance gaps between the OGAC, RAC(O), and BWC surfaces and the DGAC are now smaller. For OGAC and RAC(O) pavements, the levels are now within about 1 to 2 dB of the DGAC while for the BWC, the levels are higher than the DGAC. For the two quietest pavements, the OGAC 75mm thick and the RAC(O), the initial ranking of the OGAC being slightly quieter has almost reserved with the RAC(O) now being equal to or even slightly quieter than the OGAC.

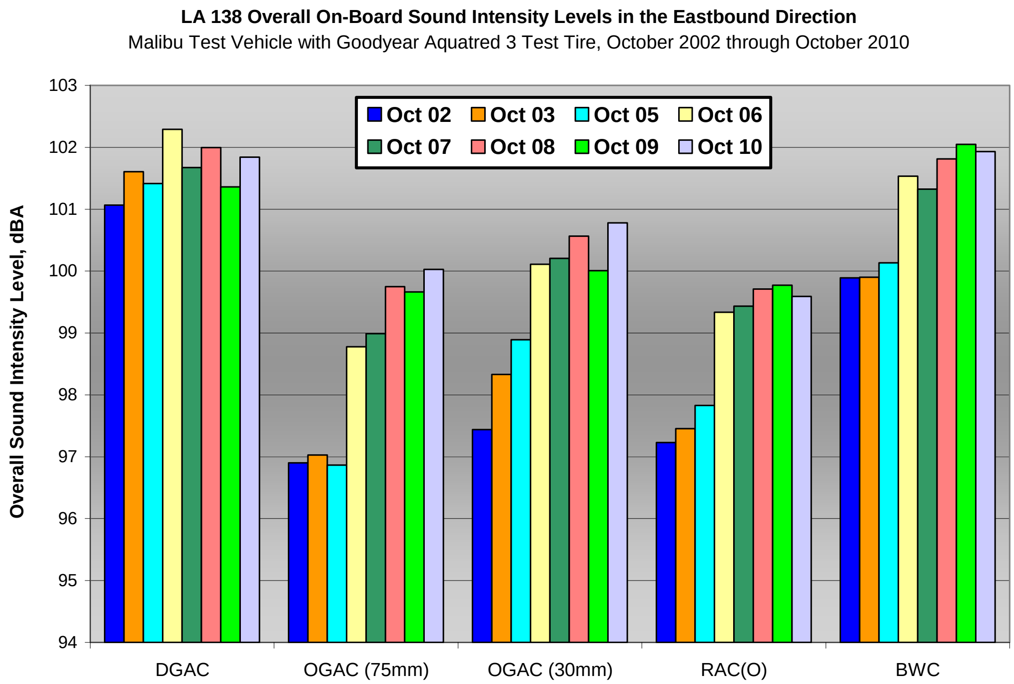


Figure 6.6. Overall A-Weighted OBSI levels for each test pavement from October 2002 through October 2010

As may be expected from Figure 6.6, there is little change in the one-third octave spectra for the DGAC of Section 1 as shown in Figure 6.7. The highest levels actually occur in 2006, however, the after 2006, the levels virtually overlay. For the two OGAC sections (2 & 3), the spectra

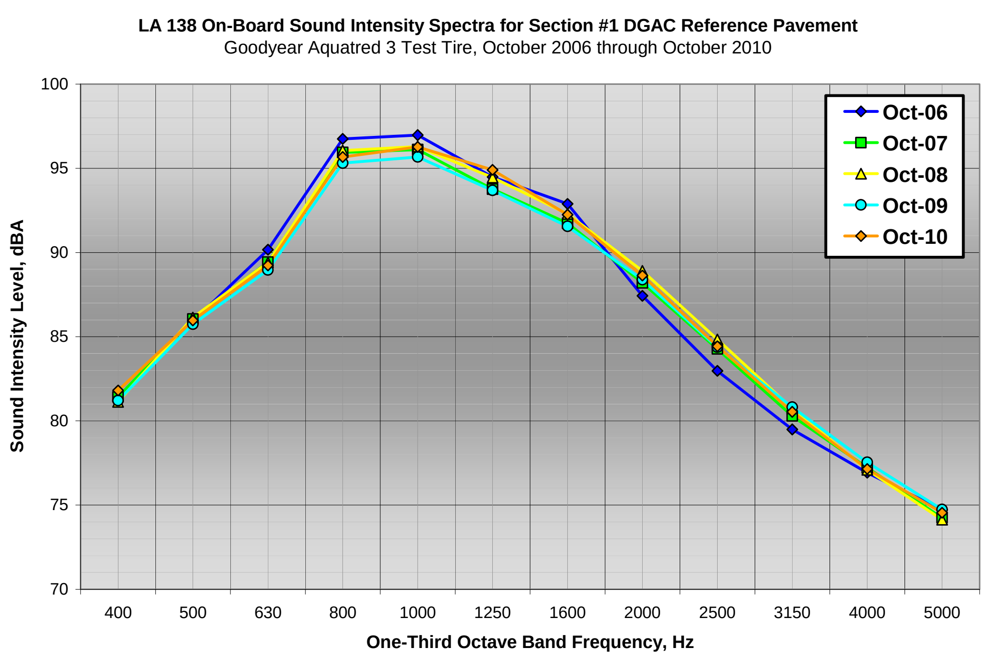


Figure 6.7. One-third octave band levels for DGAC Section 1 pavement from October 20062 through October 2010

as shown in Figures 6.8 and 6.9, respectively, display some increase with pavement age particularly for 1000 Hz and above. By 2010, individual one-third octave levels in this

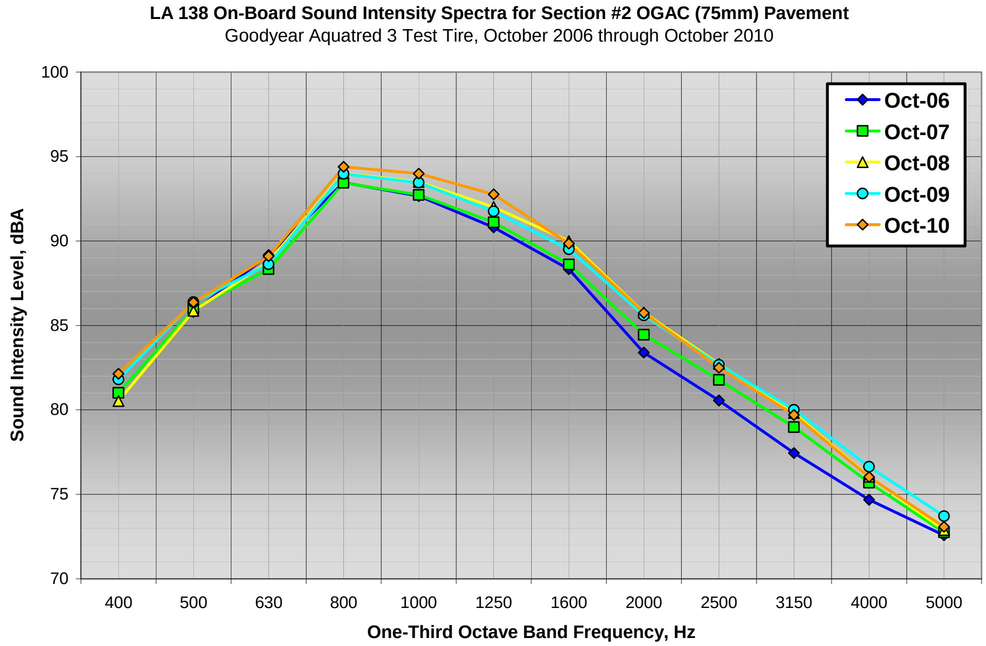


Figure 6.8. One-third octave band levels for 75mm OGAC Section 2 pavement from October 2006 through October 2010

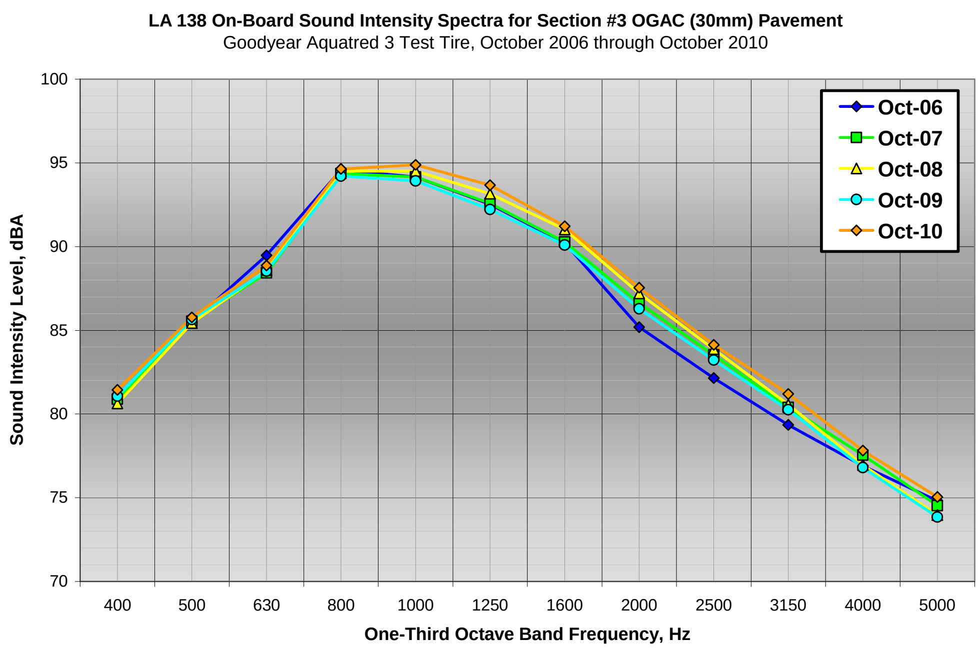


Figure 6.9. One-third octave band levels for 30mm OGAC Section 3 pavement from October 2006 through October 2010

frequency range have increased by about 1 to 2 dB over the four year span. For the RAC(O) (Figure 6.10), other than the 2006 levels, the 2007 to 2010 data above 630 Hz are nearly identical

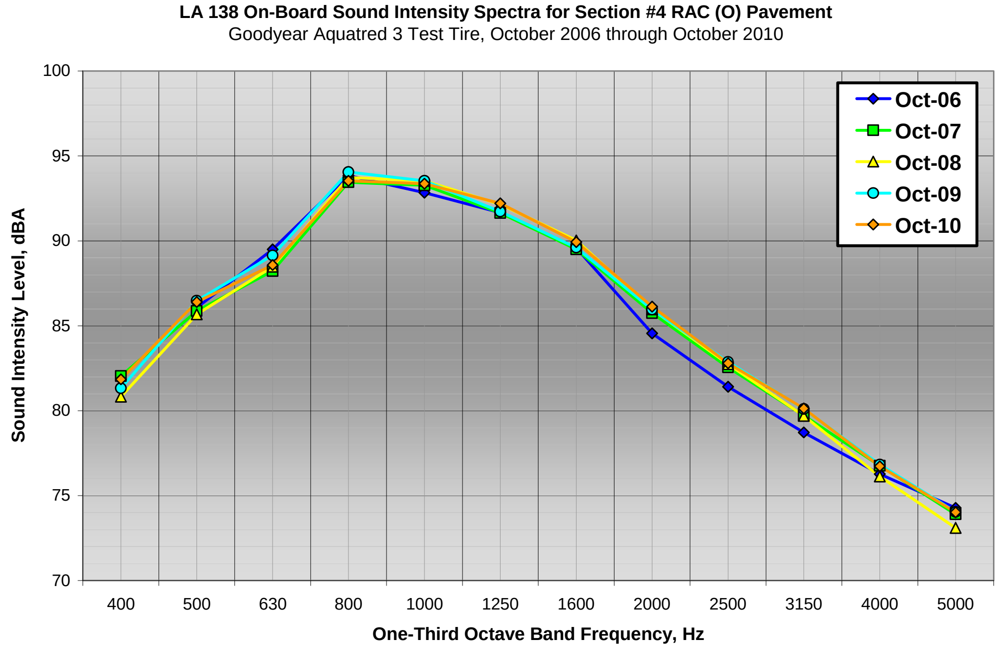


Figure 6.10. One-third octave band levels for RAC(O) Section 4 pavement from October 20062 through October 2010

with individual band differences of less than 1 dB. At 630 Hz and below, these is a little more scatter in the results (~1½ dB), however, the later data are not necessarily higher. The results for the BWC pavement of Section 5 as shown in Figure 6.11 are similar to those of the OGAC pavements with most of the increases in level with time occurring at 1000 Hz and above.

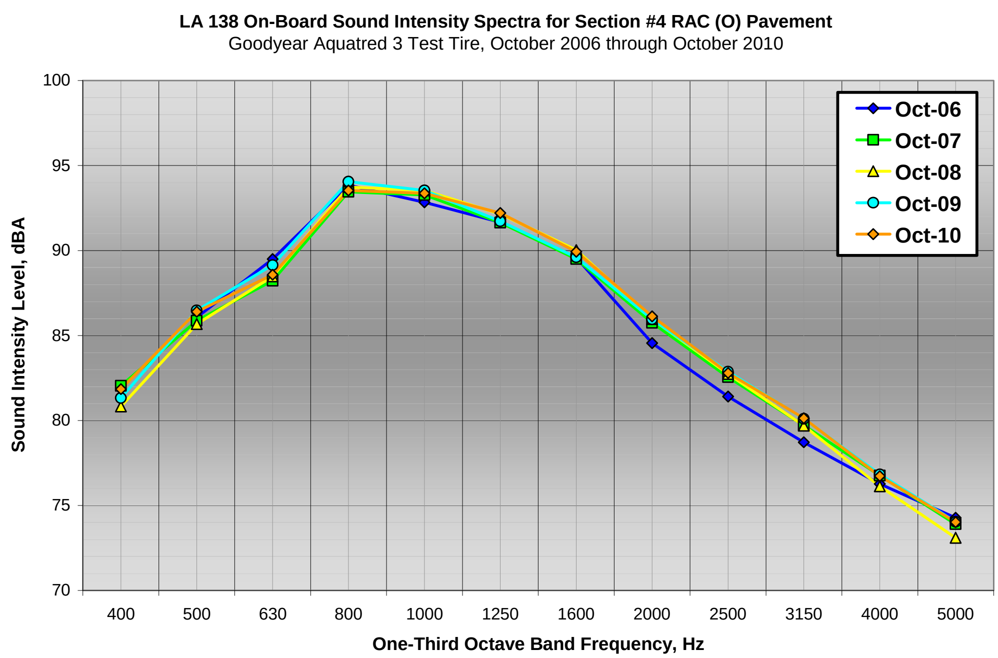


Figure 6.11. One-third octave band levels for BWC Section 5 pavement from October 20062 through October 2010

The linearized rates of overall A-weighted OBSI level versus time since construction are in Figure 6.12 for the five different pavements. Of these, the lowest rate, 0.06 dB/year belongs to

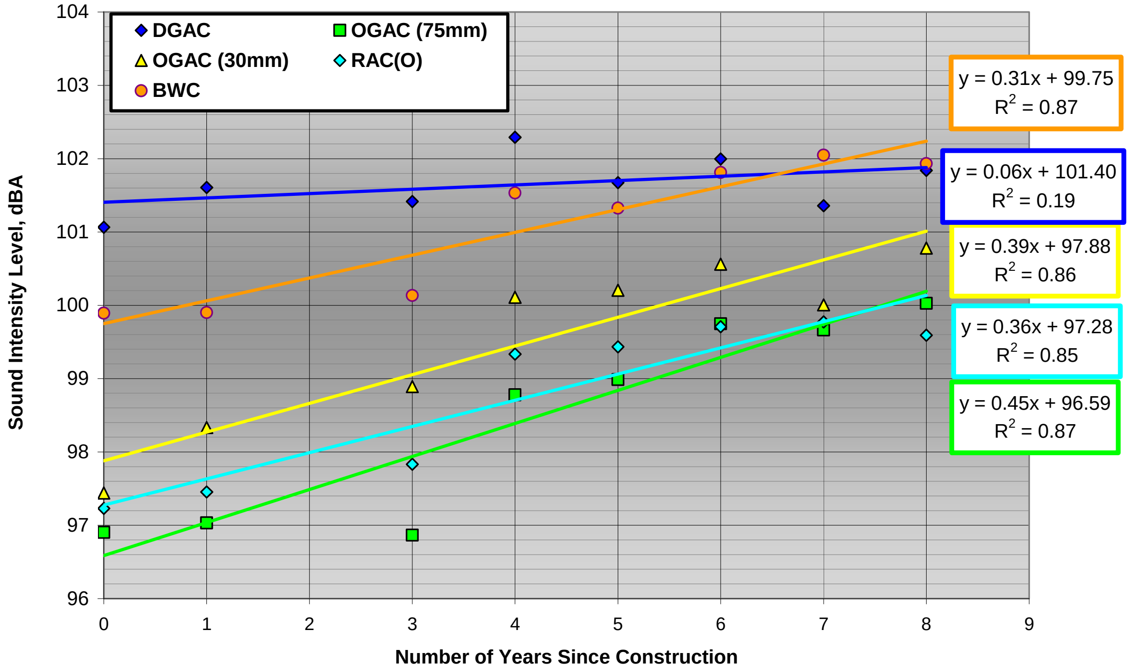


Figure 6.12. Overall A-Weighted OBSI levels for each test pavement from October 2002 through October 2010 versus years since construction

the DGAC pavement. This rate is actually more consistent with PCC pavements that were found to be in the range from 0.08 to 0.13 dB/year from the Mojave Bypass PCC test sections[16]. Other AC pavements fall into a range from 0.31 to 0.45 dB/year which are more typical of rates reported in the literature[17]. Of the quieter pavements, the RAC(O) pavement had the best acoustic longevity performance at 0.36 dB/year while the initially quietest pavement, the 75mm thick OGAC on Section 2, had the worst at 0.45 dB/year. The RAC(O) rate is also close to the 0.33 dB/year rate that has been measured for the Arizona Department of Transportation asphalt rubber friction course over a period of 8 years in ADOT's Casa Grande AC research test sections[18].

Results for the ASTM Standard Reference Test Tire

As indicated in Table 3.1, the SRTT has been used in LA 138 OBSI testing since 2006. With the completion of the 2010 measurements, this tire has been tested enough to consider longevity trends unlike what could be done through the end of the 2008 testing. The overall A-weighted levels for five test events are shown in Figure 6.13 for the five pavement sections. Although the generally the results for the SRTT between 2006 and 2010 appear similar to those for the Aquatred, there are some specific differences in the behavior of the tire noise levels from these tests. For the SRTT, the levels measured in 2010 are consistently higher than the other years, typically on the order 1 dB or more. For the Aquatred (Figure 6.6), the levels are relatively much closer to the other years, generally within a few tenths of 1 dB of the 2008 and 2009 data.

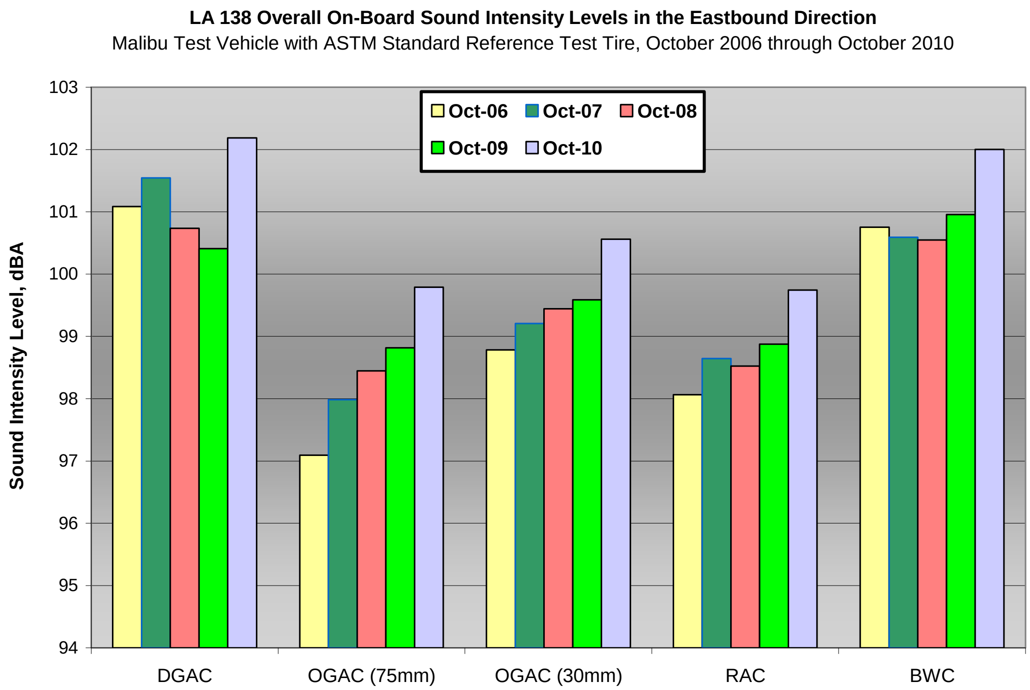


Figure 6.13. Overall A-Weighted OBSI levels for each test pavement from October 2002 through October 2010 measured with tire SRTT #1

In comparing the range between 2006 and 2010, it is much greater for the SRTT, particularly on the quieter pavements. For the 75mm OGAC, the levels for the SRTT increased almost 3 dB over the four year span, while for the Aquatred, it was only slightly more than 1 dB. For the other two pavements, the increase from 2006 to 2010 for SRTT was more than double that for the Aquatred. For the 2006 to 2010, the testing of the two tires was done on a single day under similar conditions so that measurement uncertainty should be minimal.

The one-third octave spectra for the DGAC Section 1 pavement with the SRTT as shown in Figure 6.14 display more variation than that obtained with the Aquatred (Figure 6.7) as would be expected from the overall levels of Figure 6.13. The range of difference is more typically about 2 to 2 ½ dB with the 2010 levels being higher. As with the overall levels, the differences year-to-year do not increase consistently with age. For the years from 2007 to 2010, the levels with the SRTT show considerably more variation than the corresponding Aquatred results. For the SRTT on the other four pavements (Figures 6.15 through 6.18), the one-third octave levels show a more consistent upward trend with pavement age following the overall level trends of Figure 6.13. For the quieter pavements, magnitude of the increase for the SRTT is greater than for the Aquatred, particularly in the frequency range from 800 to 1600 Hz. This may be caused by the SRTT generally being a quieter tire than the Aquatred. Other research has shown that difference between these tires increases with quieter pavements likely due to tread design differences controlling more the source levels[19]. For noisier pavements, the pavement tends to increasing control the source levels. For the LA 138, as the pavement ages, some of this behavior may be occurring. This conjecture is somewhat supported by the spectral comparisons on the quieter LA 138 surfaces as illustrated by the results shown in Figure 6.19 which compares the results for both tires in 2007 and 2010 on the 75mm thick OGAC. Typical of the 30mm OGAC and the

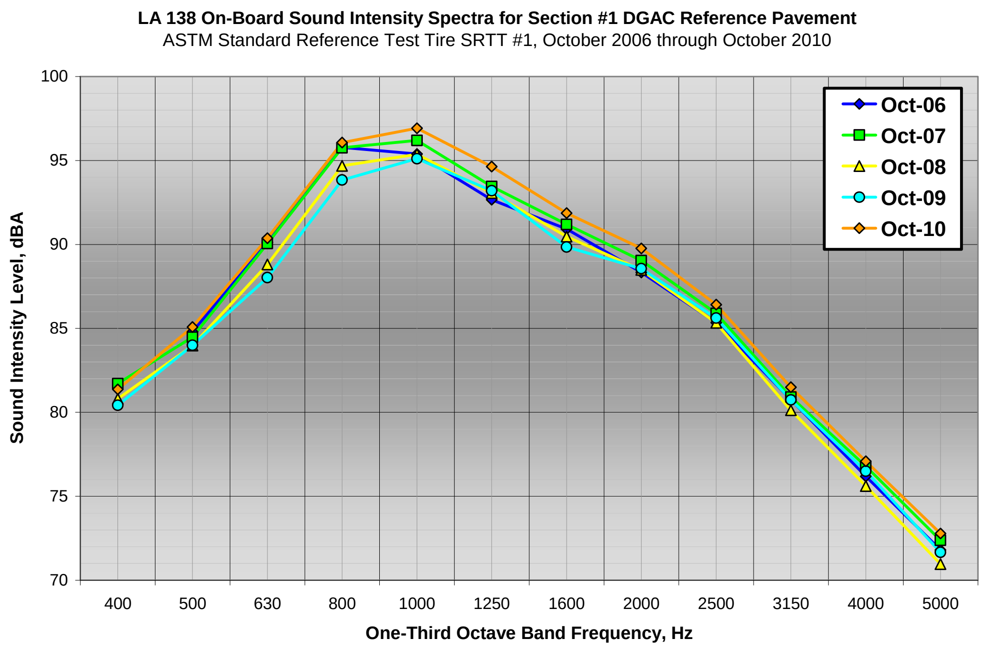


Figure 6.14. One-third octave band levels for DGAC Section 1 pavement from October 2006 through October 2010 measured with SRTT #1

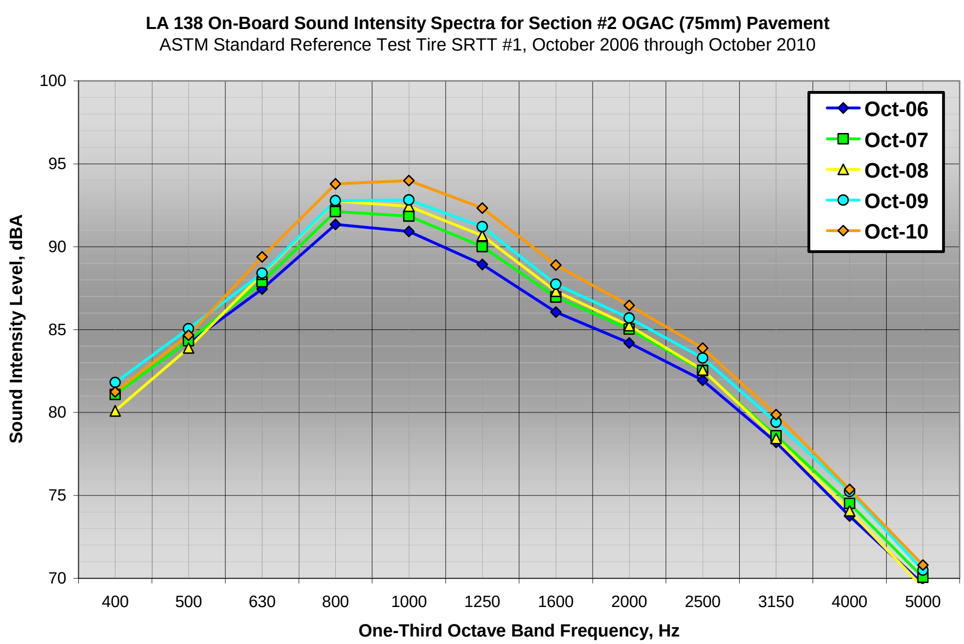


Figure 6.15. One-third octave band levels for 75mm OGAC Section 2 pavement from October 2006 through October 2010 measured with SRTT #1

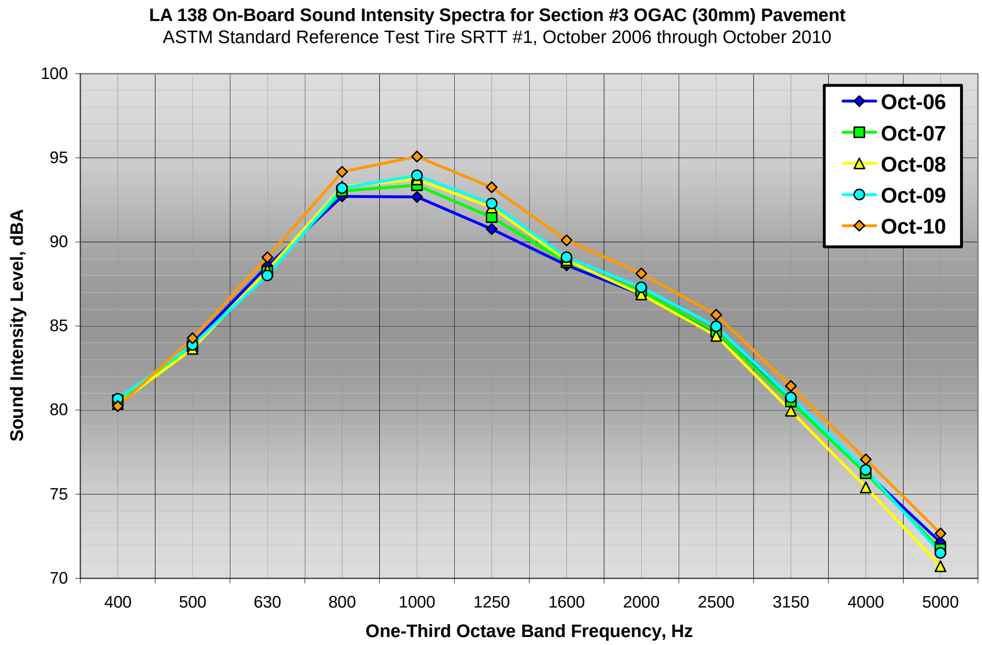


Figure 6.16. One-third octave band levels for 30mm OGAC Section 3 pavement from October 2006 through October 2010 measured with SRTT #1

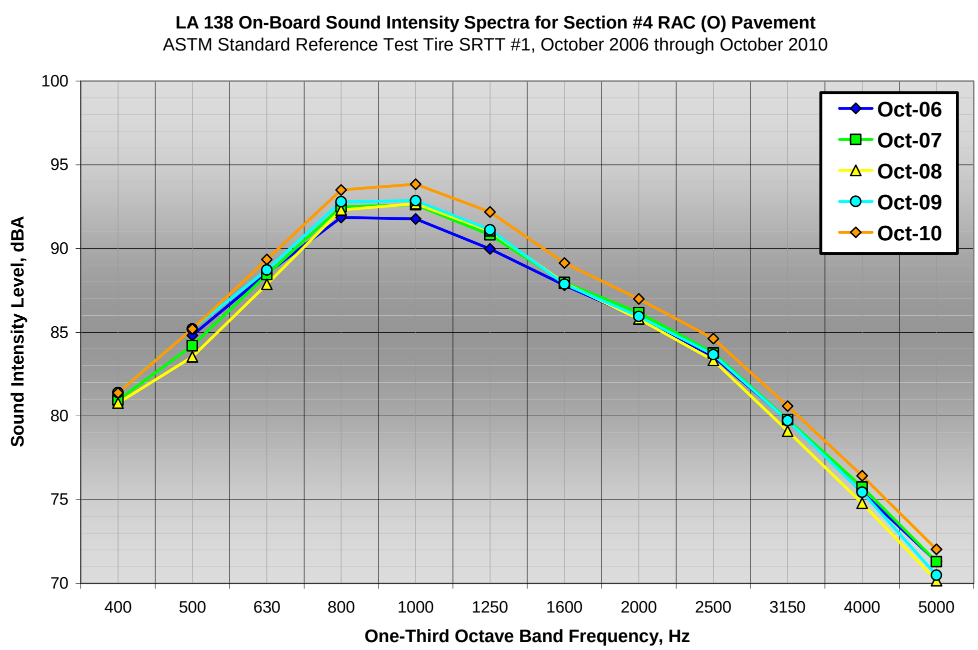


Figure 6.17. One-third octave band levels for RAC(O) Section 4 pavement from October 2006 through October 2010 measured with SRTT #1

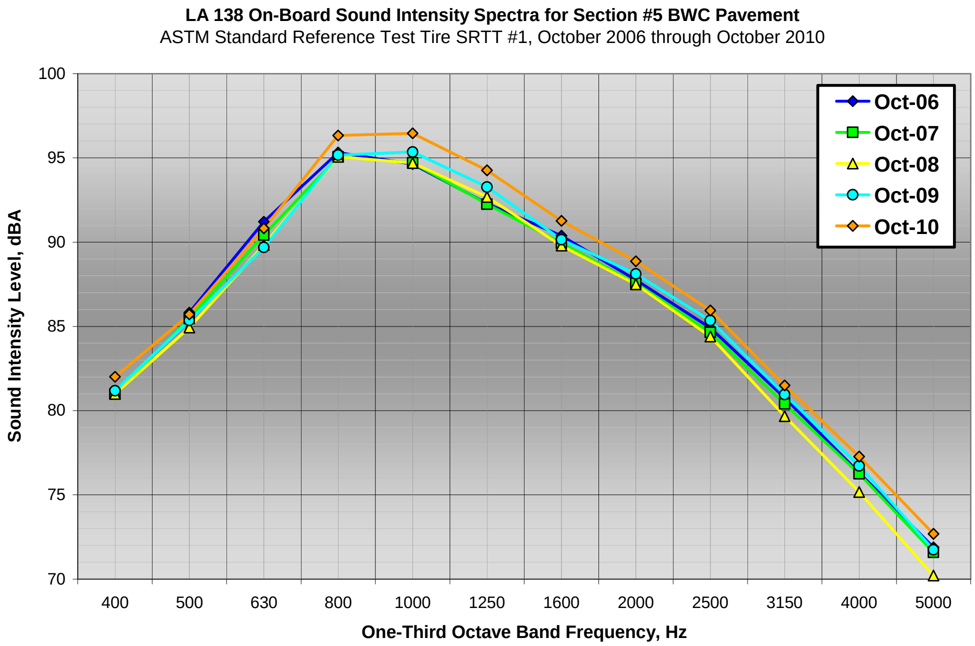


Figure 6.18. One-third octave band levels for BWC Section 5 pavement from October 2006 through October 2010 measured with SRTT #1

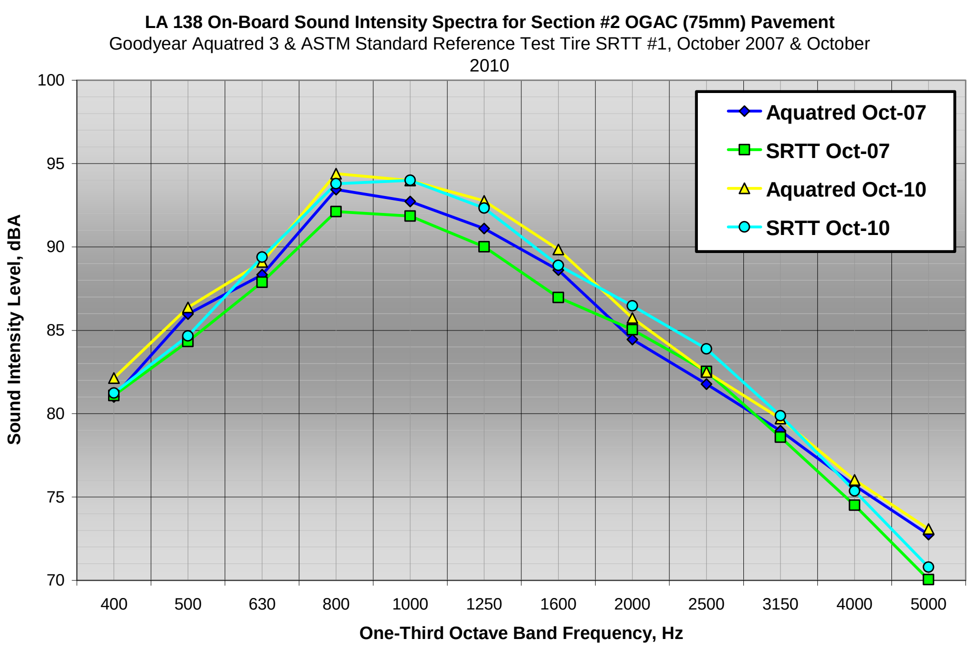


Figure 6.19. One-third octave band levels for 75mm OGAC Section 2 pavement from October 2007 and 2010 measured with the Aquatred and SRTT #1 test tires

RAC(O), in the earlier testing, the spectral differences between the two tires are greater while in 2010, the levels are identical in the range from 630 to 1250 Hz.

Even with the differences between the tires, the linearized trends of OBSI level with time are similar for the two tires. The rates for the SRTT are shown in Figure 6.20 for comparison to those of the Aquatred in Figure 6.12. The SRTT rates are the same or within 0.05 dB/year for all

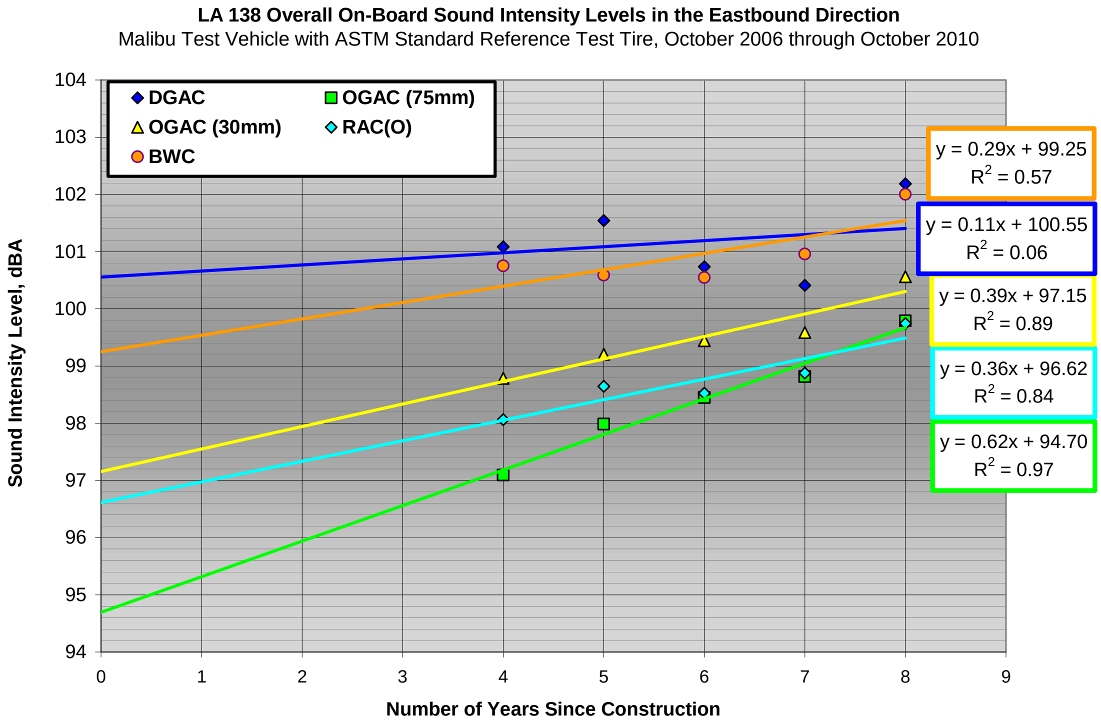


Figure 6.20. Overall A-Weighted OBSI levels for each test pavement from October 2002 through October 2010 versus years since construction as measured with SRTT #1

but the 75mm OGAC of Section 2. For Section 2, the rate with SRTT is greater by 0.17 dB/year which may be a result of the lower levels of this pavement when it was newer. For both tires, by 2010, the levels for the 75mm OGAC have increased to the point that the RAC(O) is slightly quieter.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

Tire/pavement noise measurements were made on five (5) pavement sites on LA 138, near Lancaster, California, between October 2002 and October 2010. Pavement sections included a dense grade asphalt (DGA), two overlay sections of open graded asphalt concrete (OGAC) (75-mm in thickness and 30-mm in thickness), an open graded rubberized asphalt concrete (RAC[O]), and a bonded wearing course (BWC). Principal findings developed from this data set (and those reported in the Appendices) are described below.

Pavements

- The DGA pavement was generally the loudest of the five test sections, resulting in overall OBSI levels of about 1 dBA higher than the BWC and about 4 dBA higher than the OGAC and RAC(O) pavements during the earlier years of the study. The 75mm OGAC pavement resulted in the lowest noise level, although both 30mm OGAC pavements and the RAC(O) surface resulted in levels within 0.5 dBA.

- The new OGAC and RAC(O) pavements on LA 138 were in the lower range of the pavements measured to date. The new BWC and DGA pavements were within the mid range of AC pavements and below levels generated by typical PCC sections.

- Concentrating on yearly October test data, the overall OBSI levels were found to increase at rates for the different pavements ranging from 0.06 dB/year for the DGAC to 0.45 dB/year for the 75mm OGAC with the Aquatred test tire. Similar behavior was found for the acoustic longevity data from the SRTT from 2006 to 2010 with the exception for 75mm OGAC for which rate increased at significantly higher rate of 0.62 dB/year.

- Taking into consideration the general increase in level with aging, the sound intensity spectra for the Aquatred tire have remained similar over the eight years of testing with somewhat larger increases occurring in the frequency range from 800 to 1600 Hz. Similar trends were found for the SRTT over the period from 2006 to 2010.

Process

- Generally, OBSI levels were found to decrease with air temperature, however, the results are insufficient and confounded with effects of pavement age and seasonal variation such that no clear relationships between OBSI and air temperature could be defined.

- Ten different test tires, including the Goodyear Aquatred 3, a Uniroyal Tiger Paw AWP, a Firestone FR380, a Mastercraft Glacier Grip, a Michelin RainForce, two different SRTT tires, a blank tread tire, and a straight ribbed tire, were found to consistently rank the five pavement sections by overall A-Weighted OBSI level, with the westbound DGA section resulting in the highest levels and the eastbound 75mm OGAC resulting in the lowest levels.

- Correlation between OBSI and controlled pass-by was demonstrated with pass-by level found to be predictable from OBSI to within standard deviations of 0.6 to 0.7 dB using offsets of about 24 dB for pass-by measurements made 25ft from the center of the lane of travel and about 31 dB for 50ft. The spectral comparisons were also found to correlate well between OBSI and pass-by results on an individual one-third octave basis producing standard deviations of 1.2 dB at 25ft and 1.6 dB at 50ft over the entire measurement from 400 to 5000 Hz.

- The overall A-Weighted OBSI level differences between the single probe measurement configuration installed on the Subaru test vehicle and the dual probe fixture installed on the Malibu test vehicle with a different Aquatred tire were negligible. As a result, no additional considerations were necessary for comparing overall OBSI levels before and after the transition to the dual probe configuration.

- Overall A-Weighted OBSI levels were within 1.1 dBA for six different SRTT tires for all of the individual test sections.

- For SRTT tires covering a 4 year span in age, no consistent trends of the tire noise versus age or tire durometer hardness (62 to 66 hardness numbers) was found. No consistent difference between new tires and those that had been in service for up to 1300-mi could be found. The need for a tire warm-up before testing also was not established.

- CPX data were found to correlate reasonably well with both OBSI and controlled passby data on an overall level basis even though the difference in levels between the reference DGAC and three OGAC surfaces were greater for the CPX data than for either the OBSI or passby results.

- CPX spectra were found to be distorted compared to the OBSI and passby spectra, likely due to standing waves inside the trailer enclosure.

- The Goodyear Wrangler tire has some attributes of heavy duty truck tires that may support it for further investigation as a truck tire surrogate test tire if it is determined that such an additional test tire is needed.

In addition to the above findings, several recommendations are advanced based on this work. These include:

- As a minimum, OBSI measurements should continue at least on a yearly basis in October until the pavements are replaced. Acoustic longevity of quieter pavement is and will be increasingly important in regard to comparing noise abatement options such as sound walls and quieter pavement. Caltrans already has a considerable investment in these research sites in terms of documenting acoustic performance over time which can not replicated for many years.

- Any future pavement acoustic longevity studies should be designed recognizing that the duration may be as long as the service life of the pavement itself. Although the SRTT is now place as the standard test tire, contingency plans should be made up-front for future

- Although OBSI has been shown to be the preferred method of choice for isolating the performance of pavement for tire noise generation, for future acoustic longevity studies, some statistical pass-by testing should be included in the program plan. Unlike OBSI, statistical pass-by data are not tied to a specific test tire(s) and should be more immune to changes over time, particularly for 25ft measurement distances. Intervals of repeat statistical pass-by measurements should be considered on the order of once every 3 or 4 years.

ACKNOWLEDGEMENTS

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APPENDIX A

APPENDIX B

APPENDIX C

APPENDIX D

APPENDIX A: SOUND PROPAGATION EVALUATIONS

As part of the examination of the relationship between OBSI and controlled passby data, measurements to assess sound propagation at each of the five LA 138 pavement test sites were made in October 2002 and again in October 2003. The second set of measurements used a more compact loudspeaker and is further described in this appendix.

Sound Propagation Measurement Method

The intent of the measurement arrange was to simulate the propagation of the sound from a tire to the passby microphones located at 25-ft and 50-ft from the center of the near lane of vehicle travel. To simulate a tire noise source, a 4-by-4 in. loudspeaker source was placed on the pavement at the centerline of the vehicle travel lane. Pink noise was fed into the speaker and broadcasted to the microphone locations used for the passby measurements. Figure A1 shows the loudspeaker positioned on LA 138 with respect to the microphone positions.

Figure A1. Sound propagation measurement set-up with the loudspeaker in the foreground and the pass-by microphones located at 25-ft and 50-ft

The source strength was determined at each pavement site by measuring the average sound intensity radiated through the plane of the speaker cone in the direction of the passby microphones. This was accomplished by means of a scanning method in which the OBSI probe swept over the face of the loudspeaker as close as possible without actually touching it. The source sound intensity was measured over a 20 second interval. Immediately afterward, the sound level at the two microphone locations was measured and recorded for later analysis. Once the recorded signals were reduced into one-third octave bands, sound attenuation levels were determined by subtracting the sound pressure levels measured at the 25-ft and 50-ft passby microphone locations from the measured sound intensity.

In addition to measuring the sound propagation at the passby microphones perpendicular to the roadway, measurements were also made parallel to roadway with the microphones positioned at 25-ft and 50-ft away from loudspeaker, forcing the sound propagation to take place entirely over the pavement (see Figure A2). The intent of these measurements was to examine any sound absorption differences between the test pavements. These measurements also served as references for comparison to those made perpendicular to the road that included unknown surface impedances and some geometric irregularity. For all measurements, the received levels at the 25-ft and 50-ft microphones were more 10 dB above the ambient levels over the range from 125 to 10,000 Hz.

Figure A2. Measurement Set-Up for Propagation Testing Entirely Over the Test Pavements with the Loudspeaker in the Foreground and the 25-ft and 50-ft Microphone Locations

Results and Discussion

The attenuation results, as measured entirely over the pavement and parallel to the roadway, are shown in Figure A3. At the 25 ft microphone location, the data for OGAC surfaces (Site 2 to 4) were quite similar with a typical range of about 1dB from 200 to 4000 Hz. In this same range, however, the results for the DGAC pavement were typically 1.4 dB lower than the average of the

OGAC surfaces corresponding to less attenuation (less sound absorption) than the OGAC surfaces. Although the reproducibly of these results was not examined in the LA 138 testing, measurements using the same procedure at the National Center for Asphalt Technology test track indicated that the attenuation values could be reproducible to ±1 dB. This suggests that the lower attenuation values over the DGAC pavement were beyond what would be expected for measurement-to-measurement variation. The trends of 25-ft data were more exaggerated at 50-ft with Site 1 being as much as 2.1 dB lower on average than the average of the OGAC pavements. These results are consistent with the higher air void ratios noted for the OGAC surfaces compared to the DGAC. The finding that the difference increases at 50 ft supports this in that the sound propagates even further over the pavements. The same cannot be said for the BWC pavement, however. Similar to the DGAC, the BWC surface was measured by UCPRC to have lower air void ratios than the OGAC surfaces. However, on average, there is very little difference in the attenuation values for the BWC surfaces and OGAC surfaces.

For the 25 ft microphone locations perpendicular (Figure A4) to the roadway in the passby measurement positions, the range for the OGAC surfaces was greater than that for propagation entirely over the pavement. Also, the DGAC was only slightly lower (1 dB) than the OGAC average. For this case, it is possible that some differences from site-to-site due to geometry and/or mixed ground impedances are obscuring the pavement differences especially since only a small portion of the distance between the source and receivers was over the asphalt. At 50 ft with even proportionally less propagation over the pavement, the difference between the OGAC surfaces and the DGAC are even less.

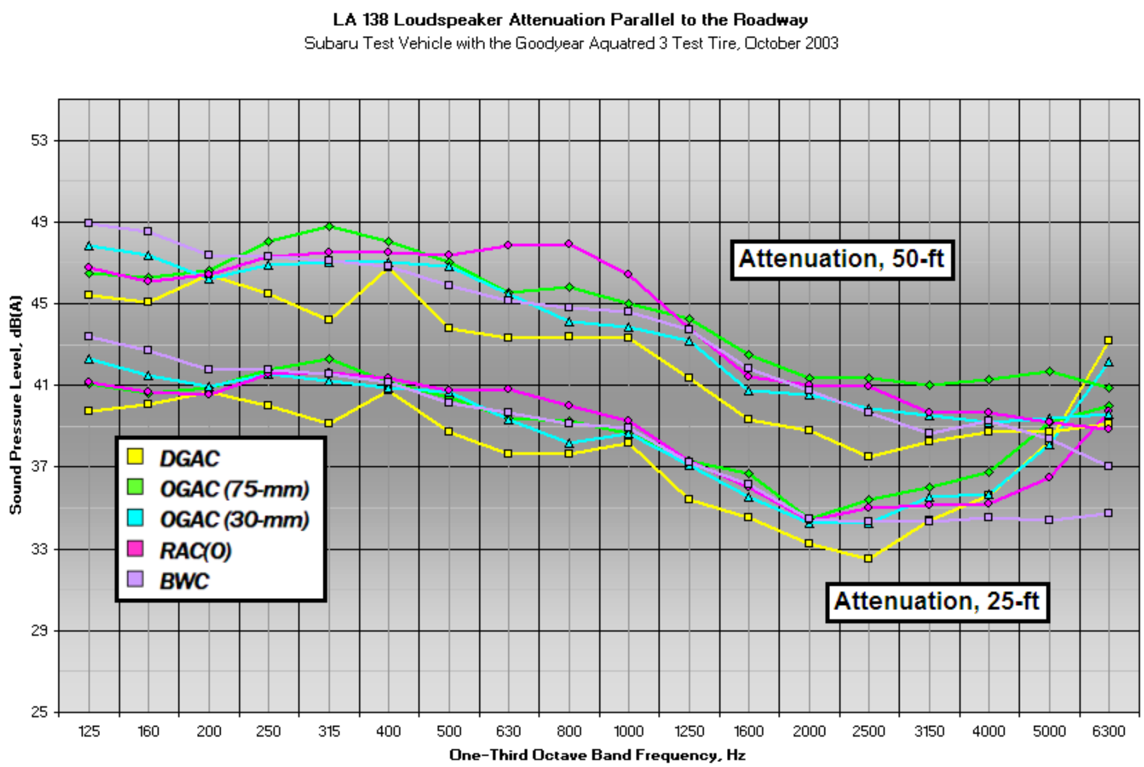


Figure A3. Attenuation of Sound Propagating from Roadway to 25-ft and 50-ft Microphones in the Parallel Direction for Each Test Pavement

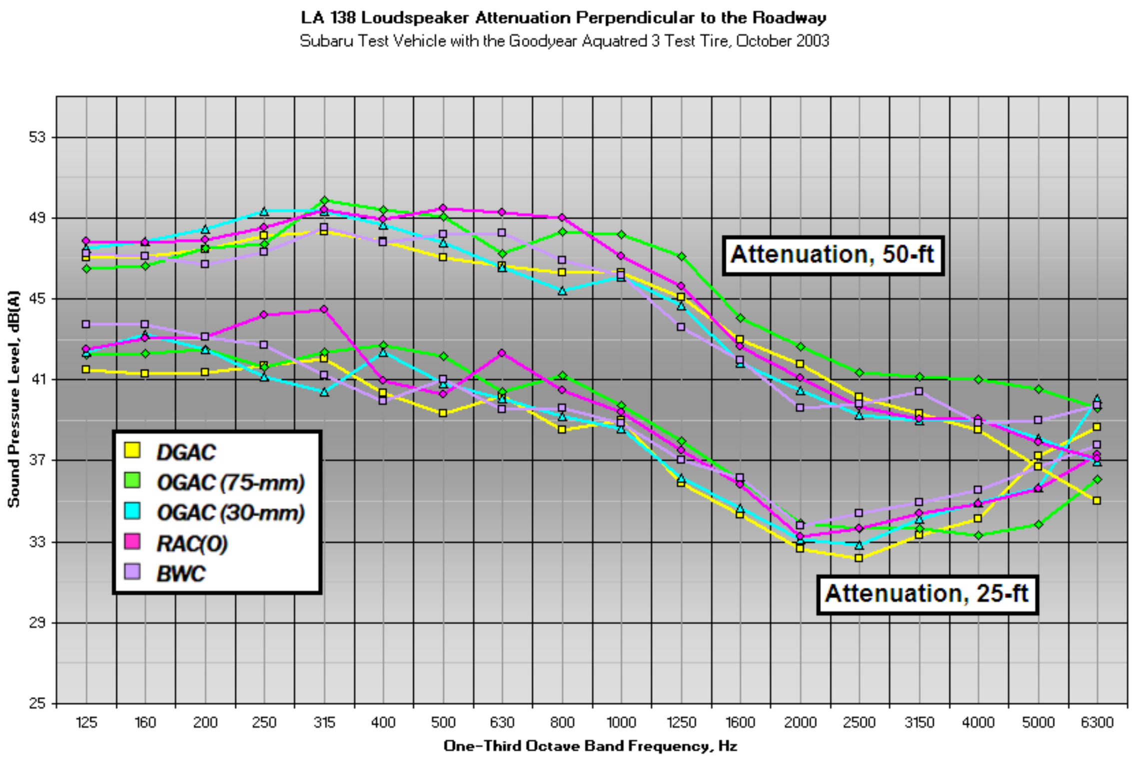
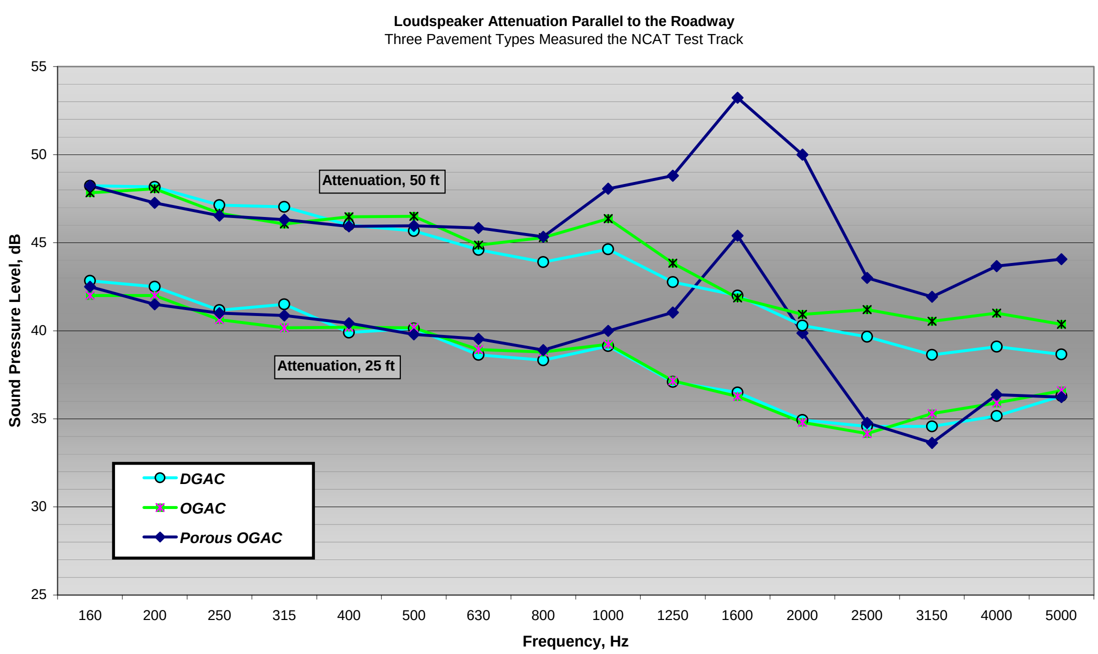


Figure A4. Attenuation of Sound Propagating from Roadway to 25-ft and 50-ft Microphones in the Perpendicular Direction for Each Test Pavement, October 2003

To the attenuation plots from LA 138 into perspective, it is useful to consider similar plots from measurements made at the NCAT test track. The measurement procedures were identical to those used on LA 138, however, measurements were made only over the pavement, parallel to the direction of travel. Shown in Figure A5 are the results for a DGAC, a relatively non-porous OGAC, and a porous OGAC. At 50 ft, the differences in propagation between the DGAC and non-porous are somewhat similar with the non-porous OGAC producing attenuations 1 to 2 dB higher the DGAC. For the porous OGAC, a remarkable amount of additional attenuation is indicated centered at 1600 Hz ⅓ octave band. At 25 ft, the attenuation at 1600 Hz is 9 dB greater for the porous pavement than that of the other pavement and at 50 ft, it is 11 dB greater. These results are quite consistent with those reported in the literature for sound propagation over porous pavements[1,2]. The finding that the non-porous OGAC has some small amount of additional attenuation relative the DGAC may be due a penetration of the sound into the upper surface of the OGAC causing either a small amount of sound absorption or some scattering of the reflected sound wave. In comparison to the LA 138 data of Figure A3, it is apparent that none of the OGAC test pavements were sufficiently porous to produce the excess attenuation measured at the NCAT test track, however, as a group, they did produce results similar to the less porous NCAT OGAC surface.

[1] Namikawa, Y. and Koshiba, T., "A Consideration on Noise Reduction Effect and Noise Reductions Mechanism of Two-Layer Asphalt Pavement", Proceddings of Inter-Noise 2004, Prague, Czech Republic, August 2004.
[2] Bérenger, M., Stinson, M., Daigle, G., and Hamet, J., "Porous Road Pavements: Acoustical Characterization and Propagation Effects', Journal of the Acoustical Society of America, 101 (1), January 1997, pp. 155-162.

Figure A5. Attenuation of Sound Propagating from Roadway to 25-ft and 50-ft Microphones in the Parallel Direction for Each Test Pavement, NCAT Test Track



APPENDIX B: COMPARISON OF TEST TIRES

For the OBSI testing conducted in October 2002, five test tires were used with the Subaru test vehicle and the single probe configuration setup. The tires consisted of the Goodyear Aquatred 3, Michelin RainForce, Mastercraft Glacier Grip, Firestone FR380, and Uniroyal Tiger Paw AWP (Figure B1). The OBSI test procedure described in the main part of this report was followed for each test tire. In addition, the controlled passby testing was also conducted in October 2002 for the RainForce test tire.

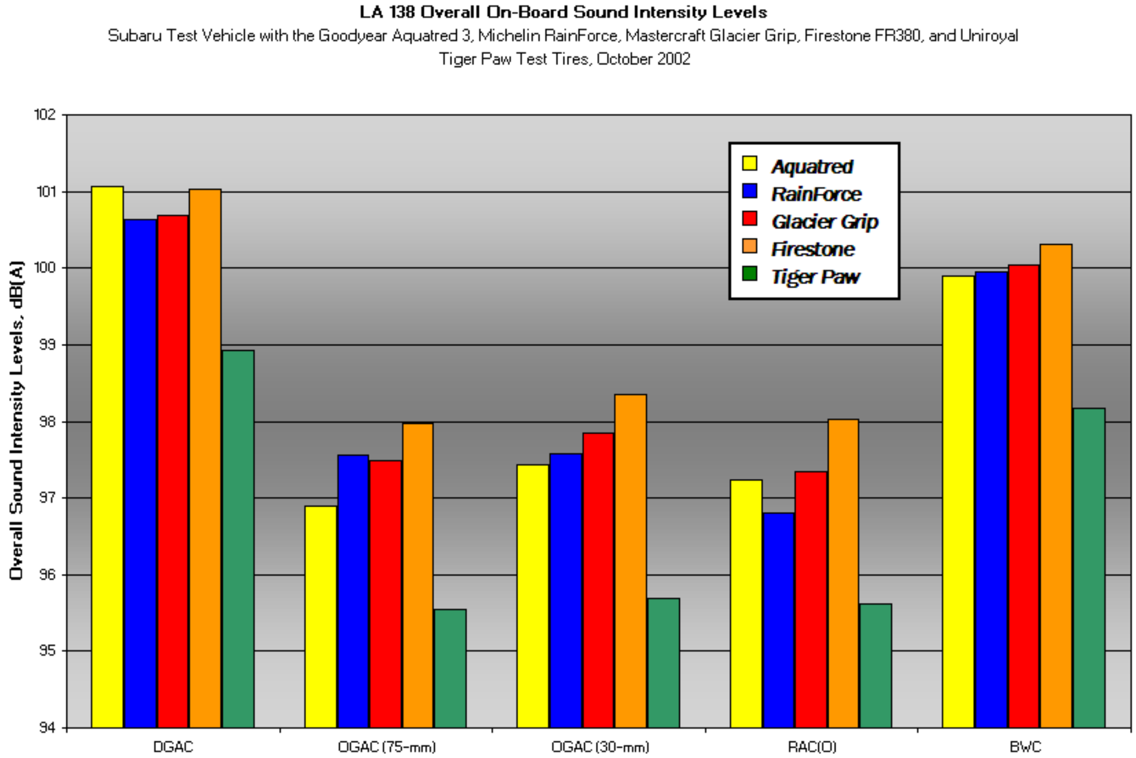
Goodyear Aquatred 3 | *Michelin RainForce* | *Mastercraft Glacier Grip* | *Firestone FR 380* | *Uniroyal Tiger PAW*

Figure B1: Photographs of Test Tires Used in October 2002 Initial LA 138 OBSI Measurements

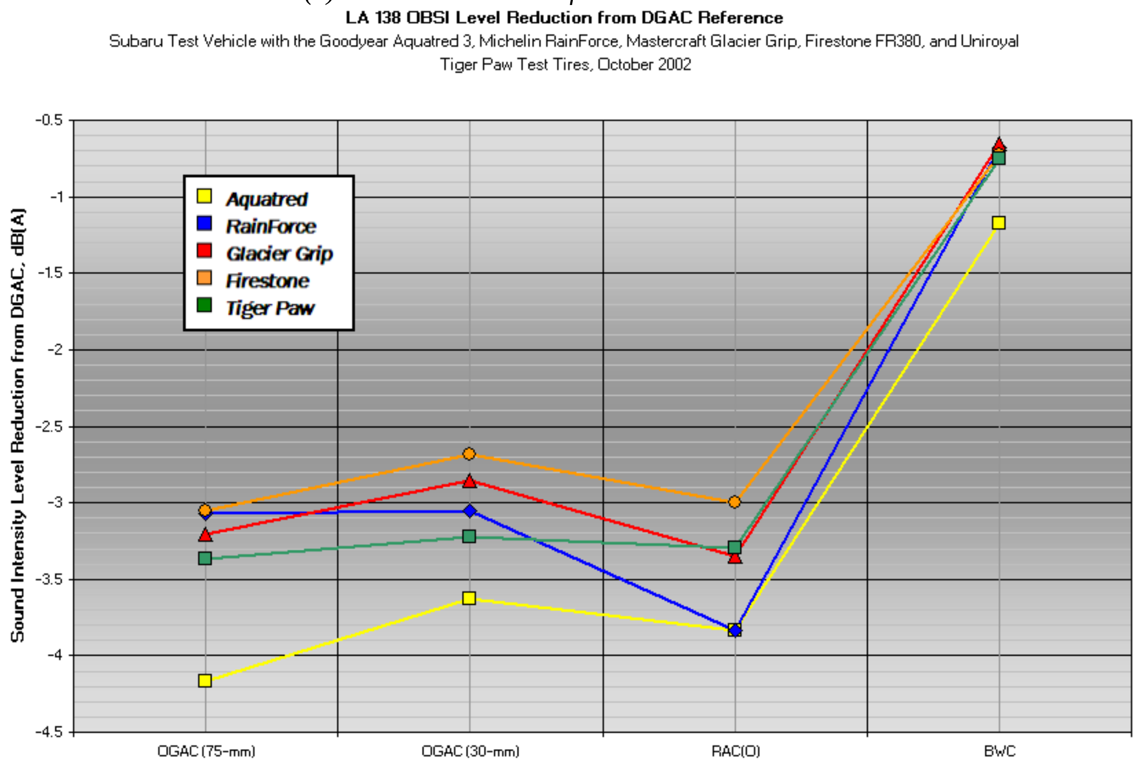
Comparison of OBSI Testing

The overall A-weighted OBSI measurements taken on the five pavement sections for each test tire are shown in Figure B2(a). In addition, the sound intensity differences for each test pavement from the DGAC reference pavement are also shown in Figure B2(b). As indicated in the figure, three of the five test tires resulted in a consistent ranking order with the OGAC (75-mm) pavement having the lowest overall level and BWC having the highest. As already discussed for the Aquatred tire, the margin of difference between sound reductions measured at the OGAC (75-mm) and RAC(O) pavements was approximately 0.4 dB; the margin of difference between both OGAC pavements was 0.6 dB. For the Firestone and Tiger Paw test tires, however, the level reductions for both OGAC and RAC(O) pavements resulted in overall levels within 1 dB of each other. The RainForce and Glacier Grip test tires showed the RAC(O) pavement to have the lowest overall levels, but again, the margin of difference between both OGAC and RAC(O) pavements was less than 1 dB. For each test tire, the pavement that resulted in the smallest reduction in sound intensity levels was the BWC pavement. However, the RainForce, Glacier Grip, Firestone, and Tiger Paw tires indicated a sound reduction at the BWC section of less than 1 dB from the DGAC reference pavement, while with the Aquatred test tire, the difference was slightly over 1 dB.

Figure B3 shows the cross plot comparison of overall OBSI levels for each test tire and the overall OBSI levels for the Aquatred test tire. The data for the RainForce test tire resulted in an average overall offset of zero ($\sigma = 0.5$), compared to the Aquatred OBSI data. The Glacier Grip was an average 0.2 dB ($\sigma = 0.4$) higher than the Aquatred tire and the Firestone tire was 0.6 dB ($\sigma = 0.4$) higher. The Tiger Paw test tire, however, had overall levels lower than the Aquatred tire, with an offset of approximately 1.7 dB with a 0.3 dB standard deviation.



(a) Overall OBSI Levels for Each Test Pavement



(b) Reduction of OBSI Levels for Each Test Pavement from DGAC Test Pavement

Figure B2. Overall A-Weighted OBSI Levels for Each Test Pavement in October 2002

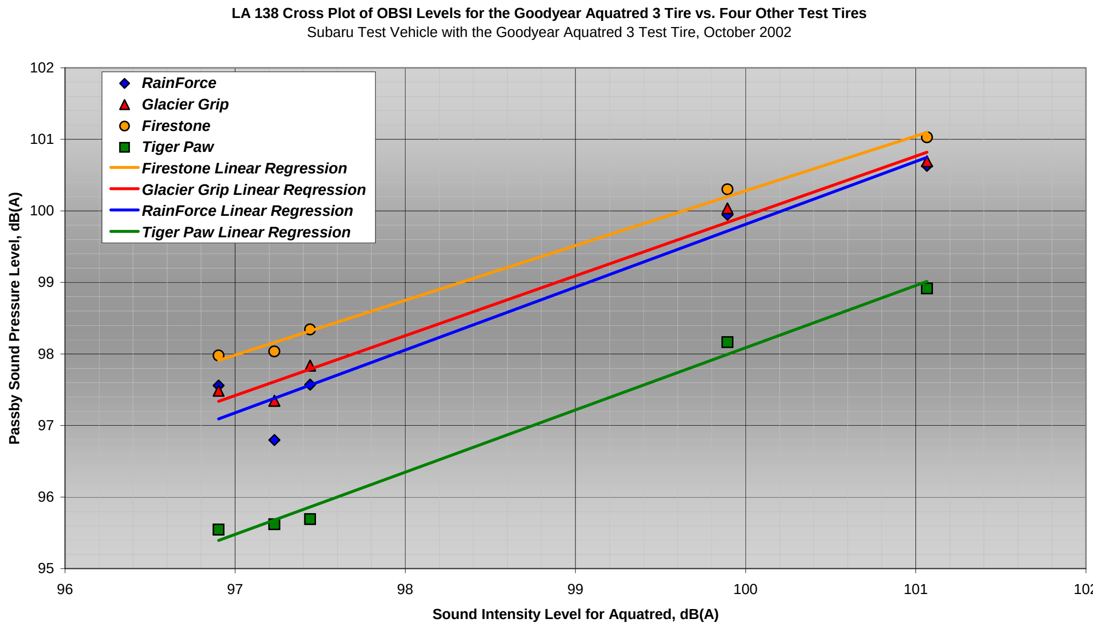


Figure B3. Cross Plot of Overall OBSI Levels for Each Test Tire Compared to OBSI Levels for the Goodyear Aquatred 3 Test Tire in October 2002

For each test tire, the maximum deviations from the one-to-one slope line were approximately 1 dB. In the cross plot of Figure B3, the linear regression lines are shown. The linear regression slopes for all four tire types range from approximately 0.8 dB to 0.9 dB and with r^2 values of 1.0 for the Glacier Grip, Firestone, and Tiger Paw tires and 0.9 for the RainForce tire.

The one-third octave band spectra for each tire as measured on the OGAC (75-mm) test pavement are shown in Figure B4. The spectra trends shown in Figure B4 were similar to those found for all pavements, but only the OGAC (75-mm) pavement results are shown. For the 500 Hz band frequency, the RainForce, Glacier Grip, and Firestone spectra were elevated above the Aquatred spectra by approximately 1.6 dB. The RainForce spectra remained elevated above the Aquatred test tire by a 1.5 dB margin until 800 Hz when the Aquatred and RainForce both resulted in a maximum level amplitude of 92 dB(A). For frequency bands above 800 Hz, the RainForce test tire was elevated above the Aquatred by an average of 0.8 dB with a 0.5 dB standard deviation. Both the Glacier Grip and Firestone test tires increase their level above Aquatred from approximately 1.6 dB at 500 Hz to 3.6 dB and 2.4 dB, respectively, at 630 Hz. At 800 Hz, the amplitude of Glacier Grip and Firestone levels above the Aquatred tire decreases to 0.6 dB. Throughout the rest of the spectra, the Glacier Grip levels fall below the Aquatred by as much as 1.6 dB while the Firestone spectra remains above the Aquatred at all frequencies considered in this study. The average increase for the Firestone spectra compared to the Aquatred for frequencies above 1000 Hz was approximately 1.2 dB with a standard deviation of 0.6 dB. The Aquatred test tire was higher in level than Tiger Paw test tire throughout the one-third octave band spectra. At 500 Hz, the Tiger Paw spectra was initially 1.3 dB lower than the Aquatred, and at 800 Hz, which was the peak amplitude for each tire spectra, the discrepancy between the two spectra increased to 2.2 dB. From 500 Hz to 1600 Hz, the

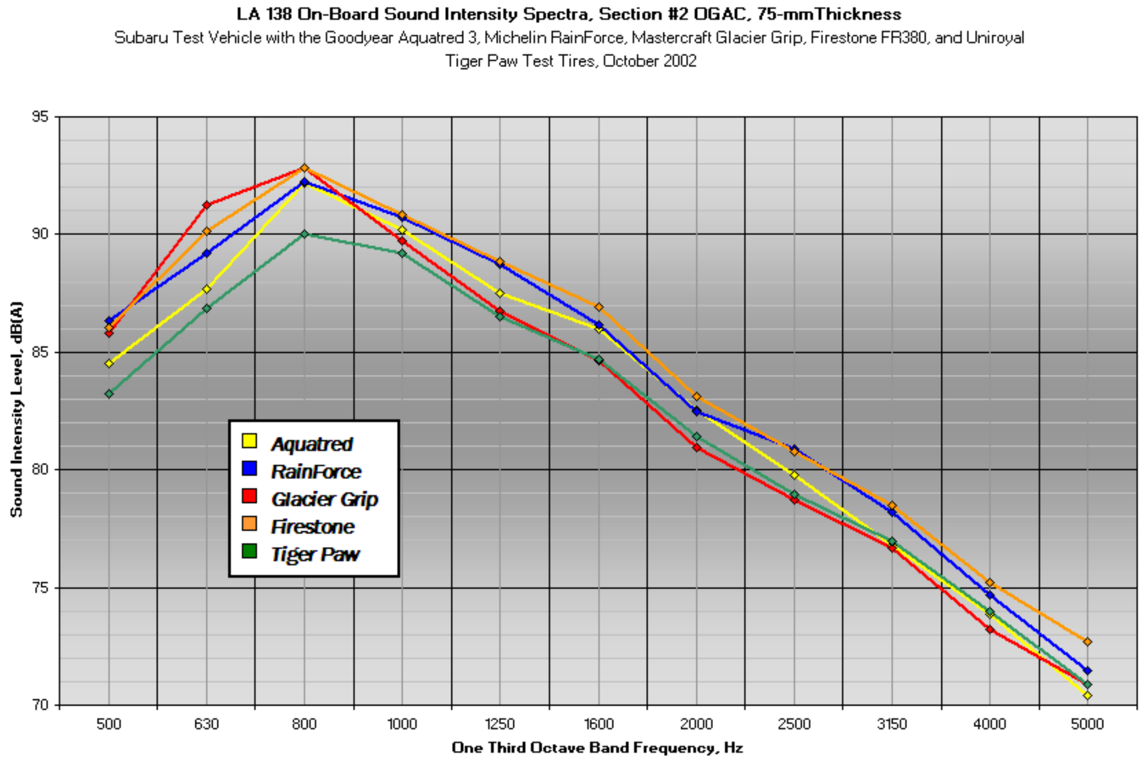


Figure B4. One-Third Octave Band Spectra of OBSI Levels for Each Tire on the OGAC (75-mm) Test Section in October 2002

Tiger Paw consistently had the lowest levels. At 1600 Hz and above, the Glacier Grip tire was nearly equivalent to the Tiger Paw with less than 0.5 dB discrepancy.

Comparison of Controlled Passby Testing

Figure B5 shows the overall A-weighted OBSI levels and SPLs measured at 25-ft and 50-ft for both the Aquatred and RainForce test tires. As discussed above, the pavement ranking order for each test tire determined from the OBSI testing indicated that the DGAC and BWC pavements resulted in the highest levels. The OGAC (75-mm) pavement had the lowest overall OBSI level, with the OGAC (30-mm) and RAC(O) having levels less than 1 dB higher. For the OBSI testing with the RainForce, the RAC(O) pavement resulted in the lowest level, with both OGAC pavements having levels approximately 0.8 dB higher.

Additionally, it was determined in the test tire comparison for the OBSI measurements that the difference between the RainForce tire and the Aquatred was zero, on average, with a standard deviation of 0.5 dB. Similarly, the passby measurements for the RainForce and the Aquatred were also compared using the overall SPLs in Figure B5. The RainForce test tire resulted in levels slightly higher than the Aquatred on the DGAC reference pavement for both microphone distances, while having levels lower than the Aquatred at the other test pavements. On average, the Aquatred had higher passby SPLs than the RainForce tire, measuring 0.7 dB ($\sigma = 0.4$) higher at the 25-ft microphone distance and 0.7 dB ($\sigma = 0.5$) higher at 50-ft.

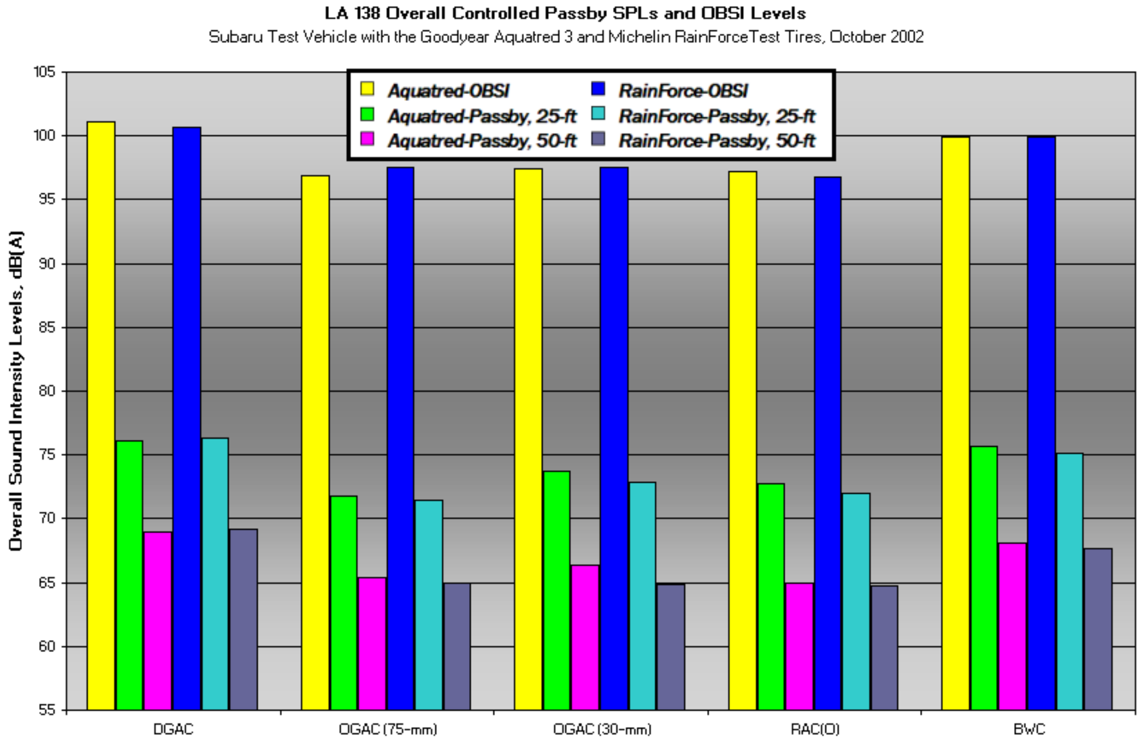


Figure B5. Overall A-Weighted Controlled Passby SPLs and OBSI Levels in October 2002

The cross plot shown in Figure B6 compares the overall A-weighted passby SPLs with the overall A-weighted OBSI levels for the RainForce tire. For the Aquatred test tire, it was determined in Chapter 4 of this report that the passby SPLs measured at the 25-ft distance were an average 23.8 dB lower than the OBSI levels with a standard deviation of 0.6 dB. At 50-ft, the average decibel reduction from the OBSI levels was 30.7 dB with a standard deviation of 0.5 dB. With the addition of the RainForce test tire data, the offset at 25-ft was determined to be 24.1 dB with a standard deviation of 0.7 dB, and at 50-ft, the offset was 31.1 dB with a standard deviation 0.6 dB. As a group, the offset for the RainForce tires are slightly larger than for the Aquatred.

The one-third octave band spectra for the two passby microphone distances are compared to the OBSI spectra in Figure B7. All three RainForce data sets indicated the DGAC and BWC pavements to have the highest levels for the entire frequency range. At 500 Hz, the OGAC (30-mm) showed the lowest levels for both passby microphone distances, while the pavement resulting in the lowest OBSI level at 500 Hz was RAC(O). From 800 Hz to 1250 Hz, the RAC(O) had the lowest levels for all three data sets, and the OGAC (75-mm) pavement had the lowest levels for frequency bands above 1250 Hz. Similar to the passby SPL and OBSI spectra comparison in Chapter 4 for the Aquatred test tire, the frequency band with the highest level for both passby data sets was one band higher than that of the OBSI data sets. For the passby microphone at both distances, the highest level occurred at 1000 Hz while for OBSI levels, it occurred at 800 Hz.

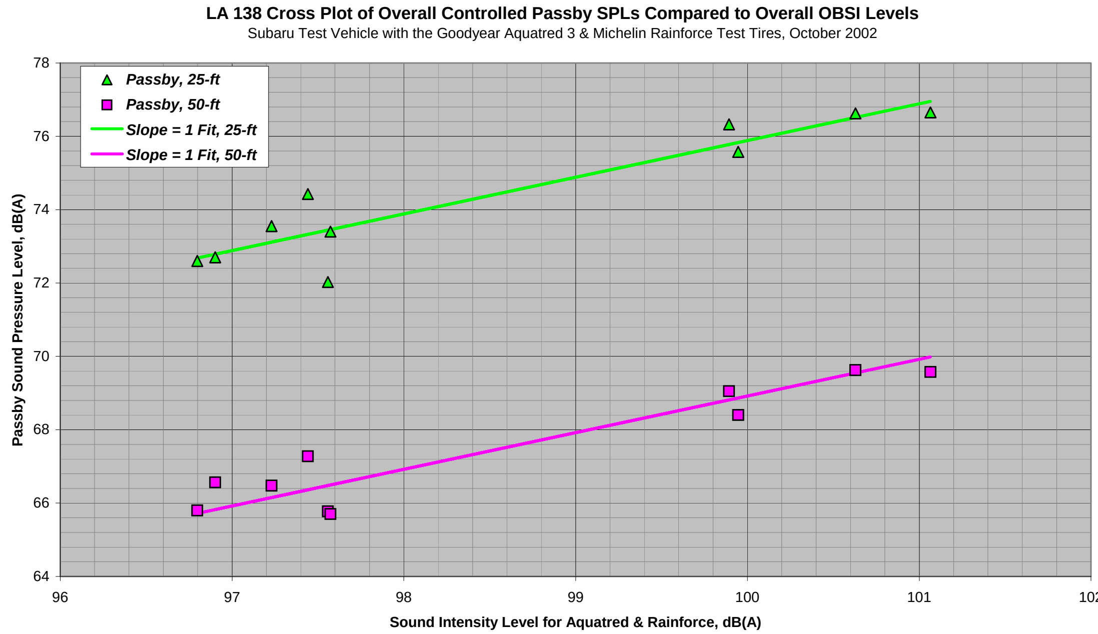


Figure B6. Cross Plot of Controlled Passby SPLs Compared to OBSI Levels for the RainForce Test Tire in October 2002

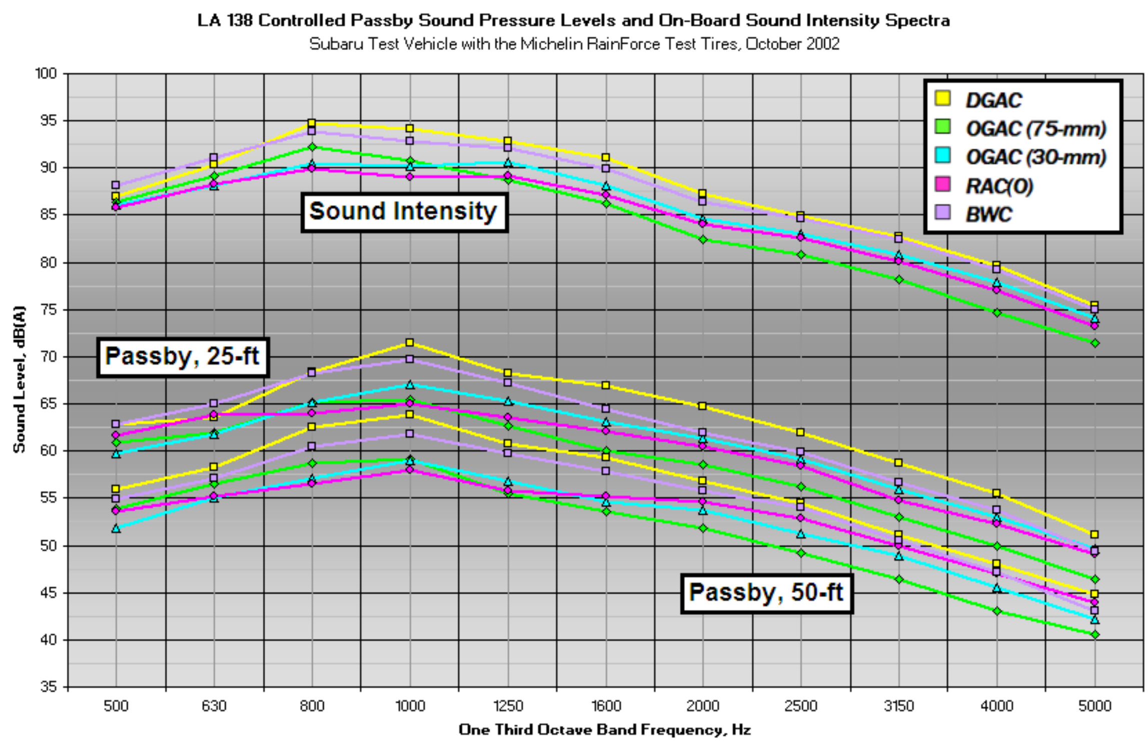


Figure B7. One-Third Octave Band Spectra for Controlled Passby SPLs and OBSI Levels as Measured with the Michelin RainForce Test Tire in October 2002

APPENDIX C: EVALUATIONS OF THE SRTT

Beginning in 2006, research began on the use of the ASTM SRTT as a common tire for OBSI measurements throughout the growing group of OBSI users in the United States and users of the ISO CPX procedure in Europe. For the duration of LA 138 testing, the Goodyear Aquatred 3 remained as the common test tire; however, to document the transition to the new standard tire, data were collected with both the Aquatred and SRTT starting with the April 2006 measurements. Initially this work focused on comparison between the two tires in order to estimate levels from one to the other. As momentum for using the SRTT grew, research on the SRTT became more focused on being the standard tire for the new AASHTO OBSI test procedure. Issues for the SRTT included variation between SRTT tires, tire break-in effects, tire warm-up effects, tire aging, and the effects of changes in tire rubber durometer.

Comparison of the SRTT to the Aquatred 3

Throughout the period from April 2006 to October 2008, the primary SRTT test tire was designated as "SRTT 1". Data for this tire is presented in Figure C1 plotted against the Goodyear Aquatred 3 as measured on the Malibu test vehicle. These data indicate a constant offset between the tires of 1.0 dB, with the Aquatred producing higher levels. The maximum deviation from the slope=1 line was less than 1 dB with standard deviation of 0.3 dB. The linear regression slope of 1.08 approached one-to-one with an r^2 value of 0.94. The differences in the third octave band spectra collected on the five test sections indicated similar behavior and was

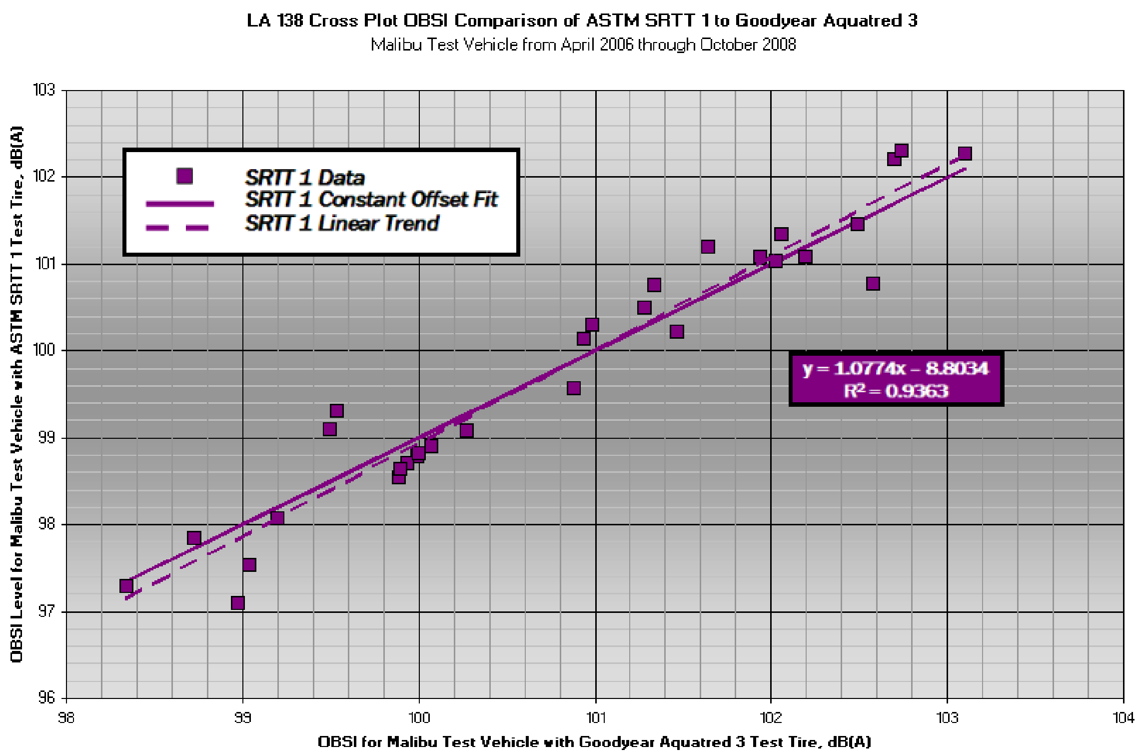


Figure C1. Cross Plot of Overall A-Weighted OBSI Levels for ASTM SRTT 1 Test Tire Compared to Goodyear Aquatred 3 from April 2006 through October 2008

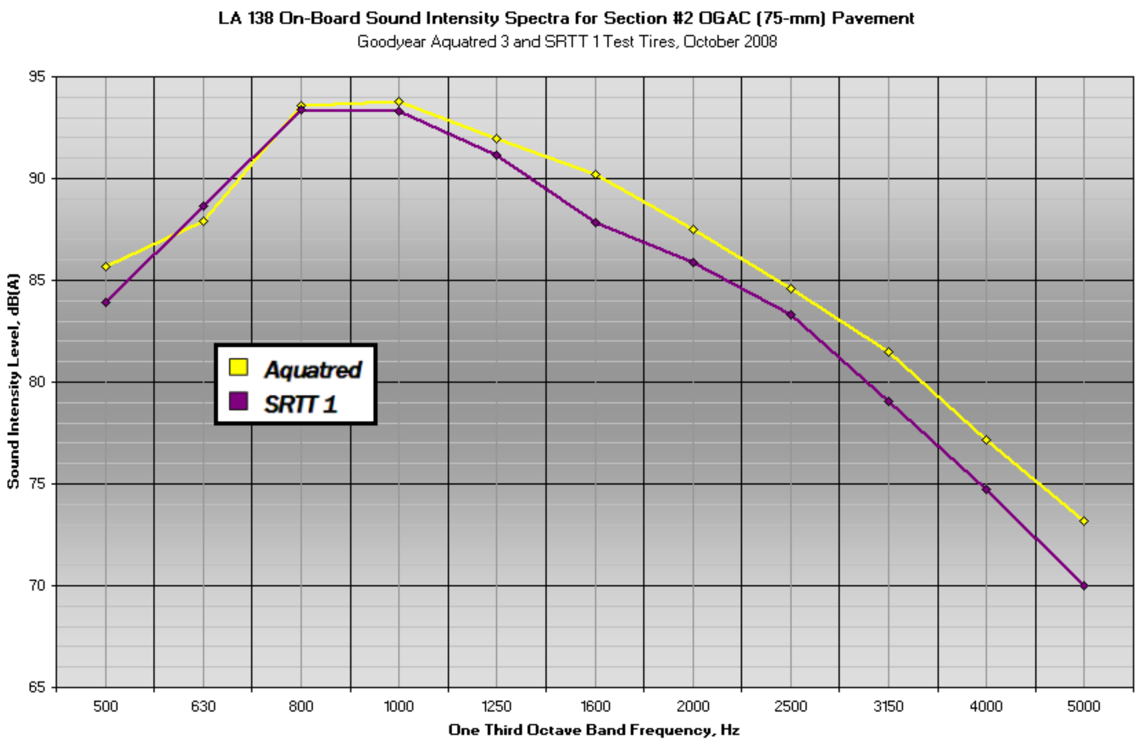


Figure C2. One-Third Octave Band Levels Measured on the OGAC Pavement with 75-mm Thickness for the Aquatred and SRTT 1 Test Tires, October 2008

typified by the spectra for the 75-mm OGAC test pavement shown in Figure C2 for both tires. The spectra for the Aquatred tire was elevated by approximately 1.7 dB above the SRTT 1 tire at the 500 Hz band frequency before dropping about 0.5 dB below the SRTT 1 tire at the 630 Hz frequency band. For the frequency bands above 800 Hz, the Aquatred levels were higher than the SRTT by approximately 1.0 dB to 4.0 dB.

Evaluations of the SRTT as a Test Tire

Tire-to-Tire Variation

For the testing conducted in May 2007, six SRTT tires were used. Two of these had been tested previously and driven for over 160 km. Four were new tires purchased for future passby testing and had not been used previously. The latter set of tires afforded the opportunity for both comparing the OBSI levels of nominally identical tires as well as investigating the effect of mileage accumulation on the four new tires. The designations and descriptions of the test tires are given in Table C1. In this data set, tires were tested on the DGAC and the 75-mm OGAC pavements in both the eastbound and westbound directions to yield four points of comparison. The tires included the Standard Reference Test Tire (SRTT 1), which was typically used to conduct OBSI testing previously, a second OBSI test tire (SRTT 2), and four tires used for passby measurements (SRTT LF Passby, SRTT LR Passby, SRTT RF Passby, and SRTT RR Passby). Figure C3 shows the overall sound intensity levels for the SRTT tires tested in May 2007.

Table C1. Test SRTT Tires as Measured in May 2007 (white background) and October 2008 (gray background)

Designation	Manufacturer Date	Purchase Date	Application	Km at Start	Average Durometer
SRTT #1	Oct-05	Mar-06	Primary OBSI	~ 1000	63
SRTT #2	Oct-05	Mar-06	Secondary OBSI	~ 200	64
LF Passby	Jul-06	Oct-06	Passby Tire	0	64
LR Passby	Jul-06	Oct-06	Passby Tire	0	65
RF Passby	Jul-06	Oct-06	Passby Tire	0	64
RR Passby	Jul-06	Oct-06	Passby Tire	0	64
SRTT #1	Oct-05	Mar-06	Secondary OBSI	~ 2000	66
RR Passby	Jul-06	Oct-06	Passby Tire	0	63
SRTT #3		Oct-08			62

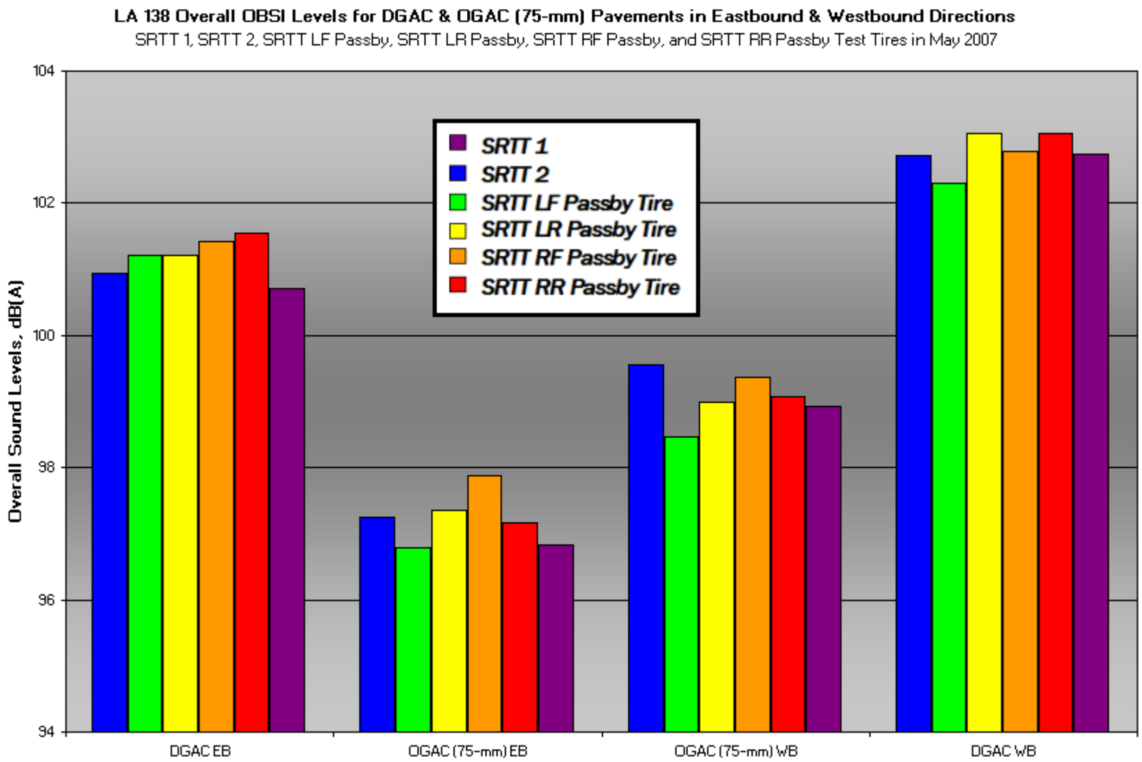


Figure C3. Overall A-Weighted OBSI Levels for the Eastbound and Westbound Directions of DGAC and OGAC (75-mm), May 2007

From Figure C3, all the SRTT tires resulted in levels similar to each other for any given pavement. The average range for all four pavements was 0.9 dB, while the standard deviation was 0.3 dB. On the DGAC pavement surface in both the eastbound and westbound directions the range, in level, was approximately 0.8 dB with 0.3 dB standard deviation; on the OGAC (75-mm) pavement, the range was 1.1 dB with a standard deviation of 0.4 dB.

The testing completed in 2008 included three tires. Two of tires were also included in the 2007 testing: SRTT 1 and SRTT RR Passby. As the primary test tire, SRTT 1 had accumulated additional mileage of approximately 1000 km. The SRTT RR Passby tire was not used in between the two sets of measurements. SRTT 3 was a new, unused tire purchased for the October 2008 evaluation. The information for these tires is also given in Table C1. For this testing, measurements were on all five AC test pavements along LA 138. The results from this testing is presented in Figure C4 as a cross-plot of the SRTT RR Passby and SRTT 3 versus SRTT 1. From this plot, the SRTT RR Passby tire was an average of 0.2 dB lower than SRTT 1, with a standard deviation of 0.2 dB. The SRTT 3, however, was slightly higher than SRTT 1, by an average of 0.1 dB , with a standard deviation of 0.2 dB. The range in level for any one surface for the three tires was, on average, 0.4 dB with a maximum range of 0.6 dB. Given the very small offsets in these data and the observed experimental uncertainty, the apparent difference in performance of the tires was negligible.

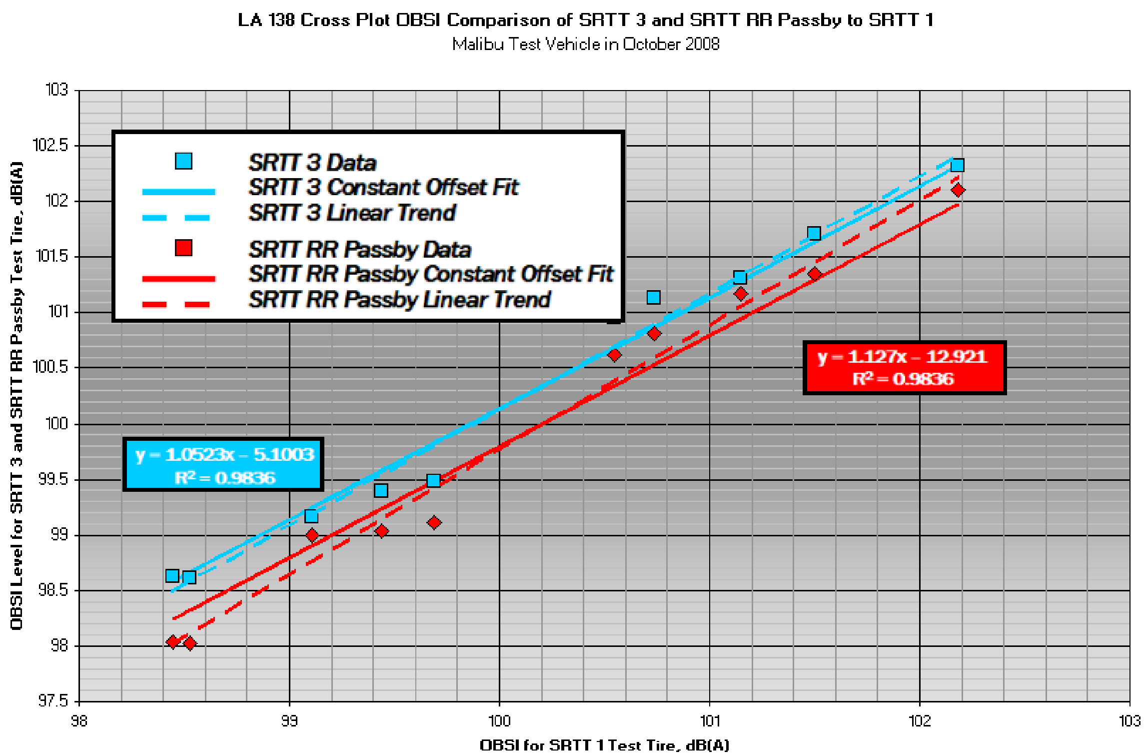


Figure C4. Cross Plot of SRTT 3 and SRTT RR Passby OBSI Levels Compared to SRTT 1 OBSI Levels in October 2008

Effect of SRTT Age

The data from Figures C3 and C4 also provide information on the effect of tire aging and usage. In the 2007 testing, no consist difference in tire noise performance was found for a tire, which had been used routinely for testing (SRTT 1) for more than one year and those that were new and never used. The data from 2008 provided an even longer term comparison as SRTT 1 had accumulated more test miles and aged another 1½ years. In Figure C4, SRTT 1 and 3 span a range in usage of more than 2½ years and the differences in durometer of 4 hardness numbers; however, the levels were nearly identical. The mid-age tire (i.e., SRTT RR Passby) was also not essentially different from either SRTT 1 or SRTT 3. Within the limits set by these tires and with the rather moderate usage of SRTT 1, no real effect of aging or change in tire rubber durometer was found.

SRTT Break-in and Warm-up

The testing conducted in May 2007 on SRTT tire-to-tire was also designed to evaluate tire warm-up and break-in. At the beginning of the testing, the four passby SRTT tires had never been used. To evaluate accumulation of early mileage, OBSI measurements were made in increments of 4 mi, as dictated by the turn around loop possible on the roadway. For all four of the passby tires and the two already used tires (i.e., SRTT 1 and 2), measurements were then made at 0 mi, 4 and 8 mi. There was no initial warm-up of any of the test tires, as this would have accumulated mileage on the new tires. SRTT 1 and 2 were also treated in this manner as a control and to examine warm-up in comparison to accumulated mileage of the new tires. For this testing, only two adjacent pavements were used, the DGAC and OGAC (75-mm), as a complete circuit of all five test pavements, would have accumulated excessive mileage. The two surfaces were tested in both directions yielding four samples for each pass. As another control, the SRTT 1 was tested first and then re-tested at the end of the test session. A representative example of the overall A-weighted levels as measured on the DGAC surface in the westbound direction are shown in Figure C5. As shown, the retest of SRTT 1 produced levels that were on average 0.3 dB lower than the first test at the beginning of the session with a standard deviation of 0.5 dB. From the beginning to the end of the testing, the air temperature ranged from 26^{o} C to 30^{o} C, possibly contributing to the slight average decrease in noise level. It should be noted that it had been reported in other research that the range in overall OBSI level from run-to-run for 10 consecutive runs is typically 0.8 dB with a standard deviation 0.3 dB for the SRTT[12].

For the new passby tires in Figure C5, the average difference between the 0 km levels and the 8 mi was an average of 0.2 dB with a standard deviation of the 0.4 dB. There was also no consistent trend in the direction of the differences; that is, for some tires, the levels were slightly higher after 8 mi and for others, lower. This lack of consistent change with mileage also infers that there was no consistent increase or decrease in level as the tire warmed-up. This observation was also the case for the previously used tires. Three tires were also re-tested two days later after a minimum of 100 mi had accumulated. Two of these were initially new passby tires that had since been used in CPB testing on SR 58. These were from the right side of the vehicle so that they were always operated in a single direction of rotation. In this retest, the right rear (RR) passby test tire produced an average increase in level of 0.5 dB, and the right front (RF) tire produced a lower level, averaging 0.3 dB. For these tires, there was no indication that 160+ km condition was better represented by the 0 mi, 4 mi, or 8 mi data. SRTT 1 was the third tire tested, and it remained an unchanged average over the three pavements. Based on these results, it was difficult to conclude that any break-in period was required prior to standardized testing with the SRTT or that a tire warm-up schedule was necessary.

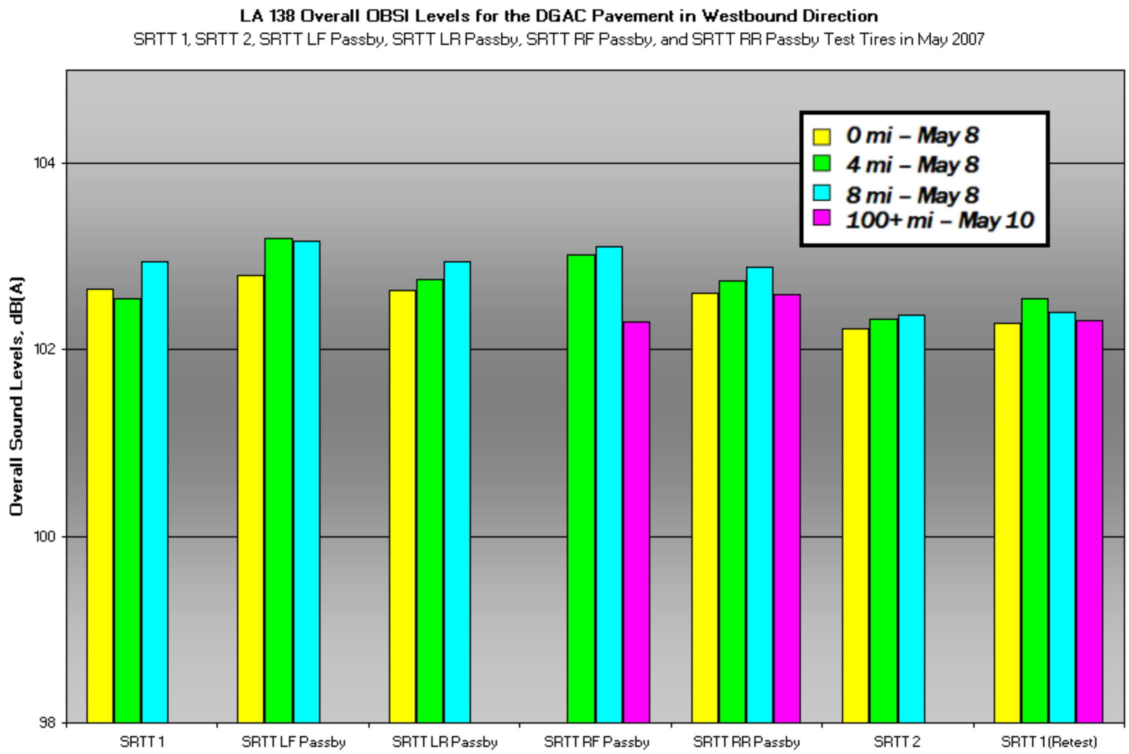


Figure C5. Overall A-Weighted OBSI Levels for Six SRTT Tires with Accumulated Mileage and No Warm-Up in May 2007

APPENDIX D: RESULTS OF CPX TIRE/PAVEMENT NOISE TESTS

At the time of the initial measurements conducted in October 2002, the Arizona Department of Transportation (ADOT) was in the process of documenting the tire/pavement noise performance of portions of the Arizona highway system using their recently purchased tire noise trailer. This trailer was built to perform at the source close proximity (CPX) tire noise measurements in accordance with the ISO Draft Standard 11819-2[3]. In a cooperative effort between ADOT and Caltrans, it was agreed to collect CPX data in conjunction with the OBSI measurements with the intent of developing an initial correlation between the two systems to facilitate future data exchange.

Test Description

Unlike the OBSI method, CPX testing uses sound pressure level measurements to quantify tire noise typically using specially built trailers such as the one used by ADOT (Figure D1). In the ADOT system, two free-field ½" G.R.A.S ICP microphones were positioned 100 mm from the

Figure D1: Photographs of the ADOT CPX Trailer

ground and 200 mm from the face of the tire in the standardized CPX positions, with one at 200 mm in front of the centerline of the tire and the other at 200mm to the rear of the centerline of the tire. The microphones were pointed towards the center of the tire contact patch and fitted with spherical windscreens. For their measurements in Arizona, the microphone signals were recorded onto a ten channel OROS OR25 PC-PCK and after the testing was complete, the recorded signals were analyzed in to ⅓ octave sound pressure levels and overall A-weighted levels calculated from ⅓ octave band levels from 315 to 5000 Hz. For the measurements made on LA 138 in October 2002, the OROS analyzer was replaced by the Larson Davis 2900 dual channel real-time analyzer used by I&R at the time for the OBSI measurements to avoid any issues with analyzer differences (evaluated at a later time). The LD 2900 was operated in by I&R personnel and the trailer was towed by an ADOT vehicle driven by Larry Scofield, the user of the CPX trailer. The ADOT ICP microphones were powered and conditioned by two PCB Model 480E09 power supplies provided by I&R and the output of the LD 2900 was also recorded to a Sony LCD-100 two channel Digital Audio Tape (DAT) recorder for backup and for

3 "ISO/CD 11819-2. Acoustics – Method for measuring the influence of road surfaces on traffic noise – Part 2: the close-proximity method", ISO, Geneva, Switzerland, 2000.

any future analysis. The measurements were conducted in the same manner as the OBSI measurements in regard to test speed, length of sample, and initiation of data acquisition for each test section.

CPX measurements were made on four test tires. Three of these were of the same design used in the OBSI measurements conducted this same test period. This included the Goodyear Aquatred, Michelin RainForce, and Uniroyal Tiger Paw (see Figure B1). The fourth test tire, a Goodyear Wrangler MT/R size LT 205/75R16 (Figure D2), was selected to represent truck tires, in particular, traction drive axle tires as well as off-road light vehicle tires. This tire is uniquely different from others distinguished by its larger tread block size, aggressive tread design, and appreciable open area in the tread.

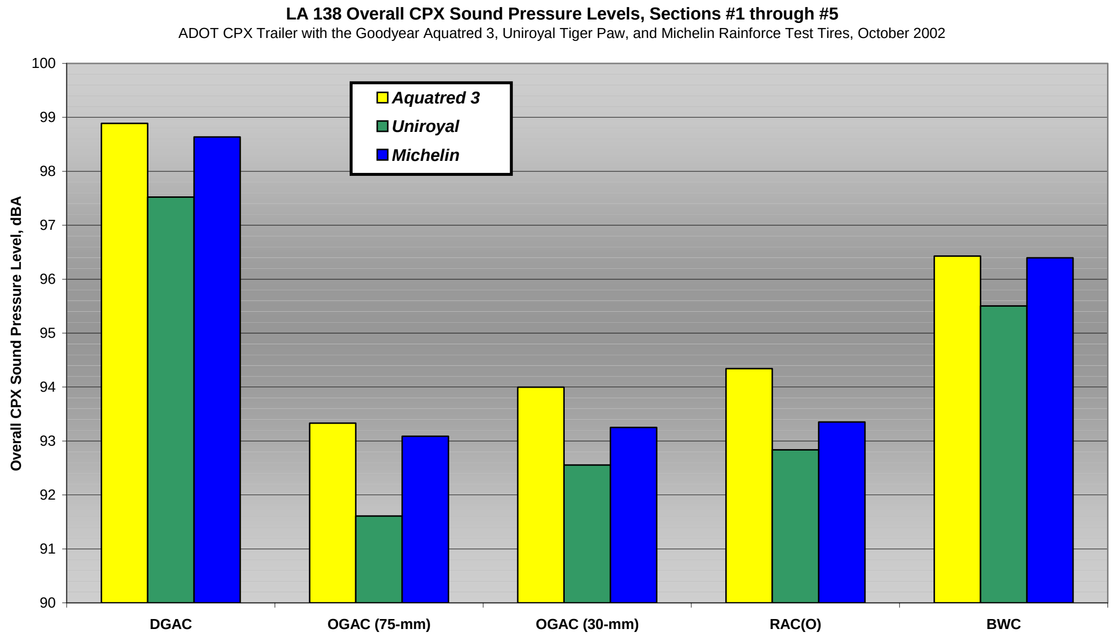
Figure D2: Photographs of Goodyear Wrangler Test Tire

Test Results

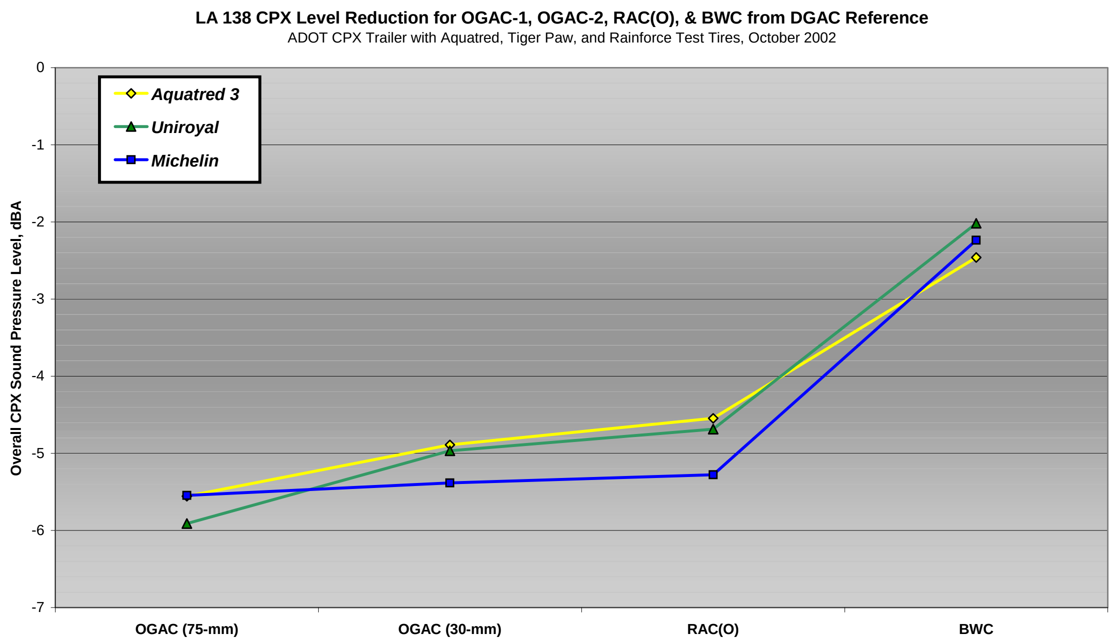
Goodyear Aquatred 3, Michelin RainForce, & Uniroyal Tiger Paw

The overall A-weighted OBSI measurements taken on the five pavement sections for three test tires common to the OBSI measurements are shown in Figure D3(a). In addition, the sound intensity differences for each test pavement from the DGAC reference pavement are also shown in Figure D3(b). In comparison to the results of OBSI measurements (see Figure B2), it is immediately apparent that the level differences between the DGAC pavement and OGAC and RAC(O) pavements is substantially greater those measured using OBSI. With the CPX method, these differences are in the range of 6 to 5 dB compared to the OBSI range of about 3 to 4 dB. The range of CPX data is also is also larger than that produced in the passby tests (see Figure B5) that ranged from 2 to 4 dB for these same surfaces. Within the grouping of the quieter OGAC and RAC(O) pavements, there is also some subtle differences in rank ordering. Unlike the OBSI and passby data, the CPX levels are higher for the RAC(O) pavement than the OGAC pavements. Further, the BWC levels remain about 2 dB lower than the DGAC pavement where the OBSI and passby data are within about 1 dB or less of the DGAC levels.

The CPX data were also cross-plotted with the passby levels obtained for the Aquatred and RainForce tires as shown in Figure D4. Like the OBSI cross-plotted data (Figure B3), the CPX



(a) Overall CPX Sound Pressure Levels for Each Test Pavement



(b) Reduction of CPX Levels for Each Test Pavement from DGAC Reference Pavement
Figure D3: Overall A-Weighted CPX Levels for Each Test Pavement in October 2002

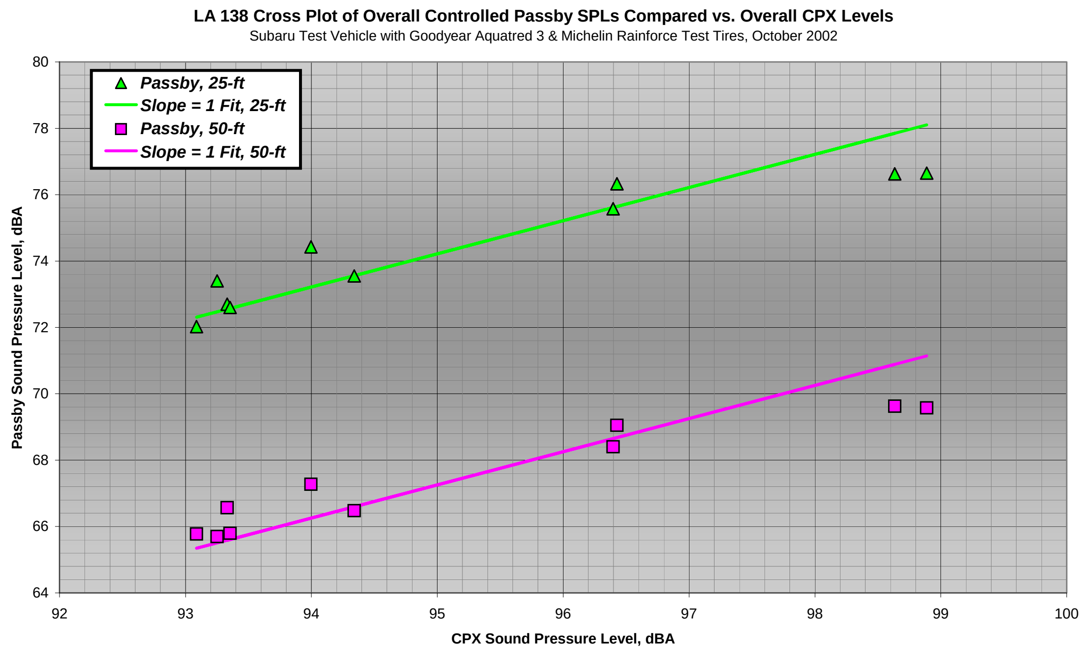


Figure D4: Cross Plot of Controlled Passby SPL's Compared to CPX Levels for Aquatred and RainForce Test Tires in October 2002

results indicate a good correlation with the passby data. Comparison of the cross plot metrics of offset above the passby data and standard deviation are provided in Table D1. From this

Table D1. Comparison of Slope = 1 fit Offsets to Passby Levels and Standard Deviations for CPX and OBSI Measurement Methods

	25-ft Passby		50-ft Passby	
	Offset	Standard Dev.	Offset	Standard Dev.
CPX	20.8 dB	0.9 dB	27.7 dB	0.9 dB
OBSI	24.1 dB	0.7 dB	31.1 dB	0.6 dB

comparison, it is seen that the offsets for the CPX data are less than for the OBSI data by 3.3 dB and 3.4 dB for 25-ft and 50-ft, respectively. Further the scatter about the slope = 1 fit line is greater for the CPX data by 0.2 and 0.3 dB. The ⅓ octave band spectra for the Goodyear Aquatred 3 data as measured on the CPX trailer and at the 25-ft passby microphone are shown in Figure D5. Above 800 Hz, the spectral shapes for the CPX and passby data are similar although the difference between the quietest pavement, the 75-mm OGAC, and the loudest, DGAC, are about 2 dB greater for the CPX data. At 800 Hz and below, the spectral shapes diverge. The CPX levels drop at a higher rate with decreasing frequency than the passby data. This spectral distortion has recently been reported in other studies[4,5,6] also and is thought to be due reflections and standing acoustical wave patterns within the trailer enclosure.

[4] Donavan, P. and Lodico, D., "Measuring Tire-Pavement Noise at the Source", NCHRP Report 630, Transportation Research Board, Washington, D.C., 2009.

[5] Donavan, P., "Comparison of On-Board Tire/Pavement Measurement Methods to Controlled Pass-by Testing", Proceedings of Inter-Noise 2008, Shanghai, China, October 2008.

[6] Donavan, P., Reyff, J., and Pommerenck, A., "Progress Report 3: Quiet Pvement Pilot Program", Arizona Department of Transportation, Arizona Transportation Research Center, Phoenix, AZ, draft report, October 2008.

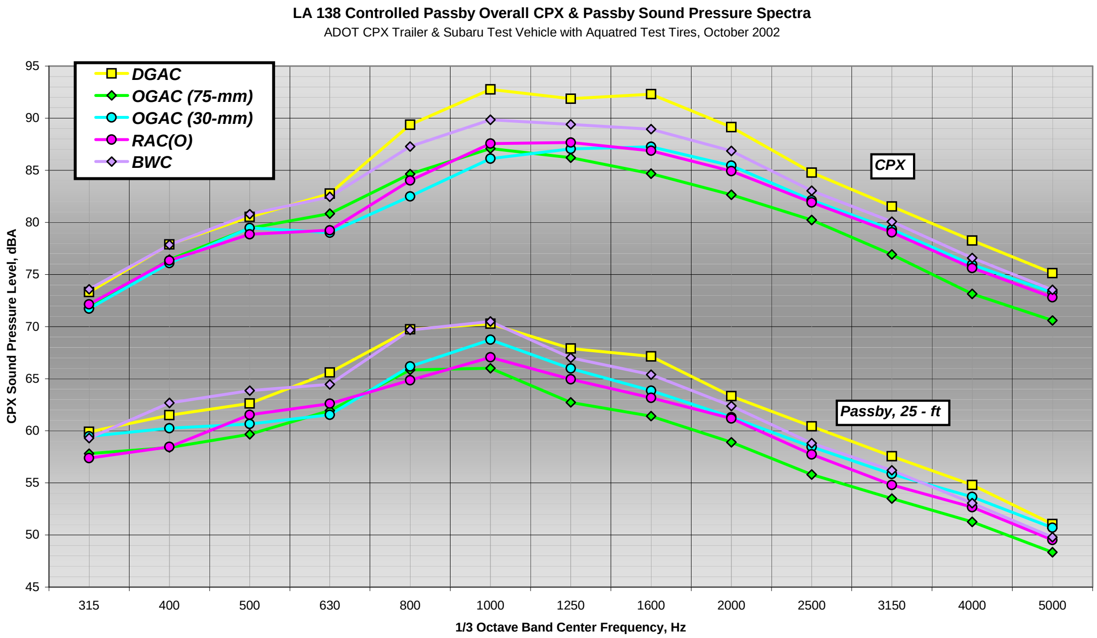


Figure D5: One-Third Octave Band Spectra for Controlled Passby Levels and CPX Levels as Measured with the Goodyear Aquatred Test Tire in October 2002

The overall CPX levels for the Aquatred, Tiger Paw, and RainForce are cross-plotted against the OBSI data in Figure D6. The offset between the two measurement methods defined by the slope = 1 fit is 3.1 dB, which is also consistent with the studies cited above. When a linear regression is fit through data points, the r^2 is 0.89 indicating good correlation between the two types of measurements. Relative to the slope = 1 fit, the standard deviation of the data points is 0.9, the same as was noted for the cross plot the CPX and passby data (Figure D4). The spectra for the CPX and OBSI are shown in Figure D7 and indicate the same trends as were noted for the comparison to passby spectra. Above 1000 Hz, the data are remarkably similar both in spectral shape and amplitude. At 800 Hz and below, however, the levels for the CPX measurements are consistently lower than the OBSI results. It is suspected that the bias noted toward the higher frequencies in the CPX spectral shape are the main reason for the discrepancies in the relative overall levels for the different pavements as noted in regard to Figure D3. For both the OBSI and passby data, the higher levels for occur in the 800 and 1000 Hz bands while for the CPX data, the higher levels occur at 1000 Hz and above.

CPX Results – Goodyear Wrangler

The Wrangler tire displayed a somewhat different behavior than the other tires used in the CPX measurements. For all sections except the DGAC pavement, the levels for this tire are about 2 to 3 dB higher than those for the other three tires as shown in Figure D8(a). This quite apparent when considered relative to the DGAC pavement in Figure D8(b). The CPX results also give a slightly different ranking of the OGAC and RAC(O) pavements. For the passenger car tires, the level for the RAC(O) pavement is slightly higher than the other two OGAC pavements, while for

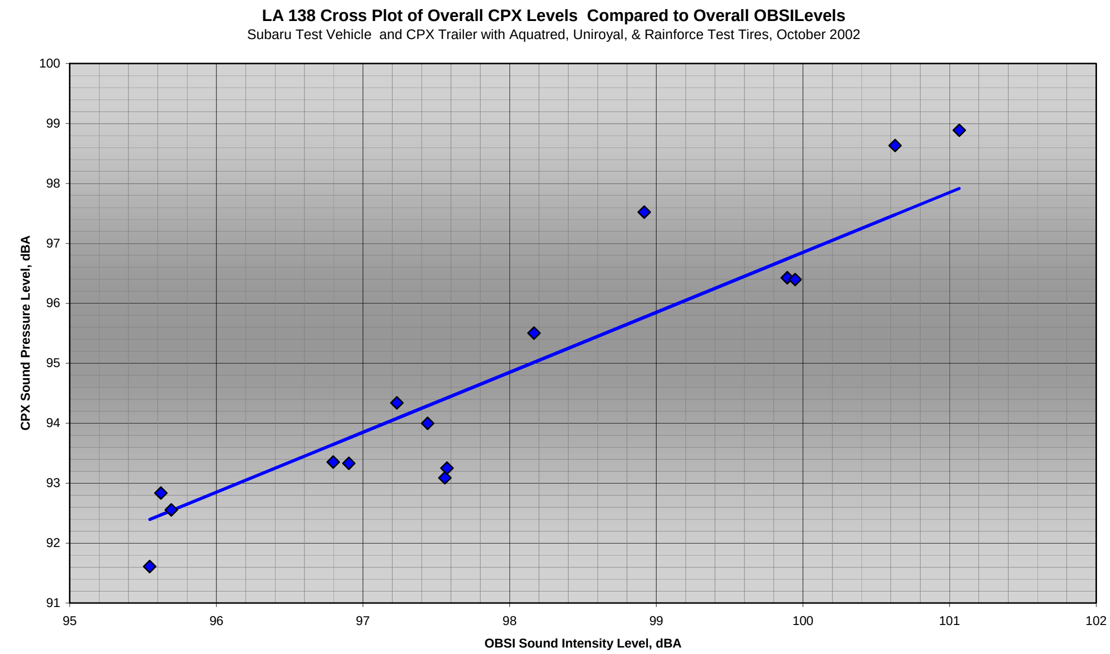


Figure D6: Cross Plot of Overall OBSI Levels and Overall CPX Levels for the Aquatred, Tiger Paw, and RainForce Test Tires in October 2002

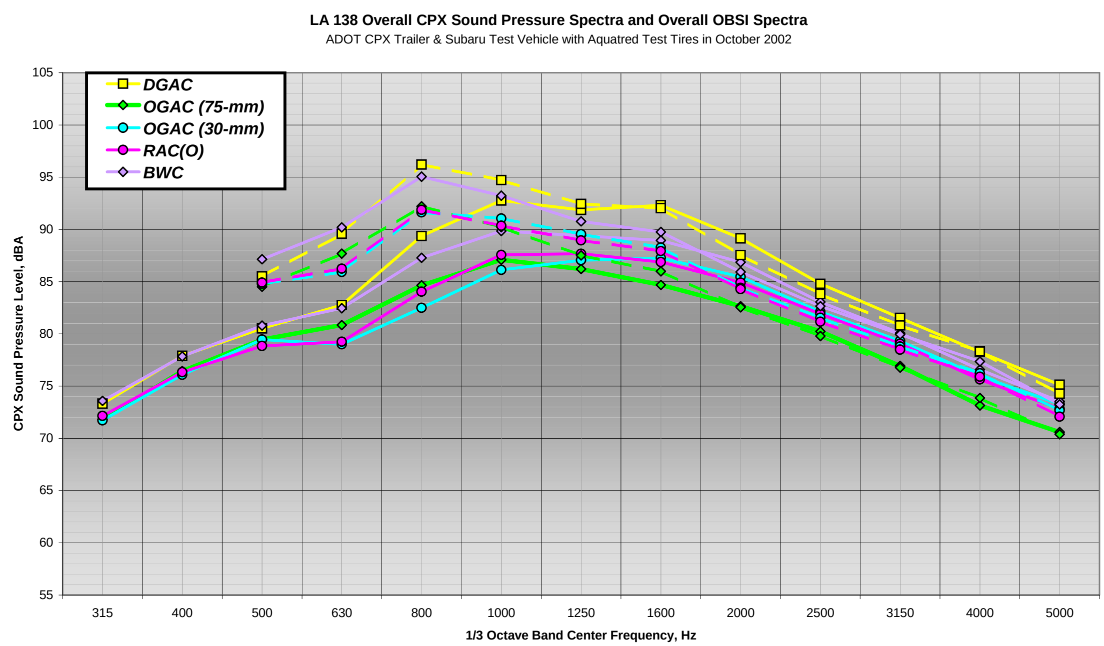
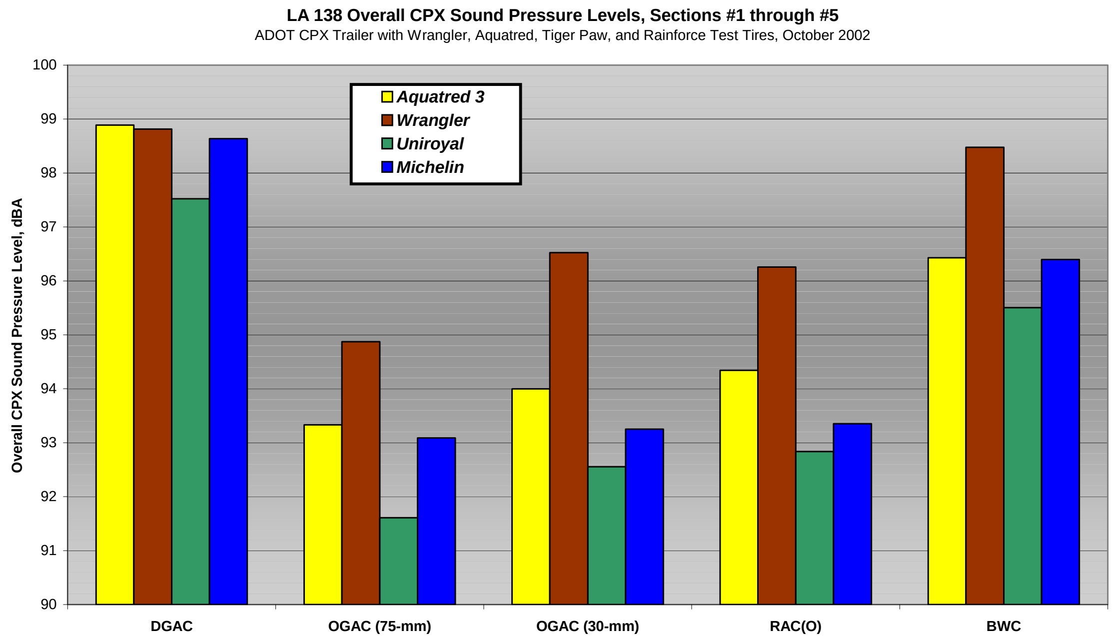
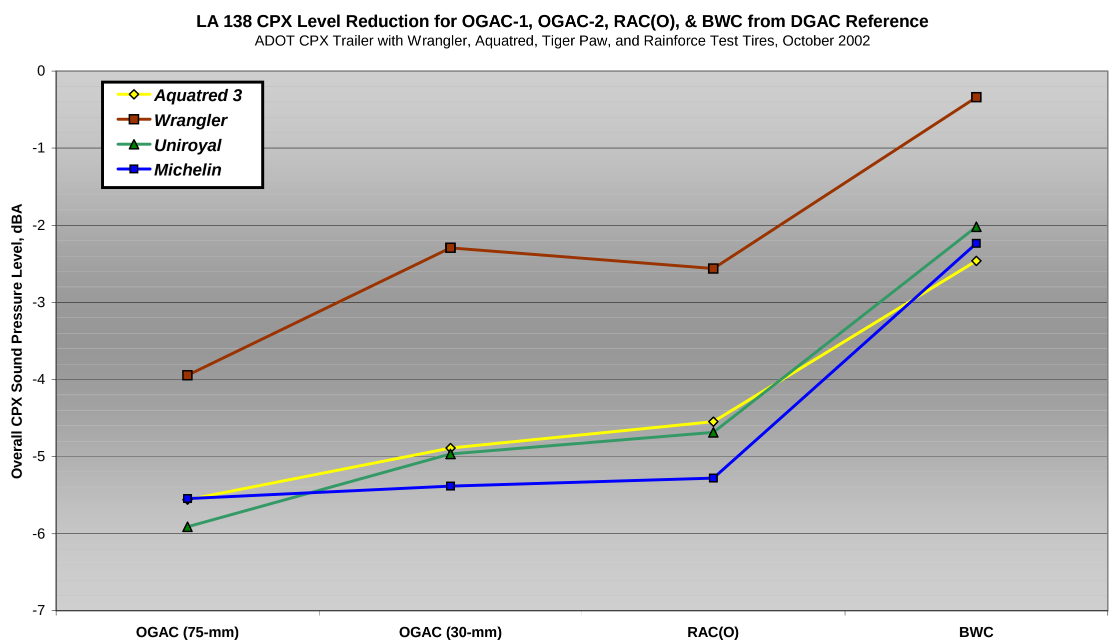


Figure D7: One-Third Octave Band Spectra for CPX and OBSI Levels as Measured with the Goodyear Aquatred Test Tire in October 2002

the Wrangler, the level is slightly lower than the 30-mm thick OGAC. This result is actually more consistent with that of the OBSI data.



(a) Overall CPX Sound Pressure Levels for Each Test Pavement



(b) Reduction of CPX Levels for Each Test Pavement from DGAC Reference Pavement
Figure D8: Overall A-Weighted CPX Levels for All Four Test Tires in October 2002

The ⅓ octave band spectra for the Wrangler tire on the five LA 138 test pavements are shown in Figure D9. Relative to the results for passenger car tires (Figure D5), the Wrangler spectra are significantly different and display more low frequency content below 800 Hz. Also, at 500 Hz and below, there is very little variation in the ⅓ octave band levels from one pavement to the next. On the 75-mm OGAC surface, the levels in the 500 Hz band are actually the highest of all

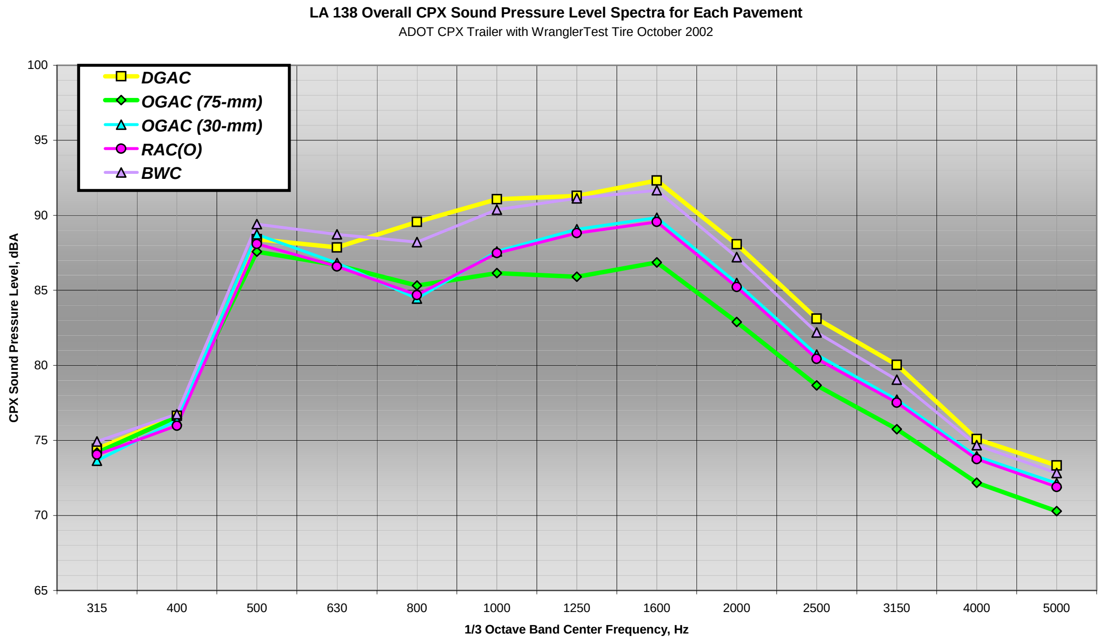


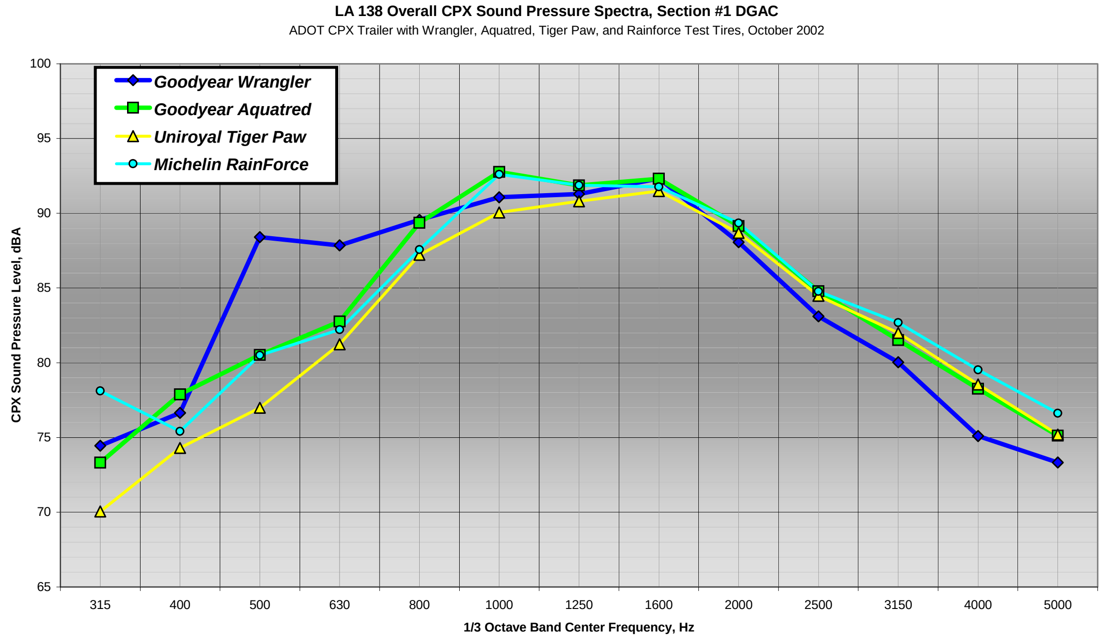
Figure D9: One-Third Octave Band CPX Spectra for with the Goodyear Wrangler Test Tire in October 2002

⅓ octave bands indicating that it would be the largest contributor to the overall level. At 800 Hz and above, the differences between the pavements are similar to those of the passenger car tires. The low frequency content of this tire is more apparent when the spectra are plotted with the passenger car tire data as shown in Figure 10D(a) and 10D(b) for the DGAC and 75-mm OGAC, respectively. From these plots, the level for the Wrangler tire in the 500 Hz ⅓ octave band is more than 7 dB higher than the three passenger car tires. This added lower frequency content relative to the passenger car tires is likely due to the larger block size of the Wrangler tire and its larger diameter, which tend to lower the fundamental tread block passage frequency. Further, with the large amount of open area between the blocks, the passage of these blocks through the contact patch will be more abrupt, potentially producing higher levels of tread band vibration and resultant noise in comparison to the passenger car tires.

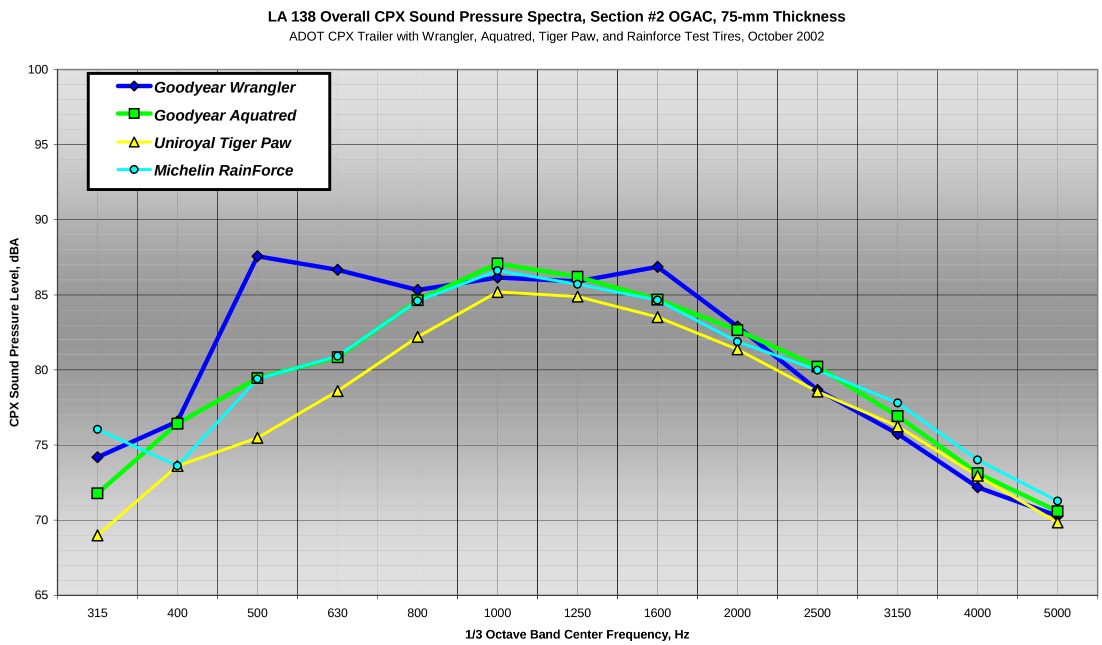
The Wrangler tire does display two behaviors that are more characteristic of the heavy duty truck tires[7]. First, it has much more lower frequency energy content than the passenger car tires as is inherent in truck tires. Second, tire noise at these lower frequencies is not influenced much by pavement changes, which is also typical of truck tires. Unfortunately, only CPX data was obtained for this tire and it suffers from the spectral distortion noted previously. Further investigation of this tire may be useful to determine if it could be used and is needed as a surrogate truck tire. The purpose of this additional test tire would be to attempt to replicate some of the differences reported between the response of the trucks and passenger cars to pavement changes[8].

[7] P. Donavan, "Generation of Noise by Truck and Car Tires on Various Types of Asphalt Concrete Pavements", Proceedings of Inter-Noise 2006, Honolulu, Hawaii, December 2006

[8] Rochat, J. and Read, D., "Variability of Pavement Noise Benefit by Vehicle Type", Institute of Noise Control Engineering, Proceedings of Noise-Con 2005, Minneapolis, Minnesota, 2005.



(a) CPX Spectra on DGAC, Section #1



(b) CPX Spectra on 75-mm OGAC, Section #2

Figure D10: One-Third Octave Band CPX Spectra for Wrangler, Aquatred, Tiger Paw, and RainForce Test Tires on LA 138 Sections #1 and #2 in October 2002