Purdue University’s Institute for Safe, Quiet, and Durable Highways and
the American Concrete Paving Association

Acoustical Effects of Grinding and Grooving on Portland Cement Concrete Pavements

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EXECUTIVE SUMMARY

Experiments were conducted on behalf the American Concrete Paving Association by Purdue University's Institute for Safe, Quiet, and Durable Highways to determine the effects of longitudinal diamond grinding and grooving on tire-pavement noise. Grinding and noise testing were conducted using Purdue's Tire-Pavement Test Apparatus. The project was divided into two Test Intervals. In Test Interval 1, samples were constructed to replicate the variety of longitudinally ground pavements in the field. It was found that Purdue's grinding system could accurately replicate the types of textures typically used. Through this grinding process, it was determined that fins left over between cutting blades could cause rough macrotexture in the contact patch and lead to higher tire-pavement noise. The effect of wearing down the fins was investigated. Removing microtexture from the fins through sanding increased tire-pavement noise, and reducing macrotexture by breaking the fins to form a more even surface decreased tire-pavement noise. The cumulative effect of wearing down the fins was negligible. Through noise testing and texture profile measurements, it was determined that an ideal Portland cement concrete (PCC) pavement should have high microtexture and low macrotexture. Test Interval 2 focused on creating such a pavement. Through the use of chopper blades, blades that have slightly smaller diameters, or by grinding with multiple passes, a pavement was created that was substantially quieter than all previously constructed concrete pavement samples. Analysis of the sound intensity spectrum of this quiet pavement was used to show that the best pavement treatment has reduced high frequency content due to high microtexture and reduced low frequency content due to low macrotexture.

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1 INTRODUCTION

Experiments were conducted at Purdue University’s Institute for Safe, Quiet, and Durable Highways to determine the effects of diamond grinding and grooving on tire-pavement noise. Several grinding parameters were studied, including the width and spacing of longitudinal grooves, the presence of microtexture within the contact patch, and the combination of cutting blades used to create the surface. First, a survey of conventional diamond grinding setups was made to establish baseline noise levels for typical longitudinally-ground PCC pavements. Then, by incorporating information from recent studies of the effects of texture on pavement noise and the original testing, an effort was made to create ground PCC pavements that would be significantly quieter than those made with the traditional grinding setups.

2 LITERATURE REVIEW

2.1 DIAMOND GRINDING OF PCC

Diamond grinding is the process of using diamond-infused steel blades to grind away part of a PCC pavement. Diamond grinding can be performed on existing roadways for the purposes of rehabilitation. By grinding away the top surface of a damaged roadway, a smoother roadway can be made with substantial cost savings over constructing a new PCC pavement. Diamond grinding can also be used to texture PCC roadways before their initial use, improving friction and water drainage.

More recently, experiments have been done to investigate the effects of diamond grinding on PCC pavement noise. In general, longitudinal diamond grinding is among the quietest finishing methods for PCC pavements. However, there are some significant differences in overall intensity levels between longitudinally ground pavements at different sites[2]. Much of this difference is believed to be the result of different techniques and equipment used to grind the pavements. However, no extensive study of the different parameters in diamond grinding has been done previously.

2.2 TEXTURAL FEATURES AFFECTING NOISE

Textural features on a pavement can be divided into four ranges, depending on textural wavelength. “Microtexture” refers to features smaller than 0.5 mm, “macrotexture” refers to features between 0.5 and 50 mm, “megatexture” refers to features between 50 and 500 mm, and “unevenness” refers to features larger than 500 mm. In general, unevenness has little influence on tire-pavement noise, but microtexture, macrotexture, and megatexture can all affect radiated noise. Several previous researchers have investigated the effects of textural wavelength on tire-pavement noise. For example, Sandberg and Descornet[3] found that sound pressure levels below 1000 Hz increase with texture amplitude for textural wavelengths of 10–500 mm, and frequencies above 1000 Hz decrease with texture amplitude for textural wavelengths of 0.5–10 mm.

Though these previous studies are not conclusive relative to the best texture design for PCC roadways, good candidates for quiet surfaces would have low macrotexture, high microtexture, and have grooves, which are narrow compared to the width of the pavement between the grooves, oriented longitudinally.

2.3 ON-BOARD SOUND INTENSITY

Tests of tire-pavement noise are often conducted with microphones mounted near the contact patch of the tire. Methods for conducting such measurements include the Close-Proximity trailer (CPX) method and the On-Board Sound Intensity (OBSI) method. The OBSI method makes use of intensity probes, which measure both the level and direction of sound. The OBSI method makes it easier to distinguish wind noise from tire-pavement noise without the bulky sound-absorbing enclosure that is needed for CPX measurements. Furthermore, sound intensity spectra obtained with the OBSI method correlate more closely with spectra measured by a microphone as a vehicle passes by, and overall sound intensity levels measured using OBSI correlate with pass-by levels slightly better than CPX sound pressure levels[4]. Examples of OBSI equipment mounted on cars and laboratory equipment are shown in Figure 1. OBSI measurements are typically reported as overall A-weighted sound intensity levels and as one-third octave band spectra.

Figure 1: OBSI equipment on laboratory equipment and car

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3 PROCEDURE

3.1 TIRE-PAVEMENT TEST APPARATUS

All tire-pavement noise experiments were conducted with Purdue University's Tire-Pavement Test Apparatus (TPTA) at the Institute for Safe, Quiet, and Durable Highways. The TPTA is a 17 000 kg, 3.7 m (12.14 ft) diameter drum containing a motor, gear box, and pulley that rotate a steel plate above the drum. Two arms are attached to the plate, and a passenger car wheel is suspended from each arm. Six PCC samples are mounted to the drum to form a ring of pavement around the TPTA. The wheels roll around the outside of the samples as the steel plate rotates. The TPTA is housed in a hemi-anechoic chamber to reduce ambient noise. A picture of the TPTA is shown in Figure 2, and a schematic drawing of the TPTA assembly is shown in Figure 3. The tires and pavement samples are easily exchanged to test multiple combinations quickly. The rotation speed of the TPTA can be adjusted for speeds up to 30 mph (48 kph). For this experiment, measurements were taken at 10, 20, and 30 mph (16, 32, and 48 kph), and the normal load on each tire was set at 2.7 kN (600 lbs). Before each test, the tire was warmed up by running the TPTA at 30 mph for 15 minutes.

Figure 2: Purdue University's Tire-Pavement Test Apparatus

Figure 3: Schematic drawing showing interior assembly of TPTA

3.2 TIRES

Two different tires were used for the experiment. The tires, a Uniroyal Tiger Paw (P205/70R15 95S M+S) and a Goodyear Aquatred (P205/70R15 95T M+S) were inflated to a pressure of 230 kPa (33 psi) and were used to test all of the samples.

3.3 DATA COLLECTION

Two intensity probes were mounted near one of the test tires on the TPTA, following the specifications in the draft AASHTO standard for On-Board Sound Intensity (OBSI)[5]. The microphones were Brüel and Kjær Type 4197 Sound Intensity Microphone Pairs with a microphone separation of 16 mm (0.63 in.). The center of the probes were located 76 mm (3 in.) from the pavement test samples and 102 mm (4 in.) above the tire near the leading and trailing edges of the contact patch. Diagrams of the microphone placement are shown in Figure 4 and Figure 5. Magnetic triggers were used to ensure that the same section of pavement was measured with each pass of the machine. The intensity probes and magnetic triggers were all connected to a Brüel and Kjær Type 3032A Input/Output Module and Type 7533 LAN Interface Module. The data were sent via wireless router to a laptop computer for further processing.

Figure 4: Placement of on-board sound intensity probes in relation to test tire and sample

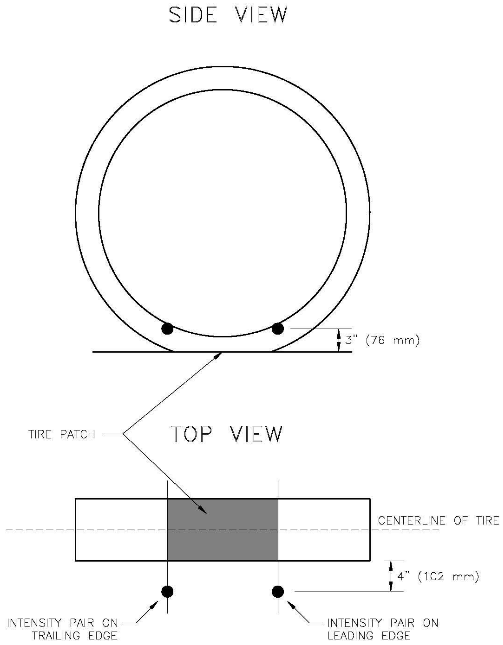

Figure 5: Sound intensity probe placement according to AASHTO provisional standard[5]

3.4 DATA PROCESSING

For each combination of a tire and a pavement sample, A-weighted, narrow-band intensity spectra were collected for 100 passes of the test tire over the pavement sample. Using the magnetic triggers, 80 ms of data were taken over the same section of pavement for each pass. The 100 spectra were averaged to get average narrow-band intensity spectra for both the leading and trailing intensity probes. The two measurements were averaged to get the narrow-band intensity spectrum for a given tire-pavement combination. The sample rate of 12 800 Hz and the 80 ms time window yielded narrow-band intensity data from 12.5 to 5 000 Hz with a resolution of 12.5 Hz. The one-third octave band intensity spectra were computed from narrow-band intensities from 630 to 4 000 Hz . Finally, overall intensity levels were calculated by summing the narrow-band intensity from 500 to 5 000 Hz.

3.5 SAMPLE CONSTRUCTION

All of the samples for the experiments started originally as smooth samples. The samples were constructed by pouring concrete into steel forms. The samples used in this study were constructed over several years, but the same mix and procedure was used for each set of samples. The PCC was specified as 4 000 psi, non-air, gravel PCC with an average slump of 6 in. The samples were allowed to set for 1–2 weeks in the steel forms before they were removed. The samples were then covered in wet burlap and plastic and allowed to cure for approximately one month. The samples were then loaded onto the TPTA for grinding.

3.6 GRINDING PROCEDURE

The samples were ground with longitudinal diamond grinding. The grinding apparatus used was attached to one of the arms of the TPTA, and the samples were ground while mounted on the TPTA as shown in Figure 6.

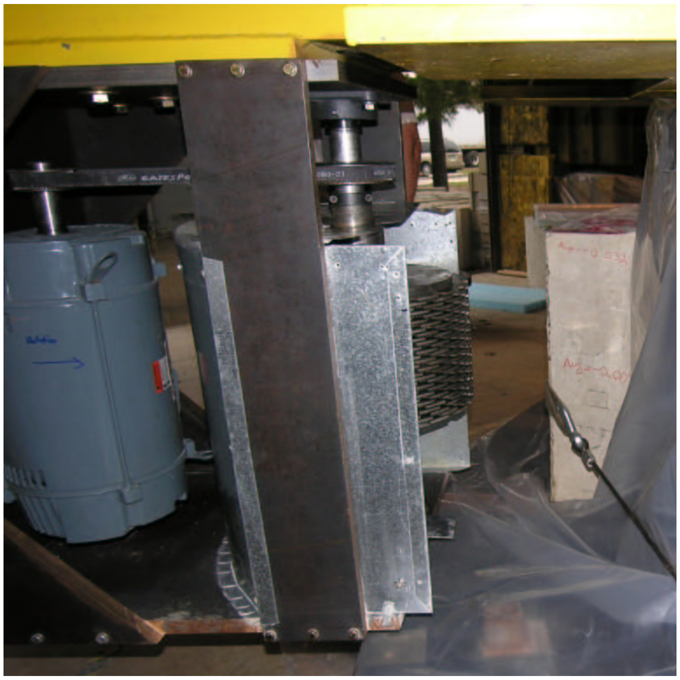

Figure 6: Grinding apparatus mounted on TPTA

The grinding apparatus consists of a 20 hp motor attached via a belt to an axle containing a stack of diamond-infused steel blades. The stack of blades rotates very quickly and cuts the outer layer of the concrete sample. The blades that make up the stack are available in several diameters and thicknesses. By combining the different sized blades with non-cutting spacers, it is possible to create a wide variety of cutting configurations. By using blades with a slightly smaller diameter, known as “chopper blades,” it is possible to make cuts at two different depths at the same time. A stack of blades is typically 200–230 mm wide. The dimensions of the blades and spacers used are shown in Table 1.

Table 1: Dimensions of blades and spacers

Blade/Spacer Name	Diameter	Thickness
B090 (Blade)	368 mm (14.5 in.)	2.29 mm (0.090 in.)
B110 (Blade)	368 mm (14.5 in.)	2.79 mm (0.110 in.)
B125 (Blade)	368 mm (14.5 in.)	3.18 mm (0.125 in.)
B165 (Blade)	368 mm (14.5 in.)	4.19 mm (0.165 in.)
Chopper (Blade)	364 mm (14.34 in.)	3.18 mm (0.125 in.)
S030 (Spacer)	343 mm (13.5 in.)	0.76 mm (0.030 in.)
S090 (Spacer)	343 mm (13.5 in.)	2.29 mm (0.090 in.)
S110 (Spacer)	343 mm (13.5 in.)	2.79 mm (0.110 in.)
S130 (Spacer)	343 mm (13.5 in.)	3.30 mm (0.130 in.)

Several different blade configurations were tested. Table 2 shows the blade configuration used to construct each of the test samples. One sample was left in its as-cast state for comparison. Two samples, “full-grind” and “full-grind w/grooves,” were created using multiple passes of the grinding machine. The result of this process is explained in section 3.7.3.

Table 2: Blade configurations for all samples

Sample Number	Sample Name	Repeating Blade Configuration	Cutting Depth
TI 1 - 1	B125 S130 D3/16”	B125 / S130	4.8 mm (3/16 in.)
TI 1 - 2	B125 S130 D1/8”	B125 / S130	3.2 mm (1/8 in.)
TI 1 - 3	B110 S130 D3/16”	B110 / S130	4.8 mm (3/16 in.)
TI 1 - 4	B110 S130 D1/8”	B110 / S130	3.2 mm (1/8 in.)
TI 1 - 5	B110 S110 D1/8”	B110 / S110	3.2 mm (1/8 in.)
TI 1 - 6	B125 S110 D1/8”	B125 / S110	3.2 mm (1/8 in.)
TI 1 - 7	B165 S130 D3/16”	B165 / S110	4.8 mm (3/16 in.)
TI 1 - 8	B125 S130 D3/16”	B125 / S130	4.8 mm (3/16 in.)

TI 1 - 9	B125 S110 D3/16”	B125 / S110	4.8 mm (3/16 in.)
TI 2 - 1	B125 S-varied D3/16”	B125 / Various Spacers	4.8 mm (3/16 in.)
TI 2 - 2	B125 S-chopper D3/16”	B125 / S030 / Chopper / S030	4.8 mm (3/16 in.)
TI 2 - 3	B125 S-chopper D3/16”	B125 / S030 / Chopper / S030	4.8 mm (3/16 in.)
TI 2 - 4	B165 S130 D3/16”	B165 / S130	4.8 mm (3/16 in.)
TI 2 - 5	Full Grind D1/4”	First Pass: B090 / S090 Second pass: S090 / B090	6.4 mm (1/4 in.)
TI 2 - 6	Full Grind w/Grooves D1/8”	First pass: B090 / S090 Second pass: S090 / B090 Third pass: B090 spaced 12.7 mm (1/2 in.) on center	3.2 mm (1/8 in.)
TI 2 - 7	Triple Chopper D1/8”	B165 / S030 / Chopper / S030 / Chopper / S030 / Chopper / S030	3.2 mm (1/8 in.)
TI 2 - 8	Double Chopper D1/8”	B165 / S030 / Chopper / S030 / Chopper / S030	3.2 mm (1/8 in.)
TI 2 - 9	Blank w/Grooves D1/8”	B090 spaced 12.7 mm (1/2 in.) on center	3.2 mm (1/8 in.)
TI 2 - 10	Blank	No grinding	None

The depth of the cut for each sample was determined by calculating the average thickness of the sample by measuring the thickness at several points. The variation in thickness was typically less than 1.2 mm. The grinding apparatus was then set to cut the desired depth (1/8 or 1/4 in.) below the average pavement height. During the grinding process, the blade stack and the sample were sprayed with water to minimize concrete dust and cool the blades.

3.7 PROJECT TEST INTERVALS

The project was separated into two test intervals, each with different objectives and categories of samples.

3.7.1 TEST INTERVAL 1

The first test interval of the project was a survey of current practices for longitudinal diamond grinding on the TPTA . An effort was made to include blade-spacer configurations that were representative of the types of practice used in the field. The effects of several parameters were investigated, including blade width, spacer width, and grinding depth. The blade configurations are shown in Table 2.

3.7.2 FIN WEAR INVESTIGATION

As explained in section 4.1, one finding from the initial Test Interval 1 testing was that when the “fins” break off, they leave a rough texture. A study was done where these fins were artificially worn down using a ceramic block and tested repeatedly on the TPTA to determine the effects of the roughness of the fins on tire-pavement noise.

In the fin wear investigation, two samples from Test Interval 1 and two from Test Interval 2 were tested using the CPX method. After the testing in the as-ground state, the fins were worn down by small amounts in stages and retested after each stage. The four fin states tested were:

1. **As ground**—immediately after the grinding process

2. **Sanded**—the samples were lightly sanded to remove microtexture from the fins

3. **Fins broken**—the samples were worked lightly with abrasive blocks to wear away the tops of the fins

4. **Final state**—the samples were worked roughly with abrasive blocks to wear away the remainder of the tops of the fins to form a uniform height

The abrasive blocks used for this study are shown in Figure 7.

Figure 7: Abrasive blocks used to wear down fins on fin wear investigation samples

These samples were tested with the CPX method before and after wearing down the fins, and then retested with the OBSI method in their final state.

3.7.3 TEST INTERVAL 2

Test Interval 2 was intended to determine how to create the quietest pavement possible with longitudinal diamond grinding and grooving using new grinding techniques based on the findings in Test Interval 1. The three techniques considered were using random blade widths, using longitudinal grooves in ground and unground pavements, and using “chopper blades.” Chopper blades have slightly smaller diameter, and can be used to grind away the residual of the fins to create a smoother texture. Samples were constructed using varying numbers of standard blades and chopper blades. The blade configurations used are shown in Table 2.

Sample TI 2–1 was ground using a blade stack with random widths of spacers. Samples TI 2–2 and TI 2–3 were ground using alternating chopper and standard blades. Sample TI 2–4 was a replica of a sample from Test Interval 1 to use for comparison. Sample TI 2–5 was constructed in two passes of the grinding apparatus. On the first pass, a set of alternating thin blades and thin spacers were used. On the second pass, the same grinding stack was used, but offset by the width of a blade so that the blades ground away the fins, leaving a surface with a sandpaper-like texture but no fins. Sample TI 2–6 was identical to TI 2–5, but had longitudinal grooves spaced 1/2 in. on center. Samples TI 2–7 and TI 2–8 were created using a blade stack with alternating standard blades with multiple chopper blades. Sample TI 2–7 had three chopper blades for each standard blade, and sample TI 2–8 had two chopper blades for each standard blade. Samples TI 2–9 and TI 2–10 were not ground at all, and so the test surfaces of these samples were smooth as constructed with the steel forms used to pour the concrete. For sample TI 2–9, 1/2 in. spaced grooves were fabricated, similar to sample TI 2–6. By comparing noise results from all Test Interval 2 samples, it was possible to investigate the effects of longitudinal grooving, random blade spacing, full grinding, and the number of chopper blades used.

3.8 TEXTURE PROFILE MEASUREMENT

After the pavements were constructed, the texture profiles were measured using a laser scanner. All of the scanning measurements and processing were conducted according to ISO 13473-4[6]. The scanner used was a RoLine Laser Sensor made by LMI Technologies. The scanner measures the distance from the laser sensor to the pavement using laser triangulation. The scanner was mounted on the TPTA and scans were taken across the entire length of each sample. A picture of the scanning process is shown in Figure 8.

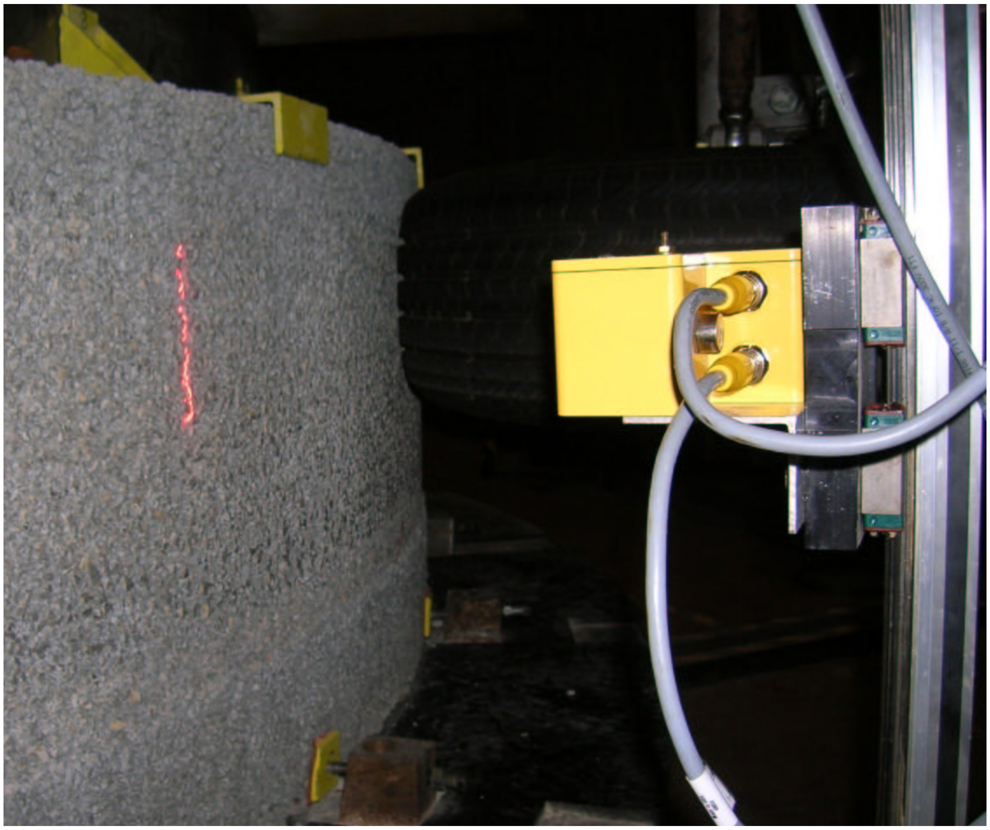

Figure 8: Laser scanner being used to take texture profile measurements of a sample

The longitudinal resolution was 0.04 mm and the transverse resolution was 0.22 mm. The vertical resolution was 0.01 mm. 400 lines of scanning data were taken in the transverse direction, resulting in a scan sample that was 88 mm (3.5 in.) wide and 1.4 m (56 in.) long.

The scanning data were processed in Matlab. For each scan, dropouts were less than 2%. The data from dropouts were replaced using linear interpolations of the surrounding points. A linear regression was removed from each scan to suppress any bias in the scanner alignment. Next, the wavelength spectrum of each of the 400 scan lines on each segment was computed using a Discrete Fourier Transform. The power spectral densities were then averaged together to get the average texture spectrum for each pavement sample. One-third octave band texture spectra were calculated according to ISO 13473-4. The texture spectra were reported as dB (re: 10^{-3} mm) and plotted against textural wavelength.

4 RESULTS

4.1 TEST INTERVAL 1 RESULTS

The purpose of Test Interval 1 was to create pavements similar to those found in the field and to investigate the effects of blade width, spacer width, and grinding depth. Table 3 shows the blade configurations for all Test Interval 1 samples. The samples produced resembled closely those found in the field. For example, Figure 9 shows the resulting pavement after grinding on TI 1–5.

Table 3: Blade configurations for Test Interval 1 samples

Sample Number	Sample Name	Repeating Blade Configuration	Cutting Depth
TI 1 - 1	B125 S130 D3/16”	B125 / S130	4.8 mm (3/16 in.)
TI 1 - 2	B125 S130 D1/8”	B125 / S130	3.2 mm (1/8 in.)
TI 1 - 3	B110 S130 D3/16”	B110 / S130	4.8 mm (3/16 in.)
TI 1 - 4	B110 S130 D1/8”	B110 / S130	3.2 mm (1/8 in.)
TI 1 - 5	B110 S110 D1/8”	B110 / S110	3.2 mm (1/8 in.)
TI 1 - 6	B125 S110 D1/8”	B125 / S110	3.2 mm (1/8 in.)
TI 1 - 7	B165 S130 D3/16”	B165 / S110	4.8 mm (3/16 in.)
TI 1 - 8	B125 S130 D3/16”	B125 / S130	4.8 mm (3/16 in.)
TI 1 - 9	B125 S110 D3/16”	B125 / S110	4.8 mm (3/16 in.)

Figure 9: Result of grinding on TI 1–5

Overall sound intensity levels for all nine Test Interval 1 samples at 48 kph (30 mph) are shown in Figure 10. The levels from the Goodyear Aquatred tire (shown in blue) are consistently 1.5–3 dB higher than those from the Uniroyal Tiger Paw tire (red).

The quietest pavement was TI 1–6 for the Uniroyal tire, and TI 1–9 for the Goodyear tire. These two samples used a combination of the wider blade (0.125 in.) and the narrower spacer (0.110 in.). However, all of the pavement levels were within 2 dB of each other, so they were all at similar overall sound intensity levels.

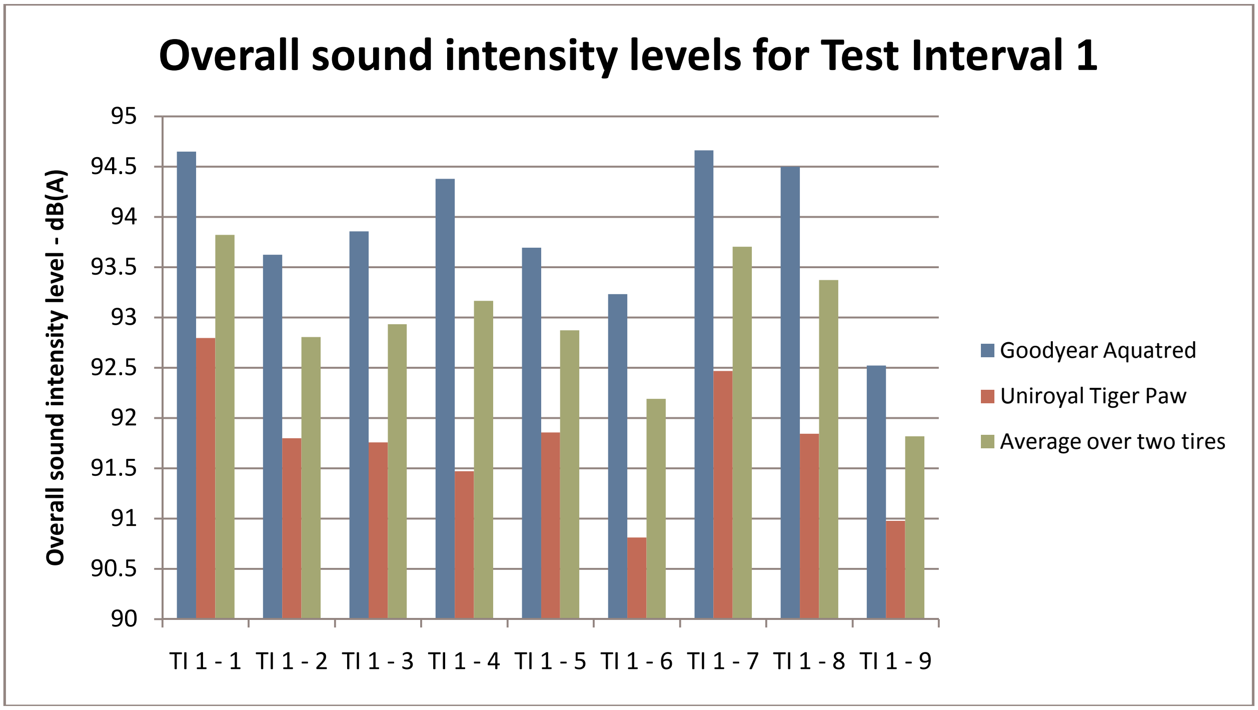

Figure 10: Overall sound intensity levels for Test Interval 1 samples at 48 kph (30 mph) with Goodyear Aquatred and Uniroyal Tiger Paw tires

By comparing samples with the same blade configurations but different grinding depths, the effect of grinding depth on noise levels was investigated. Overall sound intensity levels for these pavements are shown in Figure 11. The samples with the shallower grinding depth are quieter for four out of the six cases. The shallower grinds are on average 0.5 dB quieter, but no firm conclusions can be made about the cause of these differences.

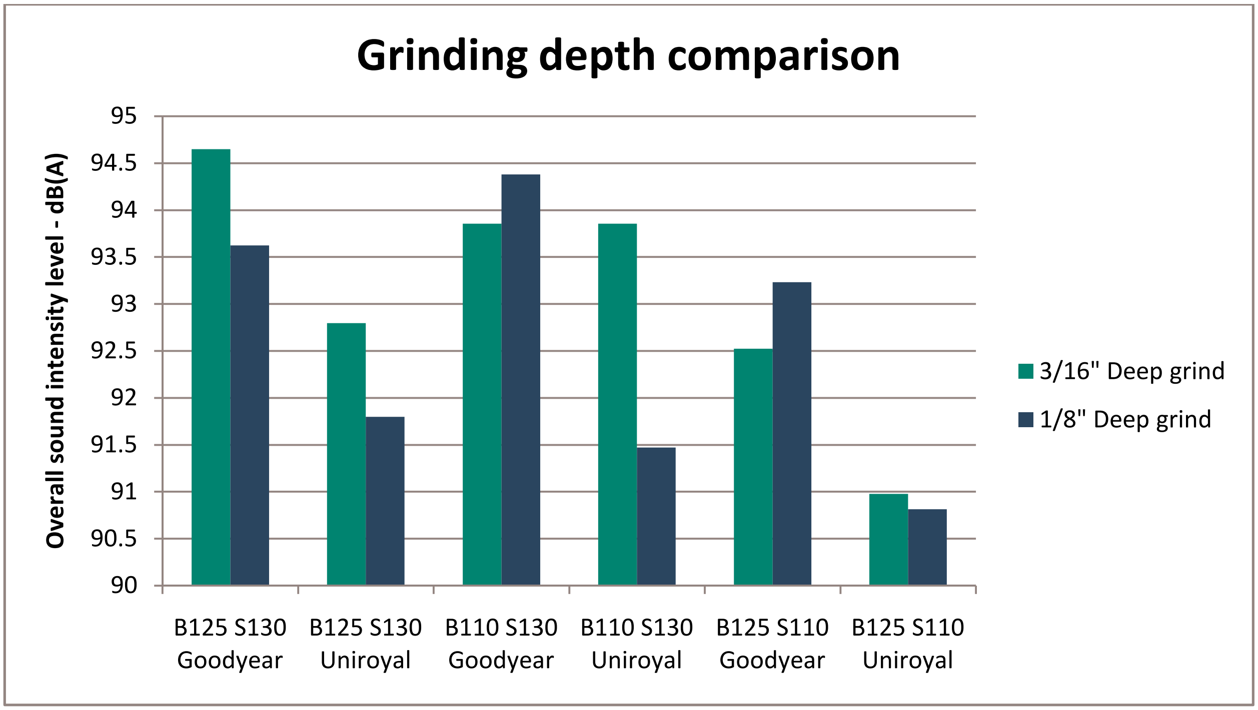

Figure 11: Comparison of grinding depth

Samples were ground with identical depths and spacer widths, but with different blade widths. By comparing these samples, the effect of blade width was investigated. Overall sound intensity levels for comparing blade widths are shown in Figure 12. The width of the blades affects the measured sound intensity level, but the effect is not always in the same direction. Wider blades are quieter for three out of the six spacer–grinding depth combinations tested, and narrower blades were quieter for the other three. One spacer–grinding depth combination was tested with three different blade widths. One of the blade widths was tested on two different samples, so that these two samples had identical grinding patterns. The sound intensity level measured on the replica was within 0.2 dB for the Goodyear tire but was about 1.0 dB quieter for the Uniroyal tire. This suggested that there is another factor involved in the sample construction that was not being considered.

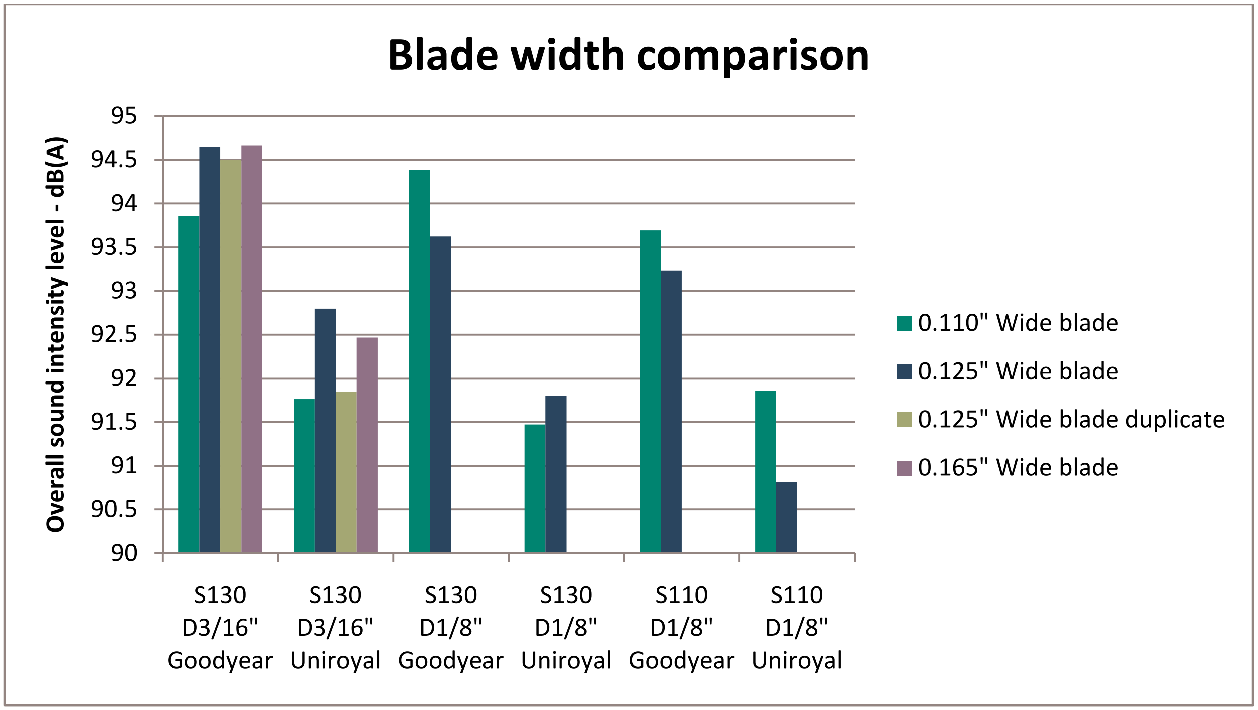

Figure 12: Blade width comparison

Another factor is the effect of spacer width on noise. Samples were constructed with the same blade width and grinding depth but with different spacer widths. A comparison of these samples is shown in Figure 13. The blade configurations with narrower spacers are quieter than the configurations with wider spacers in five out of six cases, though for most cases the difference is less than 1.0 dB. For the combination of the 0.125” blade and 3/16” cutting depth, the narrower spacer was substantially quieter for both tires. The duplicate test of the wider spacer configuration was quieter than the original for the Uniroyal tire. Though tire-pavement noise does seem to depend on spacer width, the effect is not consistent and there may be other contributing factors.

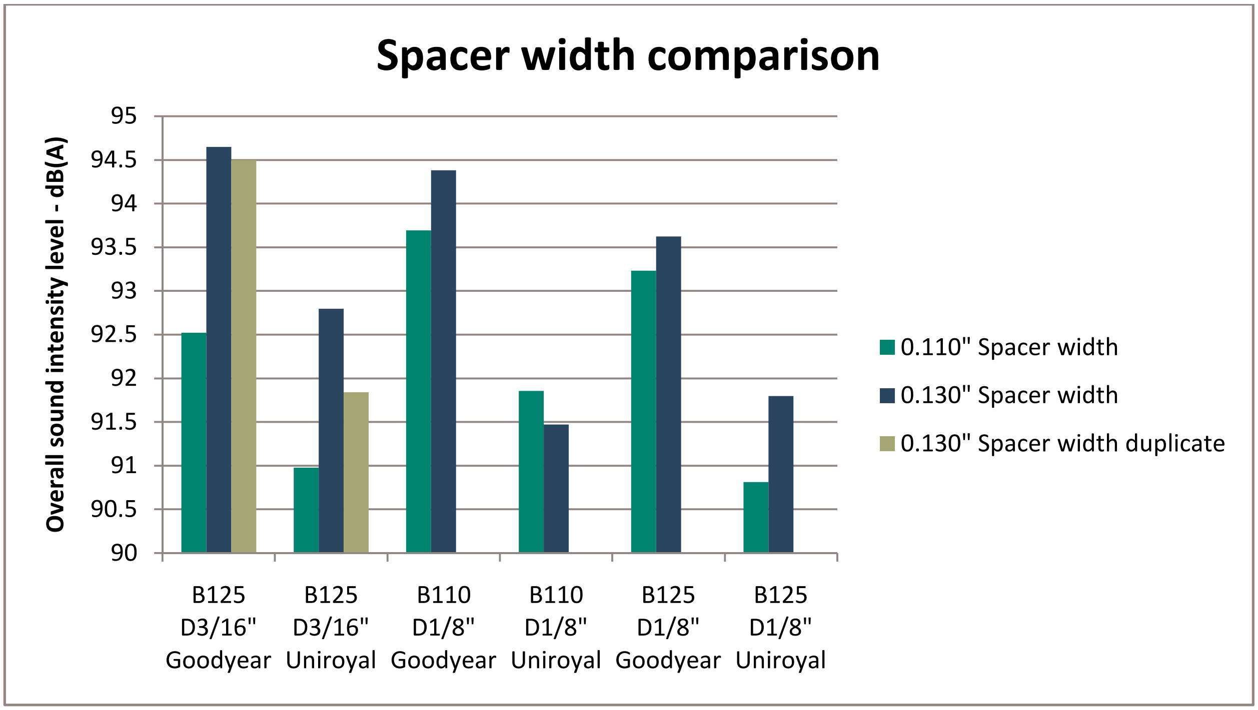

Figure 13: Spacer width comparison

One observation made during Test Interval 1 was that many of the fins left over between areas where blades had ground were breaking off, leaving a rough contact patch. It was suggested that the amount of fin breakage could be affecting the tire-pavement noise. An investigation was launched into the effects of fins and fin wear on tire-pavement noise.

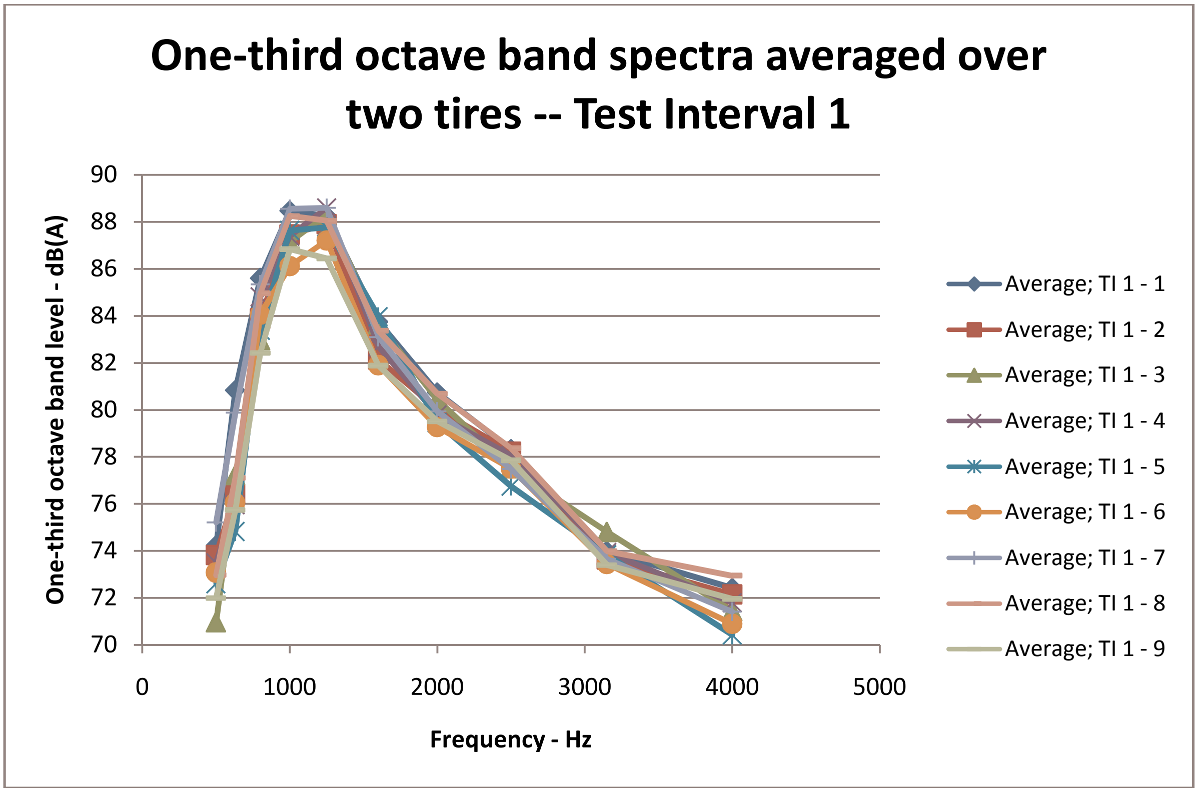

Figure 14: One-third octave band on-board sound intensity spectra for Test Interval 1

One-third octave band texture spectra for the nine pavements are shown in Figure 14. The spectra all show the same general trend, with a peak at 1 000 or 1 250 Hz and a sharp roll off at higher frequencies.

4.2 FIN WEAR INVESTIGATION

A key observation from Test Interval 1 was that the broken fins left between the places on the pavement cut by the blades affects the tire-pavement noise generated. In a side investigation, the effect of wearing down these fins was investigated. The pavement samples used for this study were a subset of Test Interval 1 and Test Interval 2 samples. The blade configurations for the samples used are shown in Table 4.

Table 4: Blade configurations for fin wear investigation

Sample Number	Sample Name	Repeating Blade Configuration	Cutting Depth
TI 1 - 7	B165 S130 D3/16”	B165 / S110	4.8 mm (3/16 in.)
TI 1 - 8	B125 S130 D3/16”	B125 / S130	4.8 mm (3/16 in.)
TI 2 - 1	B125 Svaried D3/16”	B125 / Various Spacers	4.8 mm (3/16 in.)
TI 2 - 2	B125 Schopper D3/16”	B125 / S030 / Chopper / S030	4.8 mm (3/16 in.)

As with the pavements from Test Interval 1, the two samples from Test Interval 2 initially had rough texture with partially broken fins. As the blade head grinds into the smooth pavement, the blades form grooves and the space between the blades leaves ridges between the grooves. Depending on the spacing and width of the blades, the ridges break off, leaving rough fins between the grooves. The effect of blade spacing on resulting pavement is illustrated in Figure 15 and Figure 16. An example of broken fins is shown in Figure 17.

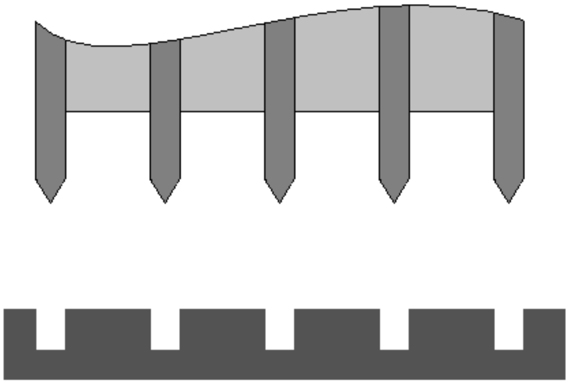

Figure 15: Longitudinal view of widely spaced blade pattern and resulting pavement

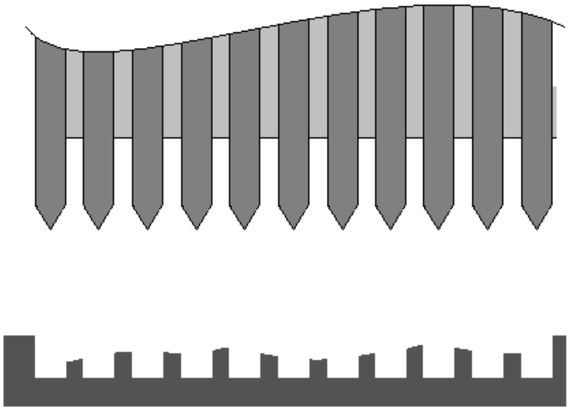

Figure 16: Longitudinal view of narrowly spaced blade pattern and resulting pavement

Figure 17: Broken fins on TI 2–2. Red circles indicate examples of points where ridges have broken off, leaving a rougher contact patch

These tests were done with progressive polishing of the partially broken fins. After the initial grinding and testing these samples, the fins were artificially worn down, and additional measurements were made. Overall sound pressure levels after each wearing state the fins are shown in Figure 18–Figure 20.

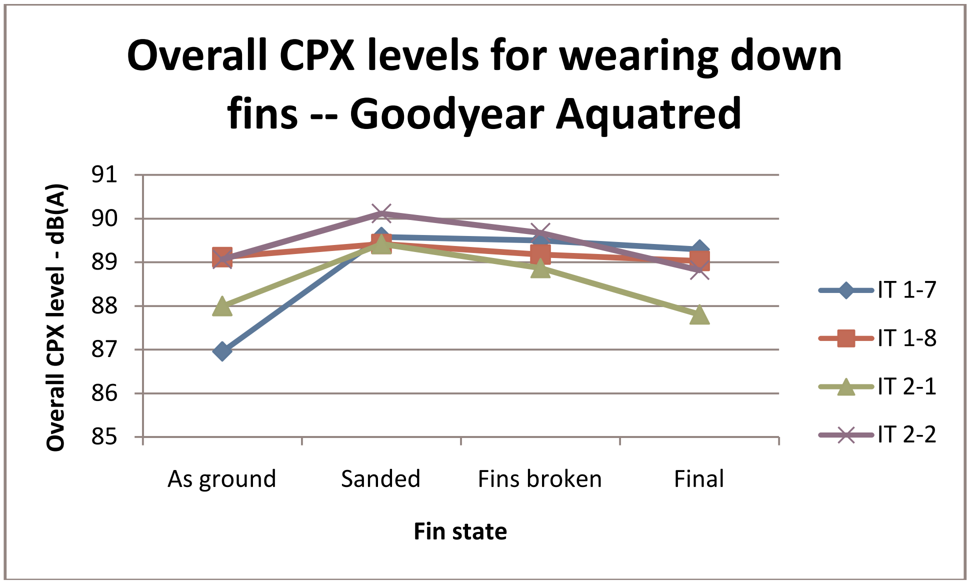

Figure 18: Overall CPX levels for wearing down fins with Goodyear Aquatred tire

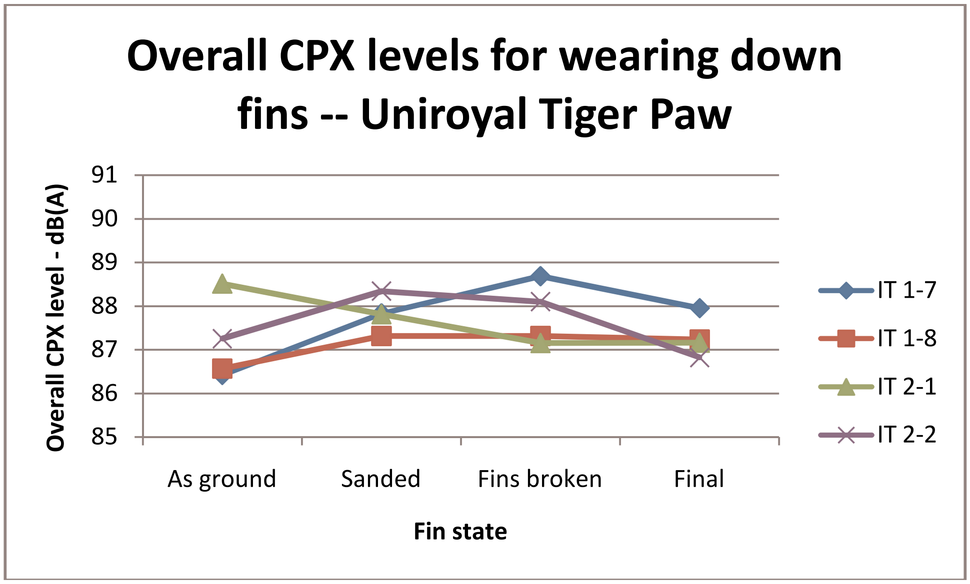

Figure 19: Overall CPX levels for wearing down with Uniroyal Tiger Paw tire

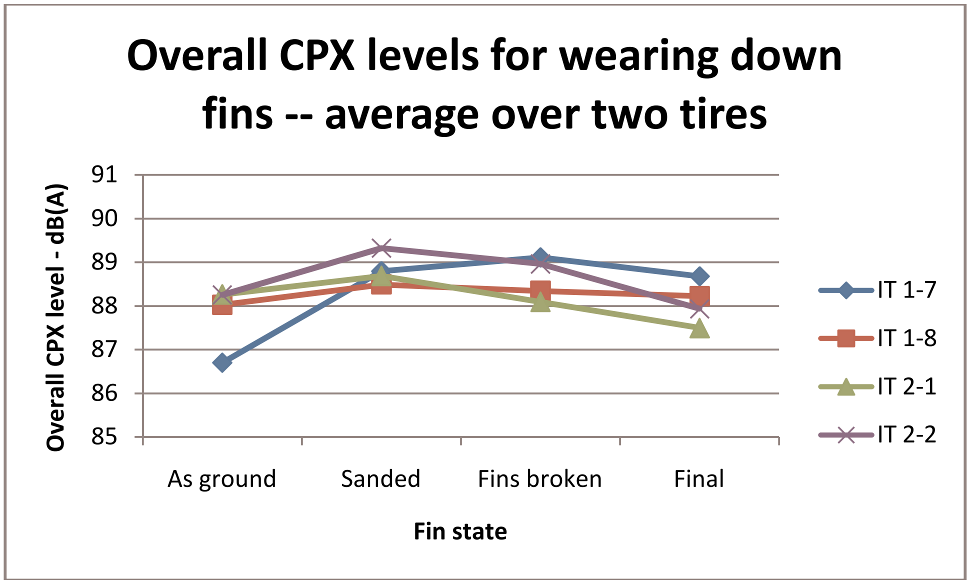

Figure 20: Overall CPX levels for wearing down fins averaged over two tires

After the first fin wearing stage, the four pavements almost all became louder with both tires. TI 2–1 was quieter with the Uniroyal tire but louder with the Goodyear tire. In the final two stages, the pavements became quieter. The final stage is not uniformly louder or quieter than the initial stage. However, the pavement spectra for these pavements were significantly different before and after polishing. Figure 21 shows the pavement spectra in the “as-cast” state and the final state.

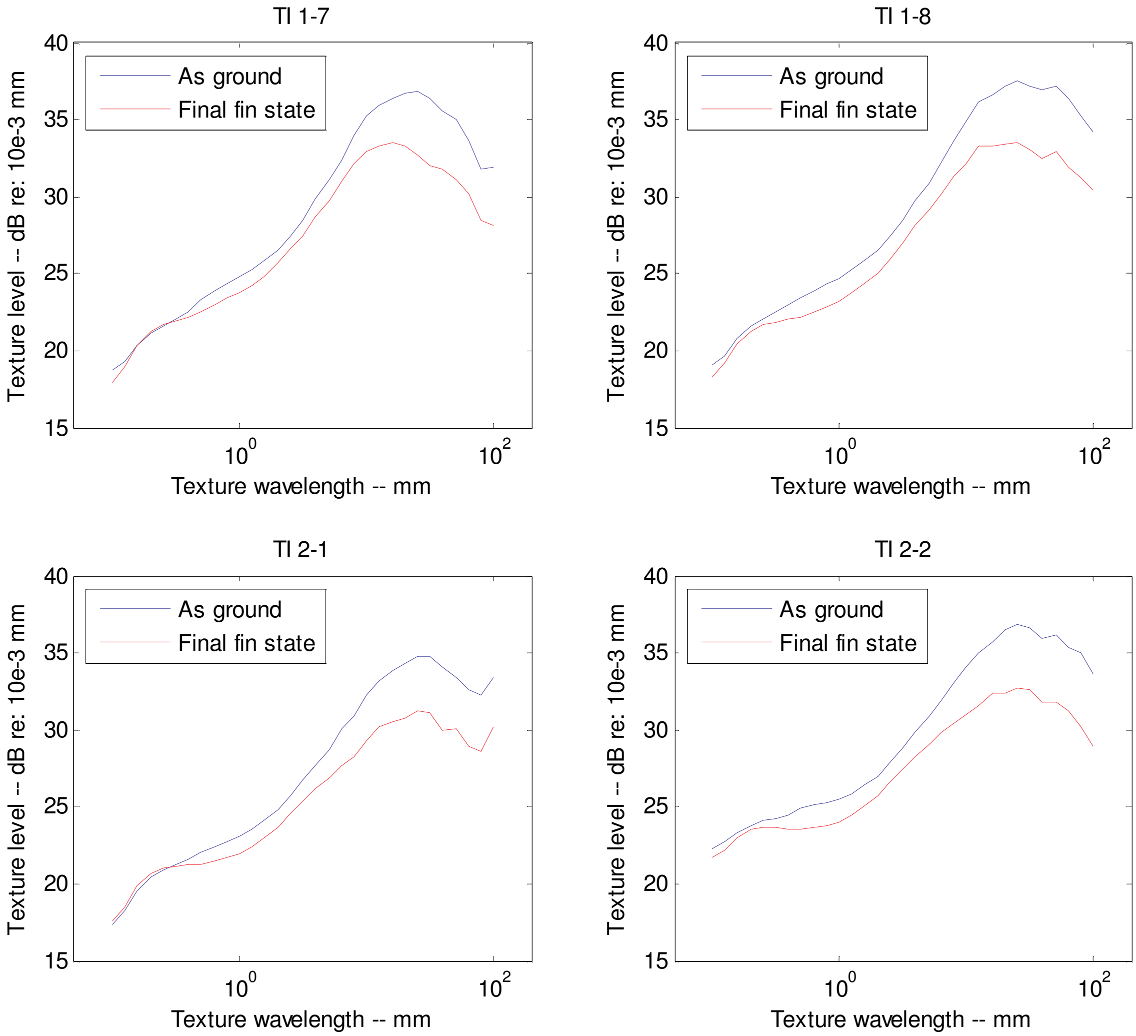

Figure 21: One-third octave band pavement spectra for fin wear investigation 2 samples in as-cast and final fin states

On all samples, the texture level at wavelengths shorter than 10 mm decreased between the initial and final fin state. The largest decrease is in the microtexture region, below 1.0 mm. The procedure for the "sanded" stage of the fin wearing process involved sanding the samples to reduce microtexture, so the results confirm that the goal of the procedure was achieved. The goal of the final two fin wearing stages, "fins broken" and "final state," was to reduce the macrotexture by breaking off and smoothing out the fins. This was also achieved in all of the samples, as indicated by the reduction in texture levels above 1.0 mm.

The spectra of the sound pressure levels also changed with the fin wearing procedure. For example, Figure 22 shows one-third octave band sound pressure levels for TI 2–1 as it was tested through the different fin states.

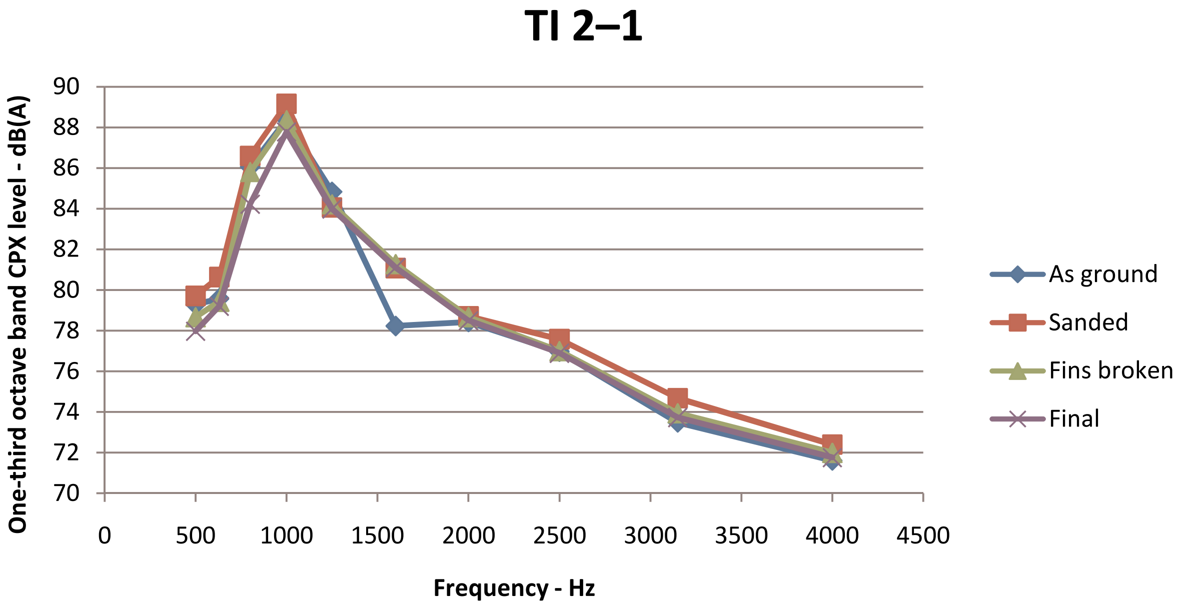

Figure 22: One-third octave band CPX level for different fin states of TI 2–1

For the transition from the initial state to the sanded state, the dip at 1600 Hz flattened out, there was a slight increase at 1200 Hz, and the sound pressure level decreased above 2000 Hz. The decrease in levels at high frequencies corroborates observations by Sandberg and Ejsmont[1] that decreases in microtexture yield increases in high frequency content. From the sanded state to the broken fin state and the final state, there is a decrease in high frequency content as well as low frequency content. It is possible that the fin wearing procedure reintroduced the microtexture removed by sanding, causing the decrease at high frequencies. Sandberg and Ejsmont observed that a decrease in macrotexture would yield decreases in sound pressure levels at low frequencies. This is evident in the decrease in low frequency content as the fins approach the final state. One-third octave band spectra from the other pavements in the fin wear investigation tested similar trends, and are shown in Appendix B. From the results of the fin wear investigation, it was determined that the quietest pavements would have as little macrotexture, in the form of broken fins as possible, while maintaining the microtexture created by the grinding process.

4.3 TEST INTERVAL 2 RESULTS

The samples designed in Test Interval 2 were created using lessons learned from Test Interval 1 and the fin wear study to create the quietest ground PCC pavement possible. A second priority was to investigate the effects of longitudinal grooving on tire-pavement noise. The blade patterns used are shown in Table 5.

Table 5: Blade patterns for Test Interval 2 samples

Sample Number	Sample Name	Repeating Blade Configuration	Cutting Depth
TI 2 - 1	B125 S-varied D3/16”	B125 / Various Spacers	4.8 mm (3/16 in.)
TI 2 - 2	B125 S-chopper D3/16”	B125 / S030 / Chopper / S030	4.8 mm (3/16 in.)
TI 2 - 3	B125 S-chopper D3/16”	B125 / S030 / Chopper / S030	4.8 mm (3/16 in.)
TI 2 - 4	B165 S130 D3/16”	B165 / S130	4.8 mm (3/16 in.)
TI 2 - 5	Full Grind D1/4”	First Pass: B090 / S090 Second pass: S090 / B090	6.4 mm (1/4 in.)
TI 2 - 6	Full Grind w/Grooves D1/8”	First pass: B090 / S090 Second pass: S090 / B090 Third pass: B090 spaced 12.7 mm (1/2 in.) on center	3.2 mm (1/8 in.)
TI 2 - 7	Triple Chopper D1/8”	B165 / S030 / Chopper / S030 / Chopper / S030 / Chopper / S030	3.2 mm (1/8 in.)
TI 2 - 8	Double Chopper D1/8”	B165 / S030 / Chopper / S030 / Chopper / S030	3.2 mm (1/8 in.)
TI 2 - 9	Blank w/Grooves D1/8”	B090 spaced 12.7 mm (1/2 in.) on center	3.2 mm (1/8 in.)
TI 2 - 10	Blank	No grinding	None

The first three samples in Test Interval 2 were designed to test new grinding techniques. TI 2–1 was ground using a blades spaced randomly instead of with the same uniform spacer. The TI 2–2 and TI 2–3 samples used chopper blades, which have slightly smaller diameter than the standard blades. The chopper blades grind away part of the fins usually left over between cutting blades. TI 2–4 was a duplicate of a sample from Test Interval 1 to use for comparison. Noise levels from these four samples are shown in Figure 23.

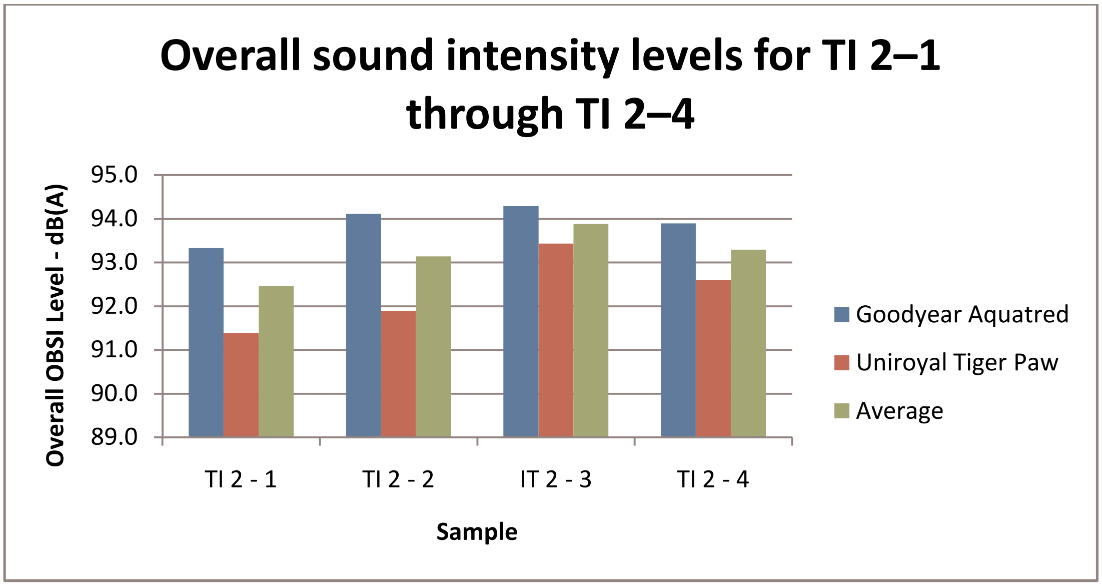

Figure 23: Overall sound intensity for TI 2-1 through TI 2-4

The random widths of the spacers in TI 2–1 may have contributed to a slightly lower intensity level, but the difference is not significant. The use of chopper blades instead of spacers in samples TI 2–2 and TI 2–3 did not make a significant difference either.

For the rest of the Test Interval 2 samples, an attempt was made to minimize the roughness of the fins while maintaining microtexture, in accordance with the results of the fin wear experiment. TI 2–5 through TI 2–8 exhibited the microtextural properties desired. They had a sandpaper-like feel, indicating a presence of significant microtexture. These samples also had little macrotexture. TI 2–5 was created with a second pass of the grinding machine to grind away all of the fins, and had almost no macrotexture. TI 2–6 was created similarly, but had longitudinal grooves as its only macrotextural feature. TI 2–7 was very similar to TI 2–6, but was created in one pass of the grinding apparatus through the use of chopper blades. TI 2–8 was similar to TI 2–7, except that the grooves were spaced closer together. Some of the fins left between the grooves broke off, leaving some macrotextural features.

The two remaining Test Interval 2 samples were blank samples that were smooth from the sample molds, so they had much less microtexture than TI 2–5 through TI 2–8. TI 2–10 had grooves installed that were the only macrotextural features of either of these two pavements.

Texture scans illustrate the textural differences between samples from the fin wear study and samples with high microtexture and low macrotexture. For example, by comparing the texture spectra for TI 2–6 with the two scans from TI 2–1, as shown in Figure 24, it is clear that TI 2–6 has less macrotexture than the original state of TI 2–1, but more macrotexture than the final state of TI 2–1. TI 2–6 has much more microtexture than either state of TI 2–1. Texture spectra for the other Test Interval 2 samples are shown in Appendix D.

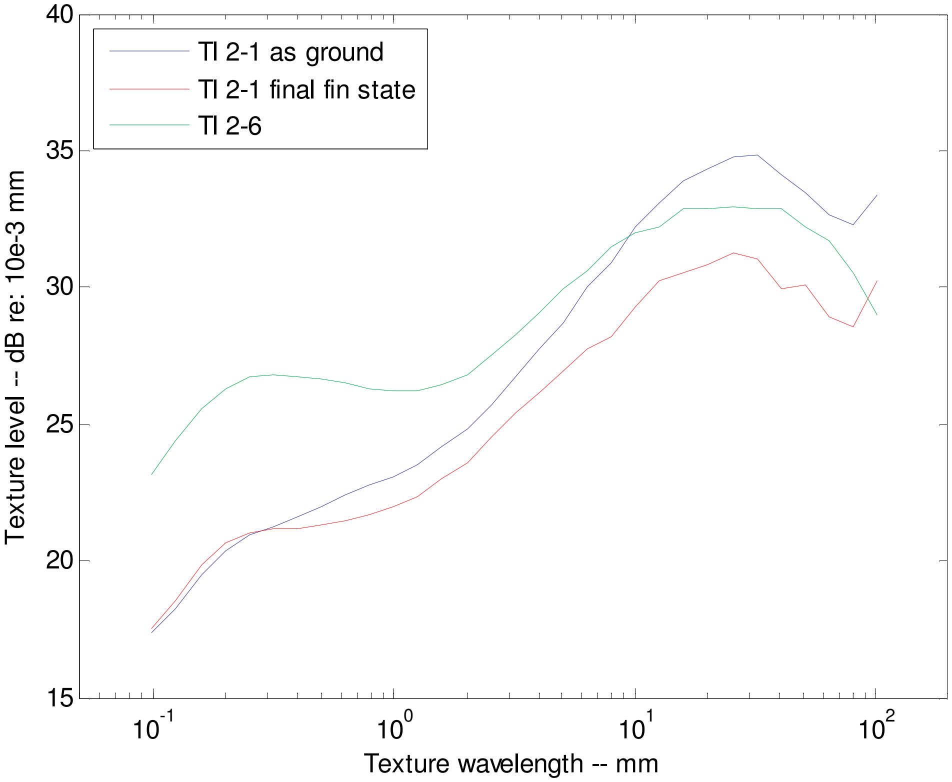

Figure 24: Pavement texture spectra of TI 2–1 and TI 2–6

Overall sound intensity levels for Test Interval 2 are shown in Figure 25. Samples TI 2–5 through TI 2–7 are significantly quieter than samples TI 2–1 through TI 2–4 and all of the samples from Test Interval 1. The average level from TI 2–8 (double chopper blades) is slightly higher than that of TI 2–7 (triple chopper blades), which is slightly higher than that of TI 2–5 (full grind with grooves). The slight differences in macrotexture among these samples with similar microtexture makes a small difference in the overall sound intensity levels. TI 2–6 is the quietest sample. Its average sound intensity level is about 3 dB below the average for most of the Test Interval 1 samples.

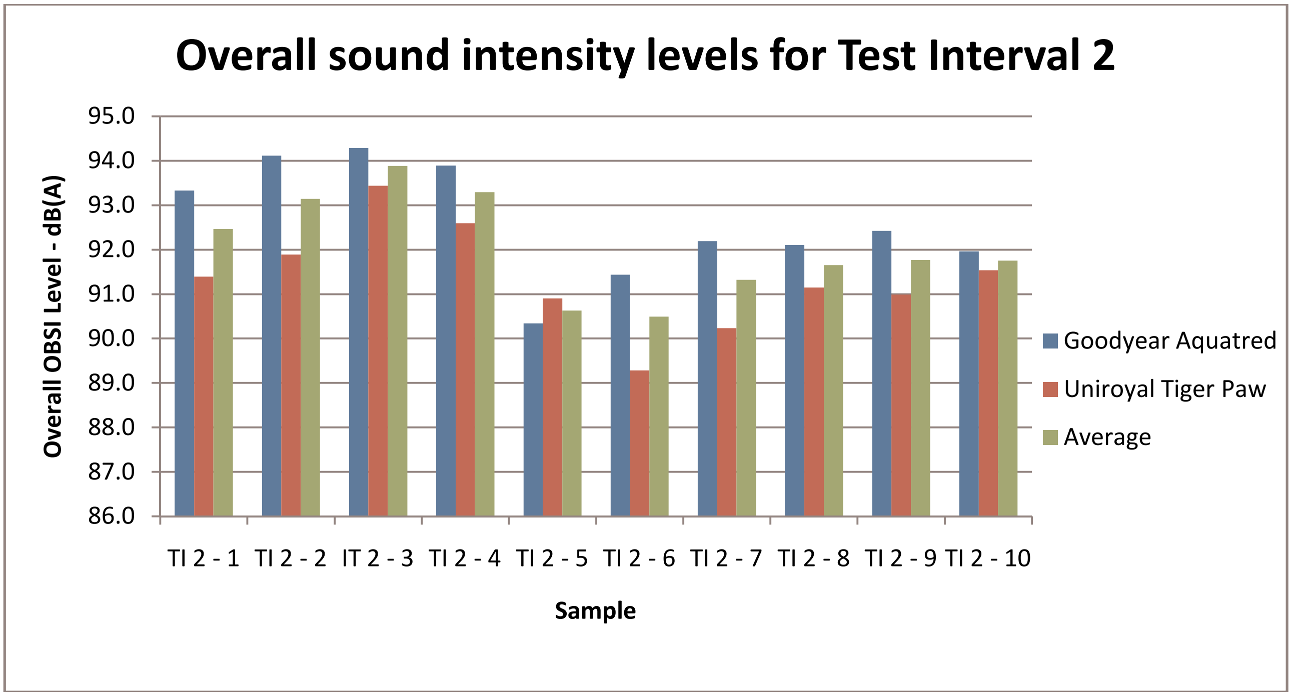

Figure 25: Overall sound intensity levels for Test Interval 2

Intensity spectra collected for Test Interval 2 illustrate the effects of microtexture on pavement noise. Figure 26 shows one-third octave band intensity levels for samples TI 2–4, TI 2–6, and TI 2–10. TI 2–4, which had both high microtexture and high macrotexture, is louder than the other samples at low frequencies but quieter at high frequencies. TI 2–10 did not have any grinding, and so had both low microtexture and low macrotexture. This sample is quieter than TI 2–4 at low frequencies, but substantially higher at high frequencies. TI 2–6 combines high microtexture and low macrotexture, yielding low sound intensity throughout the entire spectrum. Appendix D shows one-third octave band levels for all Test Interval 2 pavements.

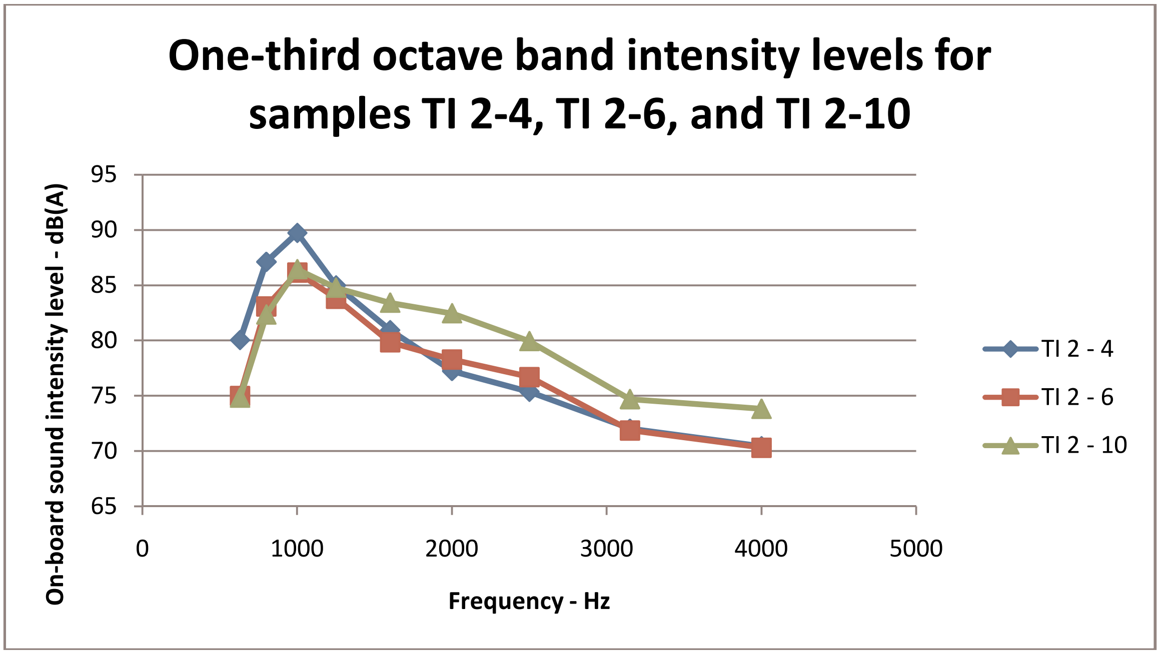

Figure 26: One-third octave band on-board sound intensity levels for TI 2–4, TI 2–6, and TI 2–10

From the Test Interval 2 data, it is possible to investigate the effects of longitudinal grooving on tire-pavement noise. TI 2–5 and TI 2–6 were identical except for the addition of longitudinal grooves on TI 2–6. TI 2–9 and TI 2–10 were also identical except for longitudinal grooves on TI 2–9. While the sound intensity levels for the individual tires differed by as much as 1.4 dB between TI 2–5 and TI 2–6, the average sound intensity levels were within 0.2 dB of each other. Similarly, for TI 2–9 and TI 2–10, the average sound intensity levels are less than 0.1 dB apart. While this was not an exhaustive test, it would appear that longitudinal grooving can affect sound intensity levels, but the result is not consistent over different tires, and the effect could be minimal when averaged over a number of different tires.

5 CONCLUSIONS

Several conclusions can be drawn from each of the two Test Intervals of this project. In Test Interval 1, it was demonstrated that the method of producing longitudinally ground PCC pavements on the TPTA produced pavements similar to those in the field. It was determined that blade width, spacer width, and grinding depth can all affect tire-pavement noise, but the effect is not consistent. It was found that the condition of the fins could substantially affect the tire-pavement noise.

The fin wear investigation focused on the possibility of reducing tire-pavement noise by wearing down the fins. Removing microtexture from the fins through sanding increased the measured noise. Reducing the macrotexture through uniformly breaking off the fins to form a more even surface reduced the noise, though the levels measured were not significantly different from those of the as-ground pavement. Using texture spectra of the four pavement samples, it was found that the finishing techniques changed the texture profile of the pavements in both the microtextural and macrotextural ranges. The fin wear investigation confirmed observations by previous researchers that an ideal PCC pavement would have high microtexture and low macrotexture.

In Test Interval 2, an attempt was made to create an ideal PCC pavement using new grinding techniques. It was found that randomizing spacer width or alternating single chopper blades with single chopper blades had little effect on the overall noise levels. By using a combination of cutting blades and multiple chopper blades, a pavement was created that was about 3 dB quieter than conventional longitudinally ground pavements at 48 kph (30 mph). By examining both the textural and sound intensity spectra of this quiet pavement, it was determined that the pavement had high microtexture, which yielded a reduction in noise at high frequencies, and low macrotexture, which yielded a reduction in noise at low frequencies. By comparing pavements of similar textures with and without longitudinal grooving, it was determined that grooving can affect tire-pavement noise, but the effects can differ depending on the tire used.

ACKNOWLEDGEMENTS

The authors wish to thank Jerry Voigt and Larry Scofield of the American Concrete Pavement Association for financial and logistical support for this project. In addition, we wish to thank Terry Kraemer of Diamond Surface, Inc. and the International Grinding and Grooving Association for providing the grinding equipment, the blades, and support to assist in the testing.

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[1] Ulf Sandberg and Jerzy A. Ejsmont, “Road surface influence on noise emission,” *Tyre/Road Noise Reference Book*, INFORMEX, Kisa, Sweden, Chapter 11, pp. 247–275, 2002.

[2] Robert Rasmussen et al., “Using On-Board Sound Intensity within the Concrete Pavement Surface Characteristics Program,” *Proc. Noise-Con 2007*, Reno, NV, 2007.

[3] Ulf Sandberg and Jerzy A. Ejsmont, “Texturing of cement concrete pavements to reduce traffic noise,” *Noise Control Eng. J.* 46 (6), 1998.

[4] Paul Donavan and Dana Lodico, “Measuring Tire-Pavement Noise at the Source, Appendix B: Test Evaluation of Candidate Methods and Recommendation for Test Procedure Development,” *NCHRP Report 630*, Transportation Research Board, 2009.

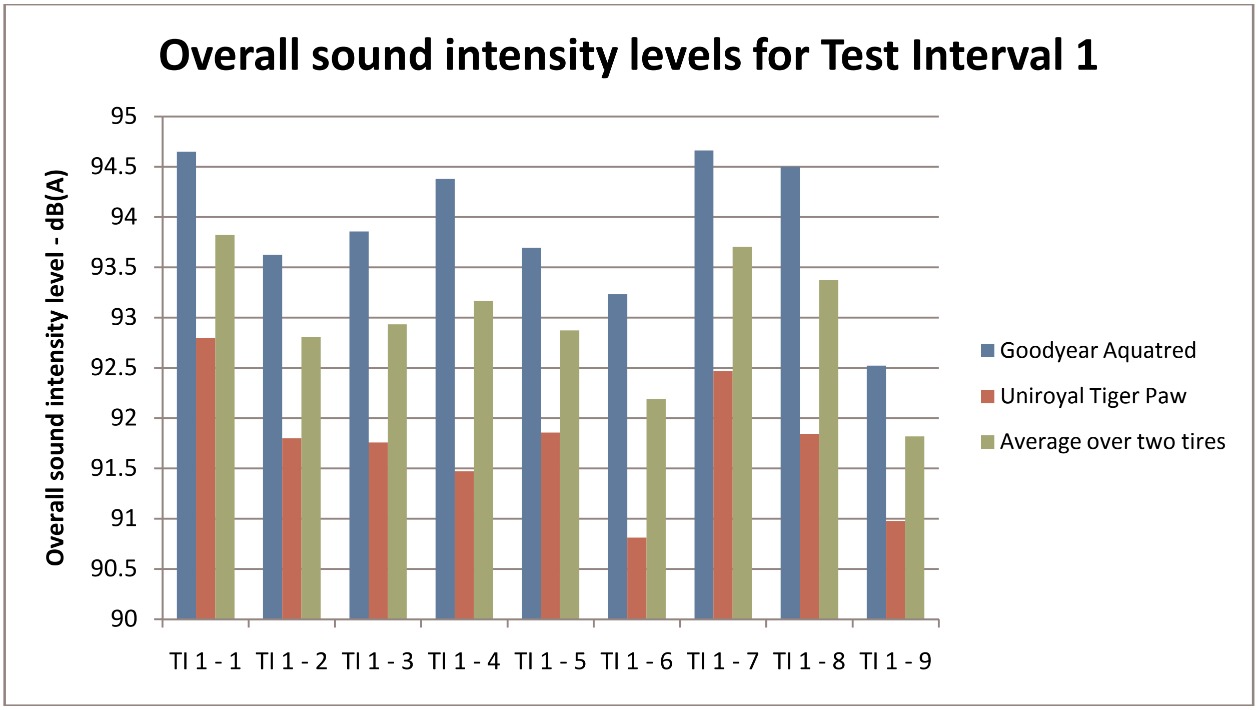
[5] AASHTO Provisional Standard: “Standard Practice for Measurement of On-Board Tire-Pavement Noise,” personal communication, FHWA Expert Task Group, 2009.

[6] ISO Standard: “Characterization of pavement texture by use of surface profiles – Part 4: Spectral analysis of surface profiles,” ISO/TS 13473-4, Geneva, Switzerland, 2008.

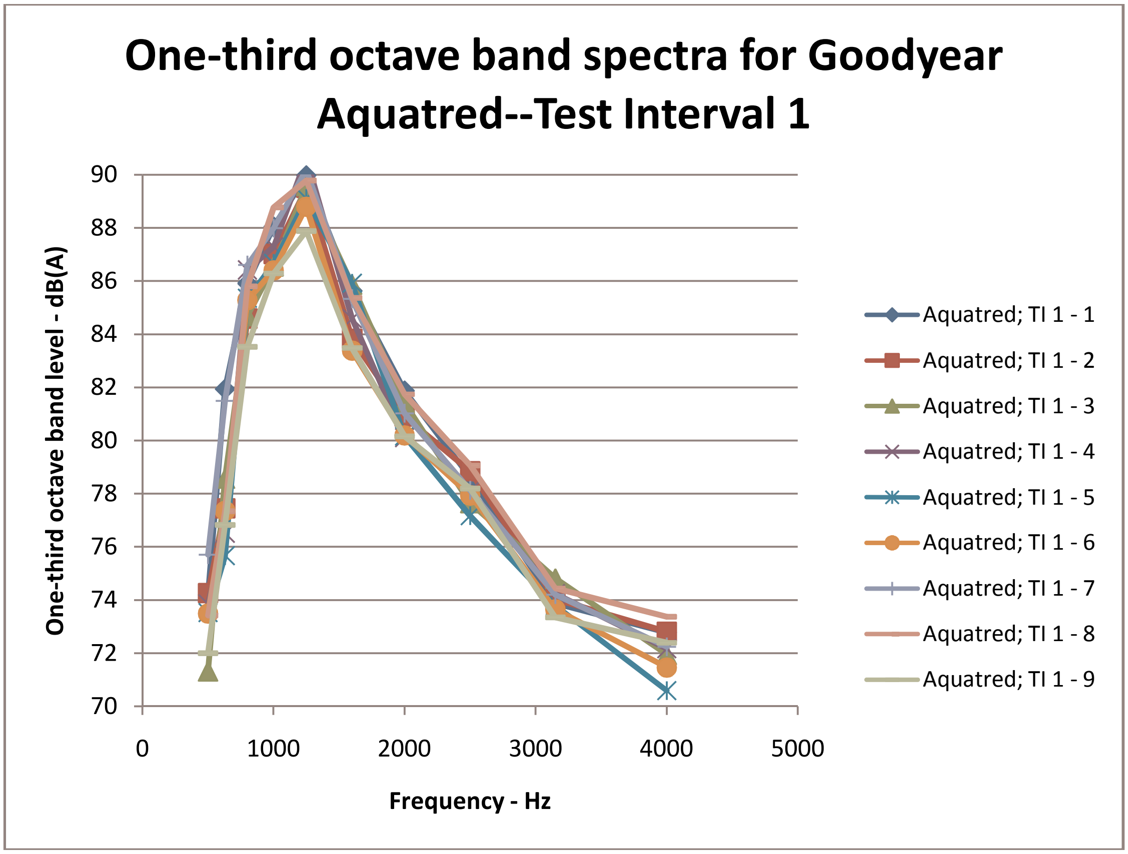
Appendix A: SUMMARY OF ON-BOARD SOUND INTENSITY DATA FOR TEST INTERVAL 1 SAMPLES AT 48 KPH (30 MPH)

Appendix Table A.1: Test Interval 1 blade configurations

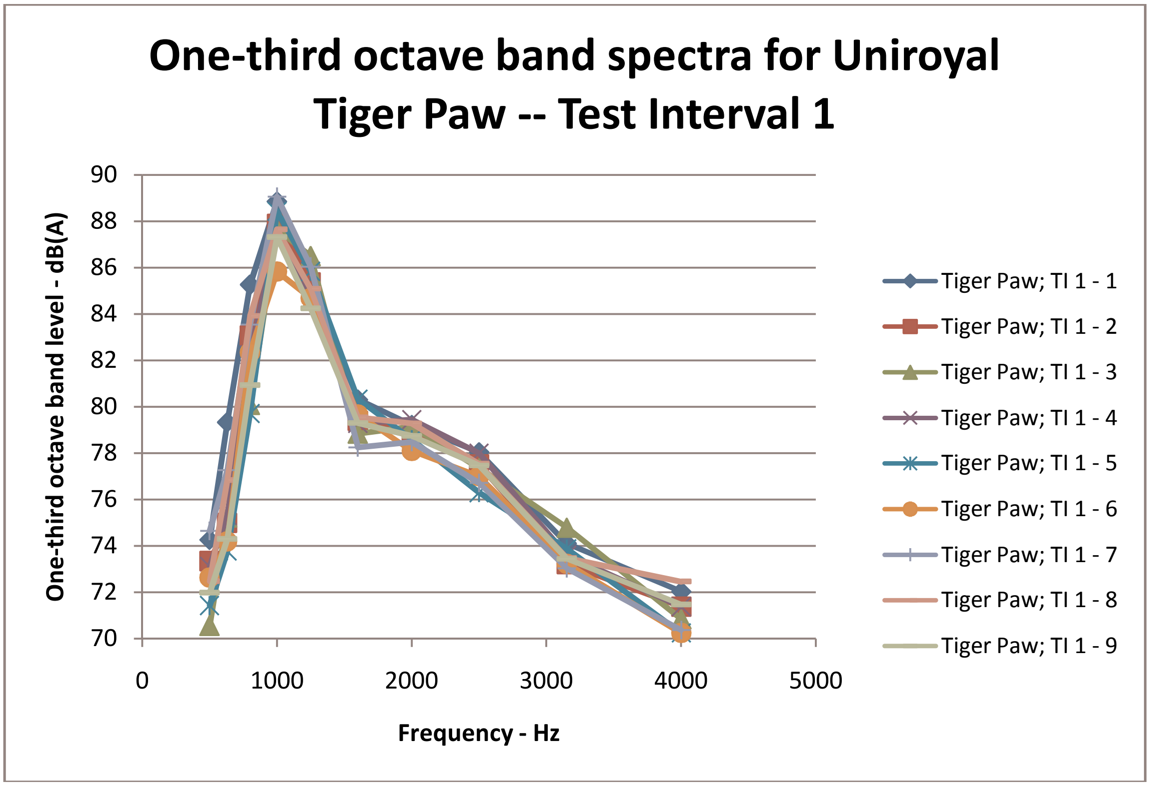
Sample Number	Sample Name	Repeating Blade Configuration	Cutting Depth
TI 1 - 1	B125 S130 D3/16"	B125 / S130	4.8 mm (3/16 in.)
TI 1 - 2	B125 S130 D1/8"	B125 / S130	3.2 mm (1/8 in.)
TI 1 - 3	B110 S130 D3/16"	B110 / S130	4.8 mm (3/16 in.)
TI 1 - 4	B110 S130 D1/8"	B110 / S130	3.2 mm (1/8 in.)
TI 1 - 5	B110 S110 D1/8"	B110 / S110	3.2 mm (1/8 in.)
TI 1 - 6	B125 S110 D1/8"	B125 / S110	3.2 mm (1/8 in.)
TI 1 - 7	B165 S130 D3/16"	B165 / S110	4.8 mm (3/16 in.)
TI 1 - 8	B125 S130 D3/16"	B125 / S130	4.8 mm (3/16 in.)
TI 1 - 9	B125 S110 D3/16"	B125 / S110	4.8 mm (3/16 in.)



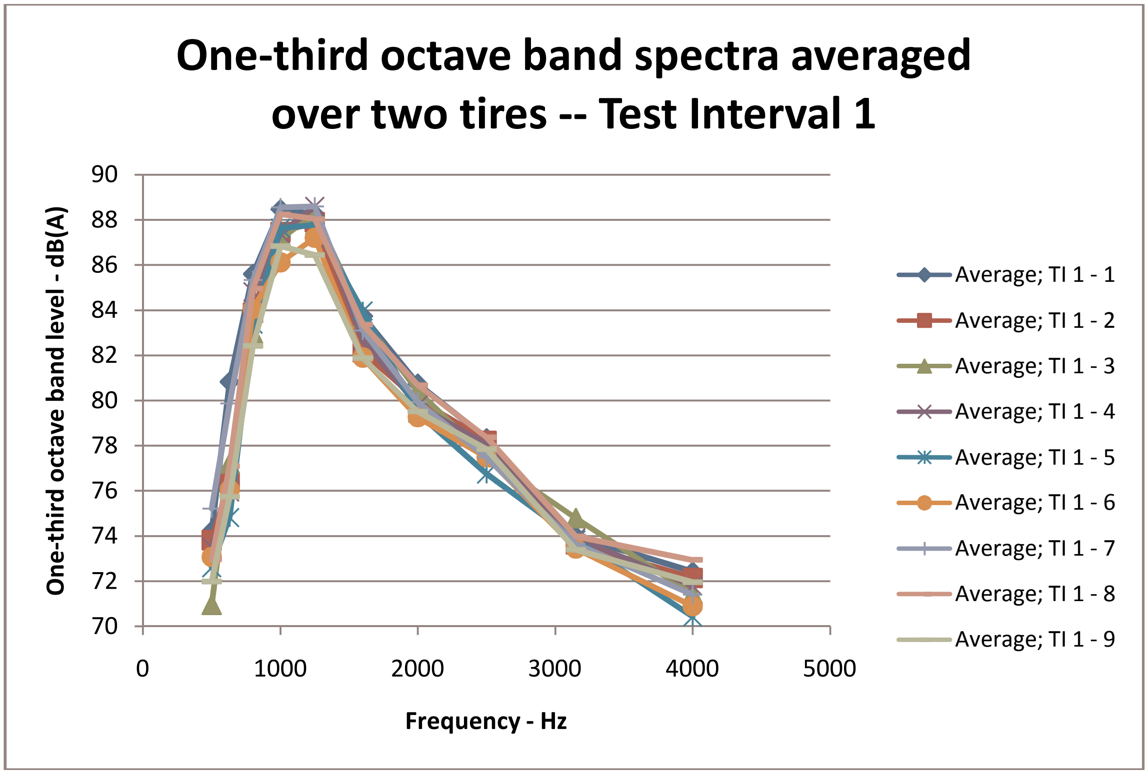
Appendix Figure A.1: Overall sound intensity levels for Test Interval 1 samples



Appendix Figure A.2: One-third octave band sound intensity spectra for Test Interval 1 samples with Goodyear Aquatred



Appendix Figure A.3: One-third octave band sound intensity spectra for Test Interval 1 samples with Uniroyal Tiger Paw

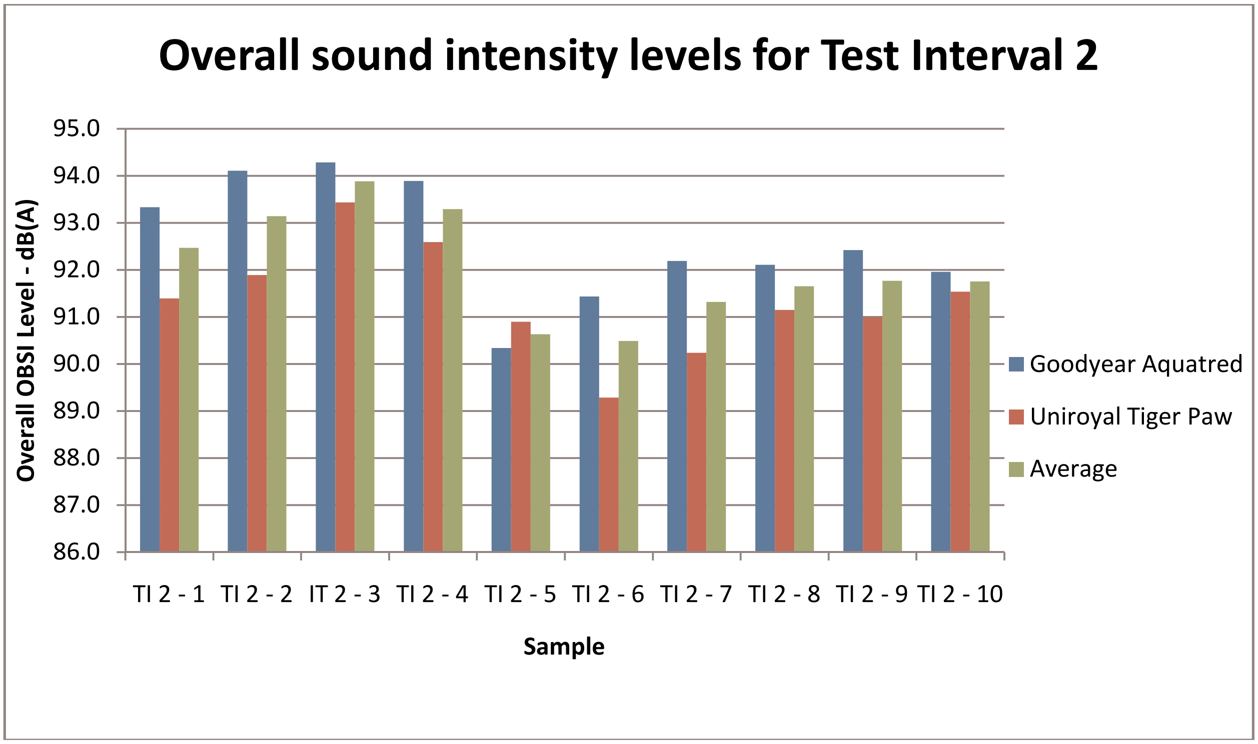


Appendix Figure A.4: One-third octave band sound intensity spectra for Test Interval 1 samples averaged over two tires

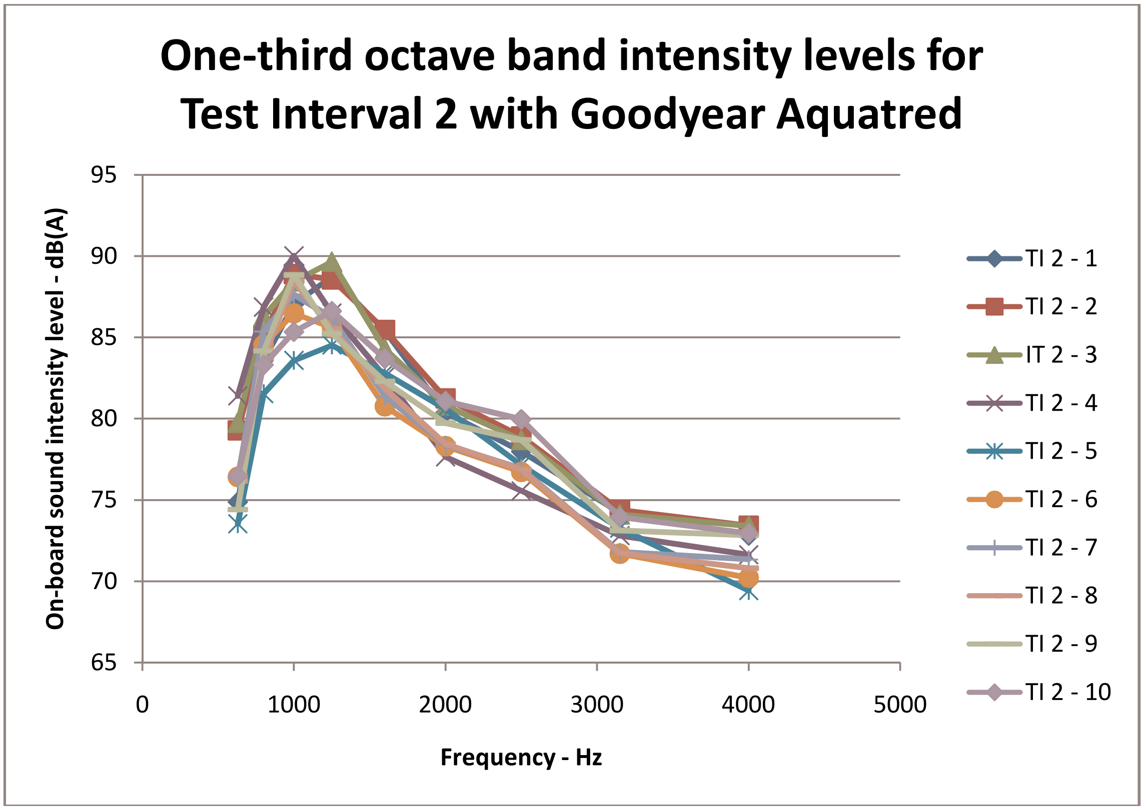
Appendix B: SUMMARY OF ON-BOARD SOUND INTENSITY DATA FOR TEST INTERVAL 2 SAMPLES AT 48 KPH (30 MPH)

Appendix Table B.1: Test Interval 2 blade configurations

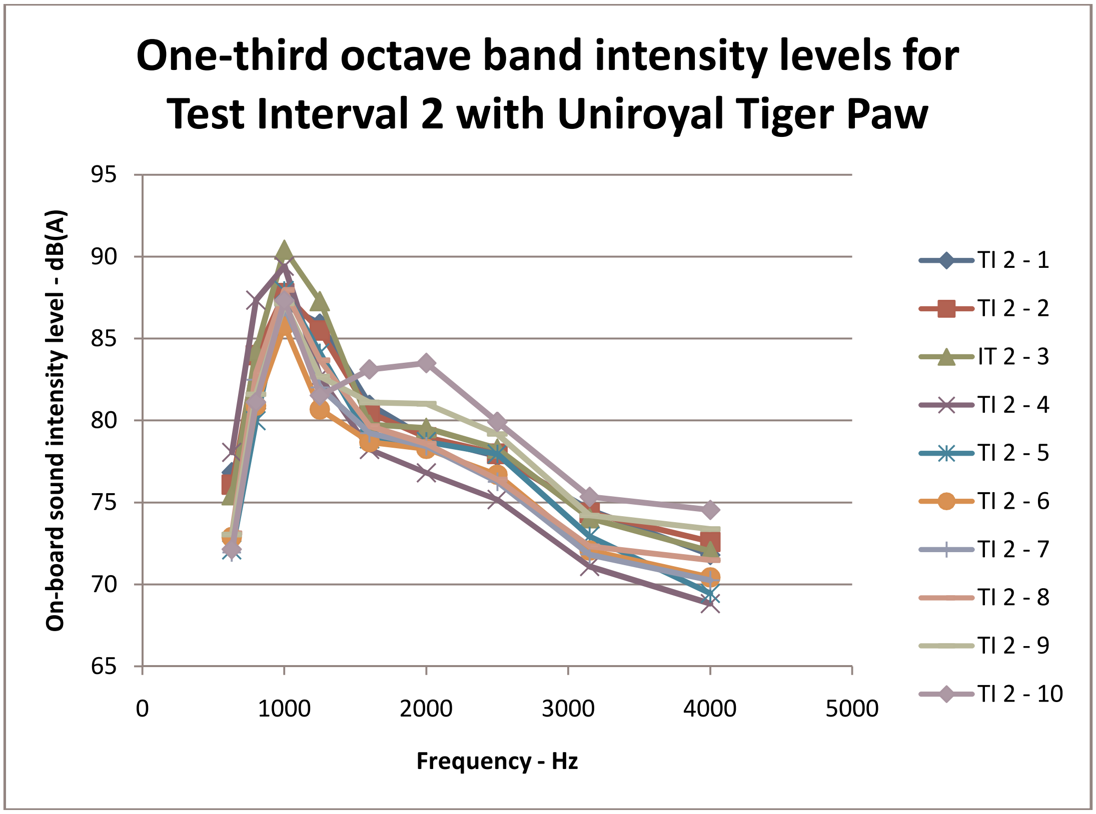
Sample Number	Sample Name	Repeating Blade Configuration	Cutting Depth
TI 2 - 1	B125 S-varied D3/16”	B125 / Various Spacers	4.8 mm (3/16 in.)
TI 2 - 2	B125 S-chopper D3/16”	B125 / S030 / Chopper / S030	4.8 mm (3/16 in.)
TI 2 - 3	B125 S-chopper D3/16”	B125 / S030 / Chopper / S030	4.8 mm (3/16 in.)
TI 2 - 4	B165 S130 D3/16”	B165 / S130	4.8 mm (3/16 in.)
TI 2 - 5	Full Grind D1/4”	First Pass: B090 / S090 Second pass: S090 / B090	6.4 mm (1/4 in.)
TI 2 - 6	Full Grind w/Grooves D1/8”	First pass: B090 / S090 Second pass: S090 / B090 Third pass: B090 spaced 12.7 mm (1/2 in.) on center	3.2 mm (1/8 in.)
TI 2 - 7	Triple Chopper D1/8”	B165 / S030 / Chopper / S030 / Chopper / S030 / Chopper / S030	3.2 mm (1/8 in.)
TI 2 - 8	Double Chopper D1/8”	B165 / S030 / Chopper / S030 / Chopper / S030	3.2 mm (1/8 in.)
TI 2 - 9	Blank w/Grooves D1/8”	B090 spaced 12.7 mm (1/2 in.) on center	3.2 mm (1/8 in.)
TI 2 - 10	Blank	No grinding	None



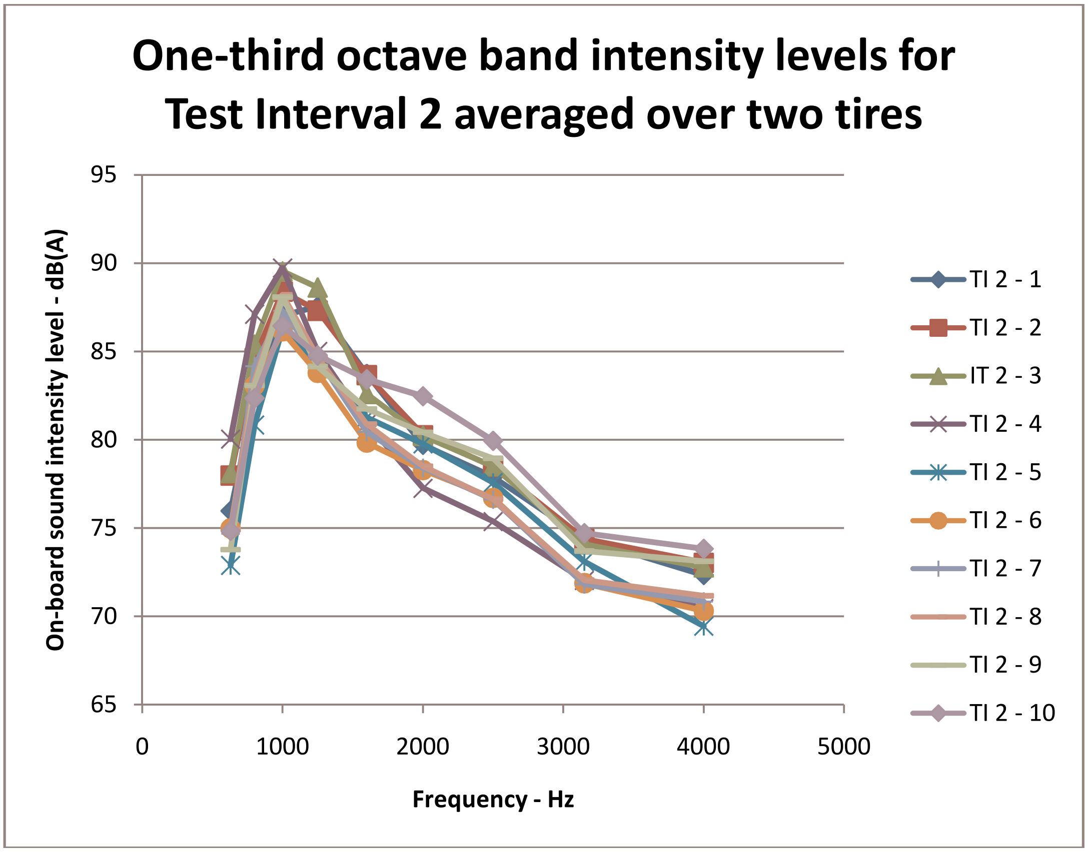
Appendix Figure B.1: Overall sound intensity levels for Test Interval 2



Appendix Figure B.2: One-third octave band sound intensity spectra for Test Interval 2 with Goodyear Aquatred



Appendix Figure B.3: One-third octave band sound intensity spectra for Test Interval 2 with Uniroyal Tiger Paw

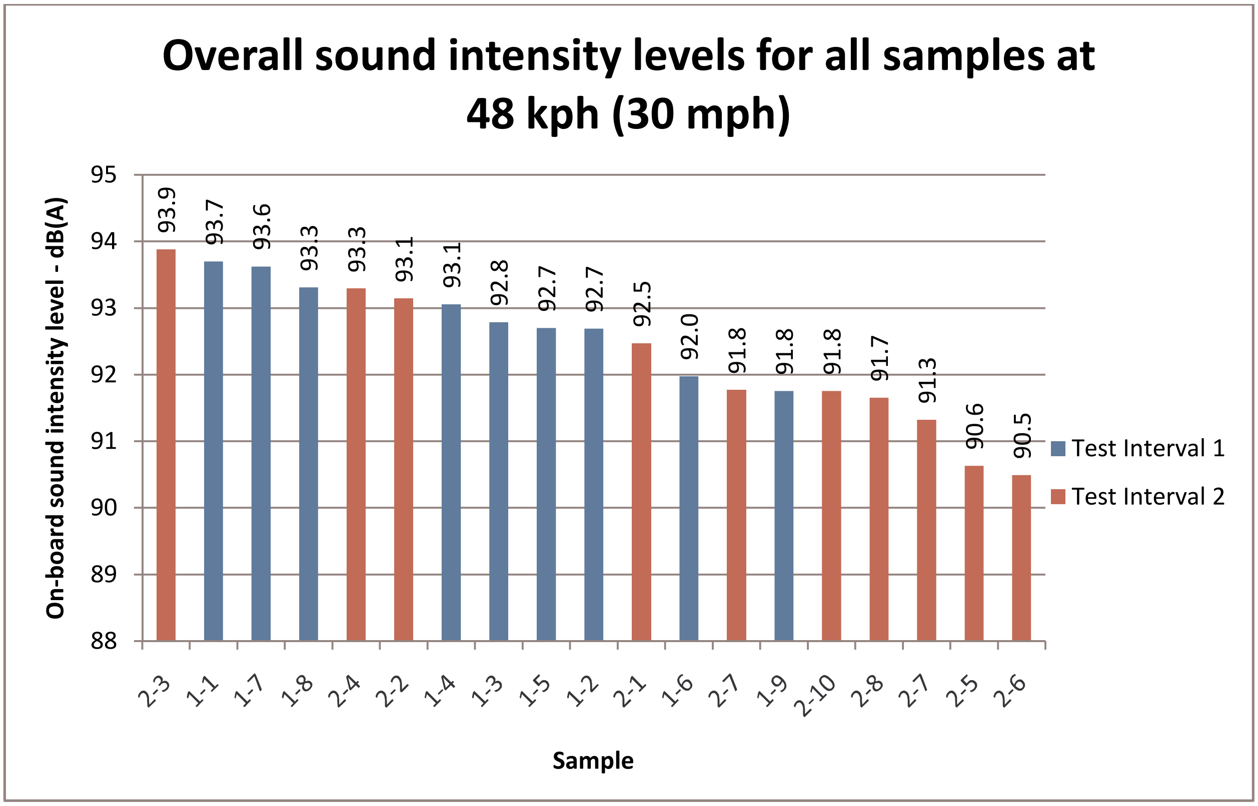


Appendix Figure B.4: One-third octave band sound intensity spectra for Test Interval 2 averaged over two tires

Appendix C: OVERALL ON-BOARD SOUND INTENSITY FOR TEST INTERVALS 1 AND 2 AT 48 KPH (30 MPH)

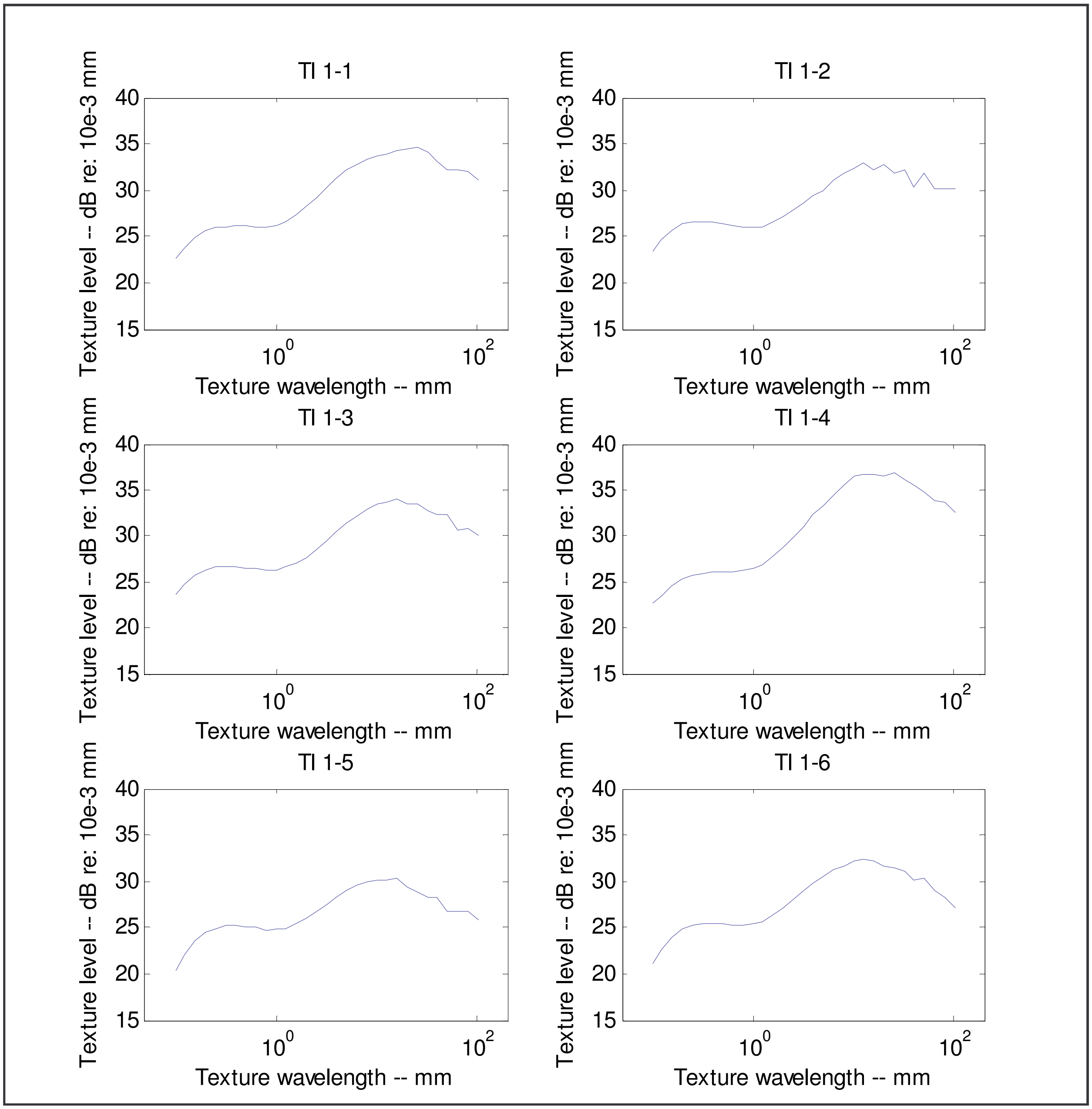
Appendix Table C.1: Blade configurations Test Intervals 1 and 2

Sample Number	Sample Name	Repeating Blade Configuration	Cutting Depth
TI 1 - 1	B125 S130 D3/16”	B125 / S130	4.8 mm (3/16 in.)
TI 1 - 2	B125 S130 D1/8”	B125 / S130	3.2 mm (1/8 in.)
TI 1 - 3	B110 S130 D3/16”	B110 / S130	4.8 mm (3/16 in.)
TI 1 - 4	B110 S130 D1/8”	B110 / S130	3.2 mm (1/8 in.)
TI 1 - 5	B110 S110 D1/8”	B110 / S110	3.2 mm (1/8 in.)
TI 1 - 6	B125 S110 D1/8”	B125 / S110	3.2 mm (1/8 in.)
TI 1 - 7	B165 S130 D3/16”	B165 / S110	4.8 mm (3/16 in.)
TI 1 - 8	B125 S130 D3/16”	B125 / S130	4.8 mm (3/16 in.)
TI 1 - 9	B125 S110 D3/16”	B125 / S110	4.8 mm (3/16 in.)
TI 2 - 1	B125 S-varied D3/16”	B125 / Various Spacers	4.8 mm (3/16 in.)
TI 2 - 2	B125 S-chopper D3/16”	B125 / S030 / Chopper / S030	4.8 mm (3/16 in.)
TI 2 - 3	B125 S-chopper D3/16”	B125 / S030 / Chopper / S030	4.8 mm (3/16 in.)
TI 2 - 4	B165 S130 D3/16”	B165 / S130	4.8 mm (3/16 in.)
TI 2 - 5	Full Grind D1/4”	First Pass: B090 / S090 Second pass: S090 / B090	6.4 mm (1/4 in.)
TI 2 - 6	Full Grind w/Grooves D1/8”	First pass: B090 / S090 Second pass: S090 / B090 Third pass: B090 spaced 12.7 mm (1/2 in.) on center	3.2 mm (1/8 in.)
TI 2 - 7	Triple Chopper D1/8”	B165 / S030 / Chopper / S030 / Chopper / S030 / Chopper / S030	3.2 mm (1/8 in.)
TI 2 - 8	Double Chopper D1/8”	B165 / S030 / Chopper / S030 / Chopper / S030	3.2 mm (1/8 in.)
TI 2 - 9	Blank w/Grooves D1/8”	B090 spaced 12.7 mm (1/2 in.) on center	3.2 mm (1/8 in.)
TI 2 - 10	Blank	No grinding	None

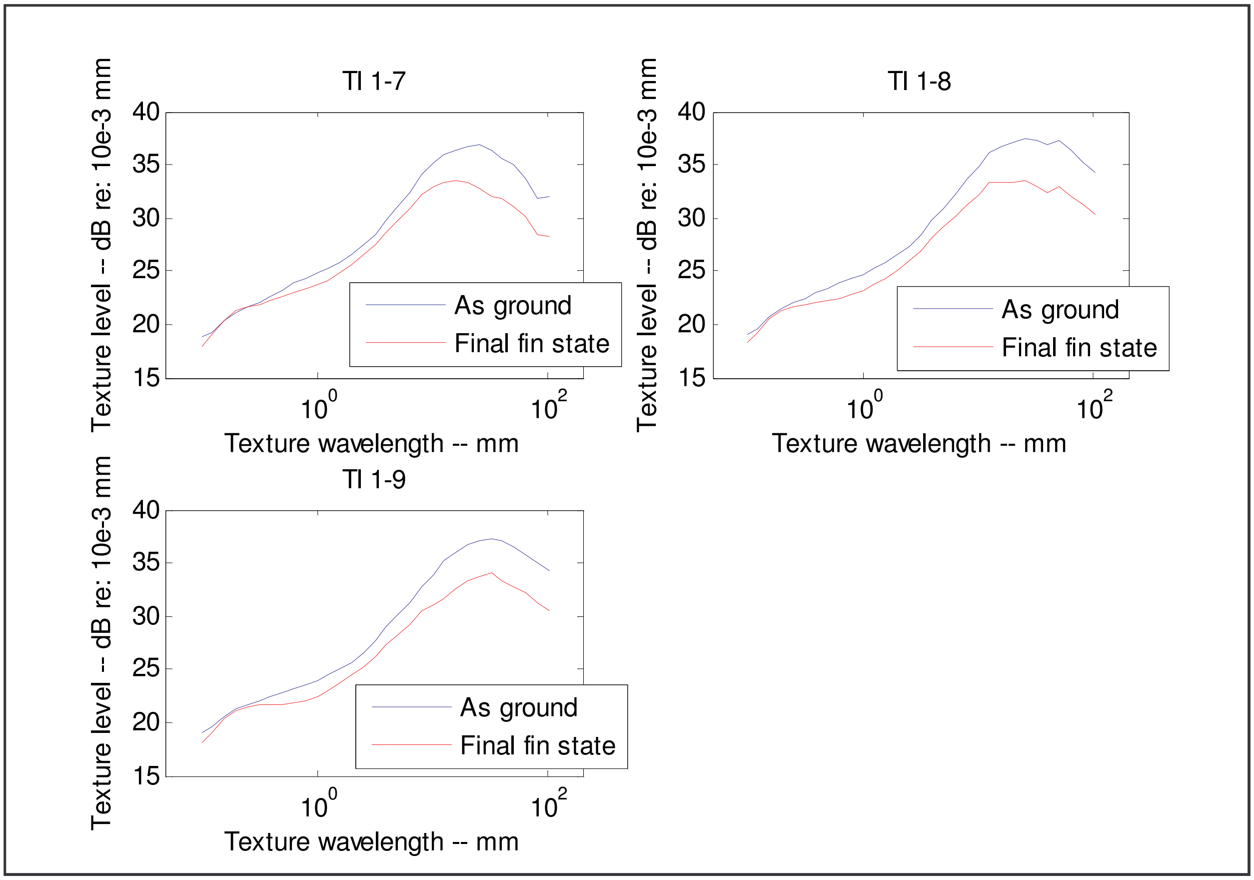


Appendix Figure C.1: Overall sound intensity levels for all samples at 48 kph (30 mph)

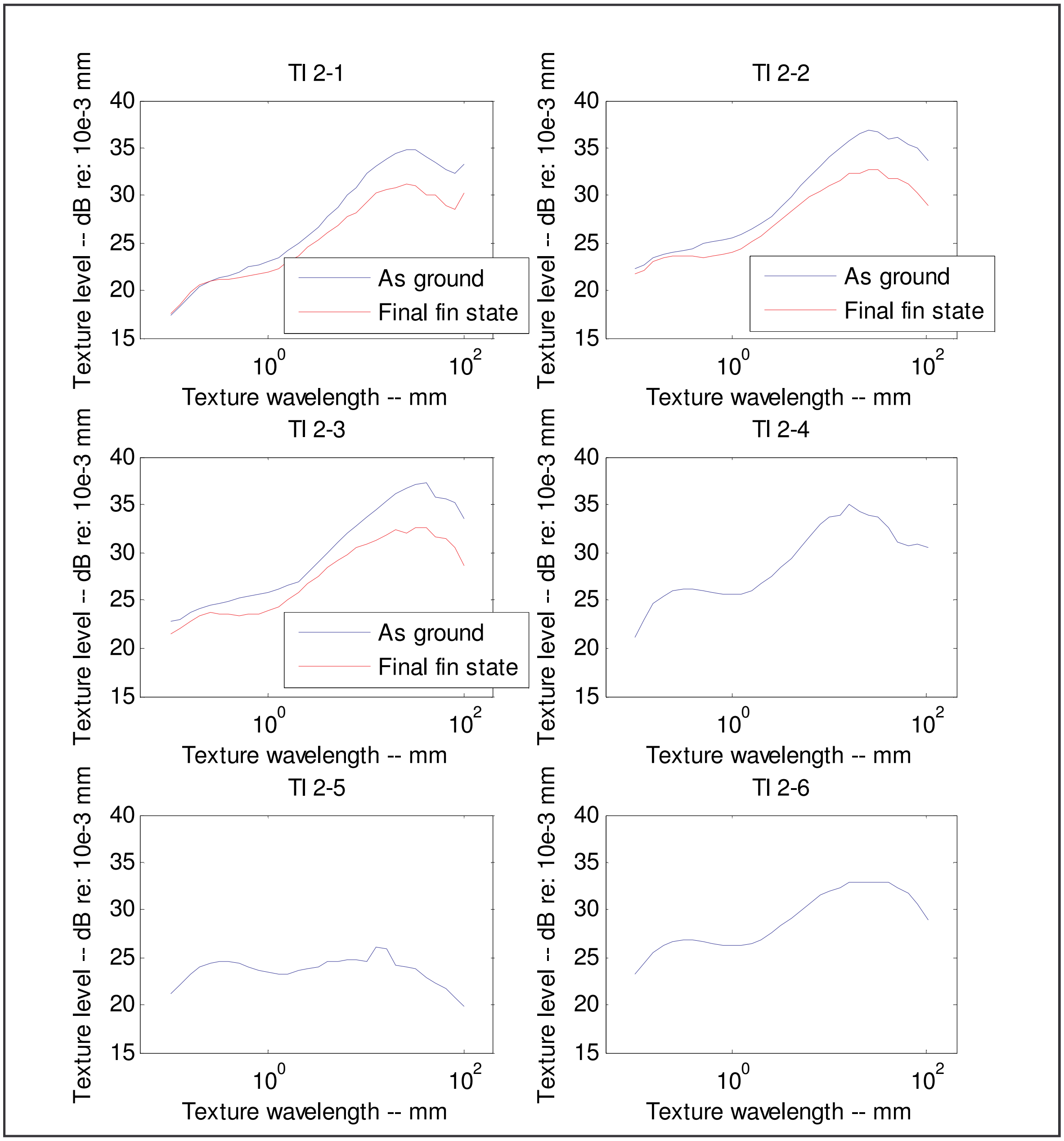
Appendix D: TEXTURE PROFILE SPECTRA FOR TEST INTERVALS 1 AND 2



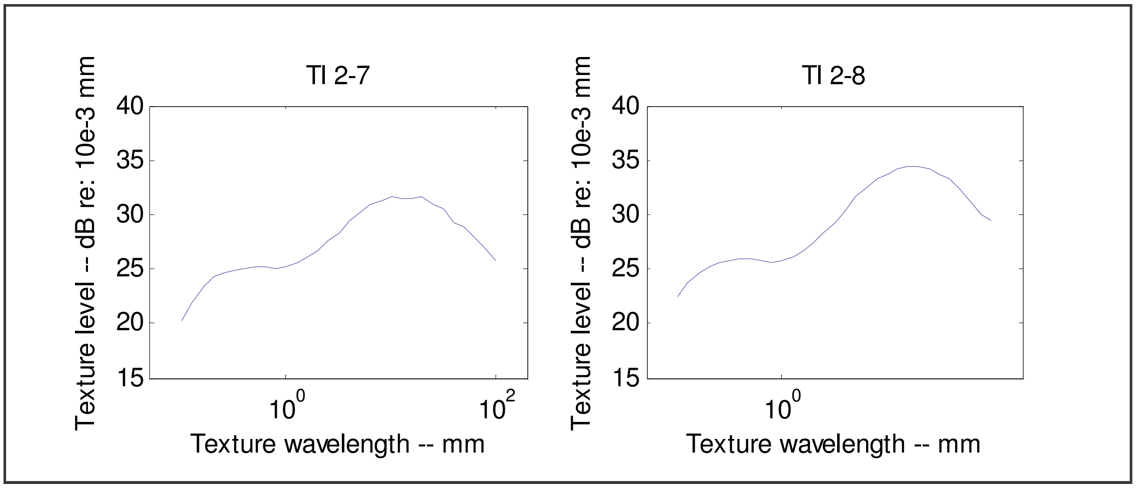
Appendix Figure D.1: Texture spectra from Test Interval 1 samples



Appendix Figure D.2: Texture spectra from Test Interval 1 samples



Appendix Figure D.3: Texture spectra from Test Interval 2 samples



Appendix Figure D.4: Texture spectra from Test Interval 2 samples