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PCC Surface Characteristics – Rehabilitation MnROAD Study

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16. Abstract (Limit: 250 words)

This report describes an extensive data collection effort, spanning five years, and the subsequent data analysis to evaluate the performance of surface characteristics on portland cement concrete pavements that have been diamond ground with various grinding configurations. The data collected were analyzed and evaluated to observe the long-term performance of the surface characteristics of noise, friction, texture, and ride quality. In addition to the basic analysis and comparison of the performance with respect to the control cell, several other studies were performed such as the correction of noise data with ambient air temperatures at the individual third-octave frequencies and evaluation of trends in the data using various statistical analysis methods. In addition, other surface characteristics were measured to provide a baseline for comparison with potential future measurements, including rolling resistance and advanced texture characteristics.

The surface characteristics evaluated indicated immediate changes were effected due to the grinding activity, and that over time (and due to the application of repetitive traffic) these immediate effects were diminished somewhat, in most cases. Based on the immediate and long-term performance of the various grinding configurations, recommendations are made in the report regarding the use of the configurations and areas suggested for further research.

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EXECUTIVE SUMMARY

This report describes an extensive data collection effort, spanning five years, and the subsequent data analysis to evaluate the performance of surface characteristics on portland cement concrete pavements that have been diamond ground with various grinding configurations. In 2007 several different grinding configurations were installed in strips on Cell 37 of the MnROAD Low-Volume Road test facility. Later in 2007 and 2008, similar grinding configurations were installed on Cells 7, 8, and 9 (the Innovative, Conventional, and Ultimate grind configurations, respectively). The difference in each of these grinding configurations is the pattern and placement of the diamond grinding blades stacked in the head of the grinding machine. In 2010 Cell 71 was ground with an updated Ultimate grind configuration and was added to the data collection and analysis program. Cell 12 was not ground, and was used as a control since it has its original transverse tine surface from its construction in 1992.

MnDOT staff conducted the field testing and data collection on a regular basis, and the results were evaluated to observe and compare the long-term performance of the surface characteristics of noise, friction, texture, and ride quality. In addition to the basic analysis and comparison of the performance with respect to the control cell, several other studies were performed such as the correction of noise data with ambient air temperatures at the individual third-octave frequencies and evaluation of trends in the data using various statistical analysis methods. In addition, other surface characteristics were measured to provide a baseline for comparison with potential future measurements. These included the rolling resistance (performed by researchers at the Technical University of Gdańsk, Poland, and extensive surface texture and other related characteristics using the RoboTex device by the Transtec Group, Inc.

The surface characteristics evaluated indicated immediate changes were effected due to the grinding activity, and that over time (and due to the application of repetitive traffic) these immediate effects were diminished somewhat, in most cases. The noise measurements had slight upward trends with cumulative traffic, in most cases. The trends of friction measurements primarily indicated no trends, with some slight decreasing trends. Friction measurements indicated that the ultimate grind may help maintain friction as tires wear over time. The texture measurements indicated an immediate increase in mean texture depth, with a quickly declining value over the first year after grinding. The texture measurements then leveled off with little further change, but in most cases at a level greater than the pre-grind state. The ride quality measurements indicated generally constant performance, with no definite trend in most cells, with the exception of Cell 9 (the Ultimate Grind), which seemed to show a rapid and continuous increase to almost unrealistic levels – possibly due, in part, to the data collection equipment.

Based on the immediate and long-term performance of the various grinding configurations, recommendations are made in the report regarding the use of the configurations and areas suggested for further research. The recommendations at the end of the report include the development of a temperature correction for friction measurements, implementation of the temperature correction for noise measurements developed as part of this project, use of a line laser or area laser for ride quality measurements, and continued development of innovative grinding configurations for safer and quieter concrete pavement surfaces.

Chapter 1. INTRODUCTION

This report describes the effects of different diamond grinding blade configurations on surface characteristics of portland cement concrete (PCC) pavements. In 2007, two concrete pavement cells at the Minnesota Road Research Project (MnROAD) research station were ground in an attempt to improve the surface characteristics of noise, friction, texture, and ride. One was a standard blade configuration and the second was a newly-developed configuration developed with the intent to produce quieter tire-pavement interactions, increased friction characteristics, and improved texture over longer periods of time. In addition, the ride quality was measured and evaluated, although dramatic improvements were not expected in this characteristic. Later, an improved blade configuration was applied to two other cells, and data collection and evaluation efforts were expanded to include these cells. The information contained in this report includes a summary of the data collection efforts, the data analysis, and evaluation of the results.

Objectives

The objectives of this project were to evaluate not only the initial effects of the various grinds on the concrete pavement surfaces, but also to observe the changes in surface characteristics during the first several years after grinding. As mentioned previously, the surface characteristics that were evaluated include noise (on-board sound intensity, or OBSI), friction, texture, and ride. Other characteristics were tested once during the project timeline including the rolling resistance and surface roughness.

In addition to the data collection performed by the Minnesota Department of Transportation (MnDOT) staff at the MnROAD facility, the project team worked to develop predictive models for expected changes in some of these surface characteristics over time. While some of these were successful, others were not, primarily due to the large inherent variability in either the materials, the testing equipment, or for other reasons. Other evaluations and investigations were conducted, however, which may advance the understanding of the processes involved.

Background

The Minnesota Department of Transportation constructed the MnROAD site between 1990 and 1994. MnROAD is located along Interstate 94, 40 miles northwest of the Minneapolis / St. Paul metropolitan area, and is an extensive pavement research facility consisting of two separate roadway segments containing 51 distinct test cells. Each MnROAD test cell is approximately 500 feet long. Subgrade, aggregate base, and surface materials, as well as roadbed structure and drainage methods vary from cell to cell. Additional information on MnROAD can be found by accessing the MnROAD web site at: http://mnroad.dot.state.mn.us/research/mnresearch.asp.

MnROAD Low Volume Road

Parallel and adjacent to Interstate 94 and the Mainline is the Low Volume Road (LVR). The LVR is a 2-lane, 2½-mile closed loop that contains 20 test cells. Cell 37 is in the LVR loop, and was utilized in this research project, as will be described later.

MnROAD Mainline

The mainline consists of a 2-lane, 3½-mile interstate roadway carrying “live” traffic. Pavements installed in the mainline were constructed in 1992 and 1993, including Cell 12, which was used as a control for the data analysis in this project. Originally, a total of 23 cells were constructed consisting of 14 hot mix asphalt (HMA) cells and 9 portland cement concrete cells.

Traffic on the mainline comes from the traveling public on westbound I-94. Typically the mainline traffic is switched to the old I-94 westbound lanes once a month for three days to allow MnROAD researchers to safely collect data. The mainline ESALs are determined from a hydraulic load scale. As of 2012 the mainline has received roughly 16 million rigid Equivalent Single Axle Loads (ESALs) in the driving lane and about 4 million ESALs in the passing lane.

History of the Diamond Grinding Initiative

Diamond grinding is the process of correcting defective surface textures and poor ride quality. Some agencies use diamond grinding as the initial pavement surface texture, and not only as a rehabilitation tool. Over the years agencies and researchers saw an added quietness benefit to diamond grinding. These observations led to research that culminated in the joint efforts of the Center for Quiet Safe and Durable Highways (SQDH) at Purdue University, the Federal Highway Administration (FHWA), the American Concrete paving Association (ACPA), and the International Grinding and Grooving Association (IGGA) towards a laboratory development of a quieter grinding blade configuration. With increased understanding of surface characteristics the group re-examined how the diamond grinding process can be reconfigured to improve performance, and to enhance quietness, safety and ride comfort. The collaboration determined that after a successful laboratory development of a quiet configuration, MnROAD studies would create an opportunity to validate the results of previous studies at Purdue University [1].

The current research was funded as a Transportation Pooled Fund (TPF) study, with funding from MnDOT (acting as the lead state), the Texas Department of Transportation and FHWA. The primary research was assigned pooled-fund study number TPF #5(134). The ACPA and IGGA performed the diamond grinding as an in-kind match. Initially, MnDOT made one cell available in the LVR loop, and two cells in the MnROAD mainline for this study. Cell 37 was used for the proof of concept, or initial validation test. After the success in Cell 37, full-scale grinding was undertaken on Cells 7 and 8 in late 2007 and Cell 9 in 2008, followed by Cell 71 in 2010.

Proof-of-Concept on MnROAD Low Volume Road

The proof of concept grinding was performed in June 2007. On-board sound intensity noise measurements, friction, texture, and ride measurements were performed by ACPA and MnDOT prior to the grinding activities. Since October 2007, MnDOT has performed all seasonal monitoring tests including OBSI measurements. The pooled fund group expressed the need for evaluating the performance of the grinding configurations over the full lane width, rather than the 2-foot test strips in the low volume road.

The research team subsequently saw the need to improve on the frictional characteristics of the innovative grind by providing additional corrugations on the kerfs. This new configuration, referred to as the Ultimate Grind or the 2008 Initiative was ground in both lanes of Cell 9 of the MnROAD Mainline on 10 October 2008. In 2010 a second attempt at the ultimate grind was made in Cell 71 on the mainline.

Project Timeline

As previously mentioned, two of the MnROAD cells evaluated for this project (Cells 7 and 8) received diamond grinding treatments in October 2007. Cell 9 was ground in October 2008, and yet another (Cell 71) was ground in May 2010. These activities occurred after the initial stage of the FHWA Pooled Fund Study which conducted grinding in strips on a cell in the Low-Volume Road at MnROAD (Cell 37) in June 2007. After each cell was ground, surface characteristics were measured at fairly regular intervals until about June 2012. A detailed schedule of data collection is provided in Chapter 3.

Report Outline

This report begins with a review of the progression of the research into diamond grinding's benefits in terms of improving noise, friction, texture, and ride. It then describes the grinding activities and the immediate effect of the grinding on the surface characteristics for each cell. Chapter 3 describes the data collection, testing methods and schedule, and the analysis conducted throughout the project. Chapter 4 discusses trend analysis and the methods for identifying potential trends in the measured characteristics over the four years of data collection. Chapter 5 presents a summary of additional testing that was conducted by others and that are fully described in other reports. The additional characteristics summarized are the rolling resistance and the RoboTex texture measurements. Chapter 6 includes a summary of the project and the collected and analyzed data, with conclusions and recommendations for further work with the information contained in this report. Several appendices contain the raw data collected throughout the project duration as well as any corrections to the data described in the report.

Chapter 2. INNOVATIVE SURFACE GRINDING

This chapter discusses the diamond grinding blade configurations that were used in the various MnROAD cells during the project. It also presents the initial effects of the grinding on the different surface characteristics that were measured throughout the project. First, however, a short history of the conceptual development of the diamond grinding initiative is presented.

Conceptual Development

For some time previous to this project, the IGGA and ACPA worked with Purdue University to develop a diamond grinding texture with improved noise characteristics. The research began by attempting to optimize blade width and spacer configurations. This had been thought to control the resulting noise characteristics produced by the tire-pavement interaction. However, the Purdue work [1] indicated that the fin profile and not the blade/spacer configuration was the controlling variable. Work then began to produce fin profiles that were essentially uniform at the point of interaction between the tire and pavement surface.

After experimentation, two different techniques appeared to work best. The first is the use of three chopper blades utilized as spacers placed between two 0.125-inch conventional diamond grinding blades, and the second is a flush grind with grooving. The flush grind was produced by using 0.090-inch width blades with 0.090-inch spacers to lightly grind the surface. This first pass left fins on the pavement surface which were suspected of producing the increased noise characteristic. The Purdue grinding head was then offset slightly, grinding a second time to remove these fins. The flush ground texture was then grooved with 0.125-inch diamond grinding blades spaced on 0.500-inch centers. The grooves produced measured 0.125 inches deep. The blade configuration used chopper blades that were dressed to 0.080 inches shorter in radius than the 0.125-inch blades.

The Purdue research used the Purdue Tire Pavement Test Apparatus (TPTA) [1] to evaluate the various textures. This laboratory-based device, shown in Figures 1 and 2, consists of a 12-foot diameter drum upon which six cast concrete segments are placed around the circumference as shown. The IGGA-developed grinding head was used to grind the various textures and is shown in Figure 1.

Noise testing using sound intensity techniques could only be conducted at speeds up to 30 mph in the laboratory, while field evaluations are typically conducted at 60 mph. The diamond ground surface, although resembling actual field grinding had not been produced using actual diamond grinding equipment in practice. The flush grind surface was produced on the TPTA by offsetting the head and making a second pass such that the fins were ground off.

The field validation was conducted as a two-part process. First, the proof-of-concept was used, with the intent to prove or disprove that textures created and measured on the TPTA can adequately represent the textures created in the field. This was conducted on the MnROAD Low Volume Road. The second stage, which makes up the primary effort of the research discussed in this report, was the actual full-width, production-based construction operation. These configurations were tested for noise, friction characteristics as well as texture and ride quality in each case.

Figure 1. Grinding head developed by IGGA.

Figure 2. Laboratory testing wheel.

Grinding Proof-of-Concept in Cell 37

As described by Izevbekhai and Wilde [2], the proof-of-concept validation experiment consisted of grinding two wheel tracks, each 18 inches wide by 500 ft long, and one wheel track 24 inches wide by 500 ft long in Cell 37 at the MnROAD Low Volume Road, as shown in the diagram in Figure 3. The first two strips ground in Cell 37 were the innovative grinding configurations.

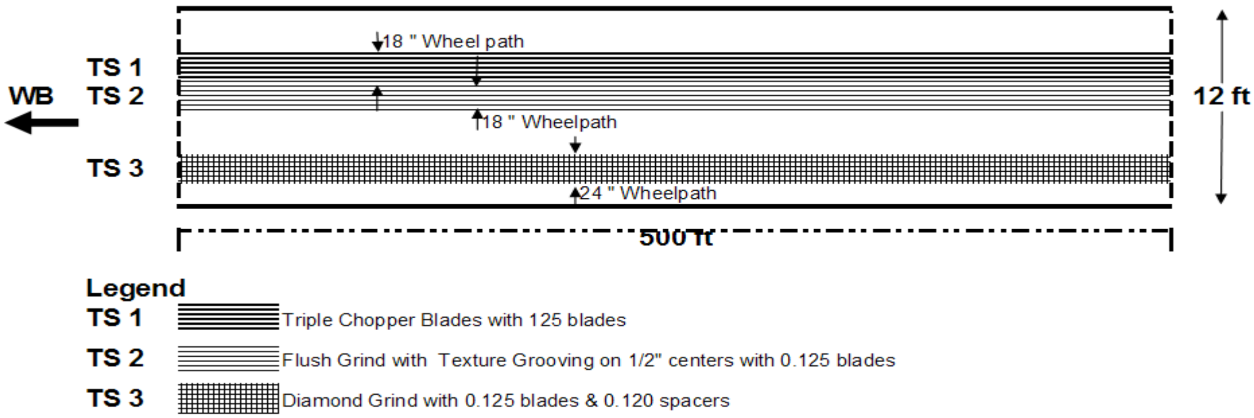

Figure 3. Diamond grinding test section layout on Cell 37.

The first configuration was created by stacking chopper blades and standard 0.125-inch grinding blades to create a lightly ground surface and grooves spaced 0.250 inch apart all in one pass. This was termed TS1, and is shown in the diagram in Figure 4. Anticipating that the existing random transverse tined texture may have an impact on the noise levels produced by the tire-pavement interaction, flush grinding was performed in part to eliminate the existing random tine texture. Uniformity of removal of the existing tine was an issue of concern.

The second grind configuration was similar to TS1, but created the lightly ground surface in two passes, similar to the Purdue work, and then created the 0.125-inch grooves at 0.500-inch centers in an additional pass. The Purdue project used 0.090-inch blades and spacers to produce this texture and then offset and reground to remove the fins. This configuration was termed TS2, and is shown in Figure 5.

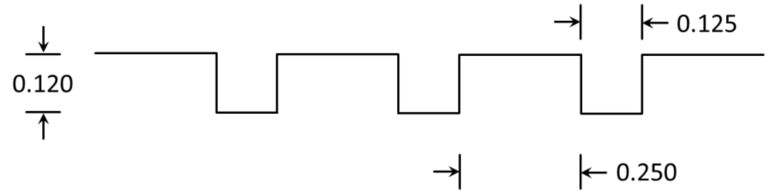

Figure 4. TS1 grinding configuration (flush grind in one pass).

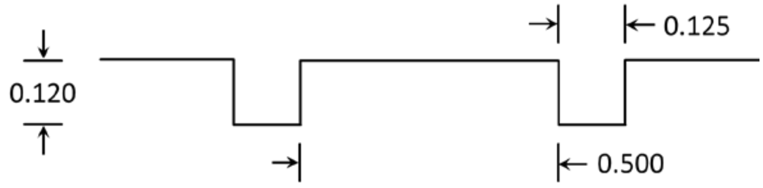

Figure 5. TS2 grinding configuration (flush grind in two passes).

The third track was ground using 0.125-inch blades with 0.120-inch spacers, as depicted in Figure 6. This was termed TS3 and is similar to a conventional grind. This wheel track was considered the control, and was used throughout the initial stage of the project as a benchmark to evaluate the other two strips. Since the standard drum head is 24 inches wide, and each configuration was made in a single pass, the TS3 strip was ground 24 inches wide.

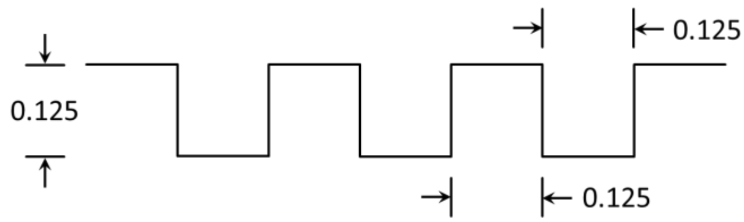

Figure 6. TS3 grinding configuration (conventional grind).

The final test strip (TS4) was left unground, with the existing random transverse tine in the right wheel path. In summary, the configurations described above resulted in the following three grinding characteristics, and one control section left unground.

- TS1 – flush grind and groove in one pass,
- TS2 – flush grind and groove in two passes,
- TS3 – conventional grind of 0.125 x 0.125 x 0.120 inch groove kerf configuration, and
- TS4 – original non-uniform transverse tine that was in the entire lane before grinding.

Later, a trial of the Ultimate grind was made on Cell 37, and was termed TS5. An early iteration of this configuration was installed in Cell 9 and the TS5 configuration was subsequently installed in Cell 71.

The grinding configurations were arranged in Cell 37 as shown in the diagram in Figure 3, and the images in Figure 7. Other images and configuration information can be found in a MnDOT report on the grinding operations at MnROAD for this project [2]. The dimensions of these configurations are provided in Table 1.

Figure 7. Grinding configurations in Cell 37, looking westbound.

Table 1. Summary Data for Innovative Grind Textures on MnROAD Cell 37.

	TS1 Innovative1		TS2 Innovative2		TS3 Conventional		TS5 2010 Ultimate	
	inch	mm	inch	mm	inch	mm	inch	mm
Mean Land Width	0.250	6.35	0.500	12.70	0.125	3.18	0.375	9.50
Mean Groove Depth	0.120	3.05	0.120	3.05	0.125	3.18	0.309	7.85
Mean Groove Width	0.125	3.18	0.125	3.18	0.125	3.18	0.129	3.28

After the initial grinding activities in Cell 37 were conducted, and the grinding configurations were evaluated, a full-scale implementation of the surface grinding techniques was conducted in Cells 7, 8, and 9. Cells 7 and 9 are Next Generation Concrete Surface grinds (NGCS) and Cell 8 is a conventionally ground surface. Cells 7 and 8 were ground in October 2007 and Cell 9 was ground in October 2008, as discussed in the next section.

Mainline Grinding Activities

Details of the construction activities and the location of grinding methods for the three cells are shown in Figure 9. The strategies chosen include the following.

- Conventional grinding on Cell 8
- Innovative grinding on Cell 7
- Partial grind on tied concrete shoulder of Cell 8
- Ultimate grind on Cell 9

An improved version of the ultimate grind was installed in Cell 71 in May 2010. The difference between the first ultimate grind (Cell 9) and the second (Cell 71) is in the width of the landing area, as can be seen in Table 2.

Initially, all three cells were ground with the conventional grinding. This was the final grind for Cell 8 and the primary grind for Cells 7 and 9. The secondary grind for Cell 7 is the innovative diamond grinding configuration, and the secondary grind for Cell 9 is the ultimate grind. The 2008 iteration of the ultimate grind mentioned above is a modification of the TS2 innovative grind in that the surface between each groove is treated with three blades at 1/16-inch depth, as can be seen in Figure 8. The configurations ground into Cells 7 and 8 are similar to TS1 and TS3, respectively, and can be seen in Figures 4 and 6. The approximate measurements of each groove and landing area configuration are given in Table 2.

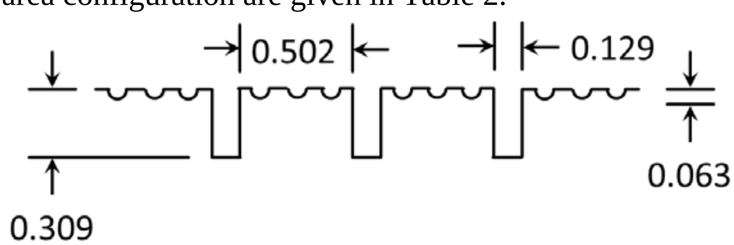

Figure 8. Ultimate grind configuration – 2008.

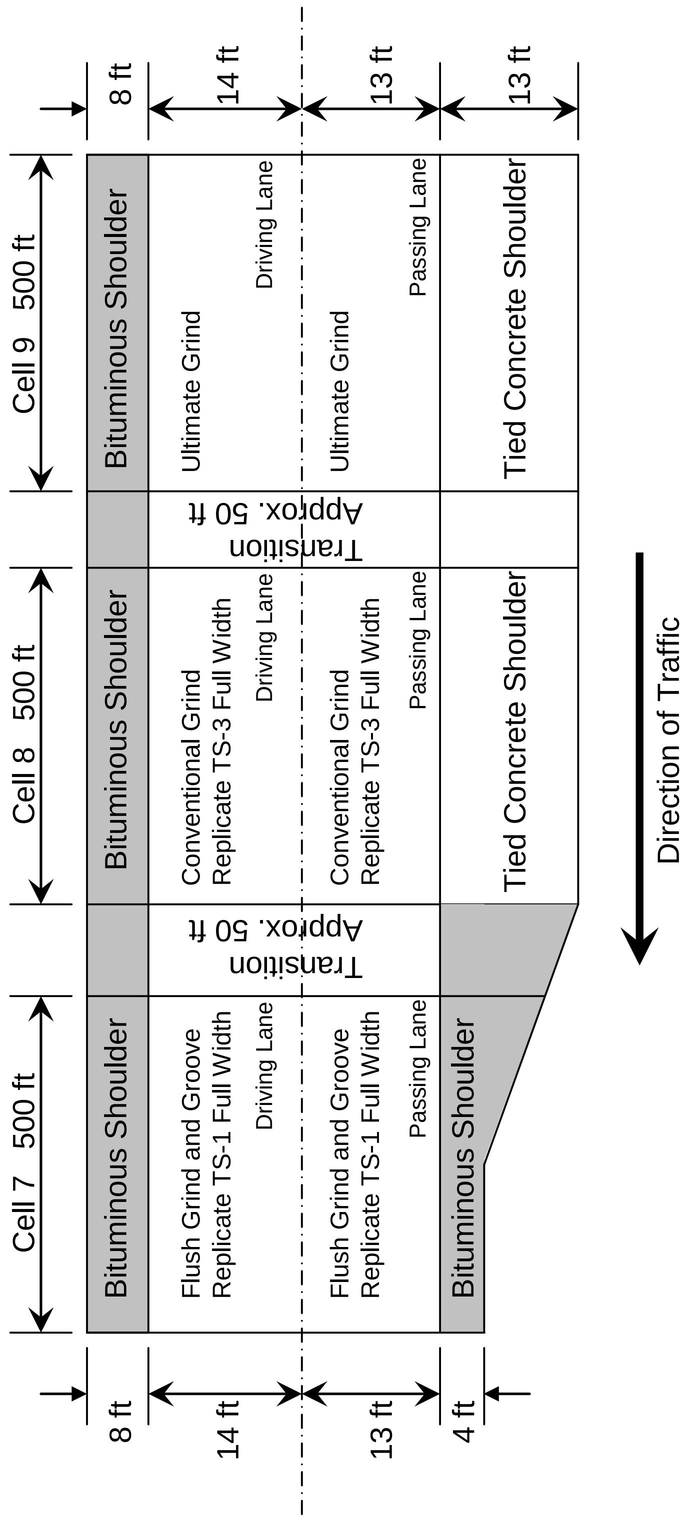

Figure 9. Layout of grinding activities – Cells 7, 8, and 9.

In 2010, the revised ultimate grind was installed in Cell 71, with a configuration very similar to that of the 2008 iteration, with the exception of the width of the landing area, which can be seen in Figure 10 and Table 2.

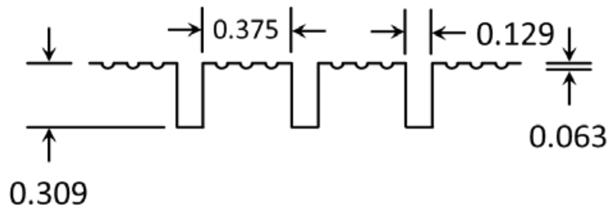

Figure 10. New Ultimate grind configuration – 2010.

Table 2. Summary Data for Innovative Grind Textures on MnROAD Mainline.

	Cell 7 Innovative		Cell 8 Conventional		Cell 9 Ultimate		Cell 71 New Ultimate	
	Inch	**Mm**	**Inch**	**mm**	**Inch**	**mm**	**Inch**	**mm**
Mean Land Width	0.375	9.50	0.125	3.28	0.502	12.75	0.375	9.50
Mean Groove Depth	0.120	3.05	0.125	3.28	0.309	7.85	0.309	7.85
Mean Groove Width	0.125	3.28	0.125	3.28	0.129	3.28	0.129	3.28
Corrugated Landing	N/A		N/A		1/16” x 1/16”		1/16” x 1/16”	

Figure 11 shows a close-up comparison of the unground surface and the conventional grind (on the right side of the image). Figure 12 shows the conventional grind (left) and the innovative grind (right). Figure 13 shows the conventional grind and the original transverse tining. A close-up of the ultimate grind in Cell 9 is shown in Figure 14.

Figure 11. Unground surface (left) and conventional grind configuration (right).

Figure 12. Conventional grind (left) and Innovative grind (right).

Figure 13. Conventional grind on Cell 8 (top) and original transverse tining (bottom).

Figure 14. Ultimate grind groove width measurement.

Throughout the remainder of this report, references to the cells included in the study are as follows.

- Conventional Grind
  Cell 8
  Grinding conducted on 20 October 2007
- Innovative Grind
  Cell 7
  Grinding conducted on 20 October 2007
- Ultimate Grind – First Attempt
  Cell 9
  Grinding conducted on or about 22 October 2008
- New Ultimate Grind
  Cell 71
  Grinding conducted in May 2010

Initial Effect on Surface Characteristics

The initial change in surface characteristics was as expected. Of the first two cells to be ground for this project (Cells 7 and 8 – October 2007) the immediate change in noise produced by a standard tire increased by about 2 dB on the conventional grind (Cell 8) and decreased by about 3 dB on the innovative grind (Cell 7). In fact, prior to grinding Cell 8 indicated a sound level of 1dB lower than that of Cell 7, and after the grinding the sound level on Cell 8 (conventional) was almost 4 dB greater than on Cell 7 (innovative). The pre-grind data for the ultimate grind (Cell 9) was not collected, but a comparison of the data obtained one year prior to grinding to that just after grinding indicates about a 2-dB decrease.

The friction measurements on the three cells indicated similar trends with the ribbed tire. The conventional grind indicated a 7-point increase in friction number (FN) whereas the conventional and ultimate grinds displayed an initial decrease of 12 and 8 points before and after grinding, respectively. With the smooth tire, all three sections indicated an initial increase in friction number.

Given the physical nature of the texture measurement on a pavement surface, it is not surprising that each of the three cells increased in texture. Since the sand patch test was used, and much of the sand in the area of the test was used to fill the grooves created by the grinding, this led to an increase in mean texture depth (MTD) for all grinds.

Ride quality measurements indicated a general decrease in International Roughness Index (IRI) and a corresponding increase in ride quality. The effect of grinding on ride quality may be limited, however, since diamond grinding results in a smoothing of the surface by reducing high points in the pavement, related to the length of the wheelbase of the grinding machine. This limits the wavelengths of surface characteristics that can be affected in the IRI calculation, which are generally between about 5 to 100 feet.

The next chapter will discuss the changes in the surface characteristics in much greater detail, and over longer periods of time.

Chapter 3. DATA COLLECTION AND ANALYSIS

This chapter describes the data collection performed by MnDOT staff over prior to the grinding and over the course of several years, and the data analysis efforts conducted by the MSU project team. Throughout the project, annual reports were developed and submitted which detailed the current status of the data collection and analysis efforts. Additionally, each annual report contained the results of additional analyses relating to the overall study.

Data Collection Schedule

The purpose of this study is to analyze the long term performance of different diamond grinding patterns ground on Portland Cement Concrete Pavement. In addition to the grinding of Cells 7, 8 and 9, Cell 71 is an improved iteration of the ultimate grind, which was conducted in May 2010. Cell 12 is used as a control section since it has not been ground, and has its original transverse tined surface texture from its construction in 1992.

The data collection for this project was conducted by MnDOT, with data analysis and reporting conducted by the research staff at the Center for Transportation Research and Implementation at Minnesota State University, Mankato. Data was collected beginning just prior to grinding Cells 7 and 8 and continued into the summer of 2012. The information in Table 3 summarizes the test data collected on the cells at MnROAD since just prior to their grinding. For brevity in this table, all data collected on various dates within the same month are indicated in a single row for that month. For example, the friction and texture testing in October 2008 were conducted on different dates during that month, but are shown in the table in a single row for October 2008. A summary of the data collected for this project is presented in Appendix A.

Testing Methods

The testing methods for each surface characteristic are described in this section. Each method was conducted according to standards published by the American Society for Testing and Materials (ASTM) standards, using properly calibrated equipment, with trained staff.

Noise

Noise testing was conducted using the OBSI method. This method uses two sets of microphones to collect sound data from both the leading edge and the trailing edge of the tire, as shown in Figure 15. A standardized tire referred to as the Standard Reference Test Tire was also used, as specified by ASTM F 2493 [3]. Each microphone dome (shown in Figure 16) houses two microphones that measure sound intensity at a range of frequencies that can be heard by the human ear. In addition to the magnitue, the two microphones are utilized to identify the direction of the sound, thus providing a measure of sound intensity, and not just sound pressure [4]. This allows the noise measurements to minimize the influence of background noise not produced by the interaction between the tire and the pavement.

It is important to note that these tests were performed at different times of the year, and at various times during the day. The temperature of the road surface, of the tire and of the air will have varied among the different testing periods. Since these temperatures affect the sound levels measured by the OBSI method, it is important for the data to be adjusted for these differences. While the temperatures have been recorded for all of the tests, an adjustment function had not been developed at the beginning of the data collection effort. A testing program was conducted in the spring and summer of 2011 to investigate this adjustment function, and will be discussed in a later section of this chapter.

Table 3. Dates and Types of Testing Conducted.

Testing Date	Characteristics Measured			
	Noise	**Friction**	**Texture**	**Ride**
Aug 2007	X			
Sep 2007	X			X
Oct 2007	X		X	X
Nov 2007		X		X
Mar 2008				X
Apr 2008	X			
May 2008		X		
Oct 2008		X	X	
Nov 2008	X		X	X
Dec 2008	X			
Mar 2009	X		X	
April 2009				X
Jun 2009		X		
Jul 2009	X			
Sep 2009	X			
Oct 2009				X
Nov 2009	X			
Mar 2010	X			X
Apr 2010				X
Jun 2010			X	
Jul 2010	X			
Sep 2010	X	X		
Oct 2010			X	X
Nov 2010	X			
Mar 2011	X			X
Apr 2011		X		
Jun 2011	X		X	X
Sep 2011	X	X		X
Nov 2011			X	
Mar 2012				X
Apr 2012	X	X		
Jun 2012		X		

Figure 15. On-Board Sound Intensity test setup.

Figure 16. Dual microphones in OBSI equipment.

The total noise generated at various sources or frequencies is computed using the A-weighted scale. Sound intensity with respect to tire-pavement interaction is computed using readings from various sources (or at various frequencies), and is calculated using the following formula to determine the total noise level from several sources or frequencies.

$$dB_{total} = 10 \cdot \log\left(10^{\frac{SI_1}{10}} + 10^{\frac{SI_2}{10}} + 10^{\frac{SI_3}{10}} + \ldots + 10^{\frac{SI_n}{10}}\right) \qquad \textit{Equation 1}$$

where:

dB_{total} = total noise level from all point sources or frequencies, and

SI_i = sound intensity measured at individual point source or frequency *i*, dB.

This formula can also be used to evaluate the difference in sound levels. For example, the test conducted on 9 September 2010 shows a difference of 3 dB between the innovative and conventional grinds, in the driving lane. Initially, a 3-dB difference in the sound pressure level may not seem significant, but this difference is equivalent to cutting the traffic volume in half, in terms of the sound level experienced by an observer. Figure 17 shows that 8 cars at 100 dB each is equivalent to 4 cars at 103 dB each.

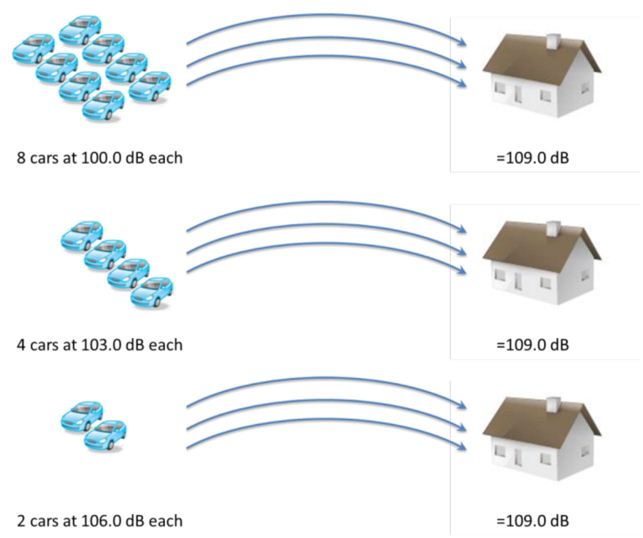

Figure 17. Relationship between perceived noise and traffic volume.

Figure 18 shows the perceived traffic reduction for both of the NGCS surfaces compared to the conventional grind in the driving lane.

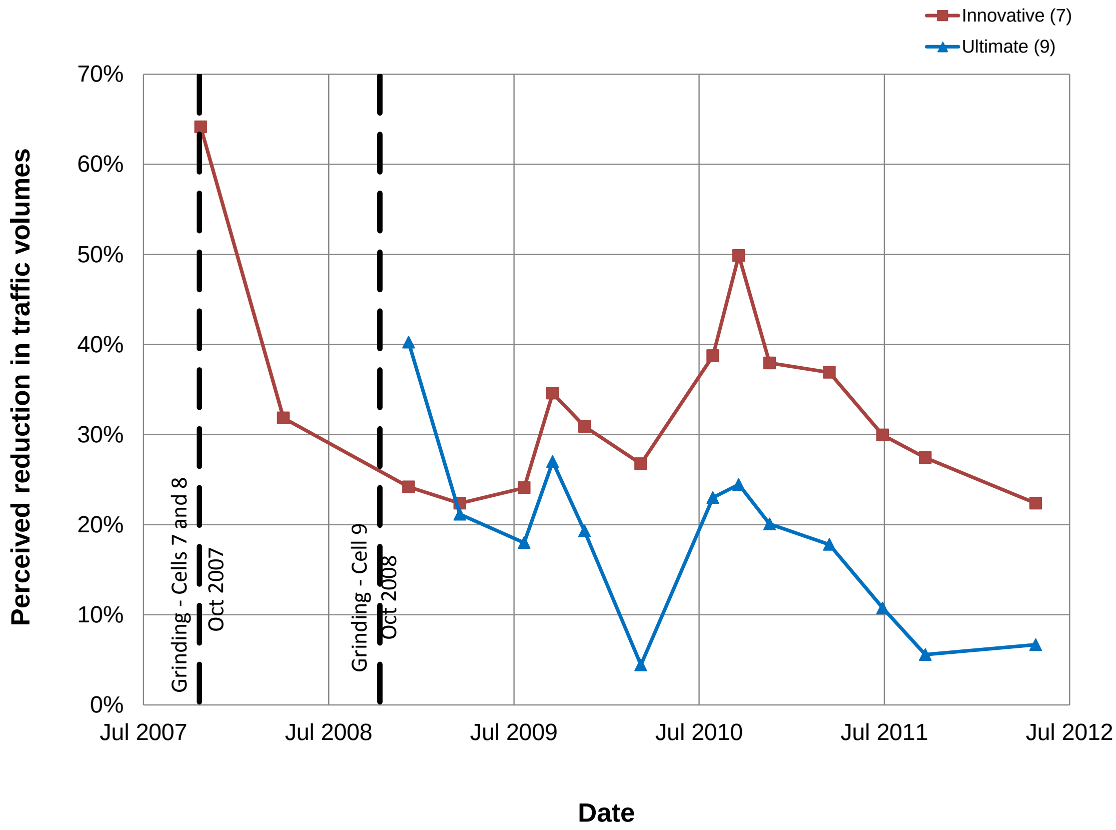

Figure 18. Perceived reduction of traffic volume, compared to conventional grind.

Friction

The friction testing was conducted using a KJ Law (Dynatest) 1295 Pavement Friction Tester according to ASTM E 274 – Specification for Skid Resistance Using a Full Scale Tire [5]. The testing device is shown in Figure 19. For the testing program in this project, both the smooth and ribbed tires were used, and testing was performed in both the driving and passing (left and right) lanes on the MnROAD facility. The friction number was used in this project to compare the friction of various surface textures over time.

Figure 19. KJ Law 1295 pavement friction tester.

Texture

Initially, the texture was measured by the sand patch method, using ASTM E 965 [6], as can be seen in Figure 7, indicated by the light-colored circles in each trial grinding strip. Later the Circular Track Meter (also known as the Circular Texture Meter, or CTM) was used for all texture measurements. Due to the time and effort required to conduct each test, these were performed less frequently than some of the other measurements.

The CTM was used to measure the MTD of each surface, according to ASTM E 2157 [7]. This device is shown in Figure 20. The CTM testing was conducted in both the driving and passing lanes, and measured the texture with a laser that spins in a circle up to 11.2 inches in diameter. As the laser spins it measures the vertical deviations in the pavement inscribed by the circle in eight segments. The mean profile depth is determined for each segment of the circle, and the reported MPD is the average of all eight segments.

Figure 20. Circular Track Meter.

Ride

Pavement profile measurements were conducted frequently during the project timeline, using the AMES LISA pavement profile device owned by MnDOT. The IRI was computed for each wheel path, in each lane, and for each cell using ASTM E 1926 [8]. The pavement profiles were measured multiple times per year throughout the project. The AMES LISA owned and operated by MnDOT is shown in Figure 21. The profiler used the TriODs triple laser arrangement, shown in Figure 22, which also shows an alternative configuration – the RoLine line laser – which may be more appropriate in some applications, as will be discussed in a later section.

Figure 21. AMES LISA pavement profile measurement device.

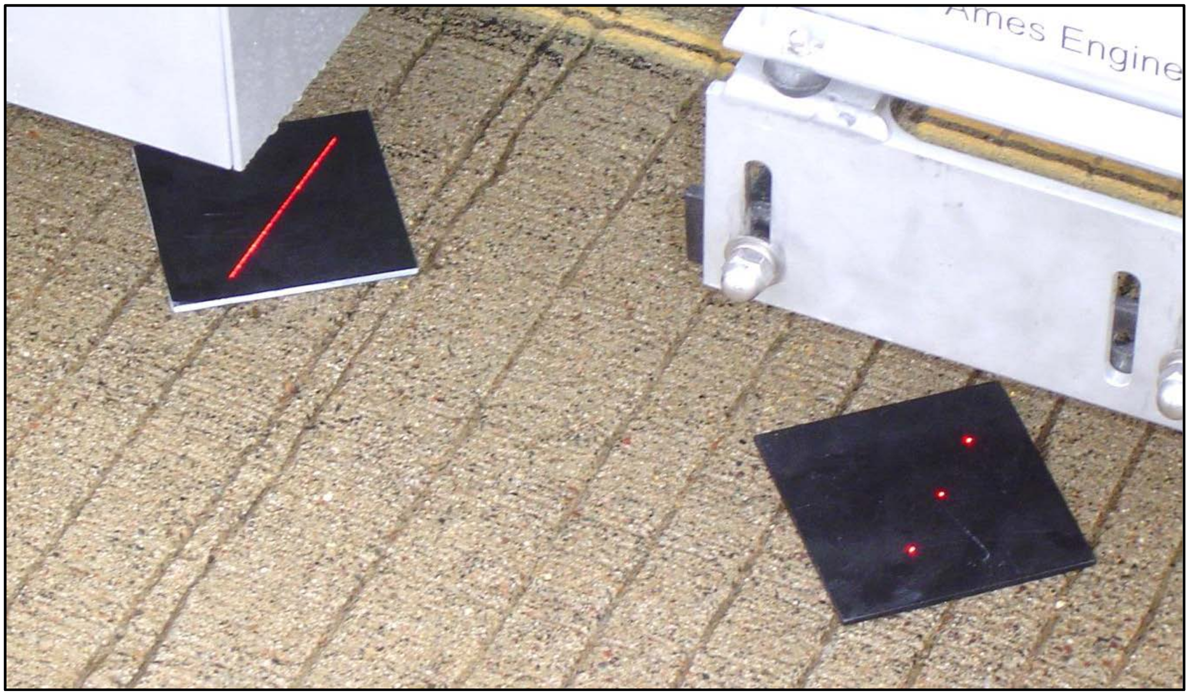

Figure 22. Profiler TriODs and RoLine configurations.

Data Adjustment

Two of the measurements can depend on the temperature of the air, the tire, and/or the pavement. Corrections for these measurements are desired but can be difficult to determine. In this section, an in-depth analysis of a correction for sound levels is discussed. The other measurement may require adjustment is the pavement friction tester. While an adjustment analysis was not conducted for this measurement, a short discussion is provided regarding its nature and how such an adjustment can be developed.

Noise-Temperature Correction – Combined Sound Levels

As mentioned previously, the sound intensity tests were performed at different times of the year, and at various times during the day, which means that the tests were necessarily conducted at different ambient temperatures. This section describes a program of data collection to develop a preliminary temperature correction function for the OBSI data. This testing program involved two full-day testing sessions where OBSI testing was conducted throughout the day at different air temperatures to determine the effect of air temperature on pavement noise. The testing was conducted on 18 April and 28 June 2011. The ambient temperature ranged from 33 to 50 °F on 18 April 2011 and from 54 to 77 °F on 28 June 2011. This provided a wide range of temperatures from which to develop a correction factor.

The testing was conducted on the entire MnROAD mainline including all of the cells in service at that time. The correction factors developed for this project are for the diamond ground concrete surfaces in Cells 7, 8, 9, 71 and the transverse-tined control cell (Cell 12), using the following parameters.

- Ambient temperatures from 30 to 77 °F
- Uniroyal TigerPaw SRTT
- Vehicle speed of 60 mph
- Two runs per hour, every hour, for 13 hours on each test date
- Datum temperature of 68°F

The data shown in Figure 23 indicates the relationship between air temperature and measured OBSI on Cell 8. A similar relationship between pavement temperature and OBSI can be seen in Figure 24. Since these figures indicate similar relationships, since air and pavement temperature are closely correlated, and since there is a well-established understanding of the physical nature of sound intensity and the temperature and density of air, the ambient air temperature will be used throughout this section to establish a preliminary correction factor for OBSI at different ambient temperatures.

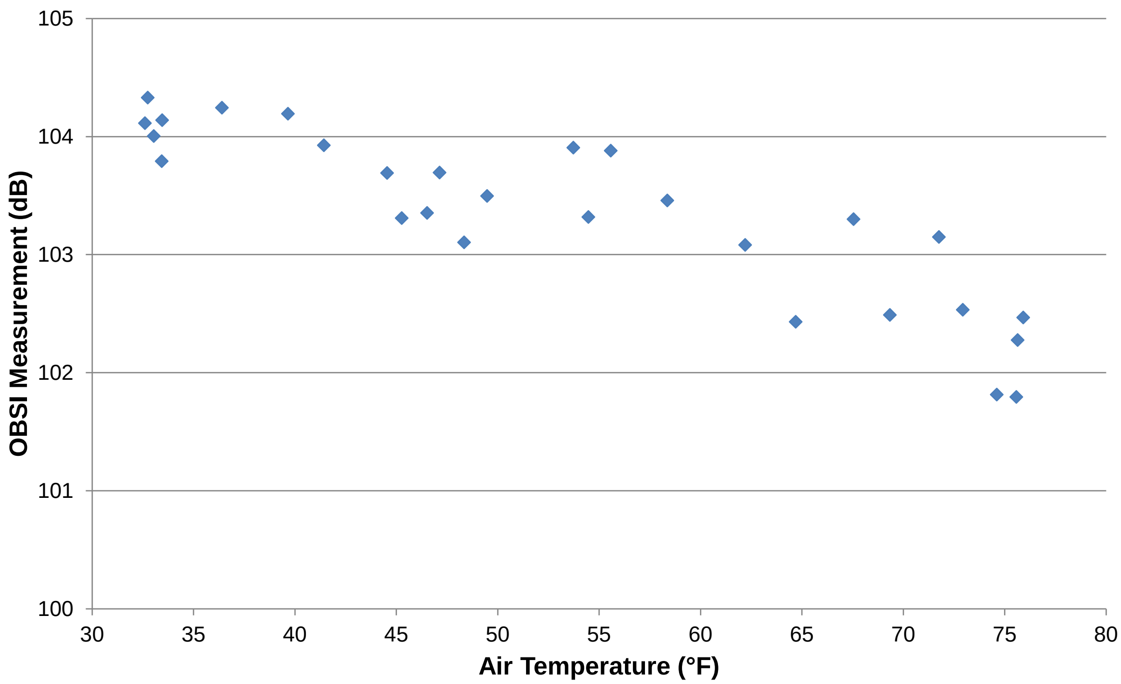

Figure 23. Noise – air temperature relationship (Cell 8).

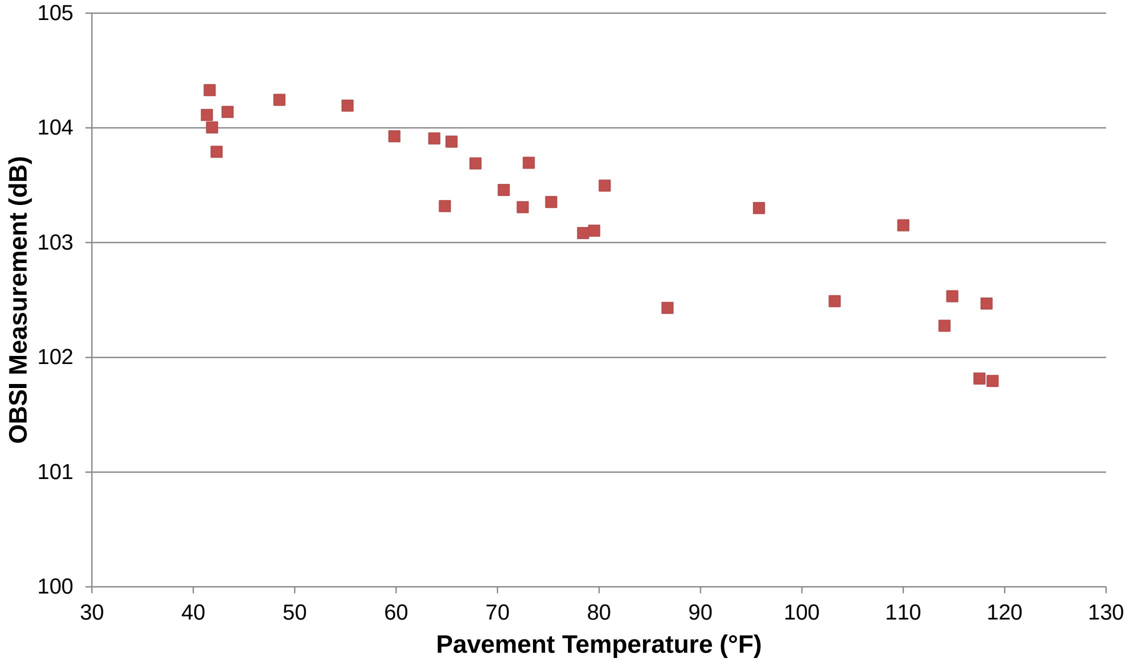

Figure 24. Noise – pavement temperature relationship (Cell 8).

For a correction factor to be established, a reference temperature must be selected as a base to which all other results are corrected. In other studies of this nature, a standard reference temperature of 68 °F (20 °C) has been used. The general form of the correction function is most often a variation of the following.

$$L_c = L_m + c(T_m - T_{ref}) \qquad \textit{Equation 2}$$

where:

- L_c = corrected sound level, dB
- L_m = measured sound level, dB
- T_m = measured air temperature (°F or °C)
- T_{ref} = reference air temperature (°F or °C)
- c = correction coefficient (dB/°F or dB/°C).

Results from other studies in Europe and the United States are discussed below. Many existing analyses compare temperature to pavement-tire noise using the Statistical Pass-By method rather than the OBSI testing that was done for this project.

The Danish Road Institute developed a correction [9] for Statistical Pass-By measurements. The report indicates that these are for the statistical pass-by rather than on-board sound intensity measurements.

$T_{corr;P} = 0.05(T_{measured} - 20)$ Passenger cars, and
$T_{corr;H} = 0.03(T_{measured} - 20)$ Heavy Vehicles.

Sandberg and Ejsmont [10] suggested coefficients for temperature correction of sound measurements using a similar form (in terms of dB/°C) and developed a table of coefficients for various types of pavement surface, textures, and aggregate gradation. Again, these are not suggested for OBSI measurements. A study was performed in 2008 in Florida by Donavan and Lodico [11] using OBSI measurements and a range of air temperatures from 86 to 104 °F. Depending on the tire used and the surface type tested, the correction ranged from -0.024 to -0.100 dB/°C. Smit and Waller [12] conducted a study on temperature effects using close-proximity (CPX) testing and found no statistically-significant correlation between air temperature and noise measurements. This is due in part to the fact that the standard deviation in some of the noise data is as large as the correction coefficient itself. They found further evidence that the temperature may affect some of the frequencies measured by the CPX equipment more than others. The effect of temperature on sound intensities at various frequencies was investigated, and is reported in the next section of this report.

Other reported results are similar to those described above, where testing and correlations are based on noise testing different than what was done at the MnROAD site. Using the data acquired at MnROAD in April and June 2011, the following correction coefficients were developed, found in Table 4. These show different coefficients for each surface configuration, although most are within a narrow range. Figure 25 shows the correction of noise data for Cell 8 (conventional). This figure indicates the original data as measured, and the corrected data using the derived correction factor, or coefficient *c* above. The slope of the trend line for the measured data in the figure is -0.042. When corrected, the slope is zero, and the point where the two trend lines intersect is the base temperature of 68 °F.

Table 4. Temperature Correction Coefficient for Different Grinds.

MnROAD Cell	**Noise-Temperature Coefficient, dB/°F (dB/°C)**
12 (Control)	-0.019 (-0.034)
8 (Conventional)	-0.042 (-0.076)
7 (Innovative)	-0.015 (-0.027)
9 (Ultimate)	-0.019 (-0.034)
71 (New Ultimate)	-0.0095 (-0.017)

It is clear that there are seasonal effects where the measured sound intensity increases and decreases on approximately an annual basis, with the general level increasing in the last two years of data. As an example, Figure 26 shows the Cell 8 driving lane sound levels over time with and without temperature correction so that the effect can be seen more readily. Data points with the preliminary correction applied indicate a lower sound intensity, and were measured when the ambient air temperature was lower than the base temperature. In the summer months, where the corrected OBSI measurement is higher than the uncorrected values, the testing was conducted in air temperatures greater than the base temperature.

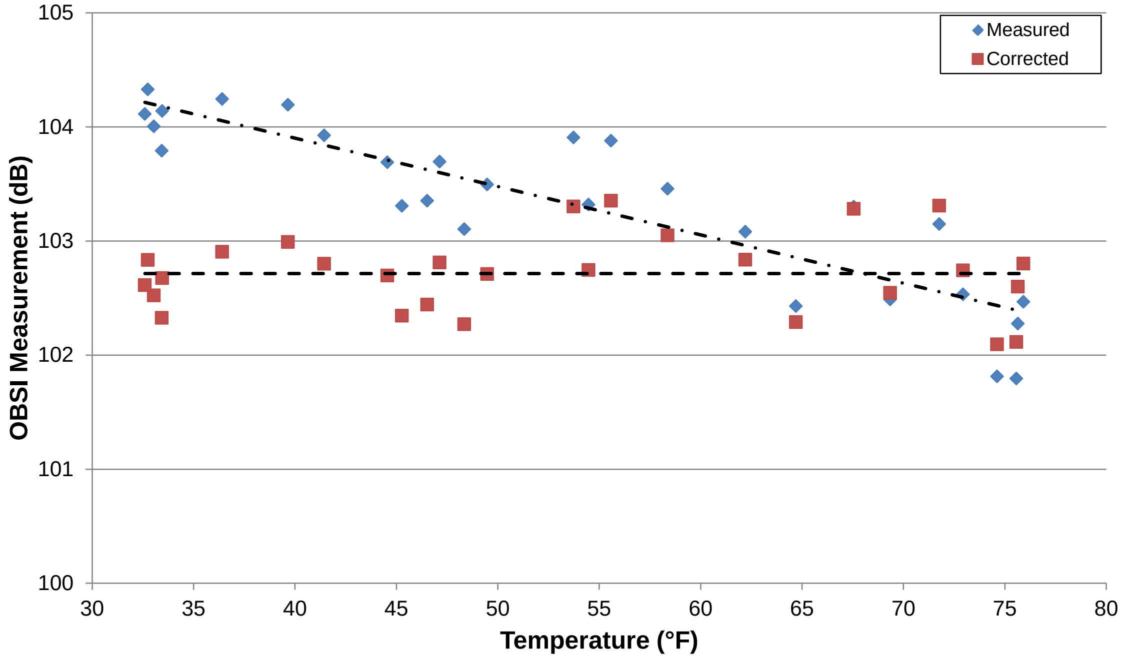

Figure 25. Measured and corrected OBSI values, Cell 8 driving lane.

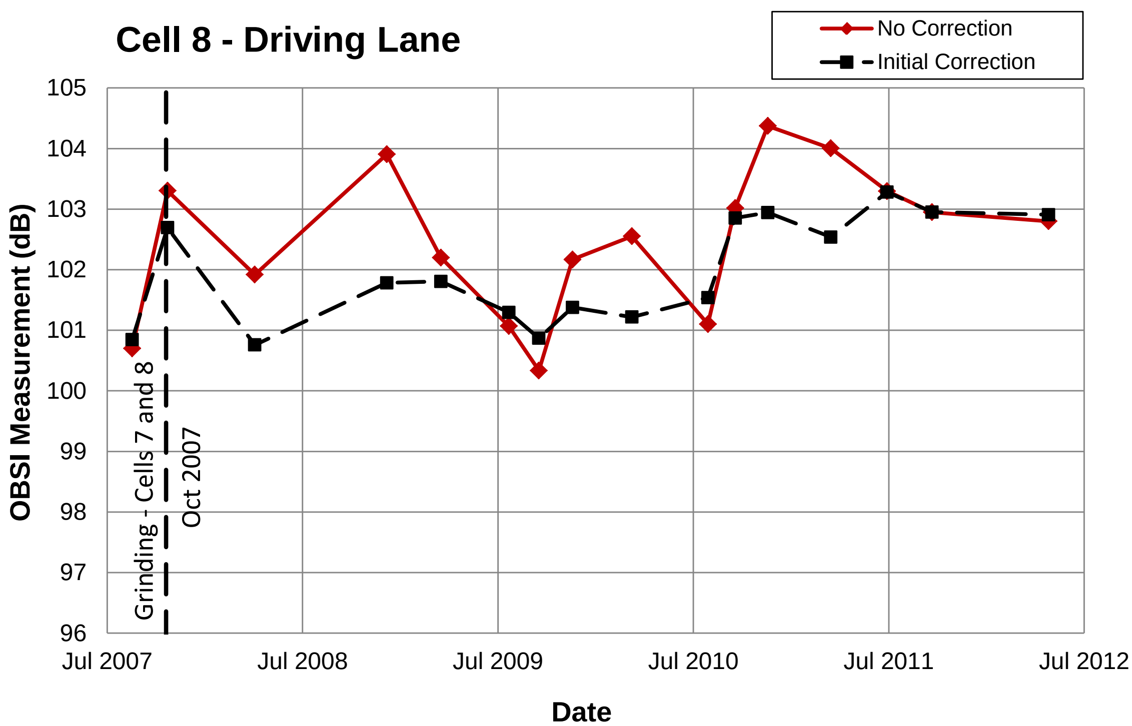

Figure 26. Preliminary temperature correction of OBSI – Cell 8 driving lane.

Noise-Temperature Correction – Individual Frequencies

Employing basic temperature correlations can help explain some of the variability of OBSI measurements. However, it became apparent that more detailed corrections were needed. As can be seen in Figure 26, not all of the variability in the noise measurements were explained. While some definite peaks and valleys were shown over a range of OBSI values in the original data, the measurements with the preliminary correction still exhibit some of this. Through further study of the OBSI data in the two day-long sets of measurements additional potential correlations were found.

The OBSI data collection device records the noise levels at third-octave frequencies from 250 to 5,000 Hz. The overall OBSI reading is a combination of the sound intensities at each third-octave frequency, as presented in Equation 1, but the overall sound intensity is only computed using the 500 Hz frequencies and greater. A sample of the data collected for one test measured in Cell 7 is shown in Table 5.

Table 5. Average OBSI Sample Calculation.

Cell 7
Driving Lane
6/28/2011

Frequency, Hz	OBSI, dB	$10^{(OBSI/10)}$
250	85.7	372,828,500
315	82.8	192,283,000
400	89.5	899,181,500
500	92.0	1,598,837,500
630	90.3	1,083,780,000
800	94.1	2,556,025,000
1000	97.0	5,064,665,000
1250	95.7	3,692,980,000
1600	93.0	1,990,790,000
2000	91.9	1,549,845,000
2500	88.6	723,493,000
3150	83.7	235,643,500
4000	81.0	126,793,500
5000	77.8	60,453,150
	Sum	18,683,305,650

Overall OBSI, dB	102.7

The project team investigated the possibility that certain frequencies may be affected by ambient temperature more readily than others. The analysis proceeded by determining a correction factor for the individual frequencies, adjusting them by the computed correction factor, and then recombining the measurements into an adjusted overall OBSI measurement.

The first step in this analysis was to find a factor linearly relating the sound intensity at each frequency to the temperature at the time of the test for each specific cell. These factors were developed using the data from the 18 Apr 2011 and 28 June 2011 dates and were then applied to the results measured over the four years of data. Not all of the frequencies exhibited a correlation with ambient temperature. Figure 27 shows data collected at four frequencies showing measured sound intensity plotted against the corresponding ambient air temperatures for

Cell 7 on the full-day tests. After viewing the data in this way for Cells 7, 8, 9, and 12, it became apparent that frequencies lower than about 1000 Hz have little correlation with temperature. However, higher frequencies quite clearly display a significant decrease in measured sound intensity with a corresponding increase in temperature. Other aspects of the data shown in this figure are that at higher frequencies the range of sound intensity over different air temperatures is much smaller – 2 to 3 dB for frequencies 1000 Hz and greater, and about 13 dB for lower frequencies. The 1000-Hz plot displays characteristics of both types – narrow range of sound intensity and little correlation with temperature.

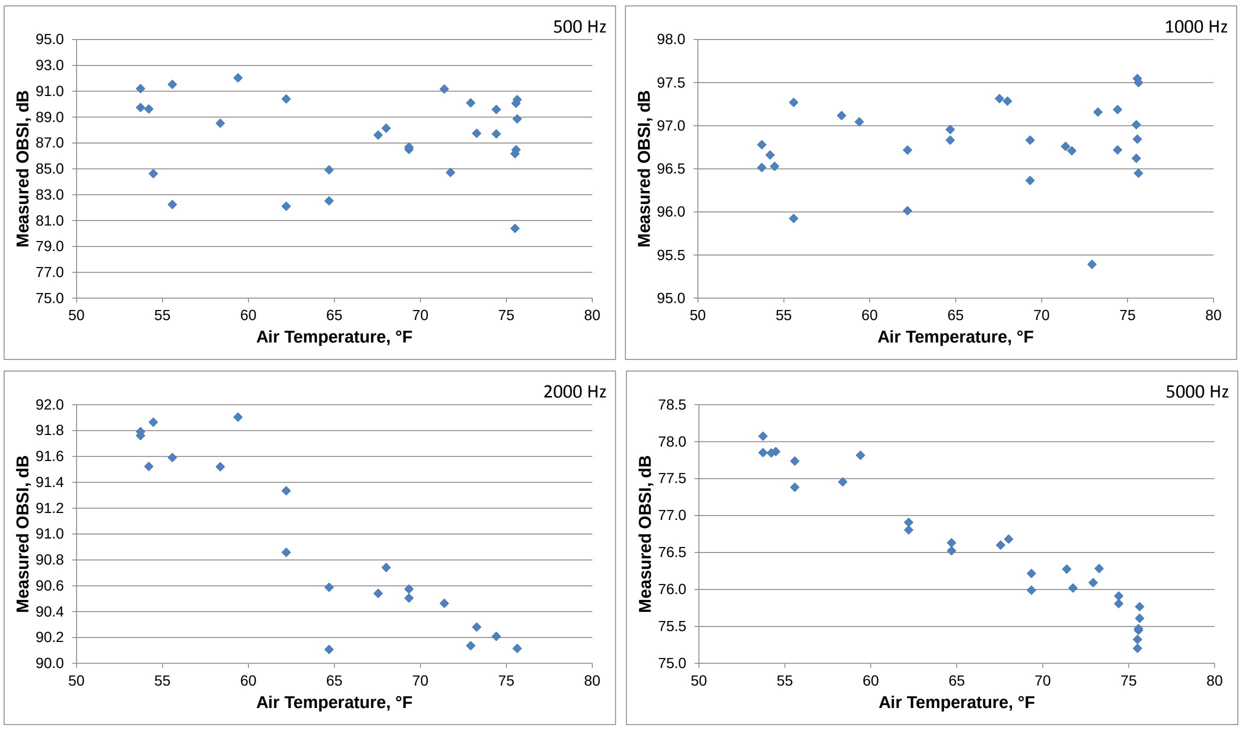

Figure 27. OBSI levels of specific frequencies vs. temperature.

To determine if this method would be sufficient to improve the data, Cell 7 was analyzed as a trial. In order to develop the correction factor from this, a trend line with the original temperature values and corrected OBSI measurements for each frequency was produced. The correction factors were developed in the same way as the overall correction factor discussed in the previous section, using the same base temperature of 68°F. Figure 28 shows a typical correction factor for the sound intensity at 5000 Hz, and a correction factor of -0.190.

This process was used to determine factors for frequencies 500 Hz and greater, since the lower frequencies generally display a very low correlation with air temperature and the OBSI equipment only uses the 500 Hz and greater frequencies. After determining the correction factors for each frequency, the overall OBSI values were recomputed. These new frequency values are then averaged across each test and new average values are obtained.
The individual frequency correction factors are shown in Table 6.

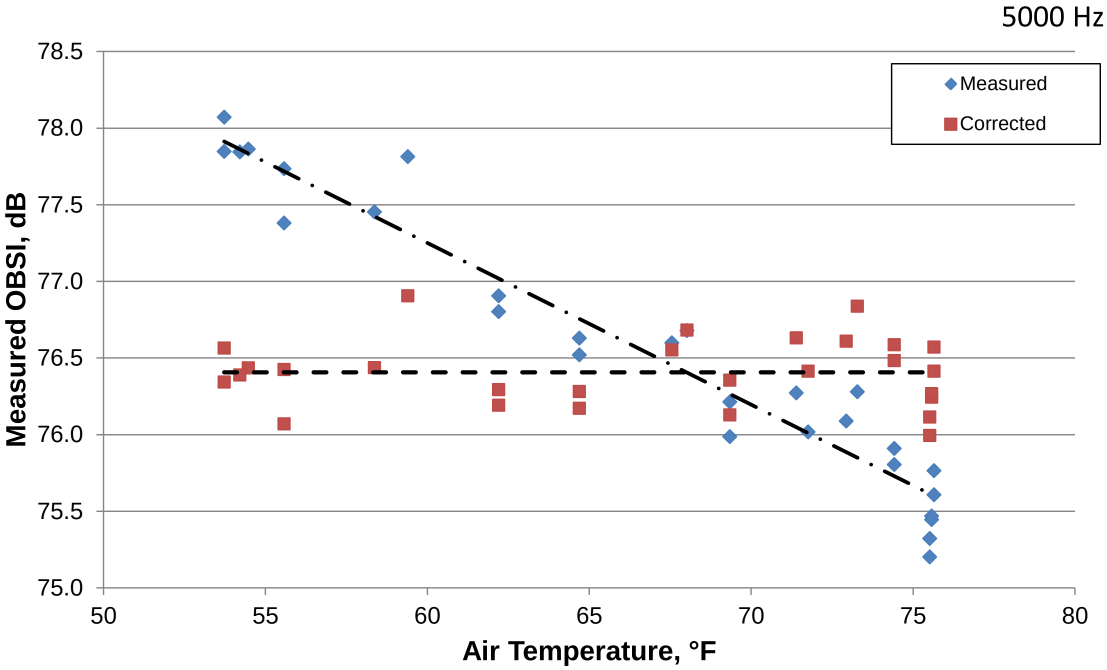

Figure 28. Development of a frequency-specific correction factor.

Table 6. Individual Noise-Temperature Correction Factors by Frequency.

Frequency	Cell 7	Cell 8	Cell 9	Cell 12	Cell 71
500	-0.058	-0.139	-0.048	-0.048	-0.149
630	-0.072	-0.151	-0.085	-0.085	-0.095
800	-0.065	-0.132	-0.076	-0.076	-0.087
1000	0.018	-0.059	-0.007	-0.007	0.048
1250	-0.067	-0.120	-0.043	-0.043	-0.023
1600	-0.222	-0.251	-0.196	-0.196	-0.162
2000	-0.170	-0.214	-0.211	-0.211	-0.157
2500	-0.170	-0.163	-0.137	-0.137	-0.086
3150	-0.240	-0.205	-0.189	-0.189	-0.197
4000	-0.205	-0.193	-0.133	-0.133	-0.129
5000	-0.190	-0.198	-0.121	-0.121	-0.109

Plotting these new values next to the original values as well as the initial temperature corrections shows the effectiveness of the new method, as shown in Figure 29. While the correction factor affects the magnitude of the corrected OBSI value depending upon the base temperature, the relative values of all measurements obtained throughout the project are more easily compared on a relative basis when corrected to a specific ambient temperature.

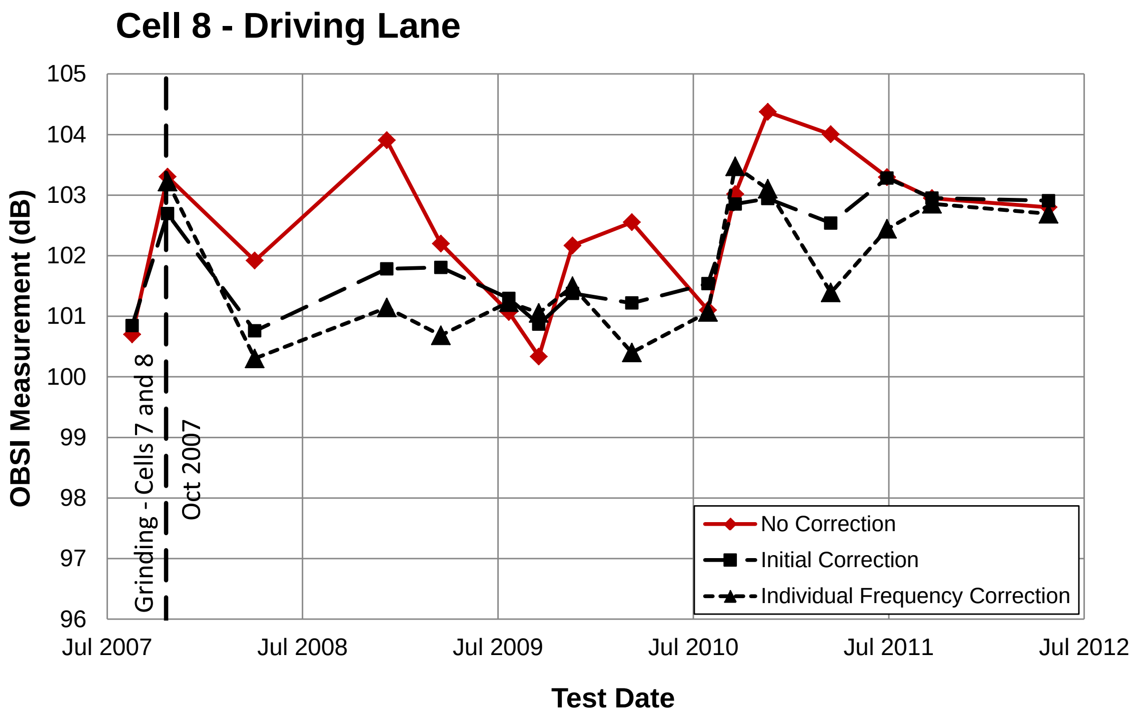

Figure 29. Comparison of uncorrected and corrected OBSI levels.

As mentioned previously, the correction for ambient temperature results in smoothed data that generally has lower high values and higher low values. In the case shown in Figure 29, with corrections on the sound intensities of the individual frequencies, the data show, with some exceptions, continuous measurements between about 100.5 and 101.5 dB for the first three years after grinding. In the fall of 2010 (just more than three years after grinding) the two data points show a dramatic increase, only to return to more reasonable values after two test dates. After these tests, the data show a gradual increase, before leveling at just below 103 dB for the last two measurements.

The results of the overall and individual frequency corrections indicate that a correlation exists between the sound intensity and air temperature. It also shows that the sound intensity at some frequencies is affected by the air temperature more than others. Later in this report, when the noise levels are discussed at greater length, the primary data analyzed and discussed will have been corrected for air temperature at individual frequencies.

Friction-Temperature Correction

Although a temperature correction for friction was not possible within the constraints of the current project, others have done similar studies and have concluded that temperature of the pavement surface may have an effect on friction measurements. Steven [13] concluded that for bituminous pavement surfaces, a correction should be applied. This work was done using a British Pendulum Tester on bituminous pavements, however, and so no conclusions should be applied to the current study.

In a report by Bazlamit and Reza [14], a change in the British Pendulum Number (BPN) is calculated as follows:

$$\Delta BPN = 0.232(T - 20) \qquad \textit{Equation 3}$$

where:

T = measured temperature, °C (from 0 to 40C)

The work by Steven [13] used the same equation and found a coefficient of 0.466. A study by Oliver et al. [15] developed a correction that accounts for temperature and the level of the BPN value.

$$BPN_{20} = \frac{BPN_T}{1 - 0.00525(T - 20)} \qquad \textit{Equation 4}$$

where:

BPN_{20} = BPN number at 20°C

BPN_T = BPN number at T°C

It is likely that a temperature correlation exists and may improve the data analysis for concrete pavements tested with the skid trailer (shown in Figure 19). As mentioned previously, such a correction factor was not possible within the scope of this project. Further study may be warranted to evaluate the potential for a correction factor's influence on the data.

Data Analysis

This section describes the analysis of the data collected by the MnROAD staff, and the observations made throughout the project as more data were collected. The data and observations discussed in this section include the noise, friction, texture, and ride. Since the changes observed in the surface characteristics are expected to be related to ESALs rather than time since grinding, most of the plots in the remainder of this report plot the characteristics against cumulative ESALs.

Noise

As described in the previous section, the data presented here has been corrected for temperature effects except where noted. Testing was conducted in each of the cells in both the driving and passing lanes. The difference in the two lanes is essentially the amount and type of traffic over the time since grinding. The data shown in Figure 30 is the OBSI measurements for the four ground cells and the control cell (Cell 12). The data in this figure are unadjusted. The dips in the data in the fall of 2009 and 2010 are evident. Figure 31 shows the same information, but corrected for temperature variations by individual frequencies. As can be seen, the control section (Cell 12) is significantly smoothed, and is more constant. The ground cells are also more consistent, and have lost most of their extreme changes. Some features in the data that remain, but that do not seem to be consistent include the sharp increase in the measurement in the conventional grind (Cell 8) at the end of 2010, and the steep increase in noise in the new ultimate grind (Cell 71) in the first three measurements after it was ground.

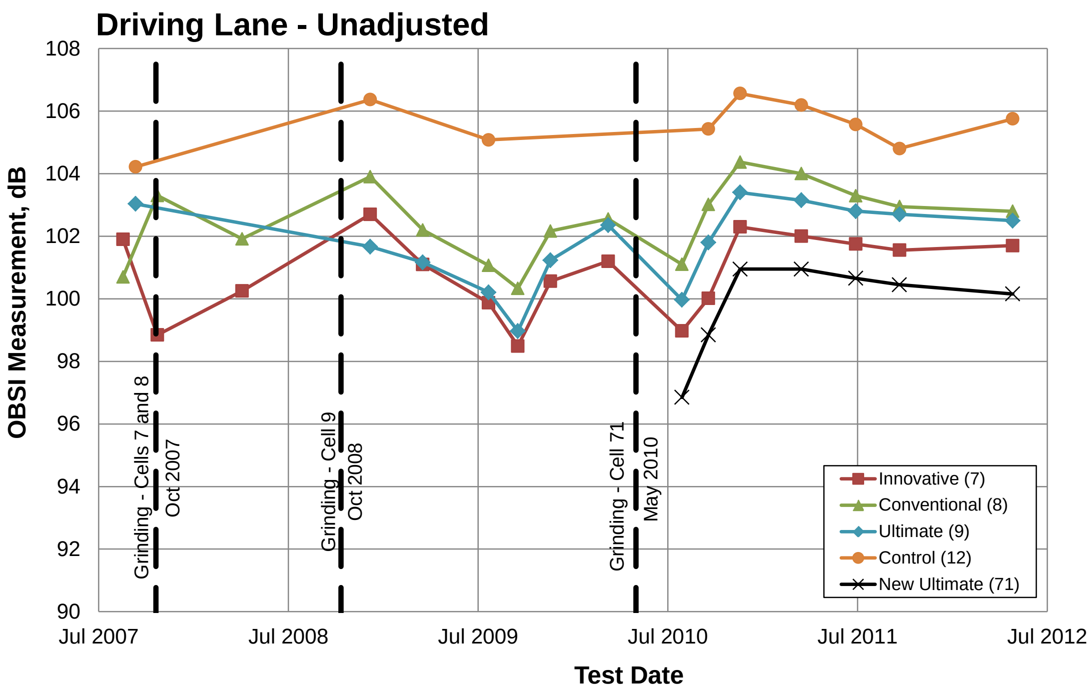

Figure 30. OBSI – Driving Lane – Unadjusted.

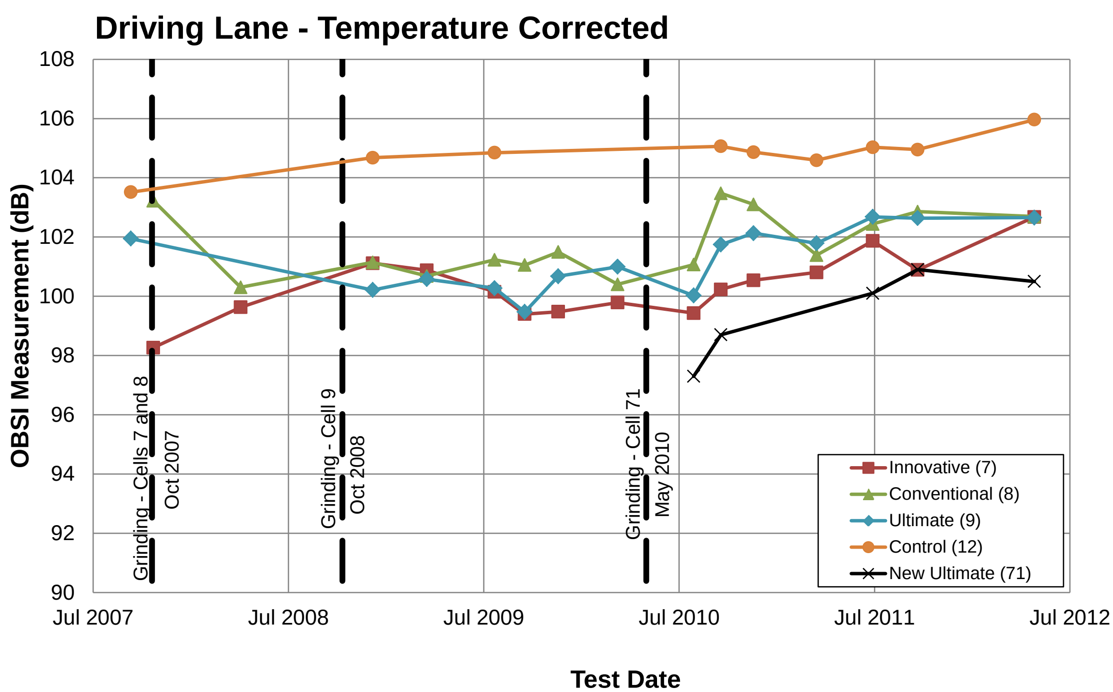

Figure 31. OBSI – Driving Lane – Temperature Correction.

As mentioned previously, the surface characteristics are better suited for plotting against cumulative ESALs since grinding. Thus, Figure 32 shows the same data as in Figure 31, but with ESALs on the horizontal axis rather than the date the test was conducted.

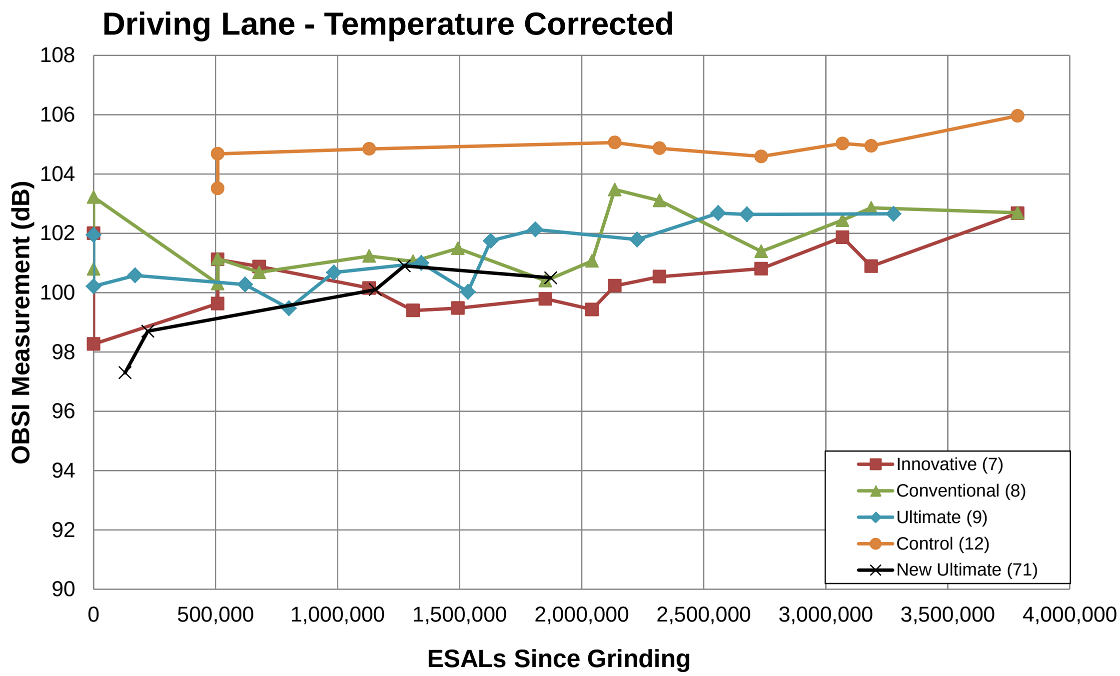

Figure 32. OBSI – Driving Lane – Temperature Correction – by ESALs.

The data shown in Figures 33 through 35 display the same data as in the previous three graphs, but with the passing lanes. Similar to the previous graphs, the corrected data shows much less variation than the unadjusted data, with some remaining inconsistencies. It should be noted that the passing lane temperature corrections were made using the correction factors developed with data from the driving lane, and thus may not be entirely accurate.

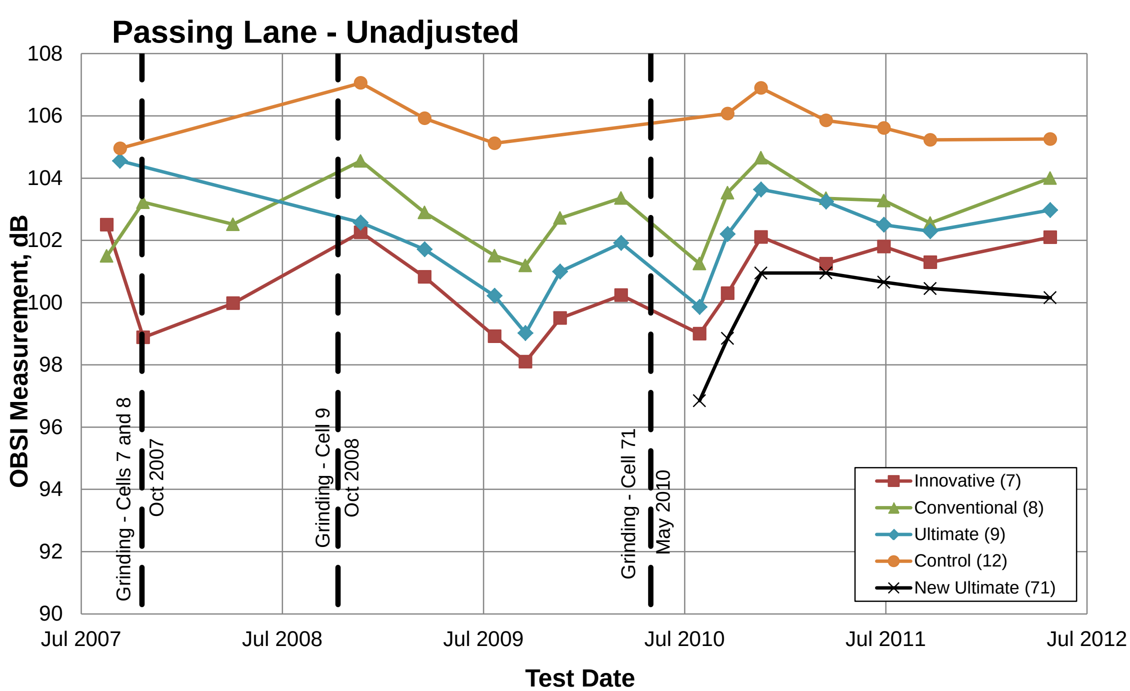

Figure 33. OBSI – Passing Lane – Unadjusted.

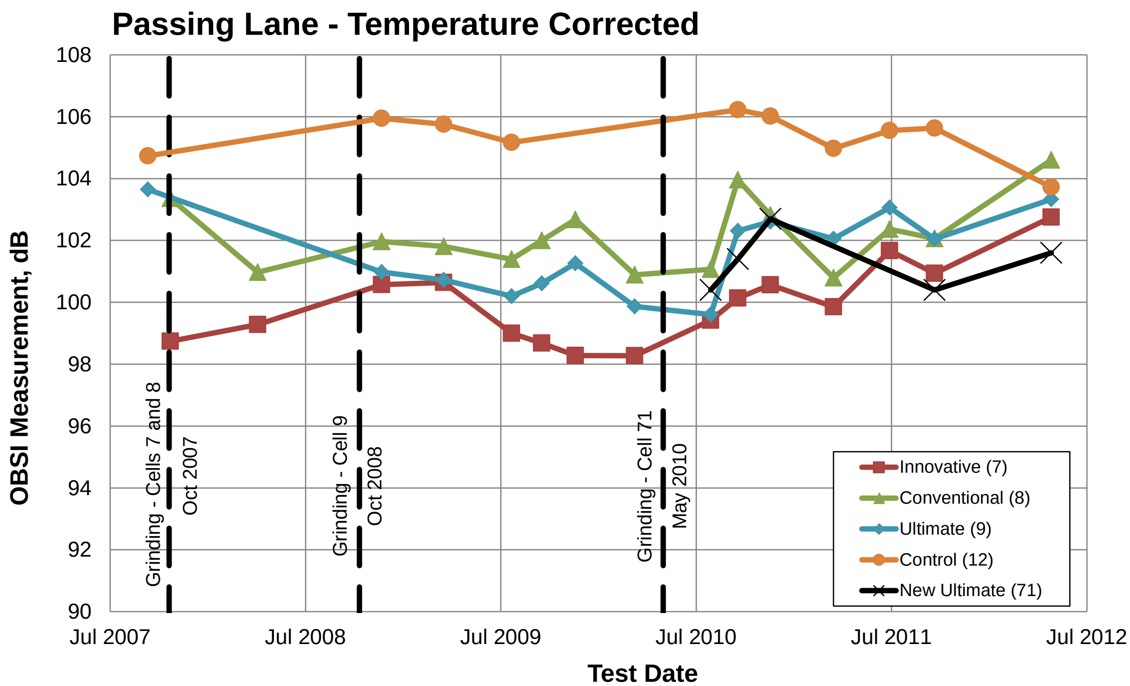

Figure 34. OBSI – Passing Lane – Temperature Correction.

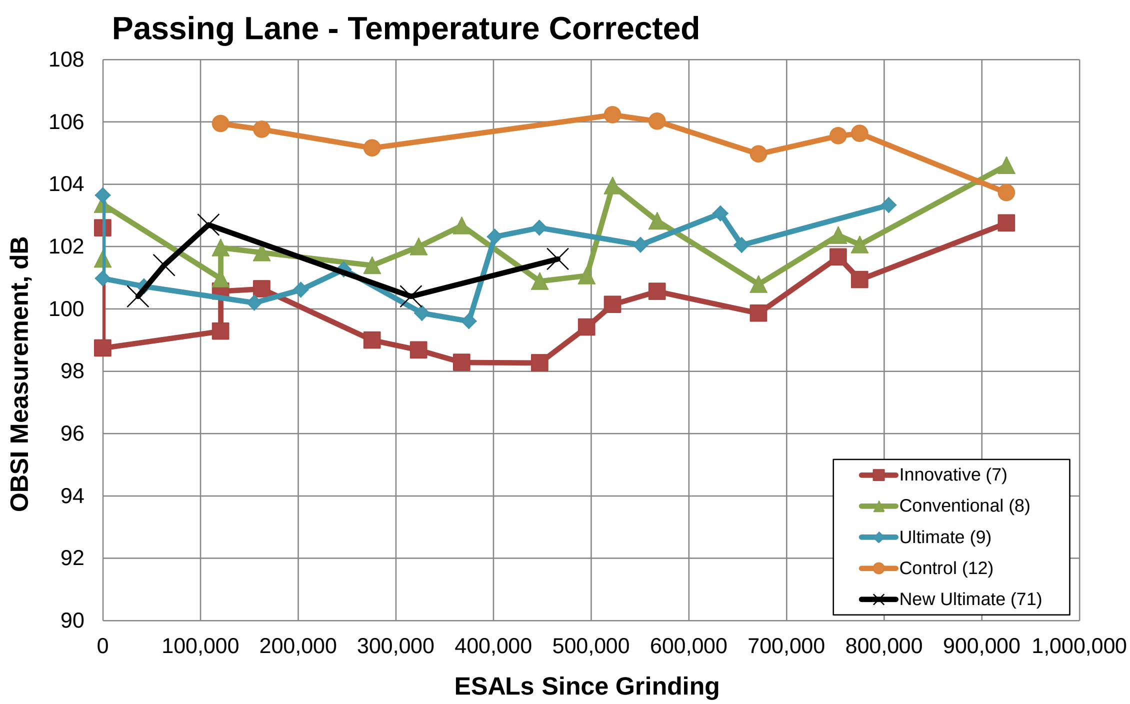

Figure 35. OBSI – Passing Lane – Temperature Correction – by ESALs.

The general range of sound intensity data over the period of data collection on each cell is indicated in Table 7 and Figure 36. As can be seen in this table and figure, the range of sound intensity in the corrected values does not deviate by more than about 1 dB, except in Cell 71, where the lowest driving lane sound measurement was more than 3 dB lower than the lowest in the passing lane.

Table 7. Range of Sound Intensity (dB) over time.

Cell	Driving Lane	Passing Lane
7 (Innovative)	98.3 – 102.7	98.3 – 102.8
8 (Conventional)	100.3 – 103.5	100.8 – 104.6
9 (Ultimate)	99.5 – 102.7	99.6 – 103.3
12 (Control)	103.5 – 106.0	103.7 – 106.2
71 (New Ultimate)	97.3 – 100.9	100.4 – 102.7

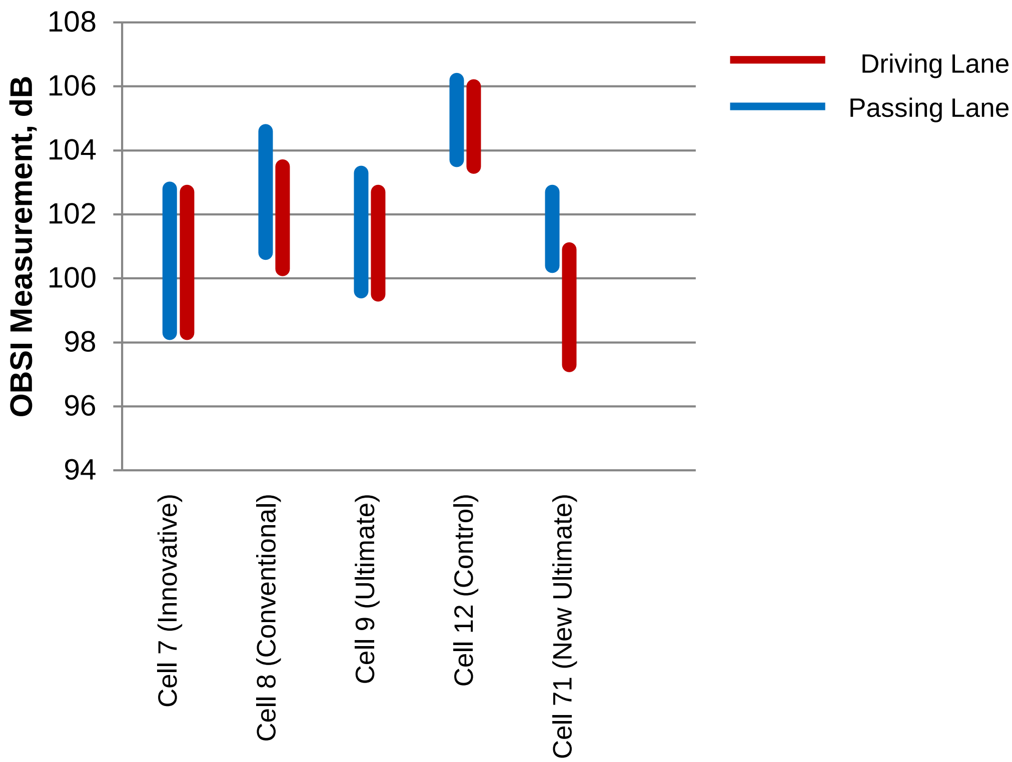

Figure 36. Range of corrected driving and passing lane sound intensity.

Initial Response

Prior to, and just after the grinding operations on Cells 7 and 8 the noise testing was conducted. Looking at the unadjusted values for these cells, it appears that the conventional grind increased in sound intensity from 100.7 to 103.3 dB in the driving lane, and from 101.5 to 103.2 dB in the passing lane. Conversely, the innovative grind decreased from 101.9 to 98.8 dB in the driving lane and from 102.5 to 98.9 dB in the passing lane. In each lane, the conventional grind *increased* by about 2 dB or more, and the innovative grind *decreased* by more than 3 dB. Since the specific dates and times of these tests are not available, only the overall temperature correction was applied for the pre- and post-grind measurements, shown in Table 8.

Table 8. Pre- and Post-Grind Sound Intensity.

Cell / Grind	Change in Sound Intensity, Unadjusted		Change in Sound Intensity, Corrected	
	Driving Lane	Passing Lane	Driving Lane	Passing Lane
7	-3.1	-3.6	-3.4	-3.9
8	+2.6	+1.7	+1.9	+1.0
9[a]	-1.3	-2.0	-2.0	-2.6

[a]No noise measurements were collected immediately prior to grinding of Cell 9.

No OBSI testing was conducted immediately prior to the grinding of Cell 9, so the immediate effects on noise levels are not known, but are inferred from a comparison of measurements taken within one year prior to grinding.

Long-Term Effects

The differences between OBSI measurements (comparing the innovative and ultimate grinds to the conventional grind) are shown in Figures 37 and 38 for the driving and passing lanes, respectively. In these figures, the legend indicates the comparison made. For example, when comparing the conventional to the innovative grind, the "Conventional – Innovative" notation indicates that the conventional grind is louder by the value in the ordinate at the particular time. In these plots, the horizontal axis is the date of the test, since appropriate data using cumulative ESALs since grinding is not available for direct comparisons such as this. It was originally thought that when comparing between cells with measurements taken on the same day, the temperature correction factors would not be needed. In fact, with the individual frequency corrections, differences may be noticed when comparing measurements of different cells taken on the same day. For example, Figure 39 shows the same information as Figure 37, but with the individual frequency temperature corrections applied.

As would be expected, the initial measurements soon after grinding indicated a significant difference between the conventional and innovative grinds (meaning that the conventional grind was more than 4 dB greater than the innovative grind). In a short time, however, and for the remaining measurements (with few exceptions) the difference was only up to 2 dB for the driving lane and up to about 3 dB for the passing lane. This seems reasonable since the conventional grind had a more significant decrease in noise after the initial fins remaining on the surface had been worn away.

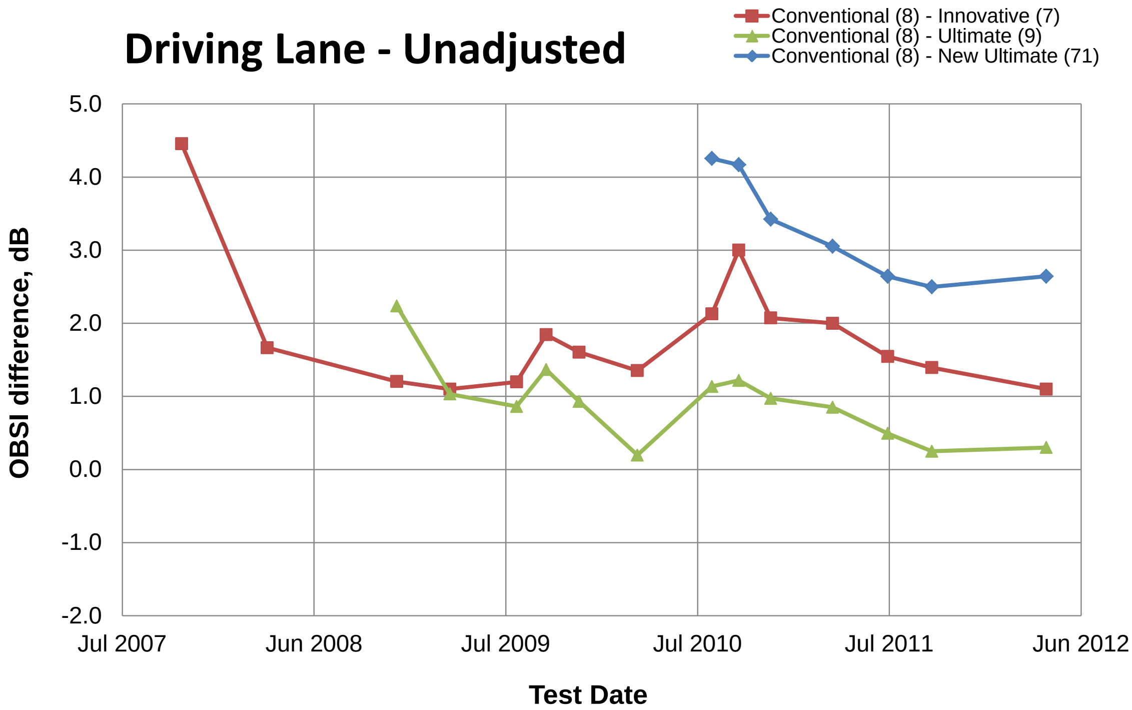

Figure 37. Difference in OBSI – Driving Lane.

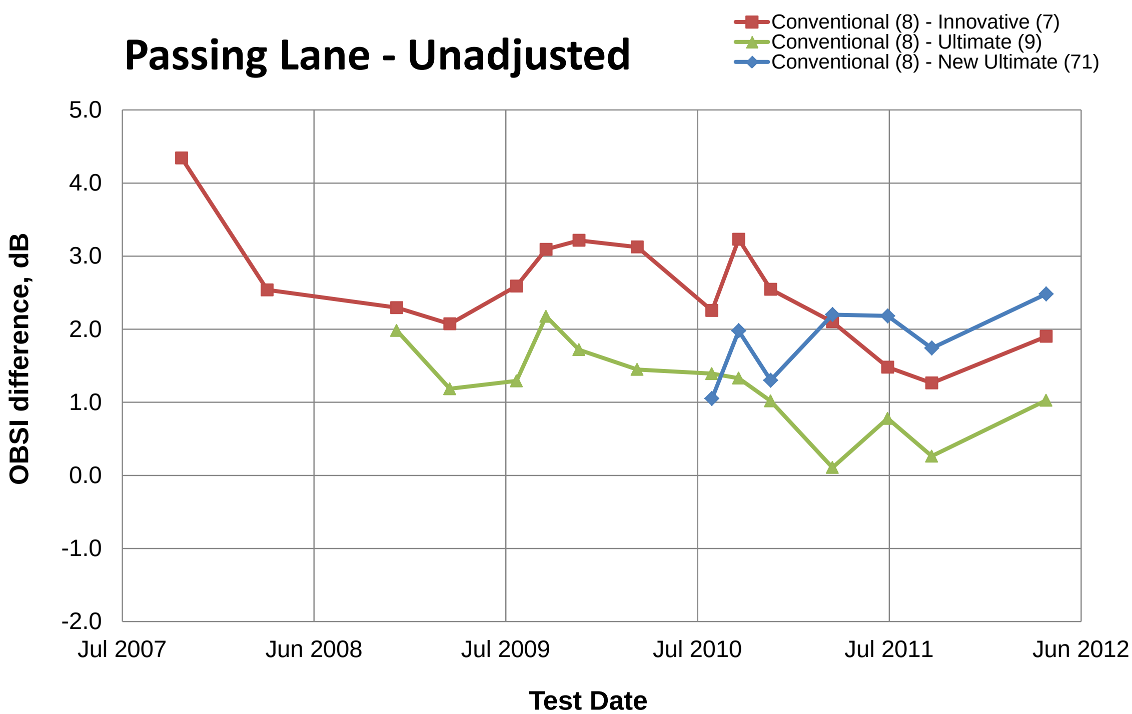

Figure 38. Difference in OBSI – Passing Lane.

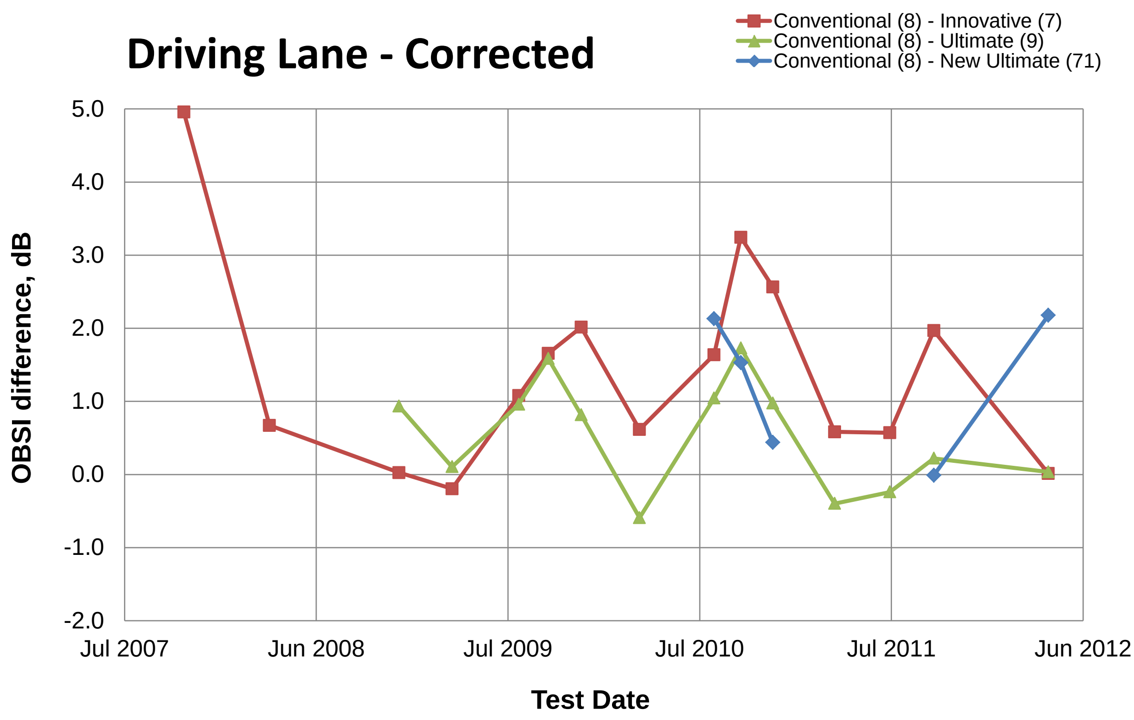

Figure 39. Difference in OBSI – Driving Lane – Corrected.

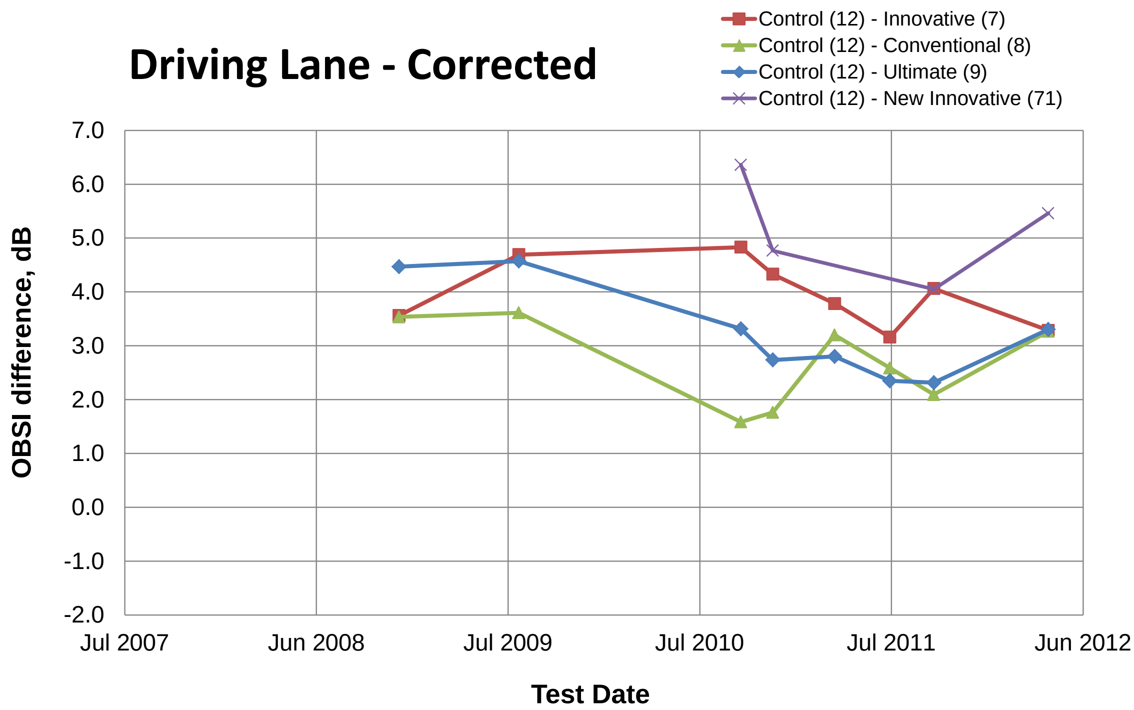

Figure 40. Difference in OBSI – Driving Lane, grinding cells compared to control.

Perhaps a better comparison of noise data is made between the grinding cells and the control cell (Cell 12). Cell 12 is a useful comparison since it has not shown much change in OBSI measurements over the four years of data collection during this project, as seen in Figures 30 through 34. The comparisons in Figures 37 through 39 reflect the variations in the measured data from the previous figures. It can be seen in Figure 40 that after the initial year or two after grinding the difference in noise levels between each of them and the control cell has been decreasing to some extent. Since the Cell 12 measurement has not changed significantly over this period of time, the conclusion may be drawn that the grinding cells have either increased in noise or remained approximately the same, relative to the control cell, since July 2009.

A surrogate for ESALs since grinding is the time since grinding on each cell for observing the differences in noise. One coincidence is that the grinding on Cell 9 occurred almost exactly one year after the grinding on Cells 7 and 8. Also, there are three testing dates subsequent to Cell 9 grinding that fall one year after testing within a few days of the same age on Cells 7 and 8. The comparison of noise measurements based on time since grinding in the driving and passing lanes are shown in Figures 41 and 42, respectively. In these figures, the temperature corrections have been applied, since the measurements were not taken on the same dates, or more importantly, at the same temperatures.

An observation that is readily noticed in the driving lane (Figure 41) is that the innovative and conventional grinds started at about 3.5 dB quieter than the control cell, whereas the ultimate grind started at just about 4.5 dB quieter. About two years after grinding through the end of the data collection, the conventional grind seems to be about 2.0 to 3.0 dB quieter than the control, the innovative grind is generally 3.0 to 5.0 dB quieter than the control, and the ultimate grind has settled into a relatively constant 2.5 to 3.5 dB quieter than the control. Additionally, the new ultimate grind has remained about 4.5 to 6.0 dB quieter than the control (in the four tests conducted since it was ground). Due to the large variability in the data, even with the temperature corrections, there is not adequate data to make specific determinations about these trends, however.

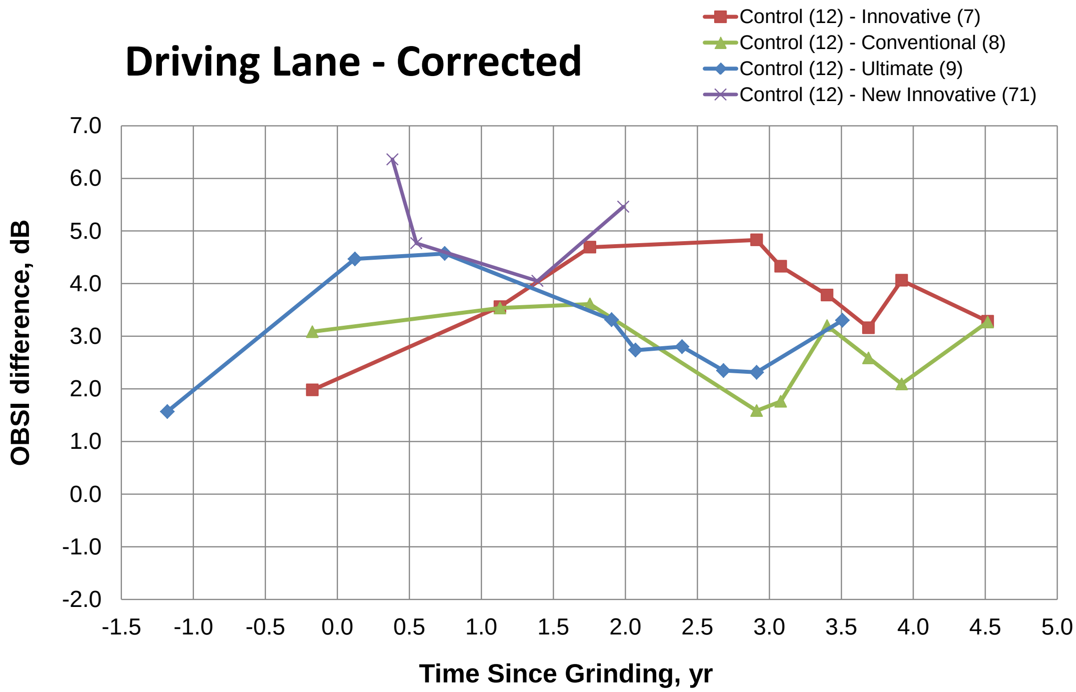

Figure 41. Difference in OBSI by Time Since Grinding – Driving Lane.

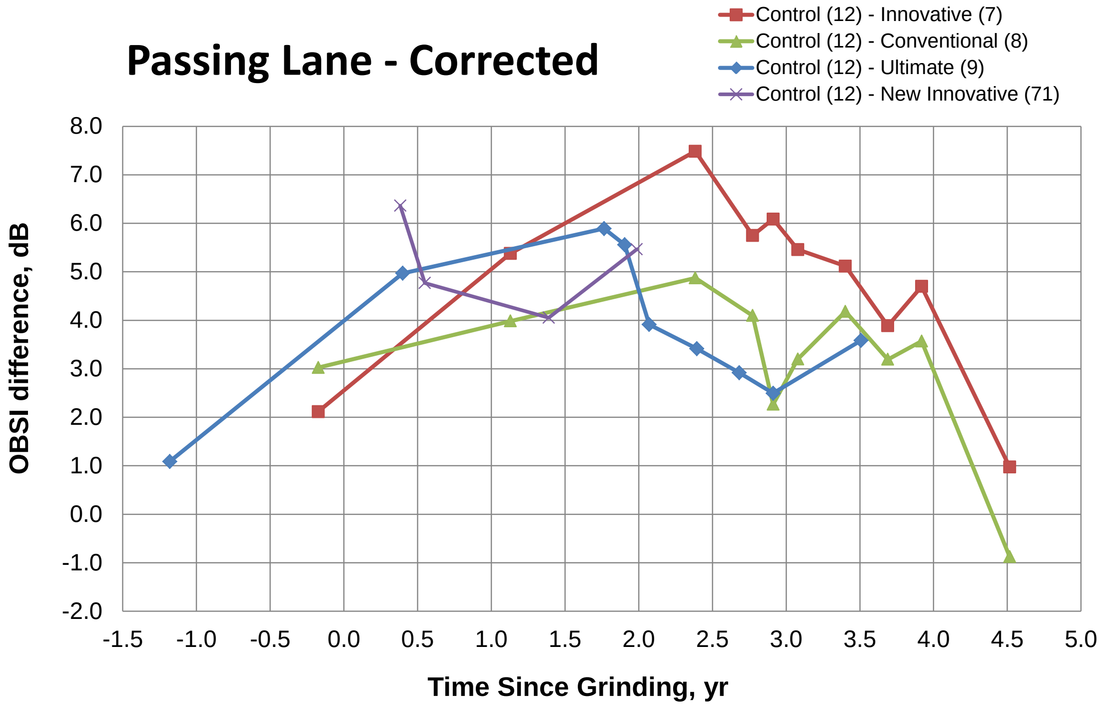

Figure 42. Difference in OBSI by Time Since Grinding – Passing Lane.

Leading vs. Trailing Edge

The OBSI measurement equipment takes sound readings at the leading edge and at the trailing edge of the tire as it rolls along the pavement surface. Figure 43 shows the OBSI measurement for both the leading edge and trailing edge from each test, in the Driving Lane. There is one key piece of information to be noted from the data in this figure, which is that the trailing edge of the three NGCS surfaces produces a higher sound pressure level than the leading edge, in most cases, and that the opposite occurs in most cases for the conventional grind. The reason for this is likely due to the grinding procedure. The grinding of the conventional surface leaves brittle tines or kerfs with positive or upward texture that eventually breaks off or “wear in” and becomes smoother. The NGCS procedure involves grinding of the entire surface creating no positive or upward texture. Passing lane data showed approximately the same result.

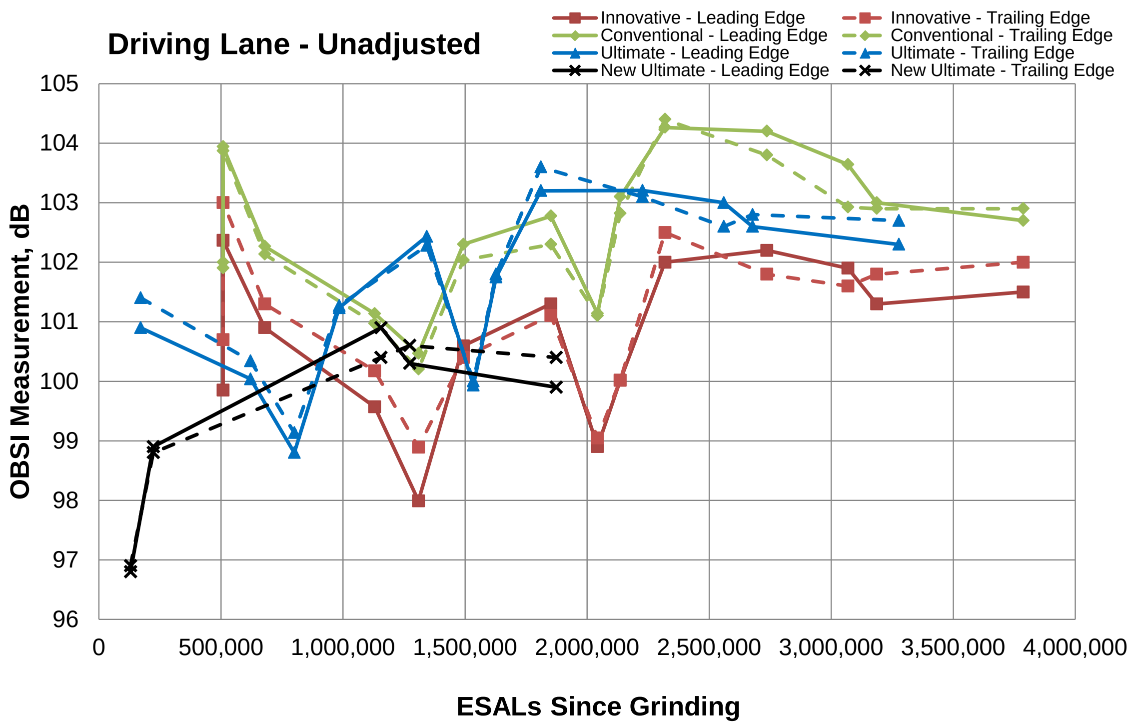

Figure 43. Leading edge and trailing edge comparison – Driving Lane.

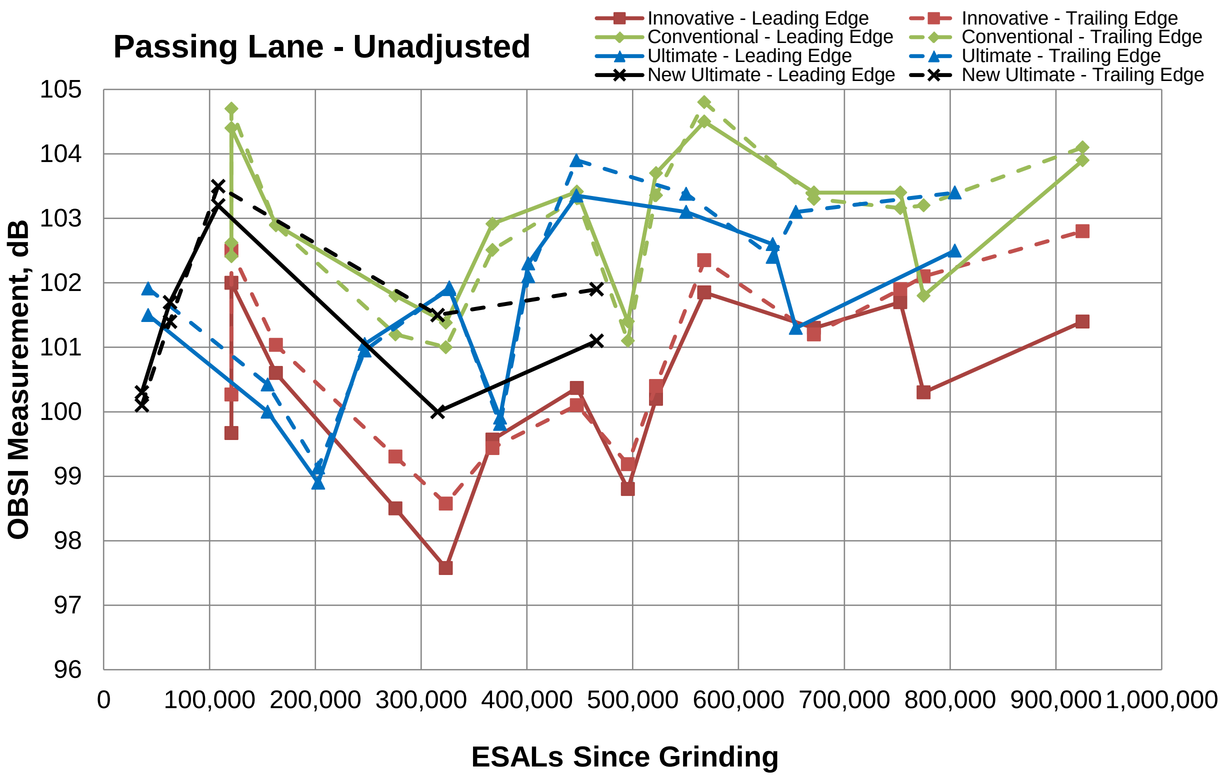

Figure 44. Leading edge and trailing edge comparison – Passing Lane.

Modeling

Attempts were made at modeling the change in OBSI measurements in the various cells. In several cases, the best regressions that were developed produced R^2 values of less than 0.30, and are not reported here. The R^2 value was greater than 0.50 in only 4 of the 10 models. Basic statistical analyses were conducted to identify potential outliers in the data, but in many cases, the regression models performed slightly better with the outliers included in the analysis. For these reasons, unless there was significant reason to suspect a data point as an outlier, these were not omitted. The regression coefficients in Table 9 are based on a linear regression between cumulative ESALs since grinding and the OBSI values corrected for temperature using the individual sound frequencies. The basic regression model is as shown below.

$$OBSI_{corr} = m(ESAL) + b \qquad \textit{Equation 5}$$

where:

- $OBSI_{corr}$ = OBSI measurement, corrected for temperature using individual frequencies,
- ESAL = Cumulative ESALs since grinding, and
- m, b = Linear regression coefficients – slope and intercept, respectively.

Table 9. Coefficients for Noise Models.

Lane	Cell	b	m	R^2
Driving	Cell 12 (Control)	99.74	3.792×10^{-7}	0.62
	Cell 7 (Innovative)	99.466	5.370×10^{-7}	0.33
	Cell 8 (Conventional)	100.339	6.950×10^{-7}	0.48
	Cell 9 (Ultimate)	99.641	1.017×10^{-6}	0.71
	Cell 71 (New Ultimate)	97.856	1.767×10^{-6}	0.78
Passing	Cell 12 (Control)			0.06
	Cell 7 (Innovative)	98.625	2.955×10^{-6}	0.34
	Cell 8 (Conventional)			0.21
	Cell 9 (Ultimate)	99.789	4.178×10^{-6}	0.56
	Cell 71 (New Ultimate)			0.14

An attempt at combining the results from the driving and passing lanes in one model did not yield better results. It was thought that if the change in OBSI measurements is related solely to historical traffic, then the passing and driving lanes could be modeled together. An example of this is shown in Figure 45, for which the best linear model yielded an R^2 of 0.05.

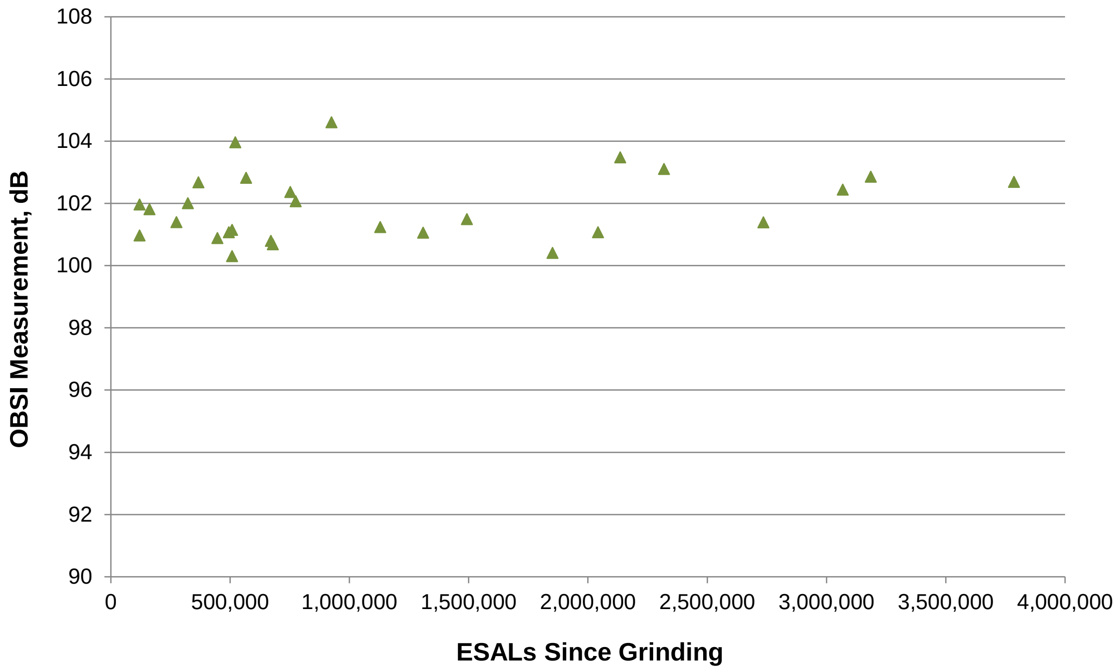

Figure 45. Example of driving and passing lanes combined modeling.

Friction

The purpose of friction testing is to compare how surfaces with various grinding configurations maintain their friction characteristics over time. While it may be important to evaluate each point and adjust for surface temperature when comparing individual test results, as described in previous sections this was not possible.

Initial Response

The friction number for the first two NGCS grinds (Cells 7 and 9) were somewhat lower immediately after the initial grinding. Friction data for Cell 71 was not available for the time period immediately prior to grinding. By contrast, the friction on Cell 8 was noticeably higher, immediately after grinding. The ultimate grind was performed on Cell 9 approximately one year after the conventional and innovative grind. The results of the friction testing in the driving and passing lanes (using the ribbed tire) are shown in Figures 46 through 49. The same results for the smooth tire testing are shown in Figures 50 through 53. Other cells shown in these figures include Cell 71, and Cell 12 which was used as a control since it has the original tined surface from its initial construction. Since Cell 12 experienced the same cumulative ESALs during the period of this project, and since it has been in service for many years prior to the grinding of the other cells, it is plotted against the cumulative ESALs of Cells 7 and 8 for comparison purposes. In reality, Cell 12 has experienced approximately 16 million ESALs in the driving lane and about 4 million in the passing lane.

After Cells 7 and 8 were ground, it appears that the friction on Cell 8 (conventional) increased for some time, while the friction of Cell 7 (innovative) decreased between the first and second tests after grinding. In the initial period fins remaining on the conventional grind break down and the overall friction decreases, whereas for the innovative grind, these fins are removed during the grinding process, and are not left behind. The conventional surface outperformed the innovative grind by an FN value of almost 10, initially, and increased to a difference of about 12 by the time of the second test period in May 2008.

Long-Term Effects

After its high point measured about 500,000 ESALs (seven or eight months) after grinding, the friction on the conventional grind decreased at approximately a constant rate for another 500,000 ESALs (about one year, with some extended MnROAD Mainline closures), and then remained mostly constant at a friction number of 50 to a cumulative 3.2 million ESALs (to about mid-2011). The innovative grind has had a relatively constant friction number of about 40 to 45 since it was ground. The ultimate grind surface has similarly remained at about 45 to 50 since grinding. The last few test periods included in this project saw all cells in the study decrease in friction. While this could be related to pavement surface temperature, there is no direct evidence to suggest this. Figure 46 includes the pavement surface temperature at each date and time that the friction test was conducted, and there is little correlation between temperature and the friction data, overall. The only possibility might be in April 2011 where all cells exhibited an increase in friction only to return to previous levels at the next measurement date. At the same time, the pavement surface temperature was lower than it had been at almost any other test date. However, this increase in friction corresponding to a decrease in surface temperature is the reverse of what would be suggested in Equations 3 and 4 on page 30.

In the first 500,000 ESALs (about six months) after the ultimate grind on Cell 9, the friction number decreased slightly. This period of “wearing in” may actually occur more quickly than this, but this cannot be determined due to the quarterly data collection frequency. As mentioned, the friction number has remained nearly constant since that time. Overall, the friction numbers of each of the three grinding configurations has remained similar after an initial period of differences immediately after grinding.

For the driving lane and ribbed tire, the friction of the control cell is very similar to the other cells – with friction numbers near 45 to 50. In the passing lane, the control and conventional grind are somewhat higher in friction number – by about 5 to 6 points. After 3 to 4 million ESALs, all cells have come to a friction number within 3 points of each other – from 43.7 to 45.6.

With the smooth tire, the control cell shows a significantly lower FN than all of the grinding cells (in the driving lane) and only slightly less in the passing lane. This seems reasonable, since the driving lane will have had much more traffic than the passing lane over time (a ratio of about 4 to 1).

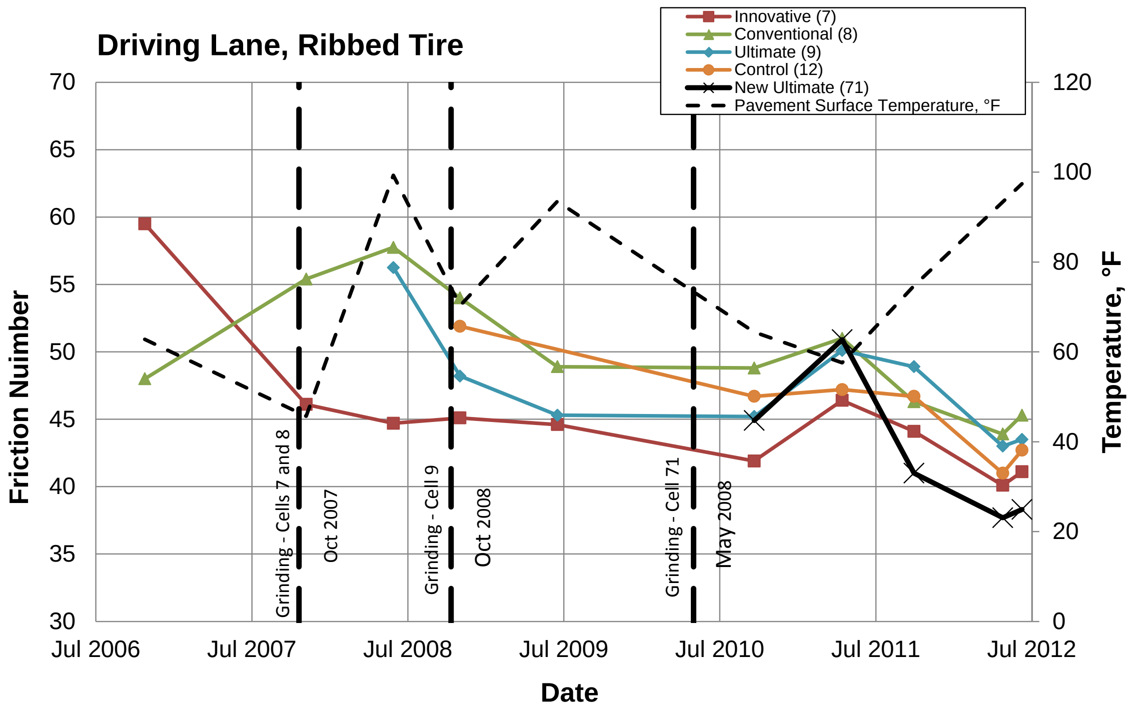

Figure 46. Friction – Driving Lane, Ribbed Tire.

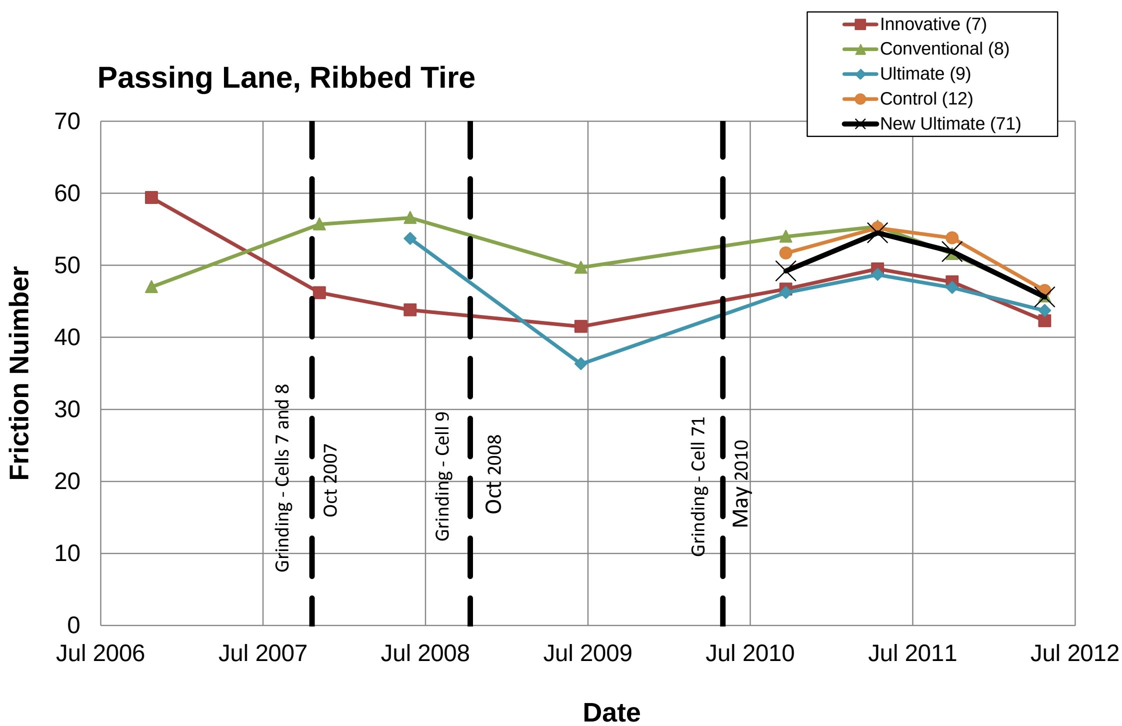

Figure 47. Friction – Passing Lane, Ribbed Tire.

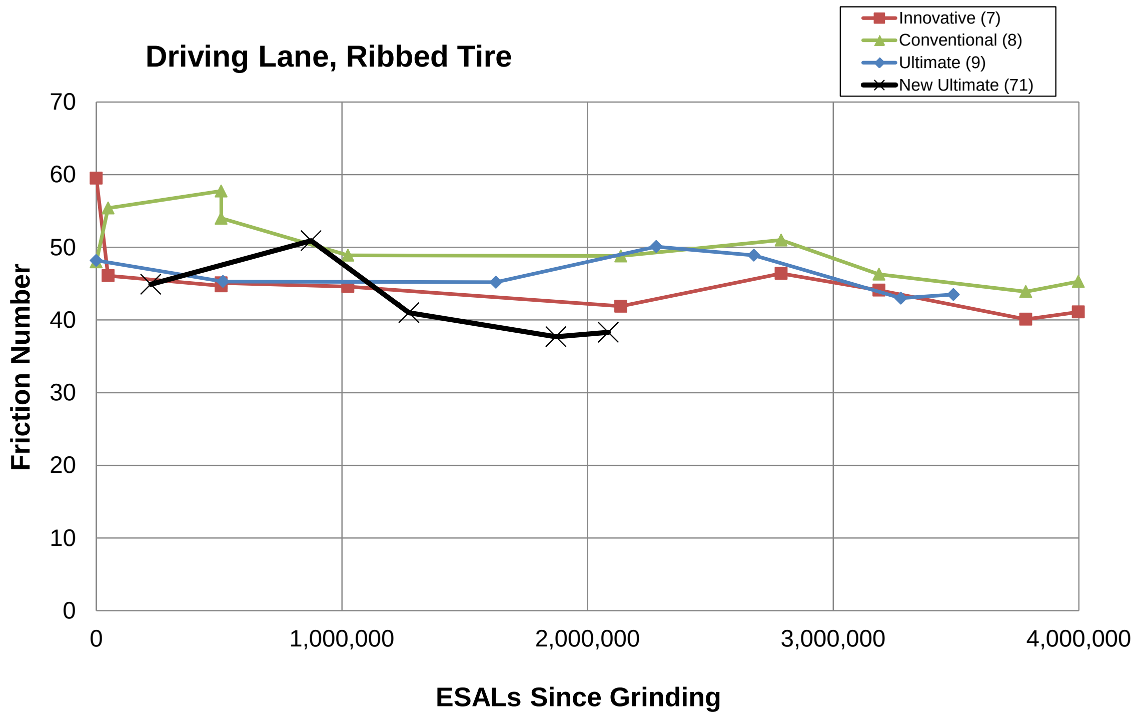

Figure 48. Friction – Driving Lane, Ribbed Tire, ESALs Since Grinding

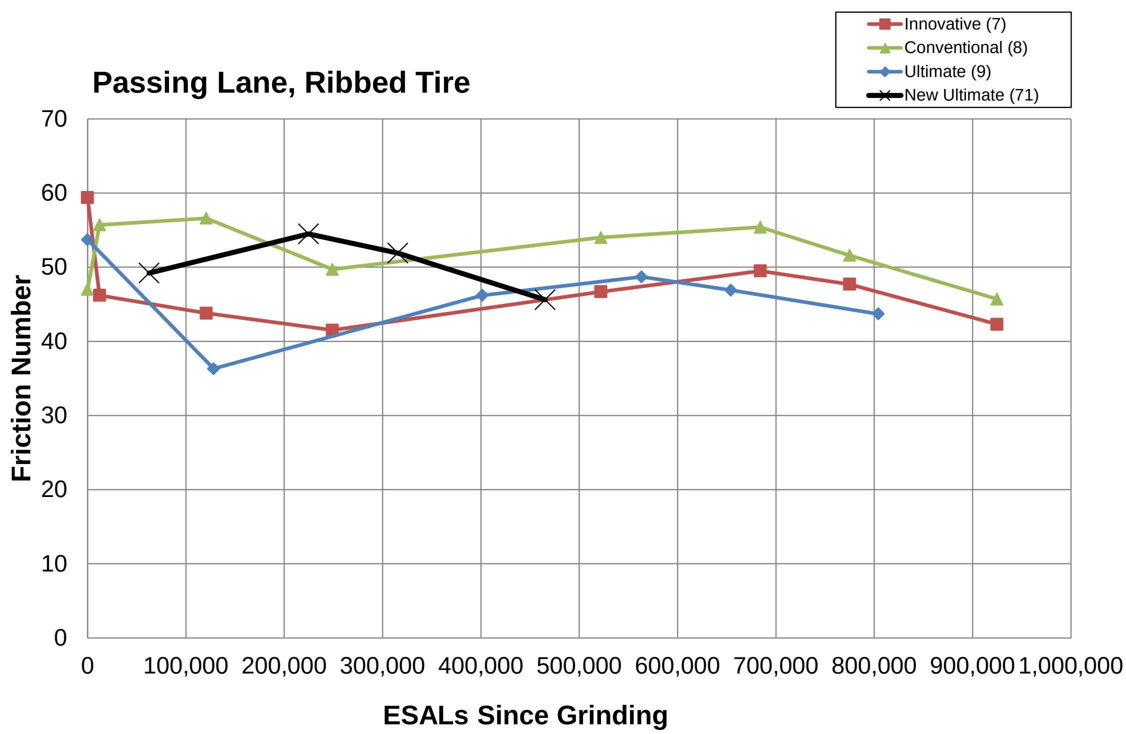

Figure 49. Friction – Passing Lane, Ribbed Tire, ESALs Since Grinding.

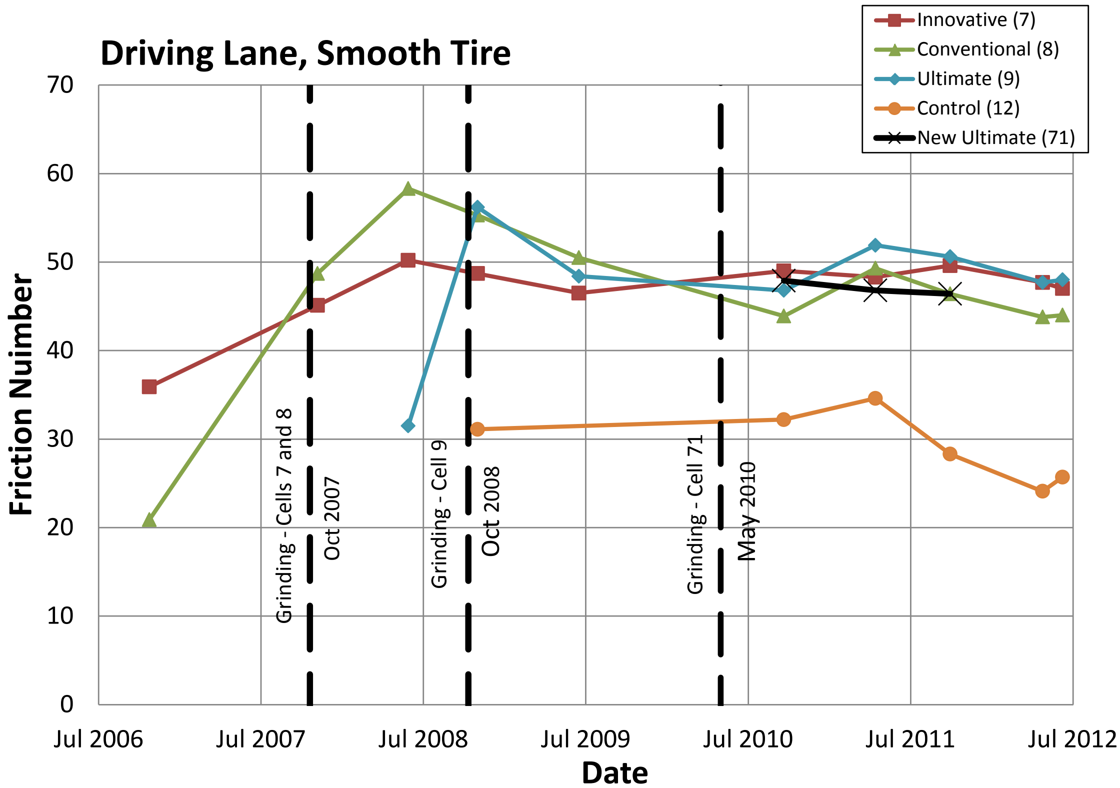

Figure 50. Friction – Driving Lane, Smooth Tire.

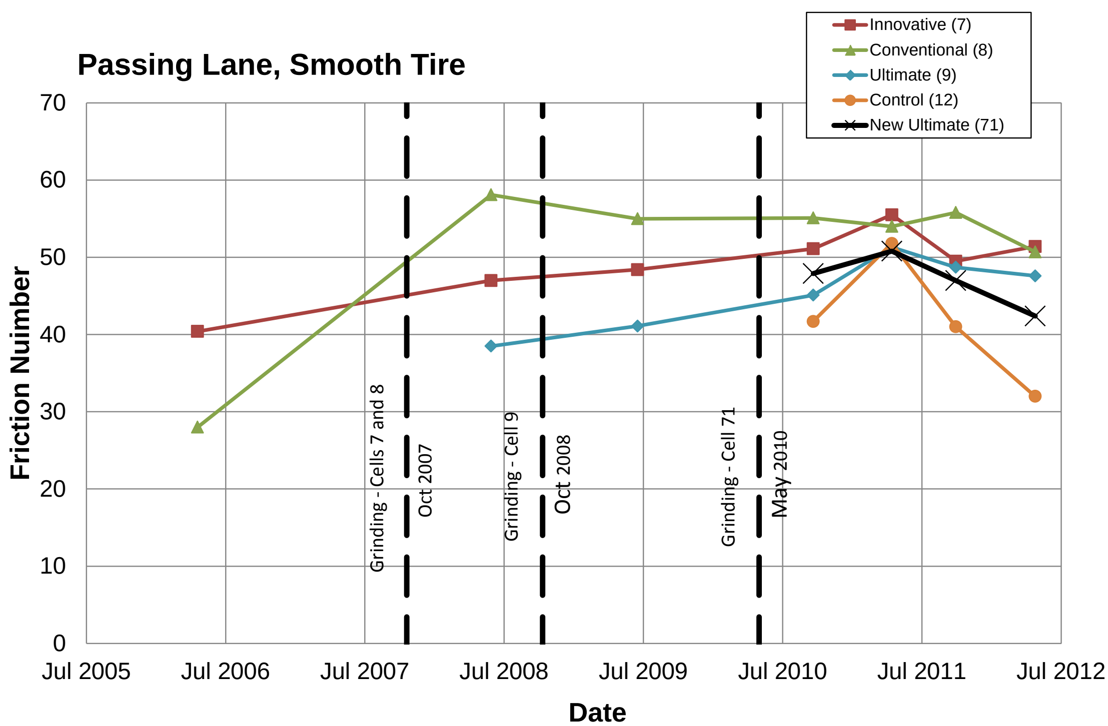

Figure 51. Friction – Passing Lane, Smooth Tire.

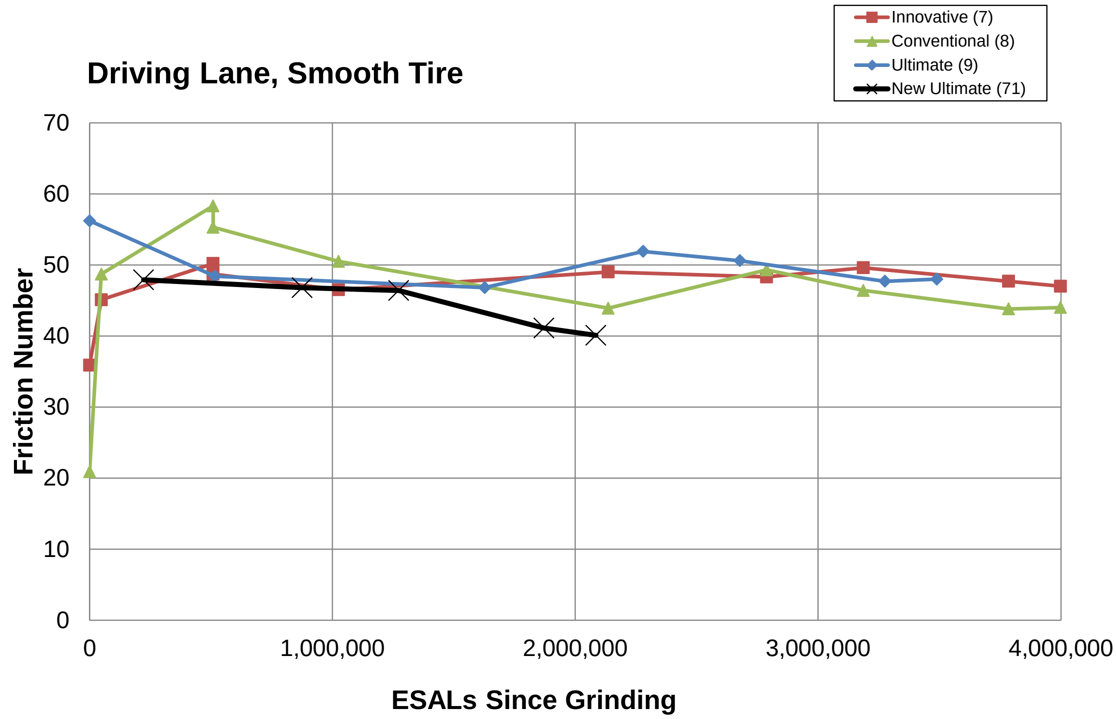

Figure 52. Friction – Driving Lane, Smooth Tire, ESALs Since Grinding.

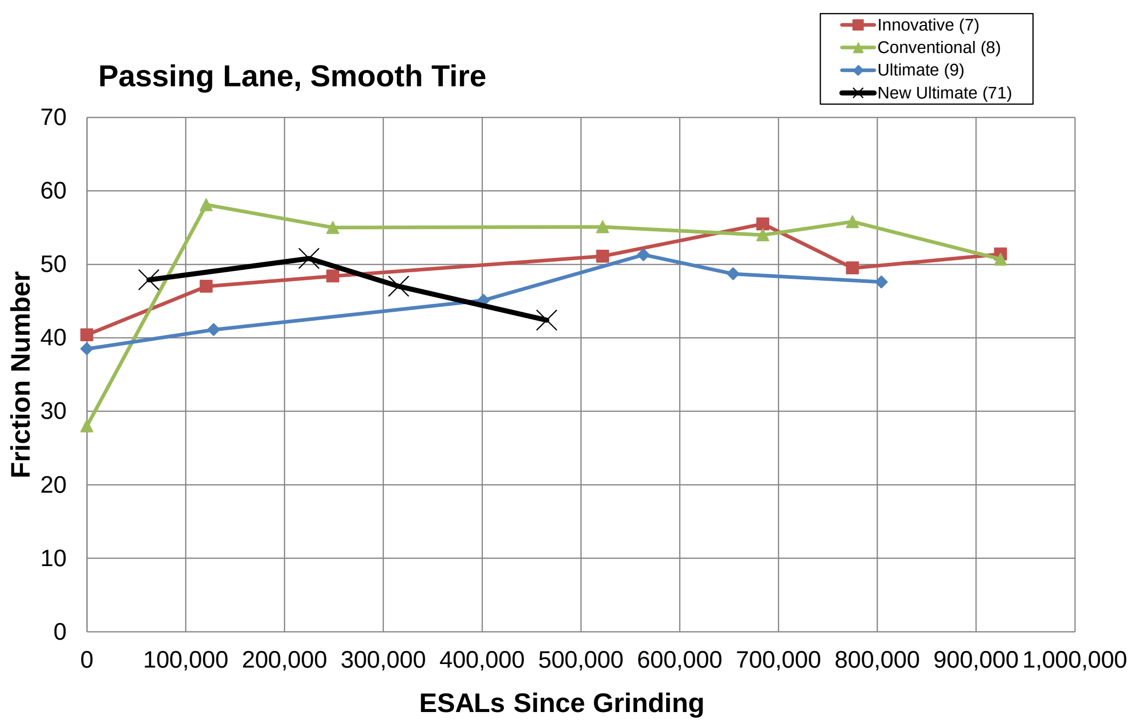

Figure 53. Friction – Passing Lane, Smooth Tire, by Time Since Grinding

The results of these tests are not entirely conclusive, but a few points of interest can be noted. The first is that the friction characteristics for the innovative and ultimate grind surfaces were lower than that of the conventional surface using the ribbed tire, and for some of the tests using the smooth tire. Since the intent of the ultimate grind surface is to maintain friction characteristics over longer periods of time, rather than to achieve high initial friction values, it seems that the innovative grinds have been successful. It should be noted, however, that in most cases the surfaces of all the ground cells seem to have settled at very similar values, and there is little difference between them.

One notable comparison is the four combinations of tire type and lanes on Cell 71 (New Ultimate), as shown in Figure 54. One item to note is that the smooth tire on this new iteration of the ultimate grind performs as well or better than the ribbed tire over several years. This means that the ground surface can be considered at least as safe from a friction standpoint for worn tires as for new tires, or that the friction provided by the pavement surface is not dependent on the quality of the surface of the tire, and that as tires wear and become more smooth, the ultimate grind configuration continues to provide friction.

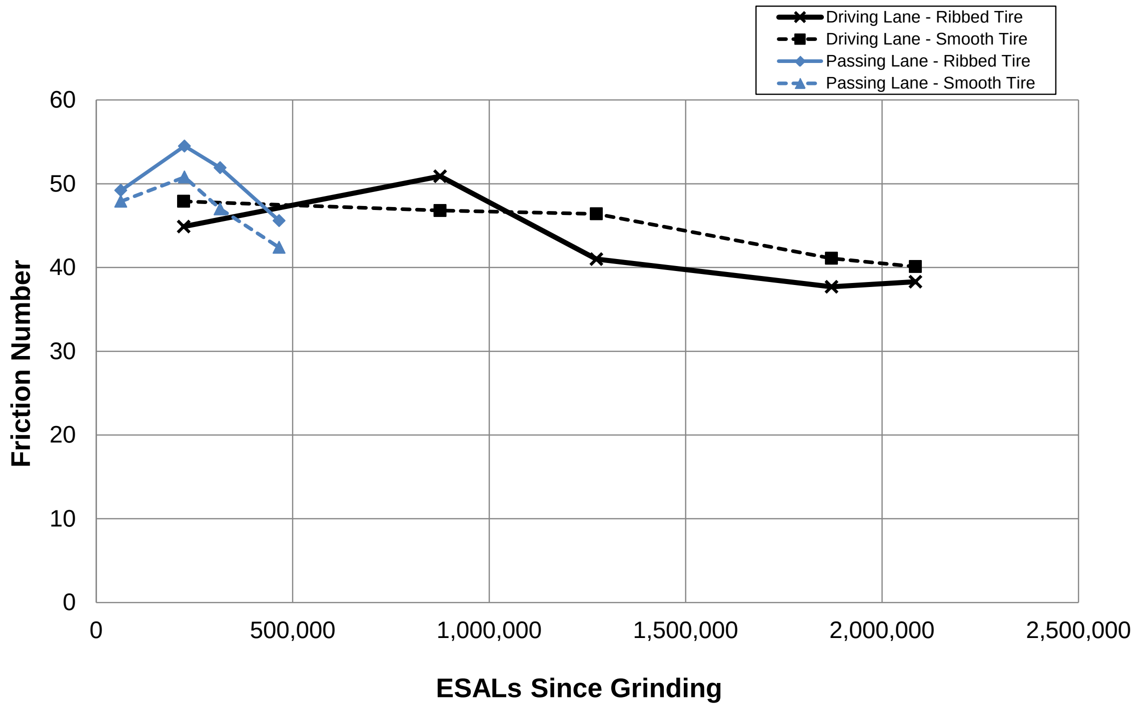

Figure 54. Friction on Cell 71.

Modeling

As with the noise modeling, the friction values measured throughout the project were analyzed to develop linear regression models to predict deterioration with traffic applications. A model similar to Equation 5 was used. Coefficients determined through the linear regression process are shown in Table 10. It should be noted that as with any regression model, the number of data points in each model affects its performance. Cell 12 indicates unrealistically high friction intercept values, but these are extrapolated by about 12 million ESALs in the driving lane and about 3.5 million ESALs in the passing lane. Thus, confidence should not be placed in the value of the intercept in the control cell friction modeling, but the slope of the friction model – the change in friction over time, may be more realistic.

Table 10. Coefficients for Friction Models.

Lane	Tire Type	Cell	b	m	R^2	N
Driving	Ribbed	Cell 7 (Innovative)	45.8	-9.98×10^{-7}	0.46	9
		Cell 8 (Conventional)	55.7	-2.76×10^{-7}	0.78	9
		Cell 9 (Ultimate)			0.04	6
		Cell 12 (Control)	84.8	-2.75×10^{-6}	0.85	6
		Cell 71 (New Ultimate)*	57.1	-9.89×10^{-7}	0.80	4
	Smooth	Cell 7 (Innovative)			0.06	9
		Cell 8 (Conventional)	56.4	-3.35×10^{-6}	0.74	9
		Cell 9 (Ultimate)			0.03	6
		Cell 12 (Control)	56.6	-1.94×10^{-6}	0.38	6
		Cell 71 (New Ultimate)*	52.9	-6.10×10^{-6}	0.94	4
Passing	Ribbed	Cell 7 (Innovative)			0.04	7
		Cell 8 (Conventional)	55.9	-6.79×10^{-6}	0.36	7
		Cell 9 (Ultimate)	38.1	1.23×10^{-5}	0.43	5
		Cell 12 (Control)	97.7	-1.26×10^{-5}	0.31	4
		Cell 71 (New Ultimate)*	63.2	-3.75×10^{-5}	0.99	3
	Smooth	Cell 7 (Innovative)*	47.2	4.48×10^{-6}	0.68	5
		Cell 8 (Conventional)	58.1	-5.99×10^{-6}	0.59	6
		Cell 9 (Ultimate)	40.8	1.16×10^{-5}	0.60	5
		Cell 12 (Control)	143.1	-2.80×10^{-5}	0.34	4
		Cell 71 (New Ultimate)*	58.3	-3.45×10^{-5}	0.99	3

*Omitting one outlier

Texture

The average texture depth was testing using the ASTM E 965 (sand patch) method [6] and ASTM E 2157 (circular texture meter) [7]. After the initial grinding of Cells 7 and 8 the test shows that the average texture depth was much greater for the conventionally ground pavement, as expected. However, because the conventional grind has narrower fins, they are more easily broken and worn down. This causes the average texture depth from Cell 8 to deteriorate more quickly than for Cell 7, although both seem to arrive at a similar texture measurement within about 2 million ESALs (about 2.5 years). The results of the texture testing are shown in Figures 55 and 56.

Initial Response

Immediately after Cells 7 and 8 were ground in October 2007, their MTD increased by about 0.50 mm and 1.15 mm, respectively. The change in texture was similar in both the driving and passing lanes. Texture measurements were not conducted on Cells 9 or 71 just prior to grinding. As an indication of the difference in grinding configuration between the innovative (Cell 7) and the conventional (Cell 8) grinds, the innovative grind increased in MTD to about 0.95 mm and the conventional grind increased to about 1.60 mm

Long-Term Effects

As mentioned previously, the ultimate grind was performed on Cell 9 one year after the grinding of Cells 7 and 8, and the new ultimate grind on Cell 71 was conducted 18 months after that. As can be seen in Figure 55, the ultimate grind begins with a higher average texture depth than both the innovative and conventional grinds, and decreases more slowly than the conventional grind. In fact, during the project period, the ultimate grind has lost about 0.50 mm of texture, while the conventional grind has lost about 0.75 mm. The innovative grind has lost the least of the original three grinds, at about 0.30 mm. The new iteration of the ultimate grind does not display texture depth any different than the other two types of grind. The measurements taken on the new ultimate grind have been consistently about 1 mm and it has not shown any loss in the driving lane, and less than 0.5 mm loss in the passing lane.

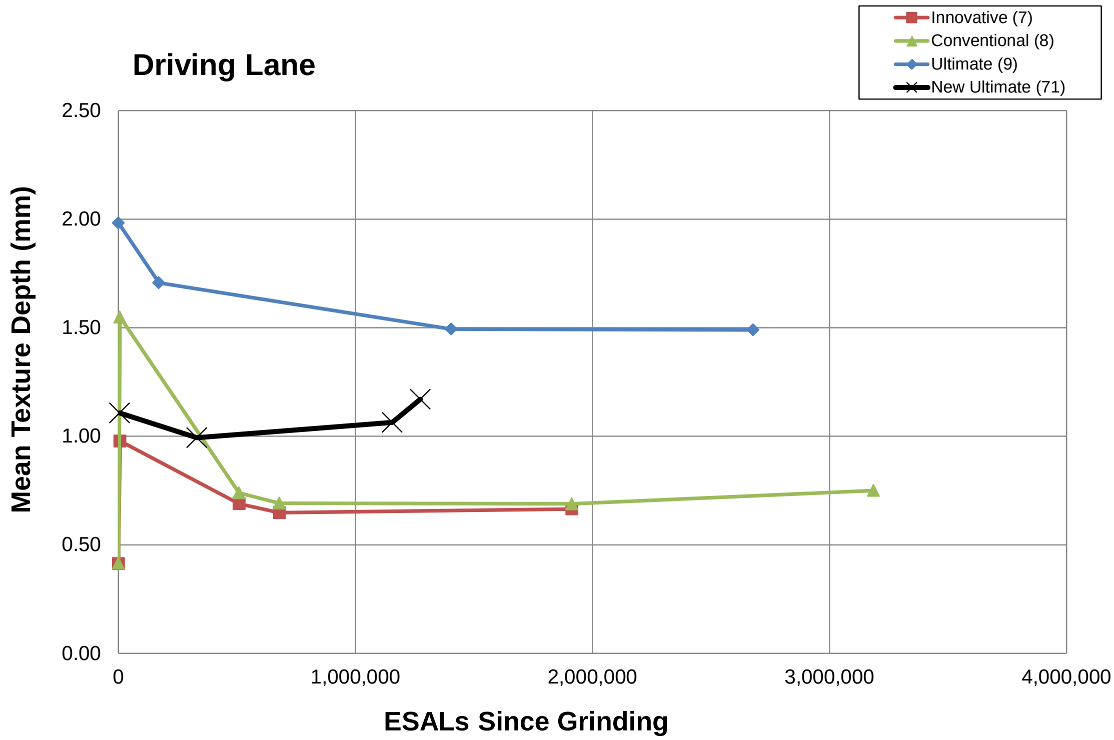

Figure 55. Mean Texture Depth – Driving Lane.

In Figure 57 the trends for both the driving and passing lanes are plotted together. The solid line indicates the data from the driving lane and the dashed line indicates the data from the passing lane. The innovative and conventional grinds show the increase in texture depth due to the grinding (both were at about 0.45 mm). In the passing lane of the ultimate grind, where fewer vehicles have traveled, the MTD decreased more quickly than in the driving lane. The other types of grind also show the more rapid decrease in MTD in the passing lanes. The data collected on these MnROAD cells compare favorably with data reported in a PCA report by Rao, Yu, and Darter [16].

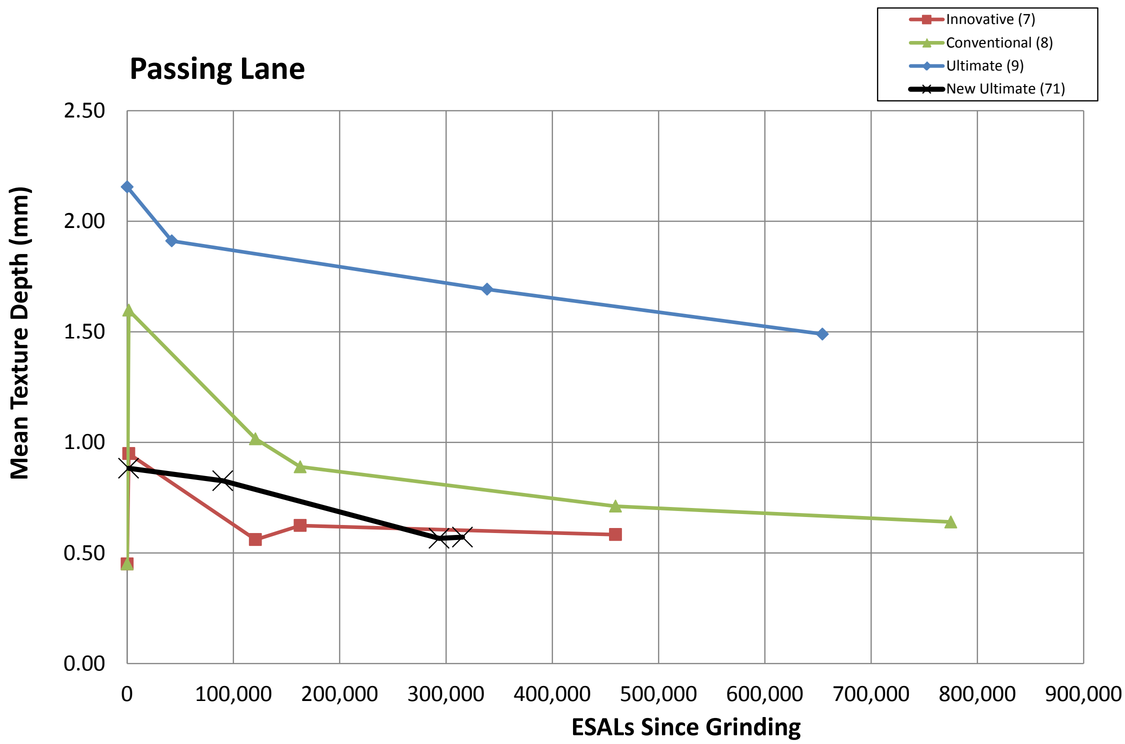

Figure 56. Mean Texture Depth – Passing Lane.

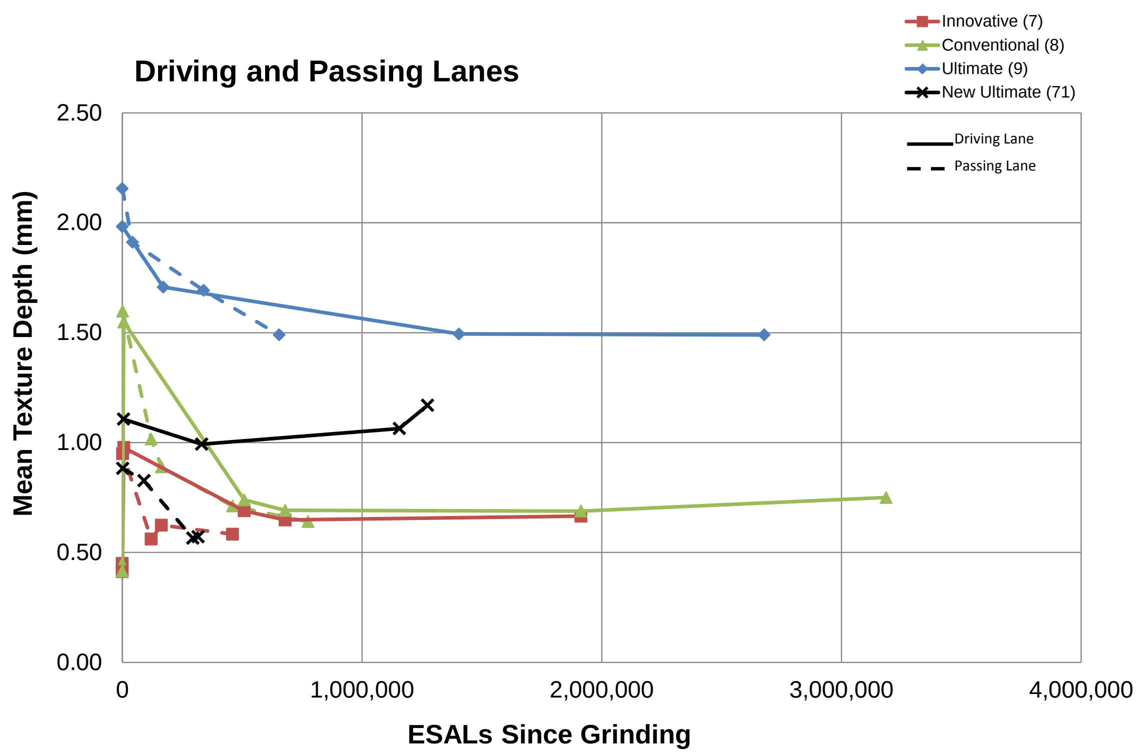

Figure 57. Mean Texture Depth – Driving and Passing Lanes.

Modeling

Throughout the project period, the texture measurements were most likely to lend themselves to prediction modeling. The performance of the grinding, in terms of texture, was most similar to what would be expected, and had much less variability than the other surface characteristic measurements. This section describes the development of predictive models for the degradation of texture over time, using the data collected by the MnROAD staff.

It is known that diamond grinding can improve the surface texture and associated friction immediately after the process is conducted. It is also understood that the initial levels of surface texture are often temporary and that after several years the surface achieves a level of texture that remains somewhat constant for a longer period of time. For example, as discussed above, the conventional grind had an immediate increase in texture of about 1.15 mm. Within about 500,000 ESALs however, the measurement indicated that the texture had returned almost to its original level prior to the grinding. The surface of Cell 8 has kept a constant MTD since that initial decline. The others have performed similarly, but have become level at different values of texture. From the figures above, it can be inferred that each grinding configuration has a characteristic MTD that it achieves after about 1 million ESALs. How long this level of MTD is maintained, however, remains to be seen.

Two mathematical models were evaluated in developing predictions for texture on the various grinding configurations – power and logarithmic. Two forms of the power model were used, with varying results. The basic power equation is

$$MTD = a(ESAL)^b$$

and the basic logarithmic equation is

$$MTD = a\ln(ESAL) + b$$

where:

MTD	=	Mean Texture Depth, mm,
ESAL	=	Cumulative ESALs since grinding, and
a, b	=	Regression coefficients.

Reimer and Pittenger [15] analyzed macrotexture and microtexture in asphalt concrete pavements in Oklahoma, testing macrotexture with the sand patch method and microtexture with the skid trailer method. They also suggested that the power model be used for predicting deterioration in microtexture and that the logarithmic model be used for macrotexture. Analyses conducted for the grinding configurations at MnROAD indicated that both models fit the small amount of data well, with R^2 values near 99%. Without further data, a specific determination regarding which form of the prediction model should be used is not possible.

The two models are shown together in Figure 58. As can be seen, there is very little difference between the two. Much of this is due to the fact that only five data points exist for Cell 8 throughout the project period. However, similar performance was observed on the other cells. In Cell 8, the power curve fits the empirical data slightly better than the logarithmic model. Each model indicates a steep decline in texture in the initial 500,000 ESALs, approximately, and match the slow but steady decline in texture measurements over longer periods of time. For ease of use, the power curve was selected to model the deterioration of texture of the ground cells.

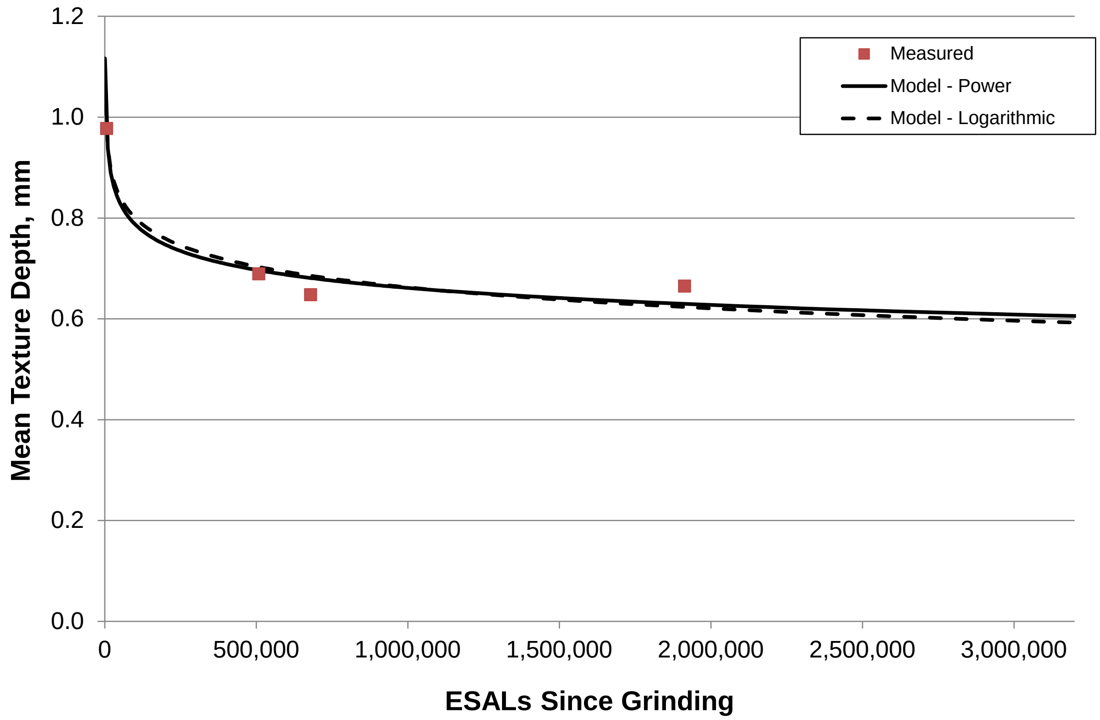

Figure 58. Texture deterioration models, Cell 7.

Using the power model to predict texture deterioration with traffic, the three original ground cells were modeled and coefficients were determined for each cell. Cell 71, the new ultimate grind, also had only four data points, but a definite deterioration trend could not be developed. It is possible that some problems arose in the data for that cell. The coefficients that fit the model best to the empirical data are included in Table 11 and a graphical representation of the models in the Driving Lane is shown in Figure 59, and in the Passing lane in Figure 60. It is interesting to note that at about 1,000,000 ESALs, both the driving and passing lanes indicate similar performance – texture measurements at about 0.6 mm MTD.

Table 11. Coefficients for Texture Deterioration Models.

Lane	**Cell**	a	b	R^2
Driving	Cell 7 (Innovative)	1.8851	-0.0758	0.97
	Cell 8 (Conventional)	5.3692	-0.1439	0.95
	Cell 9 (Ultimate)	2.5716	-0.0367	0.97
Passing	Cell 7 (Innovative)	1.9011	-0.0955	0.94
	Cell 8 (Conventional)	4.3015	-0.1330	0.98
	Cell 9 (Ultimate)	3.0761	-0.0492	0.91
	Cell 71 (New Ultimate)	1.4681	-0.0671	0.65

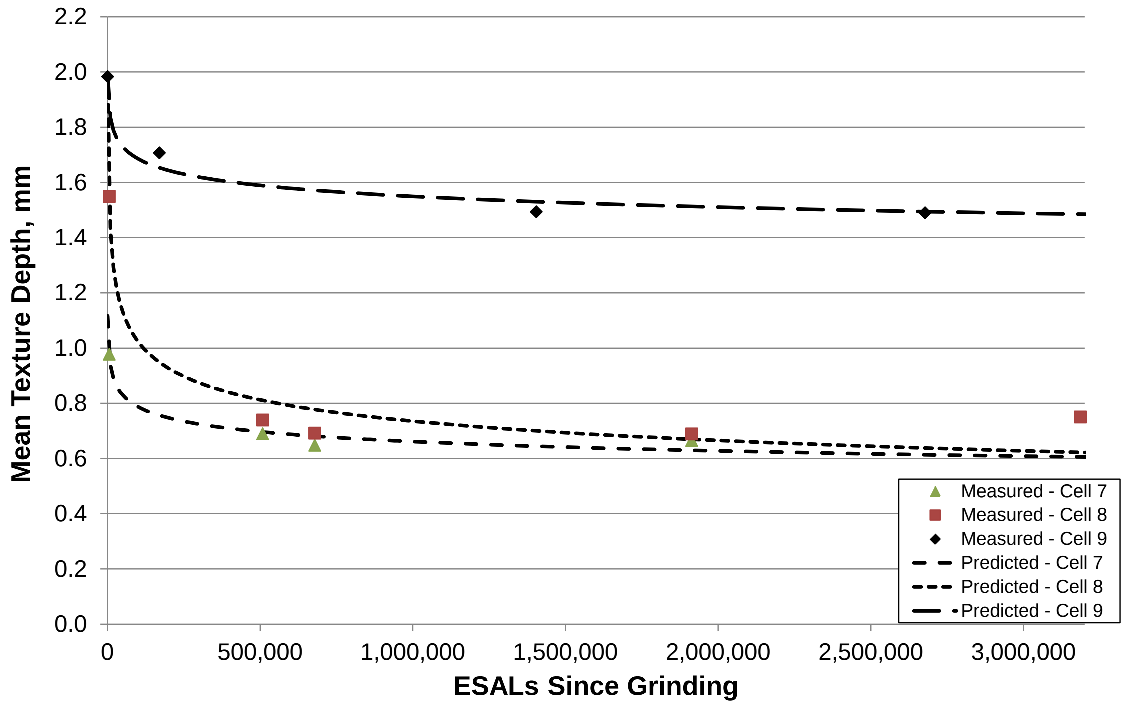

Figure 59. Modeling changes in texture – Driving Lane.

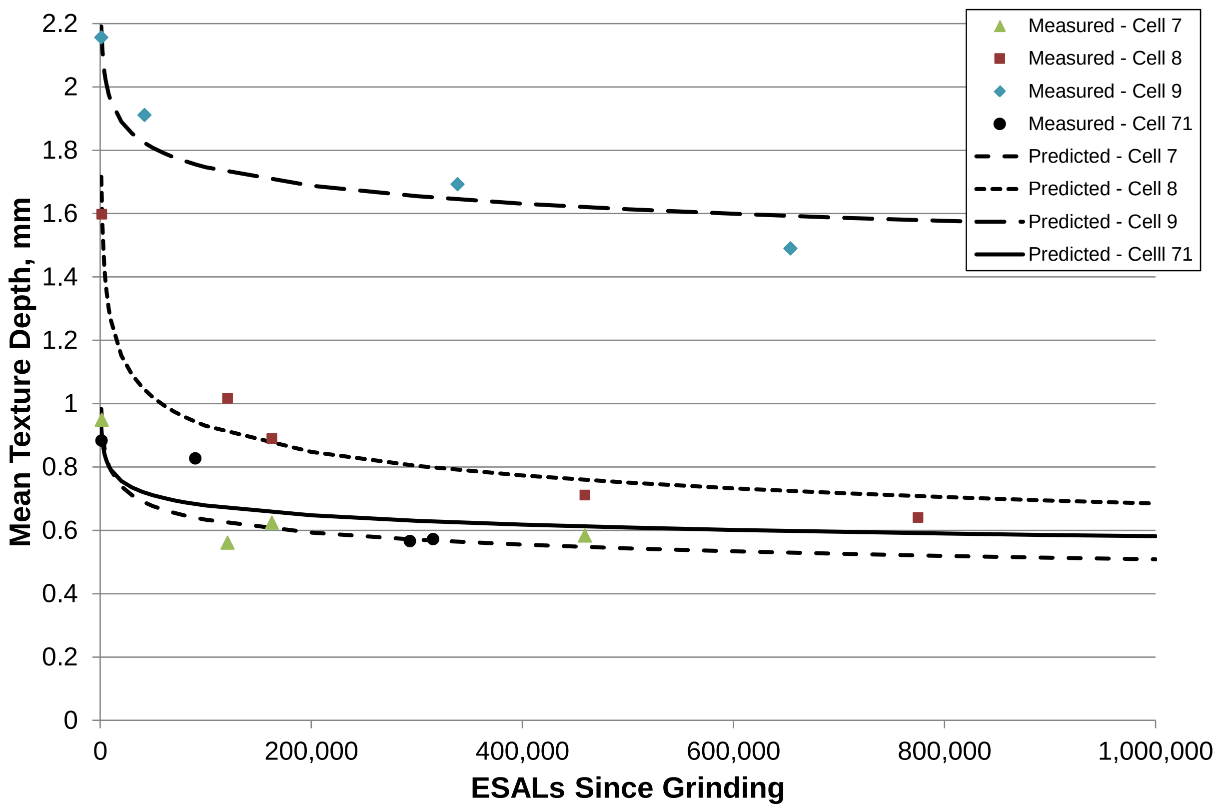

Figure 60. Modeling changes in texture – Passing Lane.

As mentioned previously, the texture measurement in Cells 7 and 8 (innovative and conventional, respectively) increased from their pre-grind measurement, and both declined quickly to approximately the same level, just slightly above that of their pre-grind state. The ultimate grind (ultimate), however, increased dramatically, and declined by a much smaller amount. At the end of data collection effort for this project, each of the three cells indicates a stabilized texture measurement that may be declining very gradually. Further testing should be conducted to confirm this.

Ride Quality

Ride quality measurements for the project were conducted using the AMES LISA light weight profiling device. The IRI was computed using the ProVAL software developed by the Federal Highway Administration. As with the other surface characteristics, the ride quality data is presented by cumulative ESALs since grinding. In general, the ride improved due to the grinding, on the innovative and conventional grind cells – each decreasing by about 30 to 40 in/mi. While all of this improvement is not necessarily due to the grinding, much of it might be attributed since only about 120,000 ESALs had been applied in that time (about six weeks), and it is unlikely that other factors contributed significantly to a decrease in roughness.

In his model defining the sources of noise in the tire-pavement interaction, Izevbekhai [17] relates the IRI as a surrogate for the sound intensity due to large scale pavement features (greater than 6 inches in length) such as joint spacing, joint width, and warping and curling. The action of diamond grinding may have reduced the impact of built-in warping or curling at the corners and edges of the concrete slabs.

As can be seen in Figures 61 through 64, the IRI for the two grinding cells completed in 2007 improved dramatically at the next measurement immediately following the grinding. The data for the ultimate grind (Cell 9) seemed reasonable prior to grinding, but the first measurement after grinding reported an IRI of over 200 in/mi, where less than 300,000 ESALs (six months, with some longer-term mainline closures) earlier it had been about 85 in/mi. In fact, the measurement at the time of the grinding of Cells 7 and 8 (one year prior to its own grinding) Cell 9 was profiled and reported only 48 in/mi. Such a dramatic increase, spanning the time of the grinding, seems unreasonable, and thus the data for this cell were removed from the analysis.

There may be several reasons for this dramatic increase, including the grind configuration. Referring to the diagrams of the grinding blade configurations in Figures 4 through 6, the lasers used in the lightweight profiling device may have fallen into the deep grooves more often on some runs than others. Although the triple lasers used in the TriODs arrangement on the LISA profiler used by MnDOT are configured to attempt to avoid this situation, it is a strong possibility with longitudinal grooving [18]. Since the data shown in Figures 61 and 63 for the driving and passing lanes in Cell 9 are similar (increasing to 250 in/mi and greater) the idea that the grinding configuration is partially responsible seems more plausible. Using a line laser such as the RoLine (which is actually 100 laser points in a 4-inch line) produces an average height over the corrugations and grooves and provides a more reliable IRI measurement. Additional testing with the RoLine laser arrangement (shown in Figure 22) was conducted on these cells to show that occasional anomalies in ride measurements may arise on diamond ground surfaces, especially with deeper grooves, such as in Cell 9.

Another seeming anomaly is the spike in IRI on the control cell (Cell 12) at about 1.3 million ESALs (measured in March 2010). Disregarding that data point, the remainder of the IRI data for Cells 7, 8 and 12 seem reasonable, and commensurate with the data on the passing lane. There are other reasons for not including much more information on ride, primarily that additional information needs to be collected about the analyses conducted on the data at different times since grinding. For example, the data filters applied to the pavement profiles need to be the same in order to make a real comparison.

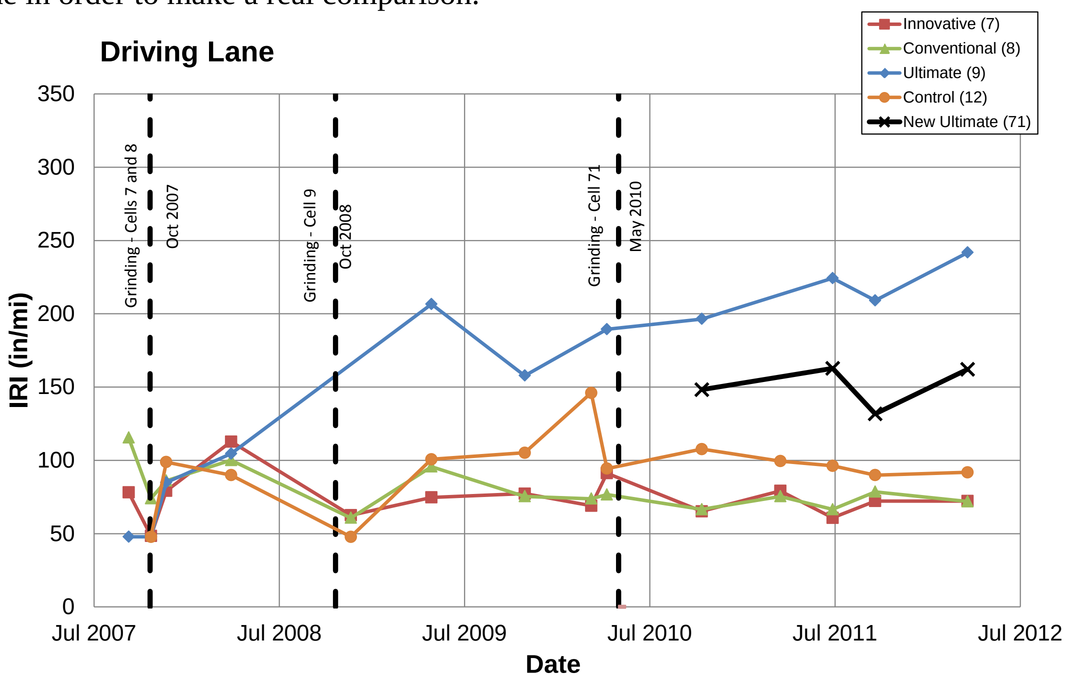

Figure 61. Ride Quality – Driving Lane by Test Date.

Cells 7 and 8 (the innovative and conventional grind cells, respectively) have relatively consistent IRI values between about 60 and 100 in/mi. The short duration of the project does not seem adequate to notice significant increases in roughness, although the small decrease indicated in the conventional and innovative grinds over almost 4 million ESALs (about 4.5 years) may be a result of the overall deterioration in texture mentioned in the previous section. Again, the use of the TriODs laser configuration may have introduced some anomalies in the measurements taken on some of these cells. As mentioned previously, the RoLine laser configuration helped identify that these anomalies occasionally occur, and that more reliable data may be collected using this system on diamond ground surfaces.

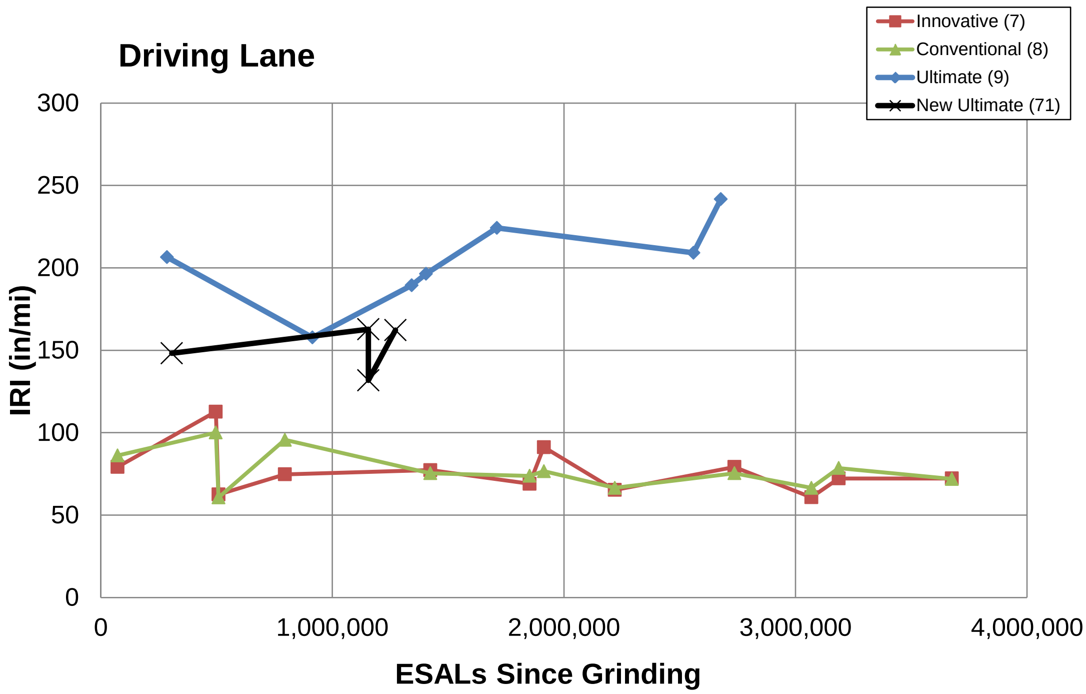

Figure 62. Ride Quality – Driving Lane, ESALs Since Grinding.

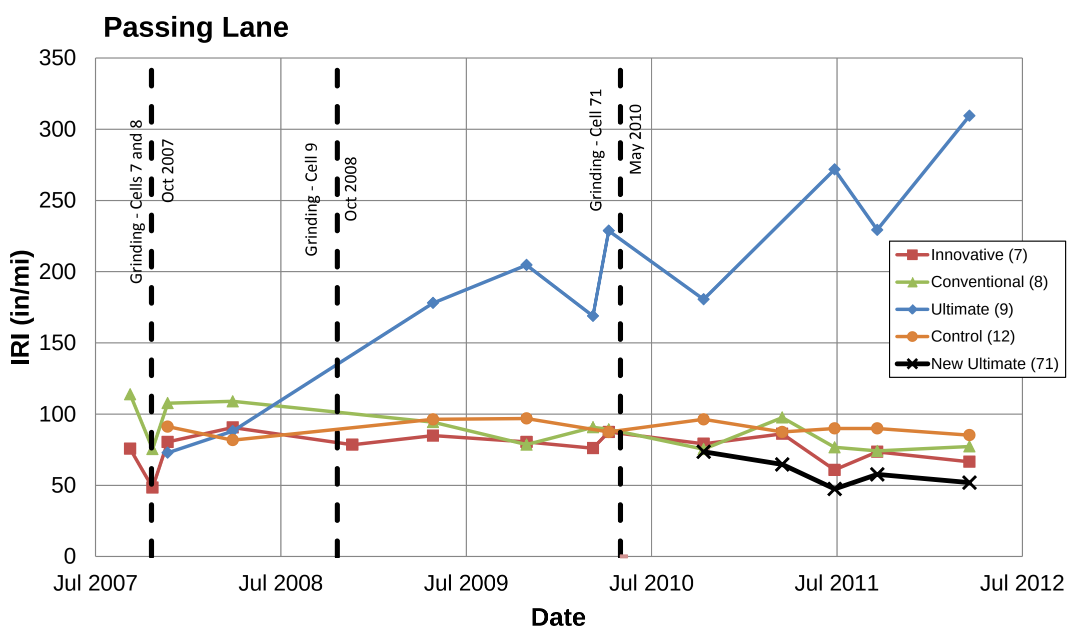

Figure 63. Ride Quality – Passing Lane by Test Date.

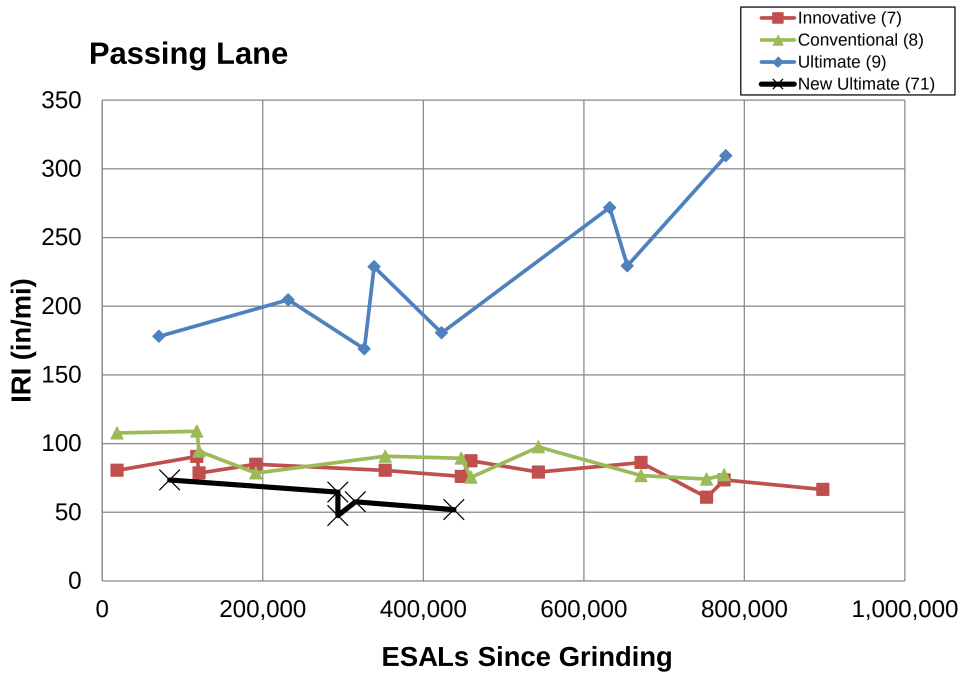

Figure 64. Ride Quality – Passing Lane, ESALs Since Grinding.

Summary of Findings

This section presents a summary of the data presented in this chapter, with comments on the general effects of the different grinding configurations immediately after grinding and after the four- to five-year period since that time. In each of the sections below, two comparisons are made – between the pre-grind and post-grind measurements, and between the immediate post-grind measurements and the final measurements taken during the data collection phase of the project. The pre- vs. post-grind comparison is termed the "Immediate Effects" and the Post-grind vs. final comparison is termed "Long-Term Effects". The values used in the long-term effects comparison are averaged over the final year of the data collection effort.

Noise

The information in Table 12 presents the effects of the grinding operation on the sound intensity as measured in the OBSI mode. The columns labeled "Immediate Effects" indicate the change in noise measured by the equipment and the correlated perception in the change in noise due to the grinding of the surface. The "Long-Term Effects Post-Grind" indicates the changes that took place in terms of noise over the four to five years after grinding, compared to the noise levels recorded immediately after grinding. The columns labeled "Change in Perceived Noise" indicate the perception of the noise that an observer might notice due to the ground surface, as described in Figure 17 and in Equation 1. Several observations can be made about the data in Table 12, as follows.

- The noise levels in Cell 7 (innovative) immediately after grinding had decreased by a much larger amount than those in Cell 9 (ultimate).
- The noise levels in Cells 7 and 9 (innovative and ultimate, respectively) decreased dramatically immediately after grinding, but by the final year of testing, both had

returned to their original sound levels. The exception is in the passing lane, to a small extent, possibly due to the lower levels of traffic.

- As discussed previously, the noise levels in Cell 8 (conventional) increased significantly immediately after grinding, and by the final year of testing had remained at about the same levels.
- The 3.6 dB increase in long term effects compared to the post-grind levels in the driving lane of Cell 71 (new ultimate) seems very large, and may be incorrect. It certainly does not compare to the 0.8 dB increase in the passing lane, nor to the 1.9 dB increase in the driving lane of Cell 9 (ultimate), after which its configuration was modeled.
- Referring to Figures 43 and 44, the noise levels recorded at the trailing edge of the test tire are slightly higher than for the leading edge for the innovative and ultimate grinds (Cells 7 and 9). The reverse is true for the conventional grind (Cell 8).

Table 12. Summary of Grinding Effects on Noise.

		Immediate Effects		Long-Term Effects Post-Grind	
Cell	**Lane**	**Change in Sound Intensity, dB**	**Change in Perceived Noise, %**	**Change in Sound Intensity, dB**	**Change in Perceived Noise, %**
7	DL	-3.4	-54	+3.0	+100
	PL	-3.9	-59	+2.8	+91
8	DL	+1.9	+55	+0.2	+5
	PL	+1.0	+26	+0.4	+10
9	DL	-2.0	-37	+1.9	+55
	PL	-2.6	-45	+0.9	+23
71	DL			+3.6	+129
	PL			+0.8	+20

Friction

The effects of the grinding treatment on the friction of the pavement surface were measured with both the ribbed and the smooth tire. Tables 13 and 14 provide a summary of this information. The immediate effects of the grinding are evident with a decrease in friction number (with the ribbed tire) in Cells 7 and 9, and an increase in Cell 8. This seems reasonable, since the innovative and ultimate grinds remove the standard transverse tine and replace it with a longitudinal, smooth surface with less texture on the kerfs than had been on the tined surface. The conventional grind is left with rugged fins and a very sharp texture. The long-term effects indicate that for the conventional grind, the friction levels decreased (as the rough texture of the fins is removed by tire action), and that the levels also decreased in the driving lanes of the other three cells which had the innovative and ultimate grinds. It is interesting to note that the friction levels in the passing lanes of the innovative and ultimate grinds increased over time, after an initial decrease, and that this was not observed in the driving lanes.

The friction levels measured with the smooth tire exhibited similar results as those for the ribbed tire, with the exception that both lanes in all three cells showed an immediate increase in friction.

In fact, in comparing the immediate effects in each lane between the ribbed and smooth tires, the smooth tire measures consistently between 20 and 32 points higher than the ribbed tire. Other observations from this data are as follows.

- The friction levels in Cells 7 and 8 (innovative and conventional) showed consistent immediate change in both the driving and passing lanes. The two lanes in Cell 9 (ultimate) did not show the same initial change in friction level.
- Referring to Figures 46 through 51, across all grinds and cells,
  - The friction level with the ribbed tire in the driving lane, were within a range of 7 points at the end of the data collection phase of the project.
  - The friction level with the ribbed tire in the passing lane, were within a range of only 2 points at the end of the data collection phase of the project.
  - The friction level with the smooth tire in the driving lane, were within a range of 4 points at the end of the data collection phase of the project.
  - However, the friction level with the smooth tire in the passing lane, were within a wide range (20 points) at the end of the data collection phase of the project.
- With the ribbed tire, all of the ground cells and the control cell were within a range of 7 points (in the driving lane) and within a range of 2 points (in the passing lane) at the end of the data collection phase.
- With the smooth tire, all of the ground cells were at least 10 points higher, and in some cases 20 points higher, than the control cell at the end of the data collection phase of the project.

Table 13. Summary of Grinding Effects on Friction – Ribbed Tire.

		Change in Friction Number	
Cell	**Lane**	**Immediate Effects**	**Long-Term Effects Post-Grind**
7	DL	-13.4	-4.3
	PL	-13.2	+0.3
8	DL	+7.4	-10.2
	PL	+8.7	-4.8
9	DL	-8.1	-3.1
	PL	-17.4	+10.1
71	DL		-5.9
	PL		+1.5

Table 14. Summary of Grinding Effects on Friction – Smooth Tire.

Cell	Lane	Change in Friction Number: Immediate Effects	Change in Friction Number: Long-Term Effects Post-Grind
7	DL	+9.2	+3.0
	PL	+6.6	+5.1
8	DL	+27.8	-4.0
	PL	+30.1	-4.6
9	DL	+24.7	-7.4
	PL	+2.6	+9.1
71	DL		-5.4
	PL		-1.2

Texture

The effects of the various grinding configurations on the texture of the pavement surface are presented in Table 15. As with the previous summary tables in this section, the immediate effects and the changes since the first post-grind measurement are shown in this table. As expected, the mean texture depth increased dramatically on the conventional grind, and about half as much on the innovative grind. Much of the increase in texture is due to the kerf left by the grinding blades, as shown in Figures 4 through 6 and in Figure 8. However, with traffic, after the initial post-grind measurement, it is apparent that much of the increase in texture in the conventional grind (Cell 8) has been removed through tire wear, and that less of the texture on the innovative grind has been removed. On a percentage basis, however, the innovative grind has lost 54 and 74 percent of its initial gains in texture, while the conventional grind lost 70 and 85 percent of its initial gains, in the driving and passing lanes, respectively. Initial measurements were not taken on the ultimate grinds (Cells 9 and 71), so the effects on these two cells are only reported for the long-term basis. Other observations on the effects on texture follow.

- The immediate effect for each cell is similar in both the driving and passing lanes.
- The long-term effects indicate that each of the four cells lost more texture in the passing lane than in the driving lane.

Table 15. Summary of Grinding Effects on Texture.

		Change in Mean Texture Depth, in	
Cell	**Lane**	**Immediate Effects**	**Long-Term Effects Post-Grind**
7	DL	+.57	-0.31
	PL	+.50	-0.37
8	DL	+1.14	-0.80
	PL	+1.25	-1.06
9	DL		-0.49
	PL		-0.67
71	DL		+.06
	PL		-0.31

Ride

Table 16 presents the effects of the different grinding configurations on the ride quality of the pavement surface. While it is difficult to ascribe all of the changes in ride quality to the grinding configuration alone, it may be possible to account for some of the changes due to the wheelbase of the grinding machine itself. As can be seen in the table below, the immediate effects of the grinding (two ride quality tests were conducted within two months, with the grinding operation occurring between the tests) are similar for Cells 7 and 8. These cells decreased in IRI by about 30 to 40 in/mi. Over the several years after grinding, the IRI on Cell 7 (Innovative) increased by about 20 in/mi while the IRI on Cell 8 (Conventional) stayed about the same. With few exceptions, Cells 7 and 8 maintained a fairly constant IRI after the first six months post-grind. In the four test periods since grinding, the IRI on Cell 71 (New Ultimate) also stayed fairly constant, although its value was very high (about 150 in/mi).

As discussed previously, the data for Cell 9 (Ultimate) and to some extent for Cell 71 (New Ultimate) are suspect, with a steady, steep increase in IRI over several years. This is likely due to other causes, and so the data will not be discussed further in this section. Other observations on the effects on IRI follow.

- Cells 7 and 8 (Innovative and Conventional, respectively) had similar decreases in IRI immediately after grinding, and Cell 8 maintained those improvements while Cell 7 lost about half of its initial benefit over the five years since grinding.
- Cells 9 and 71 (Ultimate and New Ultimate, respectively) showed unexpected IRI values, and the IRI on Cell 9 increased to over 200 in/mi in just one year (six months after grinding). Cell 71 was not measured prior to its grinding, but in the four measurements after grinding its IRI was consistently very high – about 150 in/mi.
- The IRI of Cells 7 and 8 stayed very similar throughout the testing period, and were only slightly lower than the IRI of the control (Cell 12) at each measurement.

Table 16. Summary of Grinding Effects on Ride Quality.

Cell	Lane	Change in International Roughness Index, in/mi: Immediate Effects	Change in International Roughness Index, in/mi: Long-Term Effects Post-Grind
7	DL	-29.70	+20.0
	PL	-27.30	+18.6
8	DL	-41.40	-1.72
	PL	-38.50	+0.53
9	DL	+102.0	+18.5
	PL	+90.0	+92.2
71	DL		+4.0
	PL		-21.10

Chapter 4. ADDITIONAL DATA ANALYSIS

This chapter discusses additional analyses that were conducted using the data collected for this project. The primary analysis that was conducted is a basic trend analysis for each surface characteristic included in the project, conducted using a Mann-Kendall test for identifying the existence of a trend. This test requires a minimum of 10 data points to provide meaningful results, but corrections to the statistics may be applied to series less data. This chapter includes the trend analysis of OBSI measurements corrected for temperature, as well as friction, texture, and ride.

Trend Analysis

The Kendall family of trend tests was developed to identify correlations between ranked data. In Kendall's 1962 introduction to this type of analysis [19], an example is used comparing the mathematical and musical ability in children. If the children are arranged by mathematical ability, is there a similar trend in the musical ability? While this is similar to correlation analysis, it can also be applied to time-series data where the primary rank is based on time or age of a sample, and comparisons can be made within the ranking of the specific variable in question (noise, friction, etc.). The Mann-Kendall test is a non-parametric test used to identify trends in time-series data. This method has been used to identify trends in concentration levels of trichloroethylene in wells over time by the Corps of Engineers [20] and for other environmental measurements by the United States Geological Survey [21]. The remainder of this section presents a summary of the Mann-Kendall test for identifying trends in the surface characteristics in the diamond grinding cells at MnROAD. The results of the analyses are presented in the individual characteristics sections.

The initial assumption is that there is no trend in the data, such that the Mann-Kendall statistic (S) is equal to 0. The data are ordered in a time series, as the data was collected over the past several years. For each value in the series, if a value from a later time period is greater than itself, S is incremented by 1. If a value from a later time period is less than the value in question, the test statistic is decremented by 1. The sum of all the increments and decrements is the final value of S.

This process of adding or subtracting 1 from the test statistic proceeds beginning with comparing the first value to all subsequent values, and then moving on to the second value and comparing it with all subsequent values. This process is conducted for all values that have been collected until the second to last value, which is only compared to the final value. The mathematical representation for the computation of S is shown below.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{(x_i - x_j)}{|(x_i - x_j)|} \qquad \text{(where } x_i \neq x_j\text{)} \qquad \textit{Equation 6}$$

where:

x = value in the time series, and
n = number of values in the time series.

As described above, if $x_i - x_j > 0$ then S is incremented by 1, and if $x_i - x_j < 0$ then S is decremented by 1. In the case where two subsequent values are the same, or $x_i - x_j = 0$, S is unchanged, but an adjustment must be made to the significance test for the presence of the tied data, as described below.

The test for significance involves the standard normal distribution and the variance of the data based on the number of samples and adjusted for the number and magnitude of tied values in the data set. The variance (σ^2) of the data is computed as follows.

$$\sigma^2 = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{t=1}^{g} t_t(t_t - 1)(2t_t + 5)\right] \qquad \textit{Equation 7}$$

where:

g = the number of tied groups in the data set, and

t_t = the number of tied data points in group g.

The normalized test statistic (z) is computed as 0 when S = 0, and

$$z = \frac{S-1}{\sigma} \text{ for S > 0 and}$$

$$z = \frac{S+1}{\sigma} \text{ for S < 0.}$$

The level of significance is chosen to indicate the likelihood of a trend existing in the data. Often this is chosen at 95%. In the following sections, however, the test for significance is not conducted (comparing the probability of the test statistic to the associated level of significance). Instead, the probability of the existence of a trend is left in the tables to indicate the probability of a trend existing (either upward or downward, as will be shown in the example below).

There are several assumptions inherent in this type of analysis. The first assumption is that there are at least 10 data points in the set of values. Kendall indicates that this is necessary in order to use the standard normal distribution for comparison of the test statistic, but also provides a table of values to use in cases where $n < 10$. Another assumption is that the data in a time series are taken at equal intervals. While this is not precisely the case in the MnROAD surface characteristics data, there are many data points in a short period of time, and these can be approximated to a relatively common data collection interval.

An example of this method is shown in the tables and discussion below, for the friction data on Cell 7, Passing Lane, with the Smooth Tire. For the first reading, 47, each subsequent data point is higher than itself, and thus each cell below the 47 receives a ‘1’ value. Comparing the third reading, 51, to each subsequent reading shows that one is greater (56, thus increment by 1), one is lower (50, thus decrement by 1) and the final reading is a tie (thus the 0 entry, and the adjustment for ties required in the variance equation).

Table 17. Sample Trend Analysis for Friction Data.

Date	Friction, FN
5/28/2008	47
6/16/2009	48
9/20/2010	51
4/14/2011	56
9/29/2011	50
4/24/2012	51

Friction, FN	47	48	51	56	50	51
47						
48	1					
51	1	1				
56	1	1	1			
50	1	1	-1	-1		
51	1	1	0	-1	1	

The S statistic is 8 (the sum of all -1, 0, and 1 values in the table). Since there is one set of duplicate values (two 51 values) this must be considered in the variance calculation.

The variance, σ^2, is 27.3, as shown below, with n = 6, g = 1, and t_t = 2.

$$\sigma^2 = \frac{1}{18}\left[6(6-1)(2(6)+5) - 2(2-1)(2(2)+5)\right] = 27.3$$

$$z = \frac{S-1}{\sigma} = \frac{8-1}{\sqrt{27.3}} = 1.34$$

The standard normal distribution statistic for this variance is 1.34, representing a probability of 94%, or only a 6% chance that this data does not represent a trend.

With this analysis, data that do not represent a trend have a probability statistic near 50%. Data trending upward have a probability above 90% or 95% (depending on the level of significance selected), and data trending downward have a probability below 10% or 5%, again depending on the significance level selected. A summary of the trend analysis for all data categories is presented in the next section.

Once a set of data is identified as representing a trend, a decision must be made about the type of trend, and if the data can be simulated with a regression model. Further, if a regression model is possible, the type of relationship over time or traffic must be selected. Regression models for the texture characteristic were discussed in the previous chapter.

Summary of Trend Analyses

This section is a summary of the analyses using the Mann-Kendall statistic for identifying trends in data. The final column (on the right side of each table below) provides the trend indicator (whether the data are trending upward, downward, or if no trend can be concluded). The trend indication is based on the 10% confidence criteria (values greater than 90% confidence indicate an upward trend, and those less than 10% indicate a downward trend).

The noise trend analysis is shown in Table 18. It can be seen that the noise measured in Cells 7, 9, in both the driving and the passing lanes, and the driving lane in Cell 8 show upward trends, since the time they were ground, and that only the driving lanes in Cells 12 and 71 show enough evidence to indicate a trend in noise changes. It is worth noting that while the driving lanes in both Cells 12 and 71 show a tendency toward upward trends, the passing lanes in both cells are close to the midpoint (50%) indicating no trend in either direction. The differences between the control cell (Cell 12) and the others are shown in Table 19.

The deviations from the measurements at Cell 12 indicate strong trends in the difference between Cell 12 and Cell 9, and between Cell 12 and Cell 7. The driving lane of Cell 7 is very close to be categorized as indicating a trend at 10.8%. Those not indicating trends are the same as those with very low R^2 values in the modeling section of the noise analysis, shown in Table 9.

Table 18. Analysis of Trends in OBSI.

Analysis	Number of Observations (Post-grind)	Probability of Trend	Probability (Corrected for small N)	Trend (Upward or Downward)
Cell 7 DL	15	98.5%		Up
Cell 7 PL	15	98.1%		Up
Cell 8 DL	15	96.3%		Up
Cell 8 PL	15	75.6%		None
Cell 9 DL	13	99.9%		Up
Cell 9 PL	13	97.5%		Up
Cell 12 DL	9	97.0%	97.0%	Up
Cell 12 PL	10	29.5%		None
Cell 71 DL	5	95.7%	95.8%	Up
Cell 71 PL	5	69.3%	67.5%	None

Since the cells were ground, with regard to friction, there is less consistency in the trend analysis. For example, there are four sets of data for Cell 7 (four combinations of driving and passing lanes, ribbed and smooth tires) and three different outcomes. The driving lane with the ribbed tire indicates a downward trend, but the passing lane with the ribbed tire indicates no trend. Also, the driving lane with the smooth tire indicates no trend, while the passing lane with smooth tire indicates an upward trend (opposite of the driving lane with ribbed tire). Cell 8 seems the most consistent, with three downward trends, and the fourth close to the 10% cutoff to indicate a downward trend. Cell 9 is the most consistent without any sets indicating a trend. It might be expected that after so many years of traffic, Cell 12 would not display a trend in either direction, and for the most part, it does not, but seems to lean toward the downward (decreasing friction) trend. If anything, this would be the expected direction. With only a maximum of nine samples and as few as four in the data, these results are less certain. It is possible that with greater numbers of samples, trends may be more readily identified.

Table 19. Analysis of Trends in OBSI – Deviation from Control Cell.

Analysis	Number of Observations (Post-grind)	Probability of Trend	Probability (Corrected for small N)	Trend (Upward or Downward)
Cell 12 – Cell 7 DL	8	10.8%	11.4%	None
Cell 12 – Cell 7 PL	9	4.7%	4.9%	Down
Cell 12 – Cell 8 DL	8	40.2%	40.6%	None
Cell 12 – Cell 8 PL	9	14.7%	15.5%	None
Cell 12 – Cell 9 DL	8	3.9%	4.3%	Down
Cell 12 – Cell 9 PL	9	0.5%	0.45%	Down
Cell 12 – Cell 71 DL	4	24.8%	27.1%	None
Cell 12 – Cell 71 PL	4	36.7%	37.5%	None

The summary of potential trends in the friction data is shown in Table 20. As with the noise data, those indicating little potential for trends are also those with very low R2 values in the modeling section of the friction analysis, as shown in Table 10.

Table 20. Analysis of Trends in Friction.

Analysis	Number of Observations (Post-grind)	Probability of Trend	Probability (Corrected for small N)	Trend (Upward or Downward)
Cell 7 DL, Ribbed Tire	9	2.1%	1.9%	Down
Cell 7 DL, Smooth Tire	9	45.8%	46.0%	None
Cell 7 PL, Ribbed Tire	7	61.9%	61.5%	None
Cell 7 PL, Smooth Tire	6	93.7%	93.5%	Up
Cell 8 DL, Ribbed Tire	9	0.2%	0.1%	Down
Cell 8 DL, Smooth Tire	9	2.1%	1.9%	Down
Cell 8 PL, Ribbed Tire	7	6.7%	6.8%	Down
Cell 8 PL, Smooth Tire	6	12.6%	13.2%	None
Cell 9 DL, Ribbed Tire	7	18.1%	18.8%	None
Cell 9 DL, Smooth Tire	7	18.1%	18.8%	None
Cell 9 PL, Ribbed Tire	5	59.7%	59.2%	None
Cell 9 PL, Smooth Tire	5	76.9%	76.8%	None
Cell 12 DL, Ribbed Tire	6	4.3%	4.6%	Down
Cell 12 DL, Smooth Tire	6	13.0%	13.6%	None
Cell 12 PL, Ribbed Tire	4	36.7%	37.5%	None
Cell 12 PL, Smooth Tire	4	15.4%	16.7%	None
Cell 71 DL, Ribbed Tire	5	10.3%	11.0%	None
Cell 71 DL, Smooth Tire	5	1.4%	0.8%	Down
Cell 71 PL, Ribbed Tire	4	36.7%	37.5%	None
Cell 71 PL, Smooth Tire	4	15.4%	16.7%	None

The trend analyses for measurements of texture only had four or five data points, and so are least applicable to the trend analysis of all the characteristics presented in this report. As can be seen in the figures presented in previous sections, the texture values decrease rapidly after the initial grind, but then level off after only a couple of years. Because of this, and the inherent variability in the materials and test methods, it is more likely that a subsequent test might show a higher measurement when a slightly lower measurement is expected (as can be seen in Figures 55 through 57).

Based on the trend analysis and the results shown in Table 21, both lanes in Cell 9 and the passing lane of Cells 8 and 71 indicate a downward trend in texture, since the time of grinding. The other four do not give evidence of a downward trend, although both lanes in Cell 7 are very close to the 10% threshold. It is difficult to make a comparison between those lanes with little indication of a trend and the low-R^2 models in the modeling section of the texture analysis, since with only four data points it is relatively easy to develop a mathematical model with high correlation using a power curve.

Table 21. Analysis of Trends in Texture.

Analysis	**Number of Observations (Post-grind)**	**Probability of Trend**	**Probability (Corrected for small N)**	**Trend (Upward or Downward)**
Cell 7 DL	4	13.9%	16.7%	None
Cell 7 PL	4	15.4%	16.7%	None
Cell 8 DL	5	22.4%	24.2%	None
Cell 8 PL	5	1.4%	0.8%	Down
Cell 9 DL	4	7.4%	10.4%	Down
Cell 9 PL	4	4.5%	4.2%	Down
Cell 71 DL	4	63.3%	62.5%	None
Cell 71 PL	4	7.4%	10.5%	Down

Table 22. Analysis of Trends in Ride.

Analysis	**Number of Observations (Post-grind)**	**Probability of Trend**	**Probability (Corrected for small N)**	**Trend (Upward or Downward)**
Cell 7 DL	13	42.7%		None
Cell 7 PL	13	19.6%		None
Cell 8 DL	13	17.9%		None
Cell 8 PL	12	5.7%		Down
Cell 9 DL	7	96.4%	96.5%	Up
Cell 9 PL	8	98.3%	98.5%	Up
Cell 12 DL	13	66.6%		None
Cell 12 PL	10	26.3%		None
Cell 71 DL	4	50.0%	62.5%	None
Cell 71 PL	5	8.8%	9.5%	Down

The ride data seems less variable overall, with the exception of Cell 9. This data seem suspect, however, and the cause for dramatically increasing ride data on Cell 9 may be related to the nature of the grinding, as discussed previously. However, Cell 71 was ground in a similar way, and does not show the same trends. The passing lanes of Cell 8 and of Cell 71 both indicate a slight downward trend.

Chapter 5. ADDITIONAL TESTING

This project included additional testing conducted by other agencies or corporations – the Rolling Resistance (RR) and RoboTex. These testing efforts were part of the overall pooled-fund study, but were conducted by the Technical University of Gdańsk, Poland (TUG) and by The Transtec Group, Inc., respectively. The rolling resistance testing was conducted under subcontract to Minnesota State University, while the RoboTex testing was contracted directly through MnDOT.

Rolling resistance testing measures the resistance felt by a tire when rolling over a pavement surface. Several tires were used on more than 50 different pavement surfaces. During the testing program, the measurements were conducted at various speeds, as described below. A full report [22] of the rolling resistance testing was prepared and published by MnDOT. The RoboTex testing produces measurements of pavement surface texture using a rolling, line-laser profiler that produces a three-dimensional view of the pavement surface texture. The RoboTex testing and data analysis is expected to be published by MnDOT in 2013. A summary of the testing and results of each of these efforts is presented in this chapter.

Rolling Resistance

The objective of this testing and data analysis was to evaluate the rolling resistance of each cell at the MnROAD site, and several other pavement surfaces on public highways in Minnesota. The referenced report [22] presents the results of rolling resistance testing conducted by the TUG researchers in September 2011. While the RR testing was conducted on all of the cells on the MnROAD mainline, the primary focus of the current research project is the innovative diamond grinding on Cells 7, 8, and 9.

The TUG research team developed and tested the rolling resistance device, shown in Figure 65, to isolate the resistance to forward motion of a vehicle due to the rolling resistance, or the interaction between the tire and the pavement surface.

Figure 65. Rolling resistance test trailer.

The primary focus of this research project are Cells 7, 8, 9, and 71where diamond grinding was conducted as a surface treatment in 2007 (Cells 7 and 8), 2008 (Cell 9) and 2010 (Cell 71). As mentioned previously, the grinding of these cells was described in detail in MnDOT Interim Report 2011-05 [2].

Testing Conditions

The rolling resistance measurements consisted of various passes on the same roadway segment at different speeds and using three different passenger car tires. The different tires are presented in Figure 66. From left to right, these tires are labeled SRTT, AV4, and ME16. A description of each tire is given in Table 23.

Figure 66. Test tires used in the rolling resistance testing at MnROAD.

Table 23. Description and Characteristics of Test Tires.

	SRTT	**AV4**	**ME16**
Manufacturer	Uniroyal	Avon	Michelin
Tread	Tiger Paw	AV4	Energy Sever
Size	P225/60R16	195R14C	225/60R16
Load index	97	106/104	98
Speed index	S	N	V
Hardness (Sh)	65	62	63

During the measurements the tire load was 900 lb (4000 N) and regulated tire inflation was 30.5 psi (210 kPa). Prior to taking measurements with a different tire, each one was warmed by driving for at least 20 minutes. The measurements were taken at two different speeds: 31 mph (50 km/h) and 50 mph (80 km/h). Measurements were also conducted at selected combinations of pavement surface and tire type at two other speeds: 68 mph (110 km/h) and 81 mph (130 km/h). At speeds of 31 and 50 mph (50 and 80 km/h), at least three runs in each direction were made, while at 68 and 81 mph (110 and 130 km/h) only two runs in each direction were performed.

Rolling Resistance Calculations

As previously mentioned, all rolling resistance testing was conducted during the middle of September 2011. The results discussed in the published report refer to the Coefficient of Rolling Resistance (CRR), which is defined as:

$$CRR = \frac{F_R}{L}$$

where:

F_R = Rolling resistance force, and
L = Tire load.

The results of the rolling resistance testing for the relevant cells are shown in Tables 24 through 26. For the SRTT tire, most of the cells, and speeds, give a similar CRR value, slightly increasing as speed increases until the final test at 81 mph, where it increases dramatically. The other tires that were not tested at the highest speed display similar characteristics of slight increases as speed increases. Comparing among the different grind configurations, the conventional grind produces the greatest rolling resistance in most cases, except at some of the higher speeds, where the ultimate and new ultimate grinds approach the level of the conventional grind, and even exceed it in one case. In most cases, the ground cells exceed the rolling resistance of the control cell (with traditional transverse tining).

Table 24. Coefficient of Rolling Resistance, SRTT Tire.

	Without Temperature Correction				With Temperature Correction			
Cell	**31 mph (50 km/h)**	**50 mph (80 km/h)**	**68 mph (110 km/h)**	**81 mph (130 km/h)**	**31 mph (50 km/h)**	**50 mph (80 km/h)**	**68 mph (110 km/h)**	**81 mph (130 km/h)**
7 (Innovative)	0.0076	0.0079	0.0086	0.0095	0.0073	0.0076	0.0083	0.0092
8 (Conventional)	0.0081	0.0084	0.0091	0.0102	0.0079	0.0081	0.0088	0.0099
9 (Ultimate)	0.0075	0.0080	0.0086	0.0096	0.0072	0.0077	0.0083	0.0093
71 (New Ultimate)	0.0068	0.0072	0.0074	0.0093	0.0072	0.0076	0.0078	0.0099
12 (Control)	0.0070	0.0071	0.0072	0.0093	0.0074	0.0075	0.0076	0.0099

Table 25. Coefficient of Rolling Resistance, AV4 Tire.

	Without Temperature Correction			With Temperature Correction		
Cell	**31 mph (50 km/h)**	**50 mph (80 km/h)**	**68 mph (110 km/h)**	**31 mph (50 km/h)**	**50 mph (80 km/h)**	**68 mph (110 km/h)**
7 (Innovative)	0.0136	0.0136	0.0141	0.0133	0.0132	0.0137
8 (Conventional)	0.0140	0.0140	0.0146	0.0136	0.0136	0.0141
9 (Ultimate)	0.0136	0.0136	0.0142	0.0133	0.0132	0.0138
71 (New Ultimate)	0.0131	0.0134	0.0136	0.0134	0.0137	0.0139
12 (Control)	0.0133	0.0135	0.0140	0.0136	0.0138	0.0143

Table 26. Coefficient of Rolling Resistance, ME16 Tire.

	Without Temperature Correction			With Temperature Correction		
Cell	31 mph (50 km/h)	50 mph (80 km/h)	68 mph (110 km/h)	31 mph (50 km/h)	50 mph (80 km/h)	68 mph (110 km/h)
7 (Innovative)	0.0075	0.0078	0.0088	0.0073	0.0076	0.0086
8 (Conventional)	0.0082	0.0086	0.0097	0.0080	0.0084	0.0094
9 (Ultimate)	0.0077	0.0078	0.0089	0.0075	0.0075	0.0087
71 (New Ultimate)	0.0067	0.0071	0.0074	0.0072	0.0075	0.0079
12 (Control)	0.0071	0.0072	0.0075	0.0075	0.0076	0.0080

For further information regarding the nature of the Rolling Resistance measurements and interpretation of these and other results, the reader is directed to the full report on the testing at MnROAD [22].

RoboTex

As described above, measurements of pavement surface texture were conducted on the test cells at the MnROAD research facility using the RoboTex system. This section summarizes the results of the testing, provides details about the test procedure and data processing, and presents some simple, overview analyses to serve as examples of how the results can be utilized. The full report will be published by MnDOT in 2013.

The texture measurements were performed using a mobile, line-laser based, texture profiler, shown in Figure 67, that provides results with two significant attributes.

1. Texture is obtained in both the longitudinal and transverse directions. This is particularly important for portland cement concrete pavements which typically have a surface texture dependent on direction.
2. Results in the longitudinal direction include the texture spectra in third octave bands with center wavelengths from 100 to 3.15 mm.

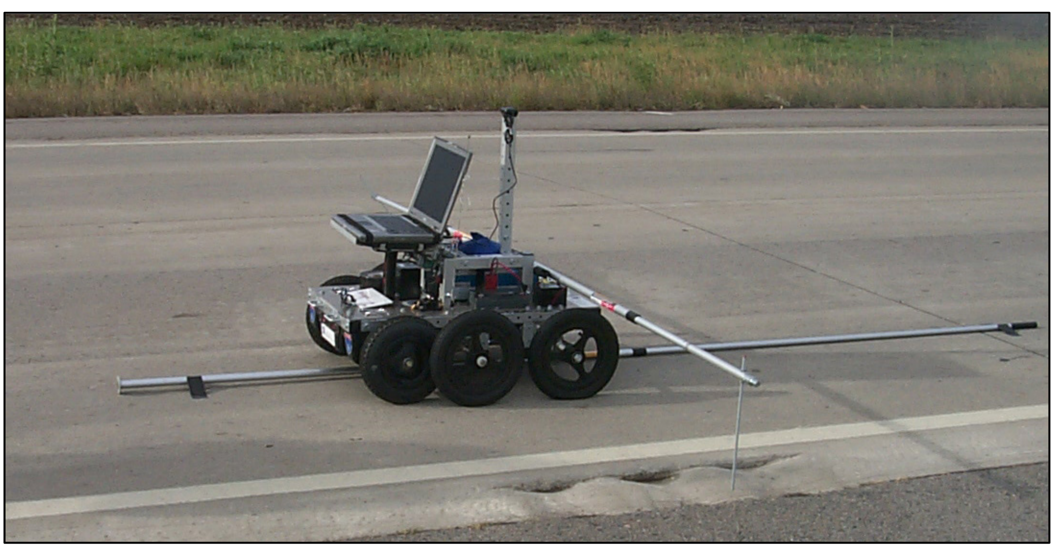

Figure 67. RoboTex texture profiler.

In addition to the common texture metric, mean profile depth (MPD), a variety of other metrics are calculated and included with the reported results. This includes metrics that can distinguish between upward and downward oriented texture (for example, skew).

The texture results are useful for a variety of pavement surface characteristic studies. Texture is a key factor in many pavement surface characteristics such as friction, tire-pavement noise, splash-spray, and rolling resistance. The texture results can be used by researchers for investigating correlations between texture and surface characteristics and for developing surface characteristics models.

Table 27. Average Texture Values.

Cell	Ave. Longitudinal MPD	Ave. Transverse MPD	Transverse-Longitudinal MPD	Ave. Longitudinal Skew	Ave. Transverse Skew	Transverse-Longitudinal Skew
7 (Innovative)	0.315	0.817	0.502	-0.590	-0.673	-0.083
8 (Conventional)	0.372	0.641	0.269	-0.418	0.075	0.493
9 (Ultimate)	1.023	2.159	1.136	-0.037	-1.311	-1.274
71 (New Ultimate)	0.518	1.515	0.997	-0.529	-1.360	-0.831
12 (Control)	0.506	0.376	-0.130	-2.136	-0.424	1.712

For further information regarding the nature of the RoboTex measurements and interpretation of these and other results, the reader is directed to the full report on the RoboTex testing at MnROAD.

Chapter 6. CONCLUSIONS AND RECOMMENDATIONS

This chapter provides a summary of the construction activities, the data collection effort, the data analysis, and relative performance analysis for the Next Generation Concrete Surface grinding techniques. The summary is then followed by recommendations for additional efforts that could be pursued by MnDOT or by others as advances in concrete pavement surface grinding continue.

Prior to the beginning of this project, MnDOT and its partners established the diamond grinding test strips in Cell 37 of the Low Volume Road at the MnROAD facility. After the initial evaluation indicated that the new grinding blade configurations could be successful, three cells on the MnROAD mainline were ground with three different configurations, including a conventional grind, a new "innovative" grind, and a further modification of the innovative grind termed the "ultimate" grind. Later a slightly modified grinding configuration was ground in Cell 71 of the MnROAD mainline.

Surface characteristic testing was conducted prior to and after the grinding activities, and continued through the summer of 2012. In addition, the testing and data collection efforts were conducted on Cell 12, which was used as a control since it still has its original transverse tined surface texture from the original construction in 1992. The surface characteristics were evaluated in terms of noise, friction, texture, and ride quality. Data were analyzed and comparisons made in this report.

Additional studies were conducted in order to improve the analysis of the data. These included the correction of noise measurements for ambient temperature, further analysis of noise-temperature correction in terms of the spectrum of frequencies contributing to the overall sound intensity, an analysis of possible trends in the data, and basic modeling of trends in the change of texture over time.

Performance

From the perspective of performance of the grinding configuration with respect to the different surface characteristics, the following conclusions can be made. Tables 28 and 29 provide a summary of the grind configurations that performed best with respect to the different surface characteristic measurements both immediately after grinding and after about 4 million ESALs in the driving lane and about 1 million ESALs in the passing lane (about 4.5 years) after grinding while the pavements were exposed to traffic loads and tires.

- *Noise*
  Immediately after the grinding, the Innovative grind performed best in terms of the greatest reduction of measured noise compared to the pre-grind condition. Comparing the different grinds over the long term, however, the Ultimate grind configuration increased in noise the least.

- *Friction*
  As would be expected, the Conventional grind increased in friction the most, immediately after grinding. Over the long term, however, the Ultimate grind decreased in friction the least, and in the passing lane even showed an increase in friction compared to the first

post-grind measurement. Using the smooth tire, however, the Innovative grind actually increased a small amount over the long term, and the Ultimate grind provided similar friction regardless of the condition of the tires (both ribbed and smooth).

- *Texture*
  Again, as expected, the Conventional grind showed the greatest immediate increase in texture compared to the pre-grind condition. The Ultimate grind did not have pre-grind measurements. The Innovative grind displayed the smallest decrease in texture over the long term, followed by the Ultimate grind.

- *Ride*
  Immediately after the grinding, the conventional grind performed best in terms of the reduction in IRI. In addition, over the long term, the conventional grinds show the best retention of gains in IRI measurements. Whereas the IRI measurements on the conventional grind decreased by about 40 in/mi immediately following the grinding, the average value remained essentially the same over the five years post-grind. The other grinding configurations had either reductions or increases in IRI immediately post-grind, and either lost most of the benefits or continued to increase in IRI during the five years post-grind. One possible issue that could explain the very large increases in the ultimate grind cells is the many longitudinal grooves resulting in larger vertical differences as the profiling machine wanders slightly to the left and right during a test. The lasers of the inertial profiler may have continuously measured high and low points in the grinding configuration, and over long distances these may have combined to produce increased IRI measurements. This should be evaluated further with the intent to make recommendations on interpreting IRI data with different surface characteristics.

Table 28. Summary of Performance – Immediate Effects.

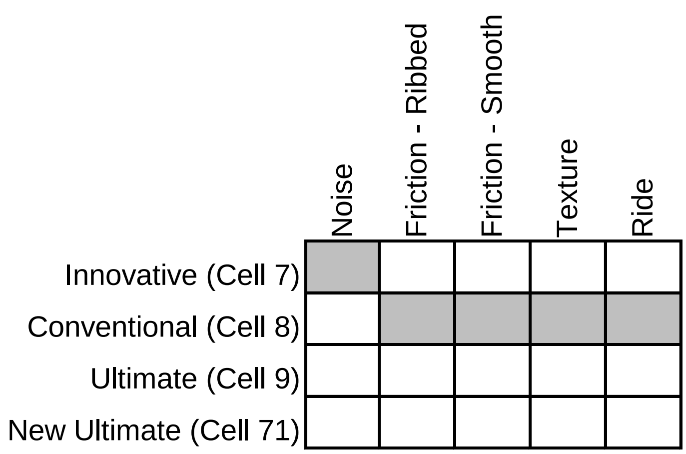

Table 29. Summary of Performance – Long-Term Effects.

	Noise	Friction - Ribbed	Friction - Smooth	Texture	Ride
Innovative (Cell 7)					
Conventional (Cell 8)					
Ultimate (Cell 9)					
New Ultimate (Cell 71)					

Recommendations

This section presents recommendations developed throughout this report to guide future research and the implementation of conventional and innovative grinding configurations, in the future.

- Continue monitoring the surface characteristics over time on these cells. Longer-term data could help with decisions regarding pavement management and rehabilitation.
- Implement the use of the a line laser such as the RoLine configuration in ride quality measurements to accommodate surfaces with corrugations and deep grooves.
- Continue to develop innovative grinding configurations. It is apparent that the industry and the research community have an understanding of configurations that produce quieter pavements that can maintain the other surface characteristics. Future configurations can build on these successes and produce quiet, durable pavement surfaces.
- Implement a form of temperature correction for OBSI measurements so that the values can be compared over long periods of time, and that a better sense of change can be developed.
- Investigate the potential for correcting friction values for temperature on concrete pavement surfaces with the skid trailer. Similar to OBSI measurements, such a correction factor could make the comparison of friction over long periods of time a viable method.
- Conduct further research into the effects of surface grooving by diamond grinding on the results of inertial profiler measurements. One possible solution could be to utilize a line laser or a large area laser to simulate the footprint of a tire, to minimize the effect that a single point (or a triple point) laser has when measuring the peaks and valleys of the innovative grinding configurations.

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APPENDIX A. SUMMARY OF DATA COLLECTION

Noise Data – OBSI Measurements, Cell 7.

Cell 7 - Innovative Grind					
	Driving Lane				
Date/time		*Air Temperature, °F*	*Measured, dB*	*Corrected, dB*	*Corrected, Individual Frequencies, dB*
8/17/07 12:00 PM		71.4	101.9	102.0	
10/22/07 1:18 PM		53.5	98.8	98.6	98.3
4/2/08 2:10 PM	508,764	40.4	100.3	99.8	99.6
12/5/08 11:18 AM	508,764	17.5	102.7	101.9	101.1
3/16/09 1:00 PM	679,192	58.6	101.1	101.0	100.9
7/21/09 12:16 PM	1,129,895	73.4	99.9	100.0	100.2
9/15/09 5:18 PM	1,309,233	80.7	98.5	98.7	99.4
11/17/09 1:29 PM	1,493,169	49.2	100.6	100.3	99.5
3/8/10 12:31 PM	1,851,629	36.2	101.2	100.7	99.8
7/28/10 2:12 PM	2,042,613	78.4	99.0	99.1	99.4
9/17/10 2:05 PM	2,135,785	64.1	100.0	100.0	100.2
11/17/10 10:59 AM	2,319,101	34.0	102.3	101.8	100.5
3/15/11 9:42 AM	2,736,100	33.1	102.0	101.5	100.8
6/28/11 10:08 AM	3,068,605	67.6	101.8	101.7	101.9
9/20/11 10:30 AM	3,186,461	68.3	101.6	101.6	100.9
4/25/12 11:32 AM	3,786,486	69.9	101.7	101.7	102.7

Cell 7 - Innovative Grind					
	Passing Lane				
Date/time	*ESALs Since Grinding*	*Air Temperature, °F*	*Measured, dB*	*Corrected, dB*	*Corrected, Individual Frequencies, dB*
8/17/07 12:00 PM		71.4	102.5	102.6	
10/22/07 1:29 PM		53.7	98.9	98.7	98.7
4/2/08 2:47 PM	120,752	40.0	100.0	99.6	99.3
11/20/08 10:40 AM	120,752	21.3	102.3	101.6	100.6
3/16/09 12:29 PM	162,778	57.5	100.8	100.7	100.6
7/21/09 12:43 PM	275,841	74.1	98.9	99.0	99.0
9/15/09 4:39 PM	323,490	81.4	98.1	98.3	98.7
11/17/09 1:55 PM	367,457	49.6	99.5	99.2	98.3
3/8/10 10:57 AM	447,369	35.5	100.2	99.8	98.3
7/28/10 1:32 PM	495,483	77.7	99.0	99.1	99.4
9/17/10 2:15 PM	522,087	64.1	100.3	100.2	100.1
11/17/10 11:08 AM	567,673	34.0	102.1	101.6	100.6
3/15/11 9:42 AM	671,371	33.1	101.3	100.7	99.9
6/28/11 10:08 AM	753,064	67.6	101.8	101.8	101.7
9/20/11 10:15 AM	774,945	67.9	101.3	101.3	100.9
4/25/12 11:32 AM	925,326	69.9	102.1	102.1	102.8

Noise Data – OBSI Measurements, Cell 8.

Cell 8 - Conventional Grind Driving Lane					
Date/time	*ESALs Since Grinding*	*Air Temperature, °F*	*Measured, dB*	*Corrected, dB*	*Corrected, Individual Frequencies, dB*
8/17/07 12:00 PM		71.4	100.7	100.8	
10/22/07 1:18 PM		53.5	103.3	102.7	103.2
4/2/08 2:10 PM	508,764	40.4	101.9	100.8	100.3
12/5/08 11:18 AM	508,764	17.5	103.9	101.8	101.1
3/16/09 1:00 PM	679,192	58.6	102.2	101.8	100.7
7/21/09 12:16 PM	1,129,895	73.4	101.1	101.3	101.2
9/15/09 5:18 PM	1,309,233	80.7	100.3	100.9	101.1
11/17/09 1:29 PM	1,493,169	49.2	102.2	101.4	101.5
3/8/10 12:31 PM	1,851,629	36.2	102.6	101.2	100.4
7/28/10 2:12 PM	2,042,613	78.4	101.1	101.5	101.1
9/17/10 2:05 PM	2,135,785	64.1	103.0	102.9	103.5
11/17/10 10:59 AM	2,319,101	34.0	104.4	102.9	103.1
3/15/11 9:42 AM	2,736,100	33.1	104.0	102.5	101.4
6/28/11 10:08 AM	3,068,605	67.6	103.3	103.3	102.4
9/20/11 10:33 AM	3,186,461	68.0	103.0	103.0	102.9
4/25/12 11:43 AM	3,786,486	70.6	102.8	102.9	102.7

Cell 8 - Conventional Grind					
	Passing Lane				
Date/time	*ESALs Since Grinding*	*Air Temperature, °F*	*Measured, dB*	*Corrected, dB*	*Corrected, Individual Frequencies, dB*
8/17/07 12:00 PM		71.4	101.5	101.6	
10/22/07 1:29 PM		53.7	103.2	102.6	103.4
4/2/08 2:47 PM	120,752	40.0	102.5	101.3	101.0
11/20/08 10:40 AM	120,752	21.3	104.6	102.6	102.0
3/16/09 12:29 PM	162,778	57.5	102.9	102.5	101.8
7/21/09 12:43 PM	275,841	74.1	101.5	101.8	101.4
9/15/09 4:39 PM	323,490	81.4	101.2	101.8	102.0
11/17/09 1:55 PM	367,457	49.6	102.7	101.9	102.7
3/8/10 10:57 AM	447,369	35.5	103.4	102.0	100.9
7/28/10 1:32 PM	495,483	77.7	101.3	101.7	101.1
9/17/10 2:15 PM	522,087	64.1	103.5	103.4	104.0
11/17/10 11:08 AM	567,673	34.0	104.7	103.2	102.8
3/15/11 9:42 AM	671,371	33.1	103.4	101.9	100.8
6/28/11 10:08 AM	753,064	67.6	103.3	103.3	102.4
9/20/11 10:33 AM	774,945	68.0	102.6	102.6	102.1
4/25/12 11:43 AM	925,326	70.6	104.0	104.1	104.6

Noise Data – OBSI Measurements, Cell 9.

Cell 9 - Ultimate Grind					
	Driving Lane				
Date/time	***ESALs Since Grinding***	***Air Temperature, °F***	***Measured, dB***	***Corrected, dB***	***Corrected, Individual Frequencies, dB***
9/10/07 1:06 PM		52.9	103.0	102.7	101.9
12/5/08 11:18 AM		17.5	101.7	100.7	100.2
3/16/09 1:00 PM	170,428	58.6	101.2	101.0	100.6
7/21/09 12:16 PM	621,131	73.4	100.2	100.3	100.3
9/15/09 5:18 PM	800,469	80.7	99.0	99.2	99.5
11/17/09 1:29 PM	984,405	49.2	101.2	100.9	100.7
3/8/10 12:31 PM	1,342,865	36.2	102.4	101.8	101.0
7/28/10 2:12 PM	1,533,848	78.4	100.0	100.2	100.0
9/17/10 2:05 PM	1,627,021	64.1	101.8	101.7	101.7
11/17/10 10:59 AM	1,810,336	34.0	103.4	102.8	102.1
3/15/11 9:42 AM	2,227,336	33.1	103.2	102.5	101.8
6/28/11 10:08 AM	2,559,841	67.6	102.8	102.8	102.7
9/20/11 10:33 AM	2,677,697	68.0	102.7	102.7	102.6
4/25/12 11:43 AM	3,277,722	70.6	102.5	102.5	102.7

Cell 9 - Ultimate Grind					
	Passing Lane				
Date/time	***ESALs Since Grinding***	***Air Temperature, °F***	***Measured, dB***	***Corrected, dB***	***Corrected, Individual Frequencies, dB***
9/10/07 10:52 AM		52.9	104.6	104.3	103.6
11/20/08 10:40 AM		21.3	102.6	101.7	101.0
3/16/09 12:29 PM	42,027	57.5	101.7	101.5	100.7
7/21/09 12:43 PM	155,089	74.1	100.2	100.3	100.2
9/15/09 4:39 PM	202,738	81.4	99.0	99.3	100.6
11/17/09 1:55 PM	246,706	49.6	101.0	100.6	101.3
3/8/10 10:57 AM	326,618	35.5	101.9	101.3	99.9
7/28/10 1:32 PM	374,732	77.7	99.9	100.0	99.6
9/17/10 2:15 PM	401,335	64.1	102.2	102.1	102.3
11/17/10 11:08 AM	446,922	34.0	103.6	103.0	102.6
3/15/11 9:42 AM	550,620	33.1	103.2	102.6	102.1
6/28/11 10:08 AM	632,313	67.6	102.5	102.5	103.1
9/20/11 10:33 AM	654,194	68.0	102.3	102.3	102.0
4/25/12 11:43 AM	804,575	70.6	103.0	103.0	103.3

Noise Data – OBSI Measurements, Cell 12.

Cell 12 - Control					
	Driving Lane				
Date/time	*ESALs Since October 2007*	*Air Temperature, °F*	*Measured, dB*	*Corrected, dB*	*Corrected, Individual Frequencies, dB*
9/10/07 1:23 PM	11,240,901	52.9	104.2	103.9	103.5
12/5/08 11:06 AM	11,865,058	17.4	106.4	105.4	104.7
7/21/09 12:03 PM	12,486,189	73.1	105.1	105.2	104.8
9/17/10 1:23 PM	13,492,079	63.4	105.4	105.3	105.1
11/17/10 10:45 AM	13,675,394	33.5	106.6	105.9	104.9
3/15/11 9:40 AM	14,092,394	33.1	106.2	105.5	104.6
6/28/11 10:08 AM	14,424,898	67.6	105.6	105.6	105.0
9/20/11 10:33 AM	14,542,755	68.0	104.8	104.8	105.0
4/25/12 11:42 AM	15,142,779	70.5	105.8	105.8	106.0

Cell 12 - Control					
	Passing Lane				
Date/time	*ESALs Since October 2007*	*Air Temperature, °F*	*Measured, dB*	*Corrected, dB*	*Corrected, Individual Frequencies, dB*
9/10/07 1:23 PM	2,873,052	52.9	105.0	104.7	104.7
11/20/08 10:32 AM	3,022,707	21.2	107.1	106.2	105.9
3/16/09 12:29 PM	3,064,733	57.5	105.9	105.7	105.8
7/21/09 12:03 PM	3,177,796	73.1	105.1	105.2	105.2
9/17/10 1:23 PM	3,424,042	63.4	106.1	106.0	106.2
11/17/10 10:45 AM	3,469,628	33.5	106.9	106.2	106.0
3/15/11 9:40 AM	3,573,326	33.1	105.9	105.2	105.0
6/28/11 10:08 AM	3,655,019	67.6	105.6	105.6	105.6
9/20/11 10:33 AM	3,676,900	68.0	105.2	105.2	105.6
4/25/12 11:42 AM	3,827,281	70.5	105.3	105.3	103.7

Noise Data – OBSI Measurements, Cell 71.

Cell 71 - New Ultimate					
	Driving Lane				
Date/time	*ESALs Since Grinding*	*Air Temperature, °F*	*Measured, dB*	*Corrected, dB*	*Corrected, Individual Frequencies, dB*
7/28/10 1:51 PM	129,240	77.9	96.9	96.9	97.3
9/17/10 2:28 PM	222,413	64.1	98.9	98.8	98.7
11/17/10 11:34 AM	405,729	34.1	101.0	100.6	#N/A
3/15/11 10:17 AM	822,728	33.1	101.0	100.6	#N/A
6/28/11 10:08 AM	1,155,233	67.6	100.7	100.7	100.1
9/20/11 9:55 AM	1,273,089	67.6	100.5	100.4	100.9
4/25/12 11:43 AM	1,873,114	70.6	100.2	100.2	100.5

Cell 71 - New Ultimate					
	Passing Lane				
Date/time	*ESALs Since Grinding*	*Air Temperature, °F*	*Measured, dB*	*Corrected, dB*	*Corrected, Individual Frequencies, dB*
7/28/10 1:51 PM	36,032	77.9	100.2	100.3	100.4
9/17/10 2:28 PM	62,635	64.1	101.6	101.5	101.4
11/17/10 11:34 AM	108,222	34.1	103.4	103.0	102.7
3/15/11 10:17 AM	211,920	33.1	101.2	100.8	#N/A
6/28/11 10:23 AM	293,613	68.0	101.1	101.1	#N/A
9/20/11 9:55 AM	315,494	67.6	100.8	100.8	100.4
4/25/12 11:43 AM	465,875	70.6	101.5	101.5	101.6

Friction Data – Skid Trailer Measurements, Cell 7.

Cell 7 - Innovative Grind					
	Driving Lane				
		Ribbed Tire		Smooth Tire	
Date	ESALs Since Grinding	Pavement Temperature (°F)	FN	Pavement Temperature (°F)	FN
4/19/2006			55.7		26.2
10/24/2006		62.8	59.5	63.0	35.9
11/6/2007	48,128	45.7	46.1	46.9	45.1
5/28/2008	508,764	99.3	44.7	96.5	50.2
10/31/2008	508,764	70.3	45.1	67.8	48.7
6/16/2009	1,024,811	93.5	44.6	88.0	46.5
9/20/2010	2,135,785	64.4	41.9	64.4	49.0
4/14/2011	2,788,311	57.6	46.4	55.5	48.3
9/29/2011	3,186,461	74.7	44.1	69.9	49.6
4/24/2012	3,784,546		40.1		47.7
6/8/2012	3,998,246	97.4	41.1	95.5	47.0

Cell 7 - Innovative Grind					
	Passing Lane				
		Ribbed Tire		Smooth Tire	
Date	ESALs Since Grinding	Pavement Temperature (°F)	FN	Pavement Temperature (°F)	FN
4/19/2006			57.5		40.4
10/24/2006		64.0	59.4		
11/6/2007	12,237	48.7	46.2		
5/28/2008	120,752	100.9	43.8	97.7	47.0
6/16/2009	248,976	89.1	41.5	90.8	48.4
9/20/2010	522,087	66.1	46.7	64.4	51.1
4/14/2011	684,168	58.1	49.5	60.5	55.5
9/29/2011	774,945	75.0	47.7	73.0	49.5
4/24/2012	924,836		42.3		51.4

Friction Data – Skid Trailer Measurements, Cell 8.

Cell 8 - Conventional Grind					
	Driving Lane				
		Ribbed Tire		Smooth Tire	
Date	ESALs Since Grinding	Pavement Temperature (°F)	FN	Pavement Temperature (°F)	FN
4/19/2006			60.7		30.2
10/24/2006		61.7	48.0	61.0	20.9
11/6/2007	48,128	45.4	55.4	45.9	48.7
5/28/2008	508,764	98.8	57.8	92.4	58.3
10/31/2008	508,764	69.8	54.0	68.6	55.3
6/16/2009	1,024,811	93.2	48.9	88.8	50.5
9/20/2010	2,135,785	63.9	48.8	63.4	43.9
4/14/2011	2,788,311	58.1	51.0	55.4	49.3
9/29/2011	3,186,461	74.7	46.3	69.4	46.4
4/24/2012	3,784,546		43.9		43.8
6/8/2012	3,998,246	97.9	45.3	97.2	44.0

Cell 8 - Conventional Grind					
	Passing Lane				
		Ribbed Tire		Smooth Tire	
Date	ESALs Since Grinding	Pavement Temperature (°F)	FN	Pavement Temperature (°F)	FN
4/19/2006			52.6		28.0
10/24/2006		63.3	47.0		
11/6/2007	12,237	48.2	55.7		
5/28/2008	120,752	98.6	56.6	98.0	58.1
6/16/2009	248,976	88.8	49.7	89.3	55.0
9/20/2010	522,087	65.9	54.0	64.6	55.1
4/14/2011	684,168	57.9	55.4	56.6	54.0
9/29/2011	774,945	74.6	51.6	74.5	55.8
4/24/2012	924,836		45.7		50.7

Friction Data – Skid Trailer Measurements, Cell 9.

Cell 9 - Ultimate Grind					
	Driving Lane				
		Ribbed Tire		Smooth Tire	
Date	ESALs Since Grinding	Pavement Temperature (°F)	FN	Pavement Temperature (°F)	FN
4/19/2006			66		31.4
11/6/2007		46.9	49.9	47.4	39.1
5/28/2008		101.7	56.25	96.8	31.5
10/31/2008		69.1	48.2	68.3	56.2
6/16/2009	516,047	92.2	45.3	86.8	48.4
9/20/2010	1,627,021	63.2	45.2	63.2	46.8
4/14/2011	2,279,546	55.9	50.1	54.3	51.9
9/29/2011	2,677,697	74.5	48.9	70.1	50.6
4/24/2012	3,275,782		43		47.7
6/8/2012	3,489,481	98.1	43.5	92.3	48.0

Cell 9 - Ultimate Grind					
	Passing Lane				
		Ribbed Tire		Smooth Tire	
Date	ESALs Since Grinding	Pavement Temperature (°F)	FN	Pavement Temperature (°F)	FN
4/19/2006			54.2		44.5
11/6/2007		48.6	52.9		
5/28/2008		104.6	53.7	102.3	38.5
6/16/2009	128,224	87.8	36.3	91.3	41.1
9/20/2010	401,335	65.4	46.2	64.2	45.1
4/14/2011	563,416	58.1	48.7	57.5	51.3
9/29/2011	654,194	74.2	46.9	74.2	48.7
4/24/2012	804,084		43.7		47.6

Friction Data – Skid Trailer Measurements, Cell 12.

Cell 12 - Control					
	Driving Lane				
		Ribbed Tire		Smooth Tire	
Date	ESALs Since October 2007	Pavement Temperature (°F)	FN	Pavement Temperature (°F)	FN
10/31/2008	11,865,058	69.8	51.9	68.6	31.1
9/20/2010	13,492,079	64.9	46.7	64.4	32.2
4/14/2011	14,144,604	59.3	47.2	59.4	34.6
9/29/2011	14,542,755	74.6	46.7	68.6	28.3
4/24/2012	15,140,840		41		24.1
6/8/2012	15,354,539	97.9	42.7	90.3	25.7

Cell 12 - Control					
	Passing Lane				
		Ribbed Tire		Smooth Tire	
Date	ESALs Since October 2007	Pavement Temperature (°F)	FN	Pavement Temperature (°F)	FN
9/20/2010	3,424,042	65.9	51.7	65.9	41.7
4/14/2011	3,586,123	61.1	55.2	63.9	51.8
9/29/2011	3,676,900	74.2	53.8	73.5	41.0
4/24/2012	3,826,791		46.5		32.0

Friction Data – Skid Trailer Measurements, Cell 71.

Cell 71 - New Ultimate					
	Driving Lane				
		Ribbed Tire		Smooth Tire	
Date	ESALs Since Grinding	Pavement Temperature (°F)	FN	Pavement Temperature (°F)	FN
9/20/2010	222,413	64.6	44.9	64.2	47.9
4/14/2011	874,938	58.1	50.9	55.9	46.8
9/29/2011	1,273,089	75	41	71.3	46.4
4/24/2012	1,871,174		37.7		41.1
6/8/2012	2,084,874	97.8	38.3	92.7	40.1

Cell 71 - New Ultimate					
	Passing Lane				
		Ribbed Tire		Smooth Tire	
Date	ESALs Since Grinding	Pavement Temperature (°F)	FN	Pavement Temperature (°F)	FN
9/20/2010	62,635	65.6	49.2	65.4	47.9
4/14/2011	224,716	58.6	54.5	59.3	50.8
9/29/2011	315,494	74.7	51.9	73.8	47.0
4/24/2012	465,385		45.6		42.4

Texture Data – Circular Texture Meter Measurements, Cell 7.

Cell 7 - Innovative Grind				
	ESALs Since Grinding		Mean Texture Depth, mm	
Date	Passing Lane	Driving Lane	Passing Lane	Driving Lane
10/15/2007	0	0	0.5	0.4
10/23/2007	1,566	6,217	0.9	1.0
11/2/2008	120,752	508,764	0.6	0.7
3/15/2009	162,778	679,192	0.6	0.6
6/1/2010	459,451	1,913,372	0.6	0.7

Texture Data – Circular Texture Meter Measurements, Cell 8.

Cell 8 - Conventional Grind				
	ESALs Since Grinding		Mean Texture Depth, mm	
Date	Passing Lane	Driving Lane	Passing Lane	Driving Lane
10/15/2007	0	0	0.5	0.4
10/23/2007	1,566	6,217	1.6	1.5
11/2/2008	120,752	508,764	1.0	0.7
3/15/2009	162,778	679,192	0.9	0.7
6/1/2010	459,451	1,913,372	0.7	0.7
11/1/2011	774,945	3,186,461	0.6	0.8

Texture Data – Circular Texture Meter Measurements, Cell 9.

Cell 9 - Ultimate Grind				
	ESALs Since Grinding		Mean Texture Depth, mm	
Date	Passing Lane	Driving Lane	Passing Lane	Driving Lane
10/25/2008	0	0	2.2	2.0
3/15/2009	42,027	170,428	1.9	1.7
6/1/2010	338,700	1,404,608	1.7	1.5
11/1/2011	654,194	2,677,697	1.5	1.5

Texture Data – Circular Texture Meter Measurements, Cell 71.

Cell 71 - New Ultimate Grind				
	ESALs Since Grinding		*Mean Texture Depth, mm*	
Date	*Passing Lane*	*Driving Lane*	*Passing Lane*	*Driving Lane*
6/1/2010	1,312	4,432	0.9	1.1
10/20/2010	90,056	330,534	0.8	1.0
6/24/2011	293,613	1,155,233	0.6	1.1
10/27/2011	315,494	1,273,089	0.6	1.2

Ride Quality Data – AMES LISA Measurements, Cell 7.

Cell 7 - Innovative Grind				
	ESALs Since Grinding		IRI, in/mi	
Date	Passing Lane	Driving Lane	Passing Lane	Driving Lane
9/8/2007			75.7	78.2
10/22/2007	0	0	48.4	48.5
11/21/2007	18,506	72,615	80.5	79.2
3/28/2008	117,979	496,858	90.6	112.8
11/19/2008	120,752	508,764	78.5	62.6
4/27/2009	191,526	794,972	84.9	74.8
10/28/2009	352,591	1,423,146	80.5	77.3
3/8/2010	447,369	1,851,629	76.1	69.0
4/8/2010	459,451	1,913,372	87.4	91.2
10/12/2010	543,579	2,219,688	79.2	65.3
3/16/2011	671,371	2,736,100	86.2	79.2
6/27/2011	753,064	3,068,605	60.8	60.8
9/19/2011	774,945	3,186,461	73.5	72.2
3/19/2012	897,772	3,675,470	66.5	72.2

Ride Quality Data – AMES LISA Measurements, Cell 8.

Cell 8 - Conventional Grind				
	ESALs Since Grinding		IRI, in/mi	
Date	Passing Lane	Driving Lane	Passing Lane	Driving Lane
9/8/2007			114.0	115.5
10/22/2007	0	0	75.5	74.1
11/21/2007	18,506	72,615	107.7	86.2
3/28/2008	117,979	496,858	109.0	100.1
11/19/2008	120,752	508,764	94.4	60.7
4/27/2009	191,526	794,972		95.7
10/28/2009	352,591	1,423,146	78.6	75.4
3/8/2010	447,369	1,851,629	90.8	73.8
4/8/2010	459,451	1,913,372	89.3	76.7
10/12/2010	543,579	2,219,688	75.4	66.5
3/16/2011	671,371	2,736,100	97.6	75.4
6/27/2011	753,064	3,068,605	76.7	66.5
9/19/2011	774,945	3,186,461	74.1	78.6
3/19/2012	897,772	3,675,470	77.3	71.9

Ride Quality Data – AMES LISA Measurements, Cell 9.

Cell 9 - Ultimate Grind				
	ESALs Since Grinding		IRI, in/mi	
Date	Passing Lane	Driving Lane	Passing Lane	Driving Lane
9/8/2007				47.8
10/22/2007				47.8
11/21/2007			72.9	84.9
3/28/2008	0	0	88.1	104.5
4/27/2009	70,774	286,207	178.0	206.5
10/28/2009	231,840	914,381	204.6	157.8
3/8/2010	326,618	1,342,865	168.9	
4/8/2010	338,700	1,404,608	228.7	189.4
10/12/2010	422,827	1,710,924	180.6	196.4
6/27/2011	632,313	2,559,841	271.8	224.3
9/19/2011	654,194	2,677,697	229.4	209.1
3/19/2012	777,021	3,166,705	309.5	241.7

Ride Quality Data – AMES LISA Measurements, Cell 12.

Cell 12 - Control				
	ESALs Since October 2007		IRI, in/mi	
Date	Passing Lane	Driving Lane	Passing Lane	Driving Lane
10/22/2007	2,901,955	11,356,293		47.8
11/21/2007	2,920,461	11,428,908	91.2	98.8
3/28/2008	3,019,934	11,853,152	81.7	90.0
11/19/2008	3,022,707	11,865,058		47.8
4/27/2009	3,093,481	12,151,265	96.3	100.7
10/28/2009	3,254,546	12,779,439	96.9	105.2
3/8/2010	3,349,324	13,207,922		146.1
4/8/2010	3,361,406	13,269,666	87.4	94.4
10/12/2010	3,445,534	13,575,981	96.3	107.7
3/16/2011	3,573,326	14,092,394	87.4	99.5
6/27/2011	3,655,019	14,424,898	90.0	96.3
9/19/2011	3,676,900	14,542,755	90.0	90.0
3/19/2012	3,799,727	15,031,763	85.2	91.9

Ride Quality Data – AMES LISA Measurements, Cell 71.

Cell 71 - New Ultimate Grind				
	ESALs Since Grinding		IRI, in/mi	
Date	Passing Lane	Driving Lane	Passing Lane	Driving Lane
10/12/2010	84,127	306,316	73.5	148.3
3/16/2011	205,438	796,157	64.6	
6/27/2011	293,613	1,155,233	47.5	162.8
9/19/2011	315,494	1,273,089	57.7	131.8
3/19/2012	438,321	1,762,098	52.0	162.2