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Seven Year Performance Report on MnROAD High Performance Concrete Design Test Cell 53

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Minnesota Department of Transportation

July 2015

Research Project
Final Report 2015-38

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16. Abstract (Limit: 250 words)

This report describes the 7-year performance of the 60-year concrete design test cell (Cell 53) built in 2008 in the MnROAD Low Volume Road). Many characteristics of this 115-foot cell, two 12-feet wide lanes, 12 inch thick dowelled concrete test have exhibited insignificant change in performance criteria over the 5-year period. . The test cell maintained adequate skid resistance since it was constructed in 2008. Transverse joint monitoring and fault measurements also indicated insignificant faulting over the period of review. In many cases, measured properties in the inside lane of Cell 53 were significantly different from outside lane. The International Roughness Index (IRI) was not initially low but has remained relatively constant. Additionally, a slight disparity of IRI between the inside (traffic) lane and the outside (environmental) lane was evident. The IRI in the inside lane was consistently higher than the outside lane. Seasonal deflection basins created for both summer and spring dates soon after construction in 2009 and similar summer and spring dates in 2013 showed deflections below 100 microns, which also suggests good performance. The test cell displayed excellent load transfer at all of the transverse joints tested in this research. The average load transfer was approximately 0.85, which was in some cases over four times as high as another MnROAD concrete pavement test cell which was undoweled and in poor condition. The load transfer in the 60-year design cell had not shown significant decrease over time. Researchers used the Evaluation of Layer Moduli and Overlay Design (ELMOD) to determine the layer properties of the pavement test cell. Again, similar dates in both spring and summer seasons were compared for the year 2009 and 2013. Summer results exhibited a slight decrease in calculated Moduli values for the base, subbase and subgrade layers, for both the inside and outside lane. This slight decrease over the period was not interpreted as failure in the base layers. Seven years of monitoring reveal that 60-year design concrete pavement test cell has not shown any performance issues apart from those inherent in the construction process. Most Importantly, evidence of lesser strain in the concrete when compared to thinner pavements designed for a shorter service life at the research facility.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

This report describes the 7-year performance of the 60-year concrete design test Cell 53 built in 2008 on the MnROAD Low Volume Road. Many performance criteria of this 115 ft cell, two 12–ft wide lanes, 12 inch thick dowelled concrete test cell have changed only infinitesimally in over the 5 year period. Performance criteria examined through testing and monitoring included visual distress survey, ride quality measurement, Friction (skid resistance), Noise evaluation, Load transfer evaluation as well as strain distribution. The report also compared the strain in this pavement to strain levels in other pavements in the research facilities that were not of the 60 year design.

The test cell displayed excellent load transfer at all of the transverse joints tested in this research. The average load transfer was approximately 0.85, which was in some cases over four times as high as another MnROAD concrete pavement test cell which was undoweled in poor condition. The load transfer in the 60 year design cell had not shown significant decrease over time. The test cell maintained adequate skid resistance over time. Transverse joint monitoring and measurements also indicated insignificant faulting over the period of review.

In many cases, measured properties in the inside lane of Cell 53 were significantly different between the inside and outside lane. On of the many variables examined included ride quality measured by the International Roughness Index (IRI) IRI was not initially low but has remained relatively constant. Additionally, a slight disparity of IRI between the inside (trafficked) lane and the outside (environmental) lane was evident. This report attributes this disparity to the different degrees of aggressiveness of the transverse brooming applied to the different lanes. This can be attributed to the traffic loading occurring only on the inside lane, leaving the outside lane to only be susceptible to environmental effects. The IRI in the inside lane was consistently higher than the outside lane. Conversely, the OBSI on the inside lane was consistently lower than the outside lane. The lower noise in the outside lane could be due to traffic wearing down the surface of the transverse broom finish. The outside lane generally had higher friction than the inside lane. Finally, the mean profile depth in the outside lane was consistently higher than the inside lane. Seasonal deflection basins created for both summer and spring dates soon after construction in 2009, and similar summer and spring dates in 2013 showed deflections below 100 microns, which also suggests good performance. Finally, researchers used the ELMOD to determine the layer properties of the pavement test cell. Again, similar dates in both spring and summer seasons were compared for the year 2009 and 2013. The analysis returned inconsistent results for the spring season comparison, suggesting that the base conditions may have been different between years with respect to thaw progress in spite of the deep frost free materials comprising 1 ft of class 5 aggregate base and 4 ft of MnDOT select granular material. However, the results for the summer did show a slight decrease in calculated Moduli values for the base, subbase and subgrade layers, for both the inside and outside lane. This slight decrease over the period of five years could be expected, and should not necessarily be interpreted as failure in the base layers.

After seven years of performance data have been collected and analyzed, it was found that the 60 year design concrete pavement test cell has not shown any performance issues apart from those inherent in the construction process. Most Importantly there was evidence of lesser strain in the

concrete in comparison to other pavements << 12 thick at the research facility designed for a shorter service life.

The introductory chapter references the cell construction as one of the 2008 MnROAD initiatives and discusses MnROAD as a full scale pavement facility in which this test cell was constructed. The next chapter discusses the test methods and monitoring process, thus introducing friction, ride quality, tire pavement noise and falling weight deflectometer and guided load testing to determine strain response. The next chapter discusses the results obtained and in particular compares the load transfer efficiency and strain levels to a section of lesser thickness. In all cases the strain levels are lower and the load transfer efficiencies normalized to age are higher with the 60 year design. While recommending continuous monitoring, the final chapter concludes that the 60 year design objectives of reduced strain and sustenance of performance over time are still evident at the time of this report.

Chapter 1: INTRODUCTION

Background

In the fall of 2008, a full scale pavement test section (Cell 53) was constructed at the MnROAD Low Volume Road to aid in the development of a more accurate service life prediction model for the Minnesota Department of Transportation's (MnDOT) current 60-year concrete pavement designs. MnDOT's design guide for concrete pavement design, based on the 1981 AASTHO design guide, was used. The test cell was heavily instrumented with sensors to measure dynamic strain, displacement, moisture, joint openings, maturity, elevation, temperature, and environmental strain. These sensors have been collecting data and providing valuable information on the performance of the pavement continuously since construction. The test cell was also monitored during construction for such characteristics as base and subgrade performance using light weight deflectometer testing, concrete maturity, and built-in warp and curl of the pavement slabs. Information from this testing can be found in the construction report located on the MnROAD online report database [1].

The test cell has been monitored periodically over the last five years since construction for other important properties. These included ride quality (IRI), friction (FN), surface texture (MPD), noise (OBSI), load response (FWD), and faulting. These test methods will be described in detail in the subsequent chapters of this report. The following chapters will provide the test methods, test results and performance implications to date from each of these tests. These results have provided valuable insight on the performance of the MnDOT 60-year design concrete pavements. A separate report [2] discusses the performance of 60-year designs in the MnDOT network, and determines optimal timing of intervening rehabilitations based on a deterministic Weibull analysis.

Test Facility and Cell Description

Although the Construction Report [1] and First year performance report [2] copiously describe the research facility, a current description is included in this report for two reasons. First it is expedient to make this inclusion for completeness and for the convenience of the reader. Secondly, reconstruction initiatives sequel to 2008 including the 2010, 2011, and 2013 initiatives have changed the number of cells and some cell configurations in the facility.

The MnROAD pavement research facility is located in Albertville, Minnesota. It consists of two distinct segments of roadway: the Mainline and the Low Volume Road (LVR). In 2008, there were a total of 69 test cells between the Mainline and LVR, each with a distinct pavement type and design. The Mainline test sections are located on a 3.5 mile, two lane interstate that carries live traffic diverted from Westbound Interstate 94. The 60-year design concrete pavement test cell discussed in this report, Cell 53, is located on the Low Volume Road. The LVR is a two and a half mile, two lane wide-closed loop with 24 test cells in 2008. In order to closely mimic traffic conditions on rural roads, traffic on the LVR is restricted to a single 18-wheel, 5-axle tractor with trailer. This vehicle is operated by MnROAD staff and is driven on a controlled schedule. This tractor with trailer completes 80 laps per day on the inside lane only. Except for very minimal loading from lightweight test vehicles, the outside lane is subject to environmental loading only. By placing this restriction, the pavement response due to environmental effects versus loading effects can be evaluated.

The general cross section of Cell 53 is shown in the figure below. The test cell is a total of 115 feet long, in between stations 210+85.00 and 212+00; 12 feet wide by 15 feet long panels in both the driving lane and passing lane. Five No. 13 epoxy coated tie bars per panel were used between the two lanes. Twelve 1.5 inch diameter, stainless steel dowels, were used at one foot spacing across transverse joints. Concrete shoulders were paved on both sides of the test cell. These shoulders were three inches thick on top of nine inches of Class 5 base and 8 feet wide with tooled joints every 7.5 feet. These shoulders were not tied to the driving or passing lanes. The driving lane was textured with an aggressive application of the transverse boom surface texturing and the passing lane was textured with a mild application of the transverse broom texturing.

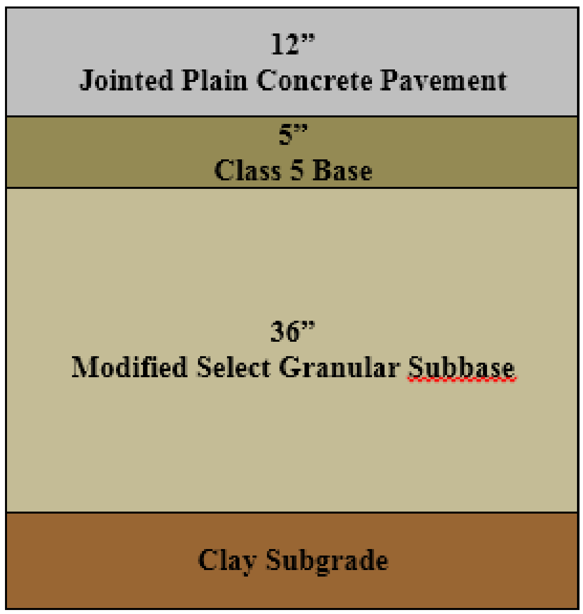

Figure 1: Test Cell Design

The next chapter describes the technologies that the researchers used in providing a 5 year assessment of the performance of the test cell.

Chapter 2: TEST METHODS

The previous chapter introduces the 60-year design test cell and provided a contextual description of the MnROAD Test Cell. This chapter describes the test methods that researchers used for a five year assessment of performance of this test cell.

Distress Survey

MnROAD test cells are surveyed twice a year (fall and spring) to test for performance and to analyze any ailments that may be present in the cells. Surface distress is typically analyzed on the basis of cracking that may be present in cells. The types of cracks that can occur are: surface initiated or top-down cracking, transverse thermal cracking, and longitudinal cracking. During the survey, the number of cracks for each type of cracking scenario is observed and counted to dictate the extent of distress that may be plaguing that particular cell. Along with cracking, joint seals and spalling were also observed in the survey.

International Roughness Index

The International Roughness Index (IRI) is the universally accepted standard measure of ride quality and pavement smoothness. IRI is a mathematical property of a two-dimensional road profile, or elevation as it varies with longitudinal distance along a travelled path. The international roughness index is based on the vertical acceleration of a quarter car's suspension in response to a pavement surface while riding at a speed of 50 miles per hour. More specifically, IRI is the sum of the quarter car's vertical acceleration induced displacement from an assumed neutral plane surface per unit horizontal distance traveled. A consequence of this scenario is the frequency related response of the quarter car to emulate the human resonant frequencies in terms of ride comfort during ride measurements. Because the rider tends to be more sensitive to certain frequencies than others, the response multiplier algorithm is applied when calculating IRI to more accurately mimic the human response. The IRI multiplier algorithm is not uniform in all wavelengths. The gain algorithm peaks at the quarter car resonant frequencies as well as what are assumed to be the body excitation frequencies. Wavelengths that are considered to significantly reduce rider comfort receive higher gain in the IRI algorithm. The gain algorithm of the quarter car model thus provides for peak gains in axle hop and body bounce wavelengths of 32-feet and 68-feet respectively. A relatively smooth pavement with wavelength features close to these two peaks will, according to the IRI algorithm, ride rough.

IRI can be calculated from profiles obtained with any valid measurement method, ranging from static rod and level surveying equipment to high-speed inertial profiling systems. MnDOT measures IRI with a Lightweight Inertial Surface Analyzer (LISA) shown in Figure 2. The LISA is a profile device that measures the amount of vertical rise over a horizontal distance. This is done with two separate laser sources on the side of the vehicle. One laser, the "ROLINE", takes continuous profile measurements over a four inch wide path. The second laser, the "TriODS" (triple laser) measures three discrete profiles across the four inch path. The raw data from these lasers is then used to calculate the IRI, with higher IRI corresponding to rougher pavement.

Figure 2: Lightweight Inertial Surface Analyzer

Friction Number

Cell 53 was tested for friction using the three ASTM standards for skid resistance of paved surfaces: ASTM E274 that uses a full-scale tire, ASTM E501 that uses standard ribbed tire, and ASTM E524 that uses a smooth tire. This method utilizes the KJ Law Friction Trailer shown in Figure 3 to perform skid testing of the pavement surface. This test is usually performed at least twice a year on all cells at MnROAD. The friction trailer is pulled at 40 miles per hour. The trailer first moistens the pavement surface with water and a brake activates locking the wheel in place. This applies both horizontal drag forces and vertical load forces to the pavement. Sensors located at the wheel assembly take the friction measurements. The test is performed on both the inside and outside lanes of the test cell. The test generates friction numbers between 0 and 100. A pavement with a friction number from a smooth tire of 25 is considered a safe pavement with adequate skid resistance. A friction number less than 15, however, would describe a pavement needing rehabilitation to achieve sufficient skid resistance [1].

Figure 3: Lock Wheel Skid Trailer

Surface Texture

The surface texture of Cell 53 was evaluated using a device called the Circular Track Meter (CTM). The CTM shown in Figure 4 below is a laser-equipped device that scans the surface of a pavement in accordance with ASTM E2157, Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter. The CTM is equipped with a Charged Coupled Device (CCD) laser displacement sensor that sweeps the pavement surface in a circle 11.2 inches in diameter and 35 inches in circumference. The displacement sensor for this instrument is mounted on an arm that rotates at 3 inches (76-mm) above the surface. The arm moves at a tangential velocity of 6 m/min (19.7 inches/min). The laser collects measurements at a sample spacing of 0.87 mm (0.034 inch), resulting in 1,024 depth measurements per revolution. The data is segmented into eight 111.5 mm (4.39 inch) arcs of 128 samples each. From each segment, the computer software computes the Mean Profile Depth (MPD), the root-mean-square texture depth (RMS) of each segment, and the average of all eight-segments. A plot of the 8 segments of MPD is also produced. Because pavement texture usually has a specific direction, effectively only 2 of the 8 segments mimic the actual surface texture.

Figure 4: Circular Texture Meter

On-Board Sound Intensity

The On Board Sound Intensity (OBSI) test measures the noise generated from the tire – pavement interaction. MnDOT became one of only five states in the U.S. to utilize OBSI when it began testing in 2007. One advantage of using the OBSI method to measure sound generation compared to the traditional Statistical-Pass-By Method, is that it allows the noise generated from the pavement-tire interaction to be isolated from other sources, such as engine noise and the surrounding landscape noise. OBSI testing is done according to the AASHTO TP 79-08 (11) procedure. The process analyzes data recorded with microphones located close to the tire-pavement contact. Because the dominant noise generation source becomes the tire-pavement interaction when cars travel at freeway speeds, the test is performed at a speed of 60 mph. A test length of 115-feet is measured to adequately capture the desired noise source.
The OBSI test set-up consists of a sedan outfitted with a standard reference test tire (SRTT), four GRAS sound intensity meters, and a BRUEL AND KJAER front-end four-channel frequency analyzer. The microphones are suspended from the vehicle frame and positioned at 3 inches

vertical displacement and 2 inches lateral displacement from the leading and trailing end of the standard reference tire and pavement contact. The microphones are anchored to a free rotating ring mounted on the right wheel that allows the microphone assembly to be fixed in position and direction without inhibiting the rotation of the tire (See Figure 5).

Figure 5: OBSI Device

To analyze the data, PULSE noise-and-vibration software is installed in a connected computer. The computer receives and analyzes the data categorizing the response into component third octave frequency output. The sound intensity captured from these meters is then used to calculate OBSI using the following logarithmically scaled, A-weighted equation to closely relate it to the human hearing spectrum.

$$OBSI = 10\log_{10}\left[\sum_{i=1}^{12} 10^{(SI_i/10)}\right] \quad (1)$$

$$i = Third - Octave\ Frequecny$$

$$SI_i = Measured\ Sound\ Intensity\ at\ frequency\ "i"$$

The OBSI is determined by averaging the sound intensity measurements from each of the following 12 third-octave frequencies: 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000, and 5000 Hertz. These frequencies are determined using the algorithm below.

$$For\ the\ n^{th}\ octave: \quad \frac{F_{n+1}}{F_n} = 2^{\left(\frac{1}{n}\right)} \quad (2)$$

$$Such\ that\ if\ \ n = 3\ \ and\ F_1 = 400\ Hz:$$

$$F_2 = 400 * 2^{\left(\frac{1}{3}\right)} = 500\ Hz, \qquad F_3 = 500 * 2^{\left(\frac{1}{3}\right)} = 630, \qquad Hz\ F_4 = 630 * 2^{\left(\frac{1}{3}\right)} \ldots$$

Using this formula to calculate OBSI, a 3-dBA reduction is equivalent to approximately 50 percent loss of sound intensity from a uniform source. If$OBSI_1 - OBSI_2 = n$, and the respective sound intensities are I_1 and I_2 in Watts /m^2 respectively, then $10\log\left(\frac{I_2}{I_0}\right) - 10\log\left(\frac{I_1}{I_0}\right)$ equals n, where I_0 is the sound intensity at the threshold of human hearing. Therefore $\left(\frac{I_2}{I_1}\right) = 10^{\frac{n}{10}}$. For instance, when the difference in OBSI is equal to 3 dBA, the ratio of actual sound intensity is 2. When the difference in OBSI is equal to 6 dBA, the ratio of sound intensity is 4.

Faulting

Concrete pavements are constructed with transverse contraction joints to relieve stresses in the slabs caused by temperature and moisture. Over time, traffic loading and erosion of the soil layers under PCC slabs results in faulting of the transverse joints. Faulting is defined as a difference in elevation across a joint of pavement. Faulted joints have a direct impact on the ride quality of the pavement.

Fault measurements at MnROAD began in the fall of 1994, shortly after traffic was first placed on the test sections, and are typically taken three times a year. Measurements are taken using an electronic digital faultmeter. MnDOT's original faultmeter was constructed to Georgia DOT specifications; however, the original design came with some inherent flaws. The design required the operator to pick up the device between each measurement. Also, since there was no storage memory on the device, the operator would have to handwrite each output of the meter on a spreadsheet. This could introduce some human error into the process.

In response to these flaws, modifications to the device were made in the winter of 2001-2002 to enhance the repeatability of the measurements. The principle change was the replacement of the four point "long feet" system, with a three point "bolt feet" system. Due to surface irregularities in the concrete pavement slabs, the four point long foot system commonly resulted in the operator having to move the device several times to avoid rocking of the base, which often led to non-repeatable measurements. By installing the three point "bolt head" feet, the device could simply be set down for a quick, stable and repeatable measurement. Paint marks were applied to the pavement for each measurement location.

Figure 6: Faultmeter

Figure 6 above shows the MnROAD device in working mode. The handle is adjustable to accommodate someone of average height. The handle can also be turned and lowered for a more compact unit for transporting. The data collection process is handled primarily by the program on the tablet computer. It is based on the Crandun Technologies library of commands for the laser and Visual Basic for Application and runs in Microsoft Excel. Once the operator opens the specific program for the cell they are in, the program instructs them through the collection process. Upon finishing the collection process for the cell, the operator presses one more button to save the data to the tablet hard drive. From there the data can be transferred via a network connection.

Dynamic Load Response

Embedded sensor testing at MnROAD is done four times a year using a five-axle tractor-trailer or any other configuration that is in line with the research plan. Ten runs are made on each cell—five slow runs (approximately five miles per hour) and five fast runs (approximately 40 miles per hour). Special load testing is also done, which includes offset runs and Falling Weight Deflectometer (FWD) testing. Offset runs are a series of low speed runs each at a specific offset from the centerline, beginning with the right steer tire on the edge-line (12 foot offset). Five runs are made with each successive run a foot closer to the centerline, and allows for a basic understanding of the range of responses from the sensor array generally located at a ten foot offset. FWD testing is a procedure which involves centering the FWD load plate on the sensor location and dropping three different loads on the pavement while collecting strain or pressure cell responses. The typical load levels are 6,000 lbs., 9,000 lbs., and 15,000 lbs. This exercise provides a baseline data set for sensor responses to a very controlled loading, assuming that the sensor position is known and the FWD is positioned properly.

Layer Moduli & Load Transfer

The Falling Weight Deflectometer (FWD) device is more typically used at MnROAD to measure the response of a pavement layer or system to a dynamic load. Measurements with the FWD are obtained both routinely (on a monthly or seasonal basis), and also for specific load test studies and sensor response verification.

The FWD device consists of a loading plate, weight package, geophone sensors, and data acquisition equipment. Mounted to a trailer, the equipment is designed to simulate the impulse load of a passing wheel. The test consists of hydraulically lifting the weight package and letting it drop in a free fall, such that a dynamic load is applied to the pavement from the plate. Simultaneously, the geophone sensors which are spaced at specific distances from the load plate capture the resulting deflection basin. The test is repeated for three different load levels, typically around 400, 600 and 750 kPa, with three drops for each load level. Nine sensors are placed at approximately 0, 200, 300, 450, 600, 900, 1200, 1500, and 1800 mm from the center of the load plate. The resulting deflection basin can be used to back-calculate the modulus of the underlying layers, as well as comparing relative deflections in the pavement layers over time to identify signs of failure. The Dynatest 8000 model has been used at MnROAD since 1994 and is shown in Figure 7 below.

Figure 7: FWD Trailer

Chapter 3: RESULTS

Distress Survey

Distress survey revealed slight spalling of joints but the joint seals were still in good condition. Most of the surface distresses resulted from topical sensor installation and not from traffic or environmental loads.

International Roughness Index Results

Figures 8 and 9 below show the historical ride quality measurements for cell 53 results from both the "ROLINE" and "TriODS" laser measured using the LISA device. In comparison of both laser types, it is clear that the inside lane has a higher IRI than the outside lane. This may be a result of the traffic loading on the inside lane only effecting the ride quality. However, this trend was already visible in the fall of 2009, only one year after paving. There does appear to be some seasonal trends, with higher IRI values generally being measured in the fall months, and lower IRI values being measured in the spring months. Some lane/wheel path combinations have very slightly increasing trends in IRI over time, while some have very slightly decreasing trends over time. Therefore, it suggests that the ride quality is not drastically changing with continued environmental or traffic effects. To further analyze the seasonal trends, Autoregressive Integrated Moving Average Modeling (ARIMA) is done in a subsequent chapter. Federal Highway Administration has published threshold values for good, acceptable and not acceptable values of IRI for ride quality performance. A value less than 95 in/mile is said to be good, and a value of less than 170 in/mile is said to be acceptable. This converts to approximately 1.5 m/km and 2.7 m/km respectively. According to the data below, all measurements except for the fall/winter of 2010/2011 in the inside RWP achieved IRI values in the acceptable range. The generally higher IRI since Cell 53 was new may be a result of the transverse broom finish, not necessarily due to poor ride quality. The other factor that could be causing high IRI is the fact that Cell 53 was constructed one lane at a time, and the concrete was placed in fixed forms.

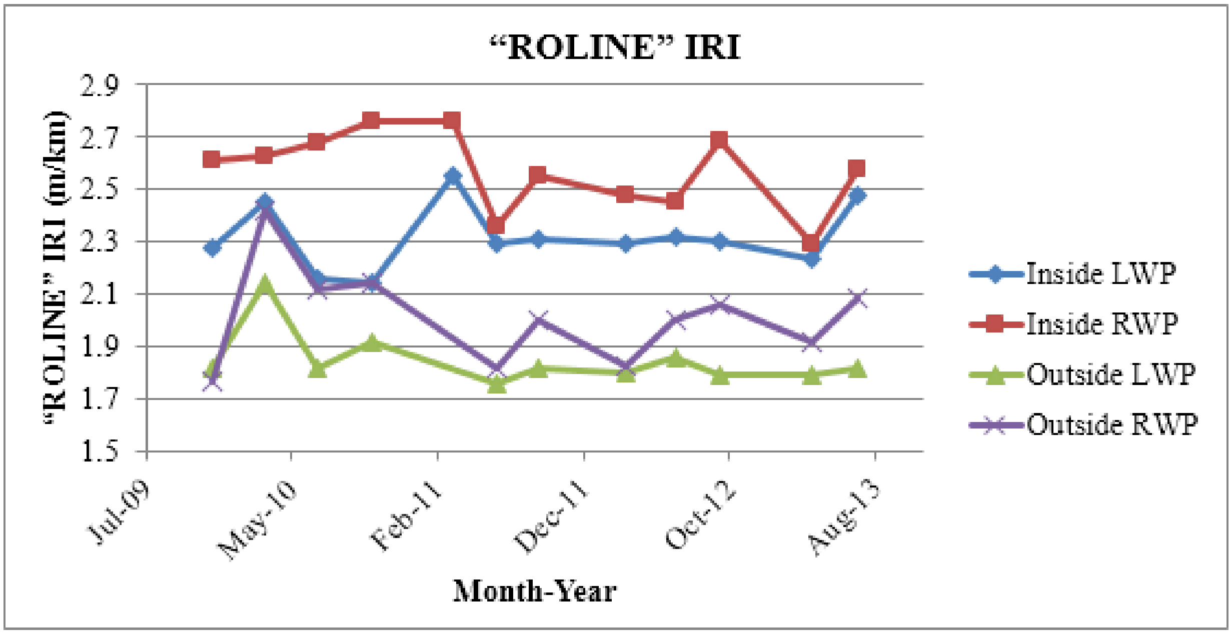

Figure 8: "ROLINE" IRI for Inside and Outside Lane

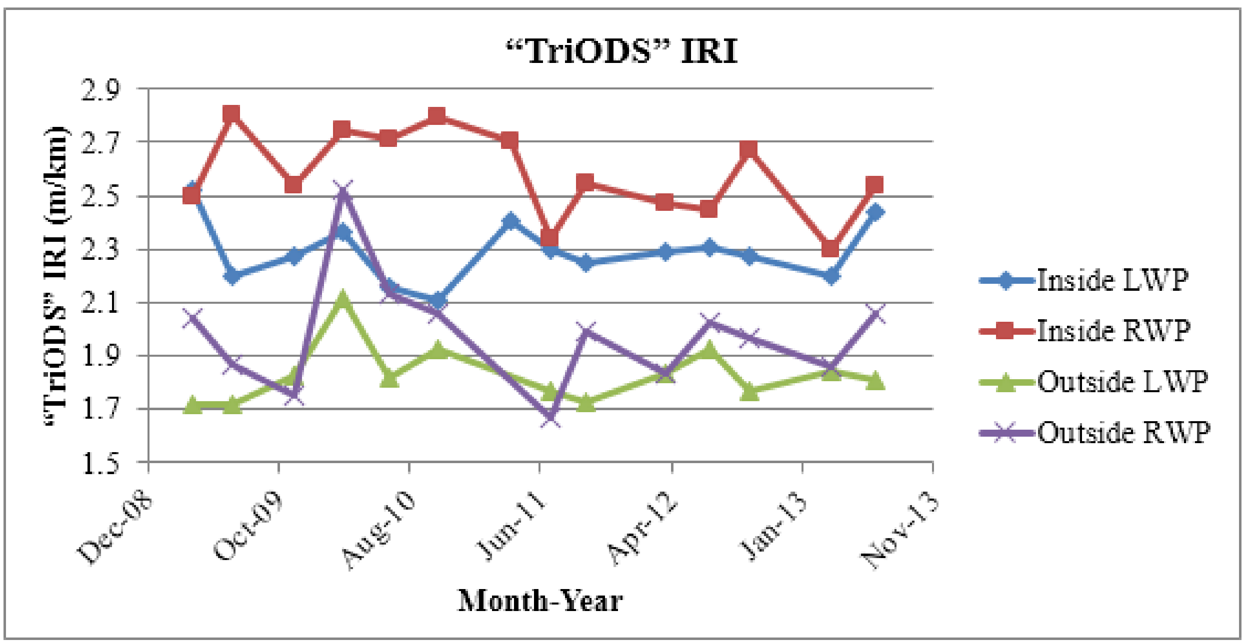

Figure 9: "TriODS" IRI for Inside and Outside Lane

Friction Number RESULTS

The skid test generates friction numbers between 0 and 100. A pavement with a friction number from a smooth tire of 25 is considered a safe pavement with adequate skid resistance. A friction number less than 15, however, would describe a pavement needing rehabilitation to achieve sufficient skid resistance [2]. The friction numbers for Cell 53 were all well above what is required for a safe pavement. In general, it appears that the outside lane has a higher FN than the inside lane. This may be due to traffic wearing down the transverse broom finish in the inside lane. The friction numbers do not appear to be decreasing or increasing significantly over time and are continuing to achieve adequate results after nearly five years of service.

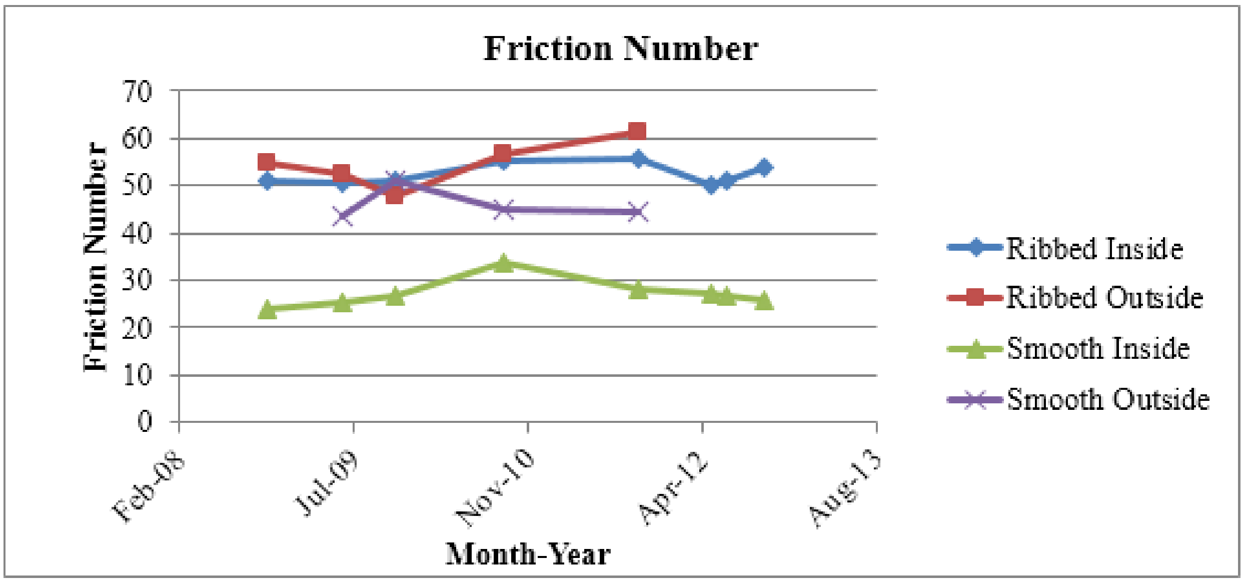

Figure 10: Friction Numbers for Inside and Outside Lane

Surface Texture Results

Figure 11 shows the average measured mean profile depth of Cell 53 over time. It is clear that the inside lane, in both wheel paths, has much lower MPD than the outside lane. Again, this may be due to the traffic on the inside lane wearing down the transverse broom surface. The outside lane does seem to have a slight decreasing trend over time, however the inside lane (with traffic) remains relatively constant around 0.45 mm. In both cases the left wheel path has a lower mean profile depth than the right wheel path.

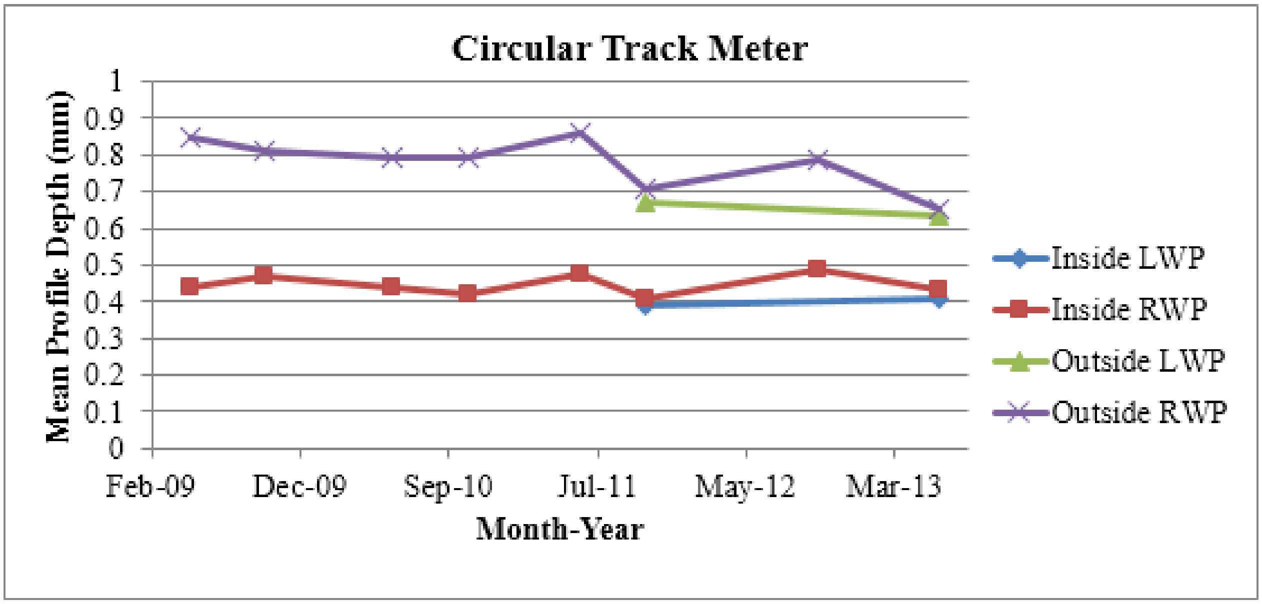

Figure 11: Mean Profile Depth for Inside and Outside Lane

On-Board Sound Intensity Results

From Figure 12, it appears that Cell 53 had a relatively high OBSI when originally constructed and tested. However, OBSI measurements do tend to be higher in winter months, and the OBSI drops down to more common OBSI levels for measurements in 2009. When the first measurement is ignored, it does appear that there is an increase in OBSI over time. The outside lane seems to be sustainably noisier than the inside lane, which may be due to the transverse broom texture being more worn down on the inside lane from traffic.

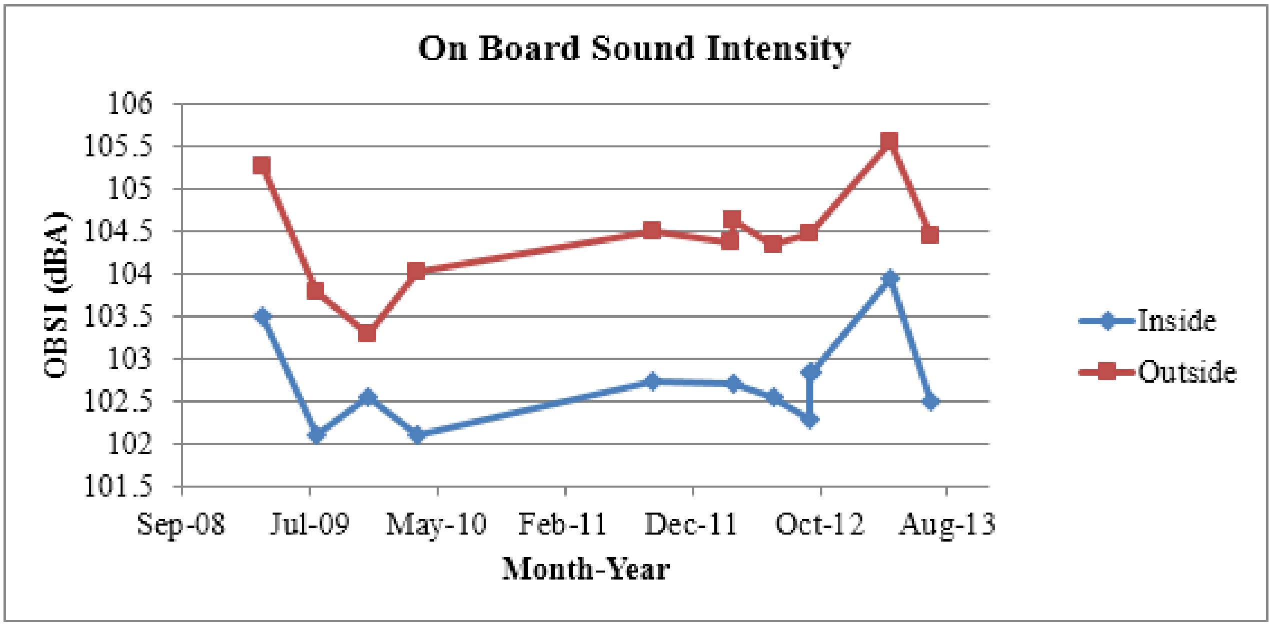

Figure 12: On Board Sound Intensity for Inside and Outside Lane

Faulting Results

Three joint locations in Cell 53 were routinely tested for faulting. Figure 13 shows that faulting in all three joints increased (negatively) in the second measurement. However, this movement was in the reverse direction with the third measurement. In general, all three locations had very little faulting, falling less than 0.4 mm for all three test dates.

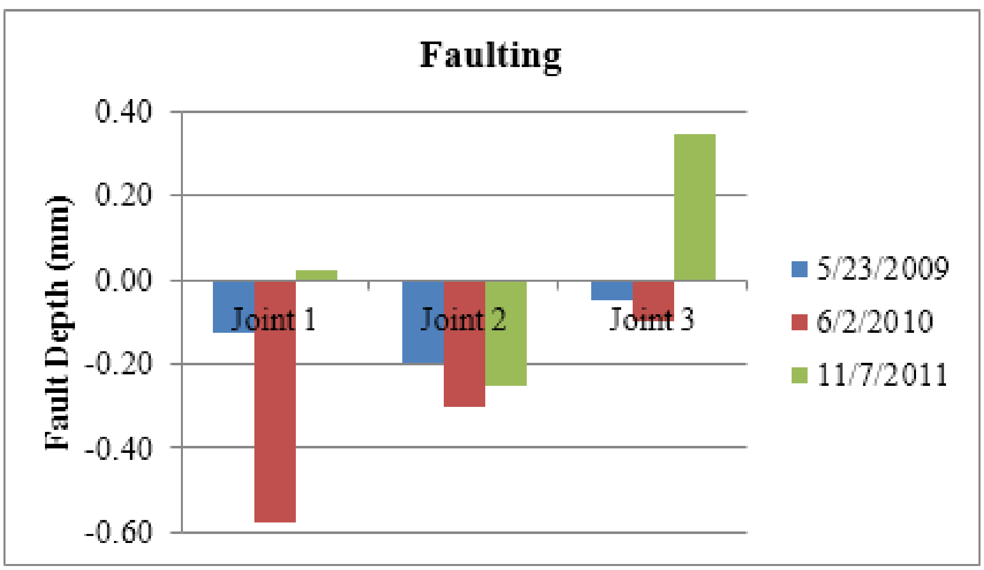

Figure 13: Joint Fault Depth

Figures 14 and 15 show time series graphs for the root mean squares (RMS) of faulting plotted for Cell 53, both for outside and inside lanes. The faulting depths were measured from offset distances of 3ft and 10ft from the centerline of the pavement for both lanes (wheel path for average vehicle) for three joint locations. The plots indicated that faulting for both outside lane and inside lane fall under 1mm in the 5-year period of performance.

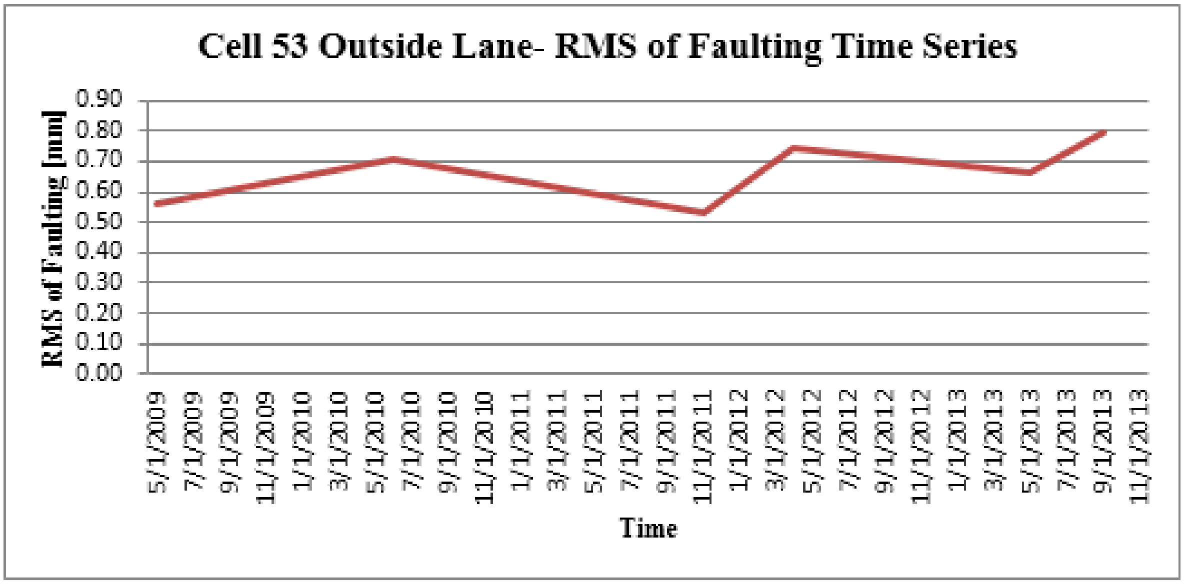

Figure 14: RMS of Faulting time series for Outside lane

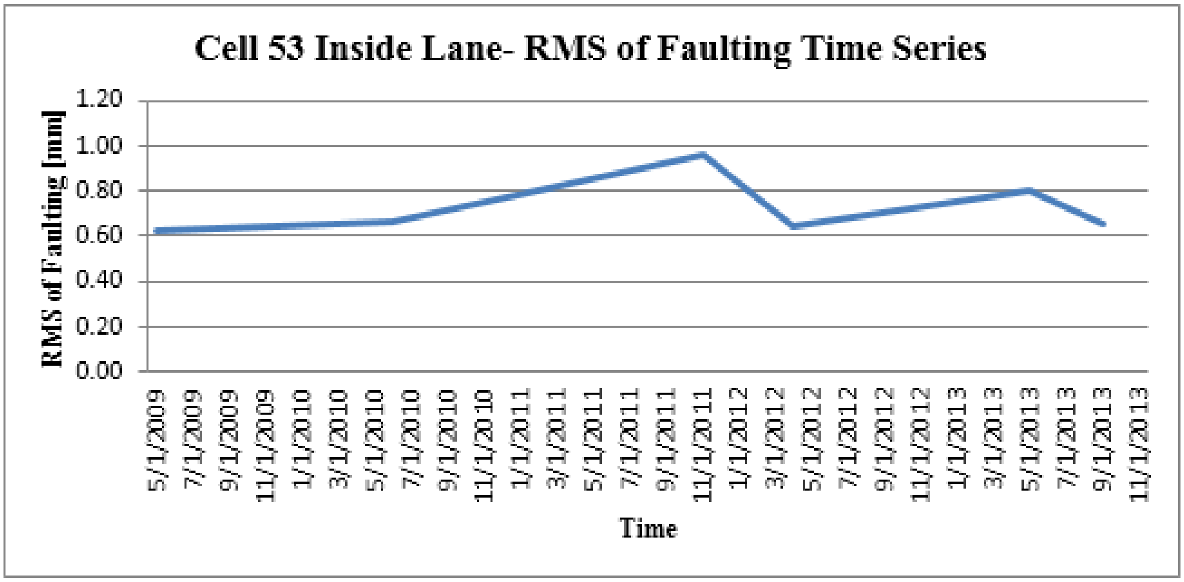

Figure 15: RMS of Faulting time series for Inside lane

Falling Weight Deflectometer

Deflection Basins

To evaluate any changes in the base and sub-base behavior since construction, the deflection basins were plotted using data collected from FWD testing. Failure in the base or sub-base might cause increased deflections from the falling weight deflectometer. One date in the spring of 2009 (4/16/2009) similarly, one date in the summer of 2009 (6/30/2009) was compared to one date in the summer of 2013 (7/24/2013). Six different slabs were tested. FWD testing is performed at multiple locations in the slab, each with a specific purpose. The slabs are tested in the center, edge, and corner, before joint and after joint. To eliminate edge effects, the deflection basins below are from FWD testing performed at the center of the slab.

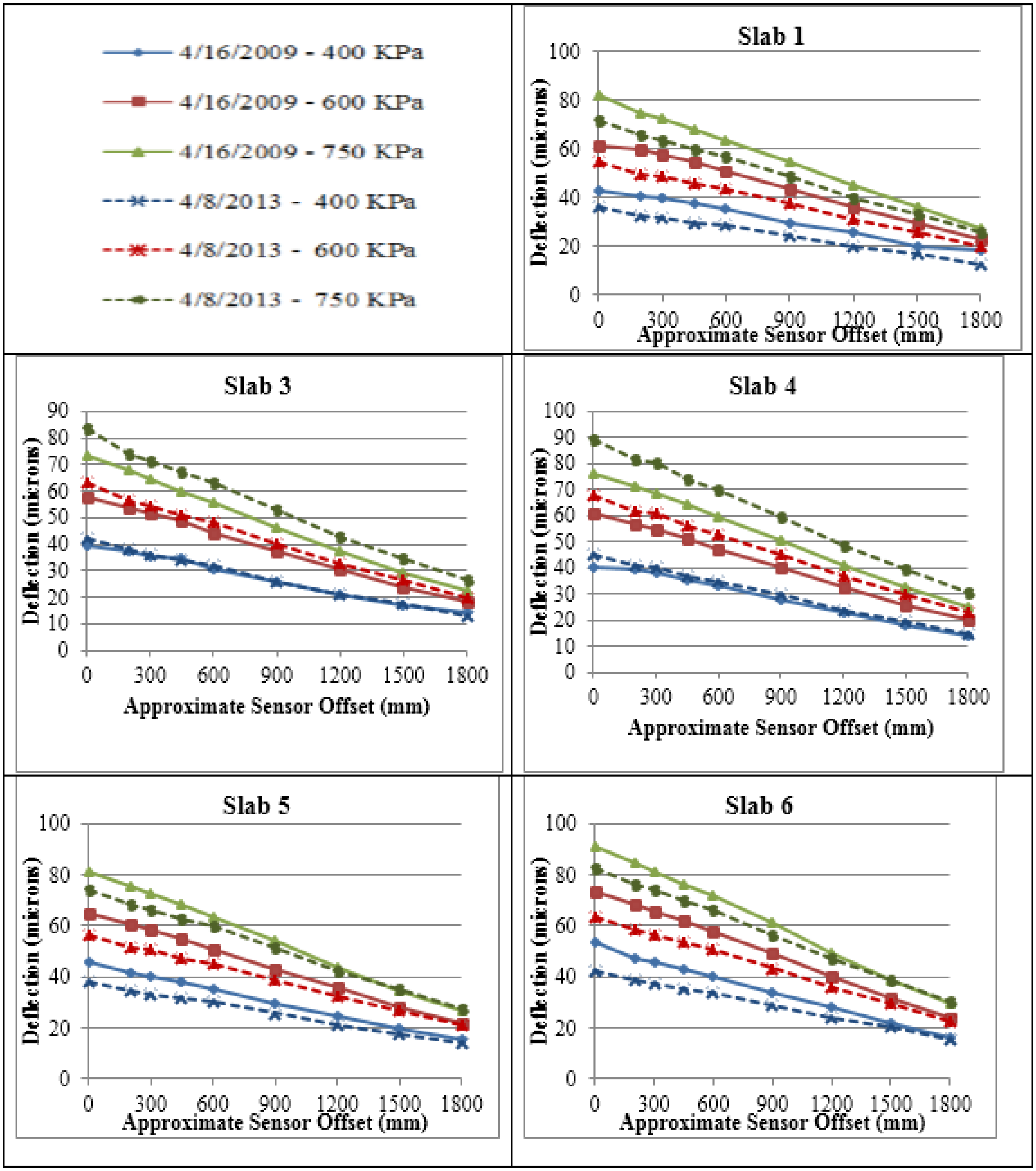

Figure 16: Spring 2009 to Spring 2013 FWD Comparison

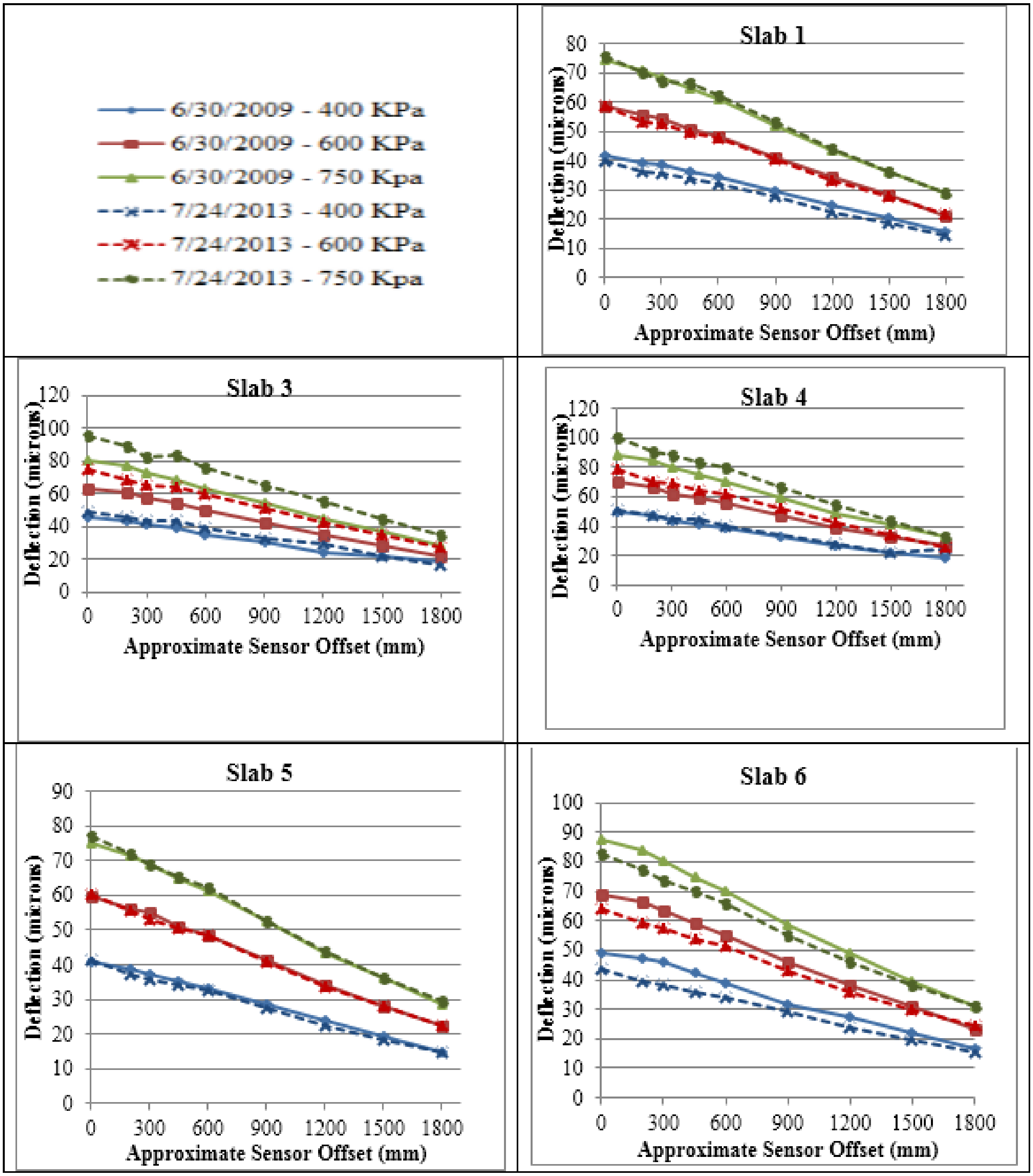

Figure 17: Summer 2009 to Summer 2013 FWD Comparison

In the deflection basins above, the dotted lines represent the FWD testing occurring in 2013, whereas the solid lines represent the testing occurring in 2009. From this analysis, there is not a consistent increase or decrease in deflection from 2009 to 2013. This observation is true for both spring and summer seasons. This could imply that there is not a significant change in base properties or support characteristics within the 4 year span. All deflections fell below 100 microns. A deflection higher than 100 microns at any load level could be a sign of poor base or subgrade support for the pavement.

Load Transfer

To test for load transfer across transverse joints, a FWD trailer is positioned so that the joint falls between sensors 10 and 1 as shown in Figure 18. The load is then applied on the leave slab, and the deflection measured on the leave slab (sensor 1) and the deflection measured on the approach slab (sensor 10) are then used to calculate the load transfer efficiency by taking the ratio between the two, respectively.

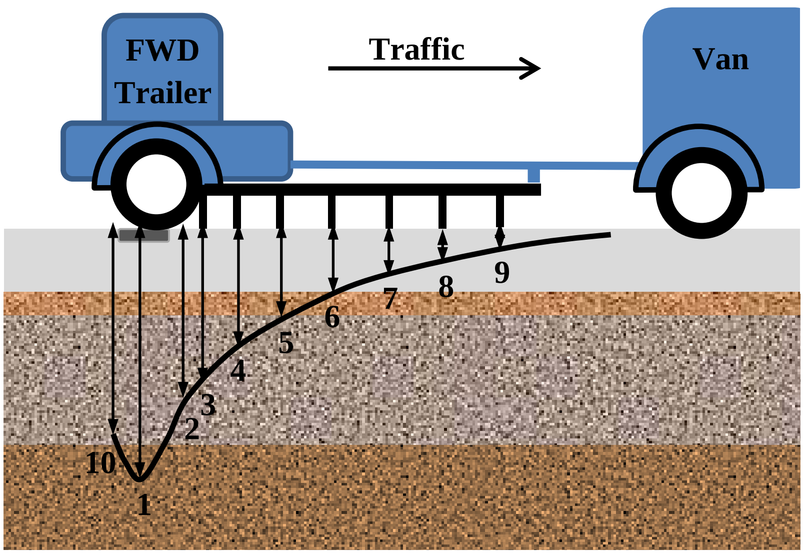

Figure 18: FWD Trailer Setup for Layer moduli Analysis

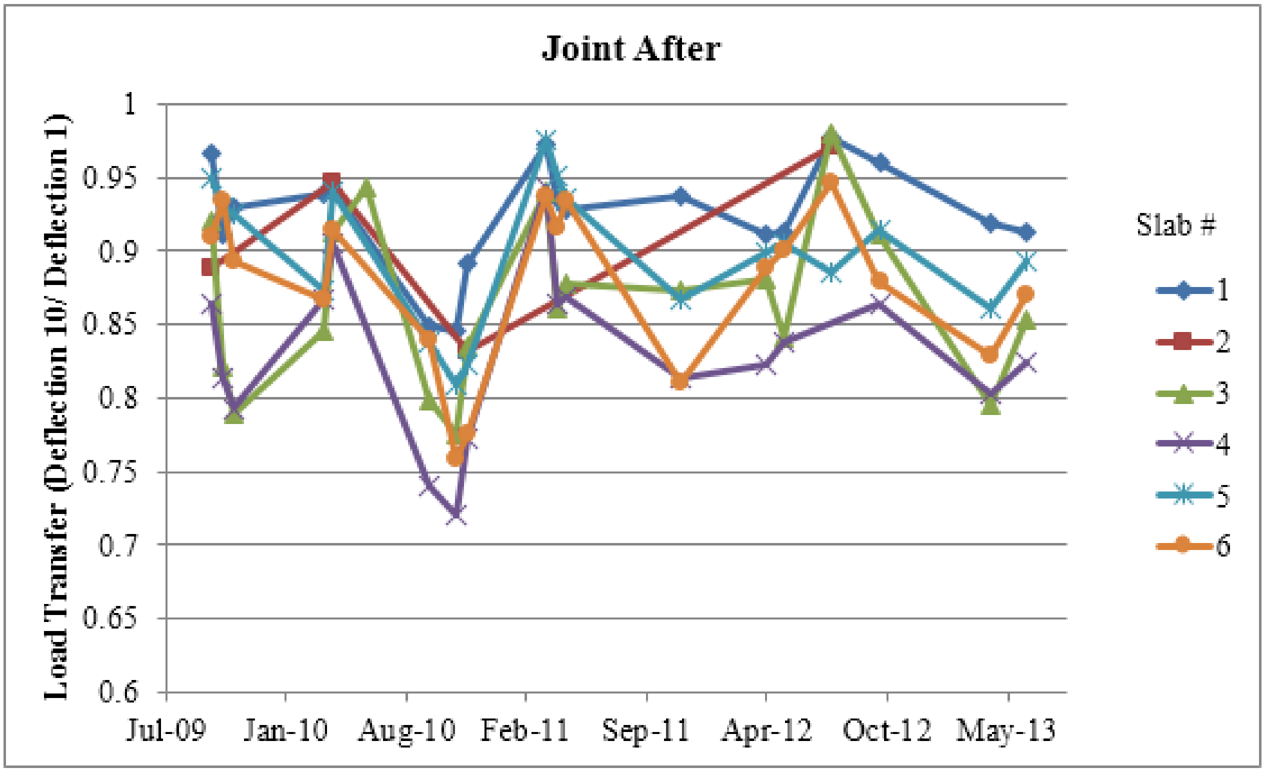

Figure 19: Load Transfer

Figure 19 shows that load transfer for all slabs measured in Cell 53 is extremely high. This could be attributed to excellent load transfer from the dowel bars, as well as added aggregate interlock at the joints in the un-sawn depth of the extra thickness of the pavement structure. There does not seem to be a significant increase or decrease in load transfer in the four years that it was monitored. Besides a few outliers, the load transfer generally fell within the range of 0.95 to 0.8.

To put these results into perspective and to compare load transfer at a doweled joint versus an undoweled joint, a similar analysis was performed on FWD data collected from Cell 32. Cell 32 is 5 inch thick, undoweled concrete pavement test cell also on MnROAD's low volume road. The load transfer of four different slabs during similar dates analyzed for Cell 53 is shown in Figure 20. As was expected, the load transfer for these thin, undoweled slabs is generally much lower than what is found in Cell 53. Although the load transfer in Cell 32 is highly variable and in some cases achieves high transfer ratios, the average for all slabs was around 0.35.

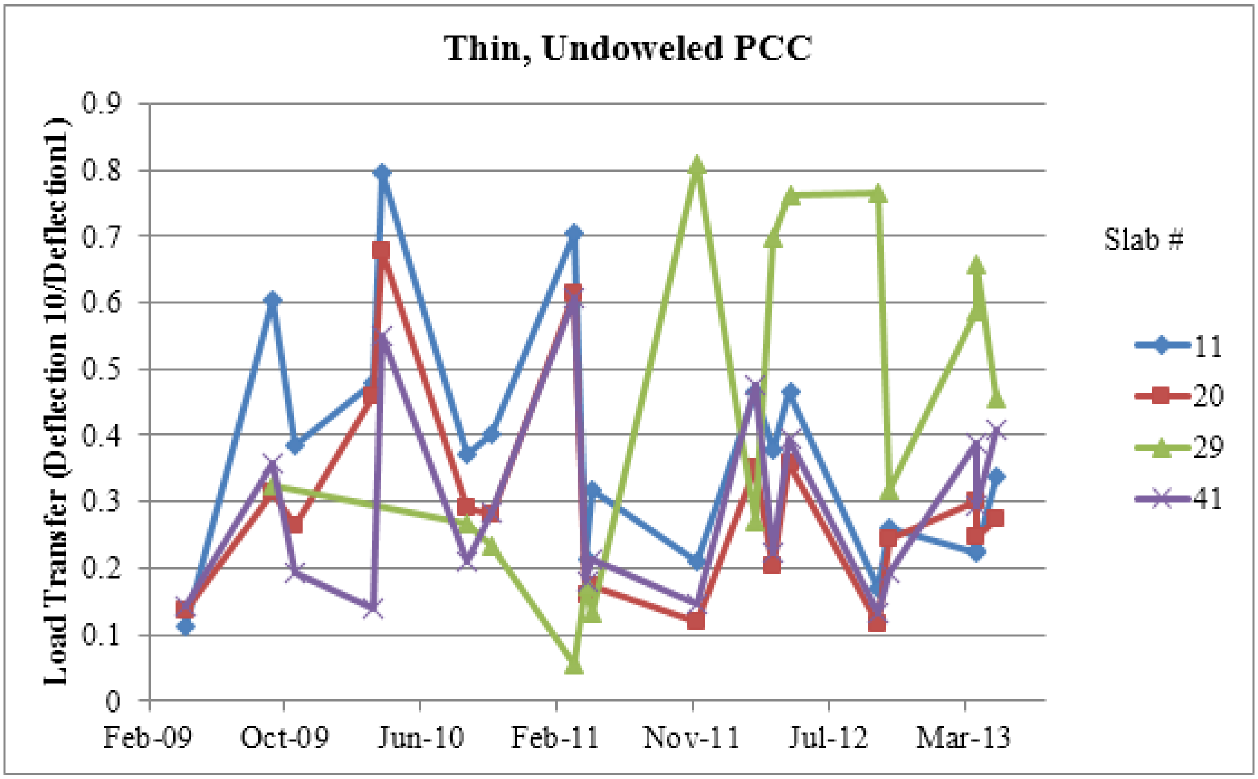

Figure 20: Undoweled Load Transfer Comparison in Cell 32

Moduli Backcalculation

Next, a software program called Evaluation of Layer Moduli and Overlay Design (ELMOD) was used to perform backcalculations of the deflection data collected from FWD testing. ELMOD can analyze the pavement response from the FWD by determining moduli, strain and stress of each of the pavement layers, as well as calculating residual life of the pavement. For the purposes of this report, ELMOD was used to calculate the Elastic Moduli of the concrete, base, sub-base and subgrade layers. This was used to determine if there was a decrease in this property in the base or subgrade layers which may indicate failure. Again, the analysis compared a spring test date in 2009 to one in 2013, as well as a summer test date in 2009 to one in 2013. This approach eliminated any differences in the results that may have been due to seasonal effects. Again, the analysis was performed on data collected in the center of the slab to eliminate edge effects. Multiple slabs were tested at each test date, and the average backcalculated moduli are shown in Figures 21 and 22.

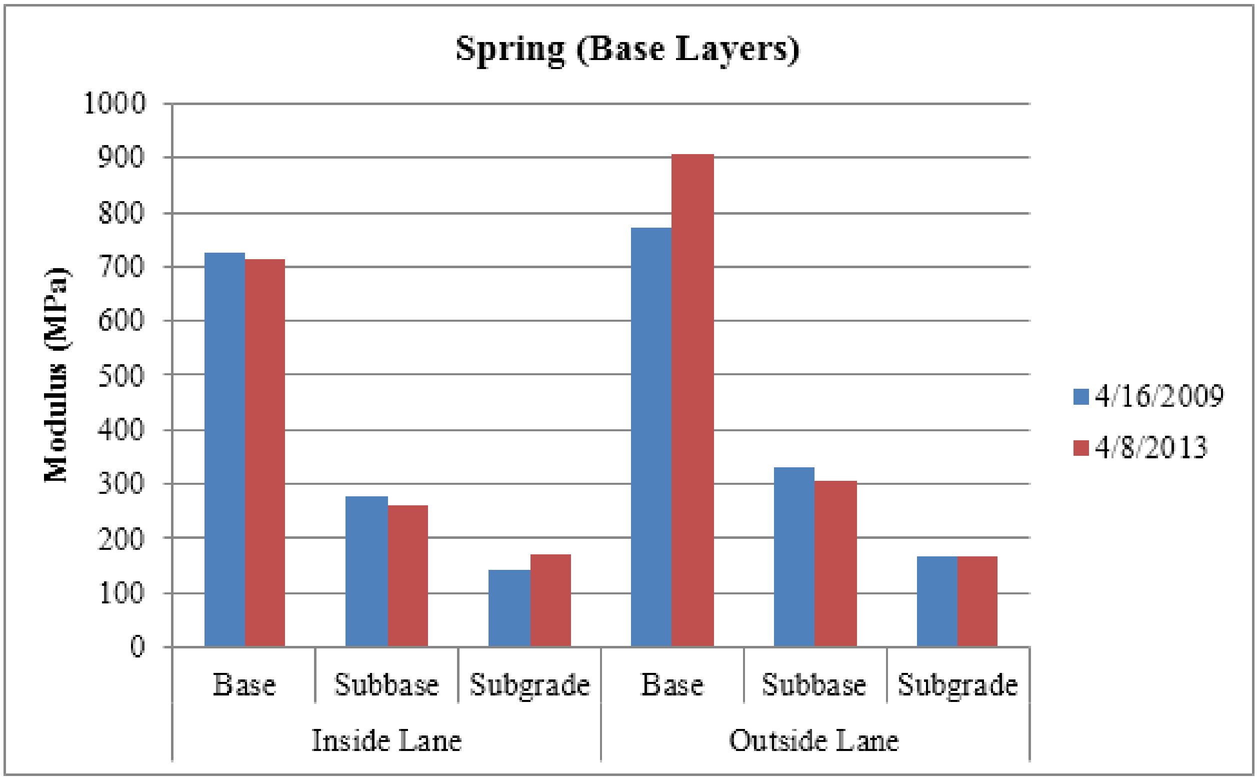

Figure 21: Elastic Modulus – Spring – Base Layers

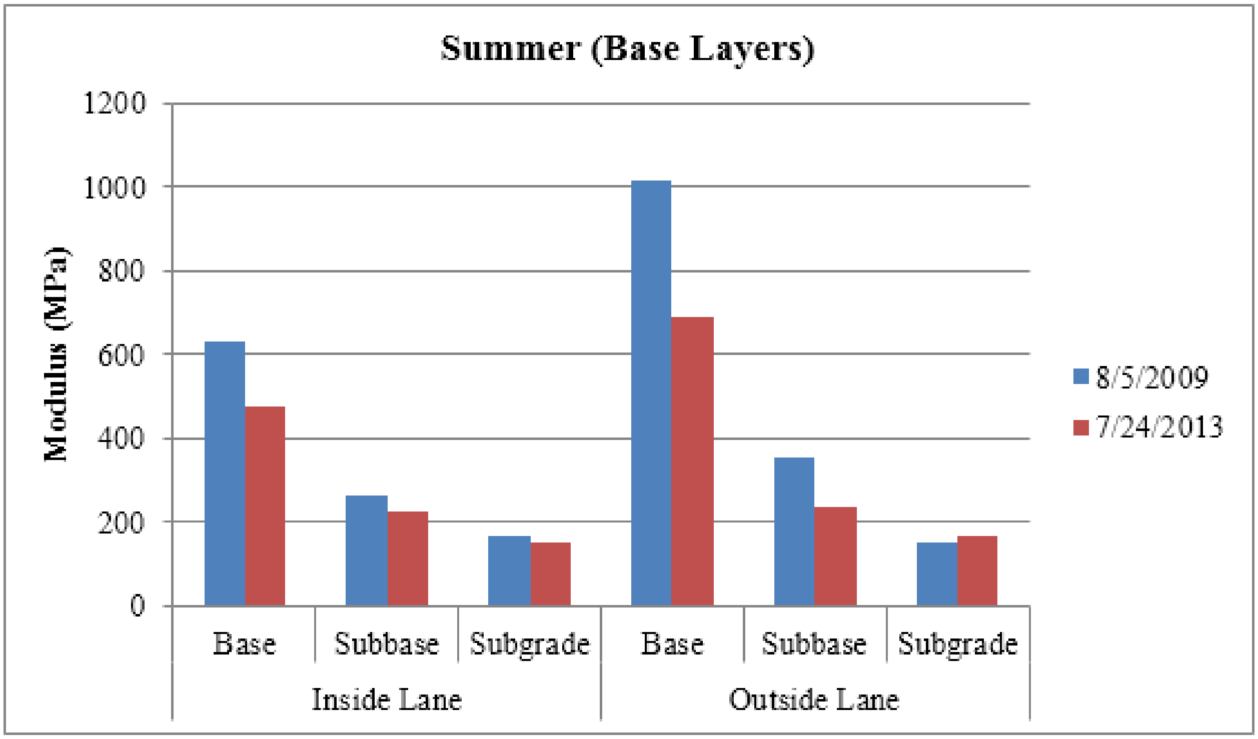

Figure 22: Elastic Modulus – Summer – Base Layers

From the figures, there was clearly no significant decrease in moduli in the base layers during the spring months from 2009 to 2013. In some cases, there was even a slight increase in moduli. It may be that the ground conditions during these two years in the spring month was not similar, with the ground not fully thawed in one year as it had in the other, making the comparison inaccurate. A more accurate representation of the material behavior may be seen in the summer months, when the ground has fully thawed in both years. In this case, as expected, the modulus slightly decreases from the year 2009 to 2013. This decrease was visible in the base, sub-base and subgrade layers.

Dynamic Load Response

The following compares dynamic load response data from the 60 year design cell (Cell 53 PCC pavement 12 inch thickness) to a thinner design with tests conducted somewhat concurrently.

The strategy selected MnROAD Cells 13, 71, and 72 for the comparison. Panel dimensions for all cells are the same; 12-feet wide by 15-feet long. Cell 13(2008 initiative) consisted of five sub-cells, Cells 113-513, with design pavement thickness varying from 5-inches to 6.5-inches respectively. Only Cells 113-313 had been instrumented (no instruments in Cell 413). Cells 71 and 72 are a nine-inch PCC concrete –concrete bonded composite pavement with different surface treatments and different lower layers. The upper three-inches of these pavements are the same. The lower layer (six-inches) in Cell 71 used recycled PCC pavement for the coarse aggregate. In Cell 72, the lower layer is constructed lower quality aggregate than the upper layer but superior to the lower layer of Cell 71 Unfortunately, at the time of this report, dynamic load response data from the sensors in Cells 71 and 72 was not processed.

There is a caveat for the time of data collection in the compared cells. The dates of data collection are different for Cell 53 and the Cell 13 sub-cells, but were logically chosen to minimize bias. Usually, the dynamic data collection for the LVR (Cell 53) is the week after the data collection for the mainline but the data collection for the LVR may be the week prior to mainline data collection. There may be slight differences in temperature between the data collection dates. Differences in temperature may account for need to adjust strain measurements. The data in the table below (Table 1) have not been adjusted for temperature.

Three sensor locations (see Figure 23) were used for this comparison: Sensor 6 is a transverse embedded strain sensor located mid-panel, near the panel joint (9-inches from the joint) within the top ½-inch of the pavement; sensor pair 11/12 (top/bottom) are longitudinal sensors located in the wheel path (C/L offset ~9-feet) at the center of the panel; sensor pair 21/22 (top/bottom) are transverse sensors located in the wheel path, near the panel joint (9-inches from the joint).

Sensor numbering and plan position for the sensors in Cells 53 and 113 are the same. Sensors in Cell 313 occupy the same plan positions but have different numbering. Sensors in Cell 213 differ in plan location and numbering except for the sensor in the same position as Sensor 6 of Cell 53 and Cell 113.

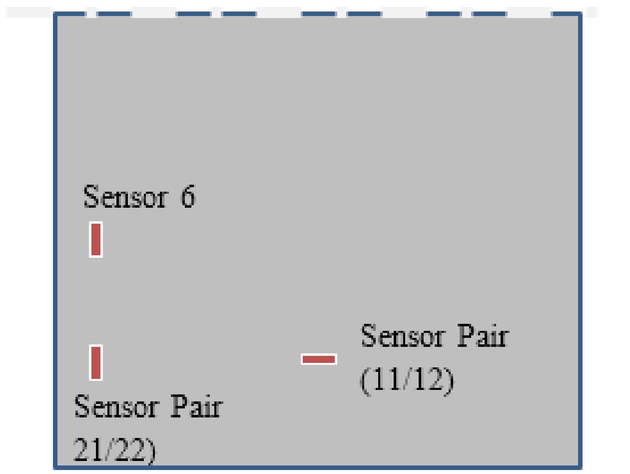

Figure 23: Plan of Sensor Arrangement in Panel

In Table 1, two strains reported for each sensor position included the strain resulting from the steer axle load and the peak strain from one of the trailer axles (whichever is highest).

For example: Given the data collection from August 5, 2009 and the sensor number 6, the strain from the steering axle is 12-micro-strain and the peak trailer strain (from the trailing drive axle in this case) is 13 micro-strain. For sensor pair 11/12, sensor 11 is at the top of the pavement and its response to the steer axle is -18 micro-strain (compression). Sensor 12 is on the bottom of the pavement and its response is 12 micro-strain (tension). The peak strain values from the pair are again taken from the second drive axle and reported -27/16 (top/bottom). Some of the sensor responses were missing. Missing data are represented by “no data”.

Table 1: Strain Comparisons, Cells 53 and 13

Date	Sensor or Sensor Pair	Strain Data from Cells 53 & 113-313							
		Cell 53		Cell 113		Cell 213		Cell 313	
		Steer (µϵ)	Peak Trailer (µϵ)	Steer (µϵ)	Peak Trailer (µϵ)	Steer (µϵ)	Peak Trailer (µϵ)	Steer (µϵ)	Peak Trailer (µϵ)
8/05/09	6	12	13						
	11/12	-18/12	-27/16						
	21/22	-5/9	-9/9						
7/21/09	6			11	12	7	8	7	8
	11/12			-12/26	-24/33			-18/20	-28/26
	21/22			-15/5	-22/11			No Data /4	No Data /8
3/31/10	6	5	7						
	11/12	-18/11	-19/14						
	21/22	-11/8	-12/8						
4/07/10	6			15	20	8	9	7	7
	11/12			-22/22	-25/26			-25/27	-30/31
	21/22			-20/19	-40/30			No Data /No Data	No Data /No Data
4/21/11	6	5	7						
	11/12	-13/ No Data	-20/ No Data						
	21/22	-9/8	-11/10						
4/12/11	6			13	17	10	10	8	8
	11/12			-28/42	-35/50			-20/29	-32/42
	21/22			-30/No Data	-45/No Data			-28/28	-30/30

Results of Dynamic Testing

This section compares strain in Cell 53 (60 year design) to Cells 113, 213, and 313, all of which based on the hypothesis that the thicker pavement section will experience comparatively reduced strain at similar loads. The summarized data comes from the two parts of each cell--steering axle (**steer**) and peak trailer axle strain (**peak**), each of which are measured in units of micro-strain (µϵ). For each sensor pair located on each pavement cell, there were top and bottom sections of the pavement measured at a ½ inch from their respective locations (top and bottom) for both steer and peak parts. The goal was to compare the top and bottom sections of each peak and steer to see how much the pavements strains differed from one another, and if so, by how much. Using a **two sample t-test**, which determines whether or not two means are equal in order to decide whether one treatment is better than the other, we calculated the t-statistic and p-values (both one and two tailed) that aligned with our results. To reach reasonable results that could be calculated with great confidence, we measured this test at a 95% confidence interval.

It is critical we understand the meaning behind both the t-statistic and p-value. The **t-statistic** measures how far our calculated values deviate from the mean hypothesis, which in this case is zero for every study. The further our t-statistic value is from zero can determine whether or not our hypothesized value is small or large enough for acceptance of our null hypothesis. Ideally, we want a hypothesized value of zero or something very close to it, so if we have a fairly large and positive t-statistic value it means our mean hypothesis is not large enough. On the other hand, if our t-statistic value is very small and negative, then it means our mean hypothesis isn't small enough. Having a t-statistic that is either too large or too small indicates whether we accept our null hypothesis or not (generally we would accept the alternative hypothesis if we rejected the null hypothesis). We must also note that our t-statistic is notably characterized by the degrees of freedom presented. The **degrees of freedom** represent the number of values in the final calculation that are free to vary. This means the more unknown values we are presented with in a given sample size, the more degrees of freedom we will have because those unknowns could represent any number that would help give us our mean value. In the case of the two sample t-test, we calculate the degrees of freedom as **2n-2** or **2cr-2**, where n= sample size or c= column and r= row. Table 2 provides an example of a pavement strain study which displays a relatively high t-statistic value of 15.5. Compared to the rest of the t-statistic values calculated for the different cells and their respective steer and peak trailer axle sections, the Cell 213 peak section computed the t-statistic value of 15.5 which appeared to deviate considerably on the positive end from the other t-statistic values calculated. It can be assumed that our mean hypothesis value for the Cell 213 peak section is too small as it could also be for the steer section of the same cell which calculated a t-statistic value of 9.4 (Table 3). However this cell section has three sensor pairs, a sample size not large enough for a definite conclusion. Additionally, the bottom sections for both the steer and peak for cell 213 had values of zero or no calculated data at all (for which we considered as zero), so that might have skewed our data considerably. The t-statistic values for the other cells and their respective steer and peak sections are reasonably being in the range of –3.1 and -2.0. Unlike cell 213 which had a smaller sample size, every other cell had nine sensor pairs (our sample variable) which means a larger sample size and therefore less variability. It would then make sense that although we have negatives, they do not stray far away from zero, and therefore our hypothesized value is considered fit for the data at hand.

Table 2: Cell 213 Peak

	Variable 1	*Variable 2*
Mean	9	0
Variance	1	0
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	15.58846	
P(T<=t) one-tail	0.002045	
t Critical one-tail	2.919986	
P(T<=t) two-tail	0.00409	
t Critical two-tail	4.302653	

Table 3: Cell 213 Strain

	Variable 1	*Variable 2*
Mean	8.333333	0
Variance	2.333333	0
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	9.449112	
P(T<=t) one-tail	0.005508	
t Critical one-tail	2.919986	
P(T<=t) two-tail	0.011015	
t Critical two-tail	4.302653	

Next, we must look at the p-value. The **p-value** is described as the estimated probability of rejecting a null hypothesis when that hypothesis is true. This value is measured on a significance level based on our chosen confidence interval that determines how certain we are about our numerical values being in accordance with our null hypothesis. For this specific analysis, we used a 95% confidence interval. This means there is still a five percent chance of uncertainty regarding our null hypothesis, and our p-value would have to fall above 0.05 in order to accept the null hypothesis which would simply state, "there is no difference between the designs for cell 53 and cells 113, 213, and 313." A p-value below 0.05 would yield a rejection of the null hypothesis, and rather make a case for our alternative hypothesis which would most likely state, "there is a difference between the designs for Cell 53 and Cells 113, 213, and 313." Using a two-tailed test, we found each of the cells to possess a p-value less than 0.05, except for Cell 113 peak as seen in Table 4. Despite the p-value being 0.06, we still have a mean difference of zero and a t-statistic close to zero, meaning our p-value is more likely to indicate that there is a considerable difference in design since it isn't too far off from 0.05.

Table 4: Cell 113 Peak

	Variable 1	*Variable 2*
Mean	-6.88889	16.66667
Variance	867.6111	348.25
Observations	9	9
Hypothesized Mean Difference	0	
df	14	
t Stat	-2.02662	
P(T<=t) one-tail	0.031094	
t Critical one-tail	1.76131	
P(T<=t) two-tail	0.062189	
t Critical two-tail	2.144787	

Based on the results described, we can confirm that based on measured strain values, there is a considerable difference between the 60 year Cell 53 design and Cells 113, 213, and 313. Much of the data calculated points towards our alternative hypothesis, while the data that doesn't align is for the most part statistically insignificant, possibly due to low sample values or other forms of data that gear towards our null hypothesis and outweigh the outliers.

T-test Equation

$$\boldsymbol{t} = \frac{[(\bar{\boldsymbol{x}}_{\mathbf{1}} + \bar{\boldsymbol{x}}_{\mathbf{2}}) - \boldsymbol{d}]}{\boldsymbol{SE}} \quad (3)$$

Where:

$\bar{\boldsymbol{x}}_1$ *is the mean of sample 1 as applicable,*
$\bar{\boldsymbol{x}}_2$ *is the mean of sample 2*
d *is the hypothesized difference between population means, and*
SE *is the standard error of the mean.*
df*= (2n-2) (or df = 2cr-2)*

Chapter 4: CONCLUSION

After five years of performance data have been collected and analyzed, it was found that the 60 year design concrete pavement test cell at MnROAD continues to perform very well in terms of ride and surface characteristics. There was no significant reduction (or decrease) in performance in any of the properties analyzed in this report. The following list summarizes the averages of the first as well as the most current measurements taken of Cell 53, to reiterate the very little change that has occurred over the first five years performance life of the cell.

- **Ride Quality--IRI** ("ROLINE") – 2.1 m/km (11/09) to 2.2 m/km (07/13)
- **Noise--OBSI** (Transverse Broom) – 104.4 dBA (03/09) to 103.4 dBA (07/13)
- **Friction--FN** (Ribbed) – 43 (10/08) to 40 (09/12)
- **Texture--MPD** – 0.64 mm (04/09) to 0.53 mm (06/13)
- **Layer moduli** – 1000MPa (08/09) to 650MPa (07/13)

It is important to note that many of the characteristics of Cell 53 were built in to the test section during construction, and have not developed as a result of poor performance over time. For example, the slightly higher IRI and OBSI measurements may be a result of the transverse broom surface texture applied to the test cell. A similar 60 year concrete pavement design with smoother textures, such as longitudinal tine or diamond grind, could maintain excellent ride quality and low tire pavement noise.

The test cell displayed excellent load transfer at all of the joints tested in this research. The average load transfer was around 0.85, which was in some cases over four times as high as another MnROAD concrete pavement test cell which was undoweled. The load transfer did not show a significant decrease over time. The test cell maintained adequate friction for driver safety over time. The faulting measurements were also relatively low, constantly falling under 1mm throughout the 5-year period.

In many cases, measured properties in the inside lane of Cell 53 were significantly different than in the outside lane. This can be attributed to the traffic loading occurring only on the inside lane, leaving the outside lane to only be susceptible to environmental effects. The IRI in the inside lane was consistently higher than the outside lane. Conversely, the OBSI on the inside lane was consistently lower than the outside lane. The lower noise in the inside lane could be due to traffic wearing down the surface of the transverse broom finish. The outside lane generally had higher friction than the inside lane. As for the mean profile depth, the outside lane has a higher value than the inside lane consistently. Finally, the faulting in outside lane was lower than the inside lane in average.

A detailed analysis was performed on the falling weight deflectometer data that went beyond calculating load transfer at joints. Deflection basins were created for both summer and spring dates soon after construction in 2009, and similar summer and spring dates in 2013. These were evaluated to determine if there was a significant increase in deflections over time, which could indicate failure in the base layers. There was not a consistent increase or decrease in these deflection basins in either of the two seasons, which helps support the theory that the base is performing well over time. Deflections were all under the threshold of 100 microns, which also suggests good performance.

Finally, back-calculation of the FWD data using the ELMOD software was performed to determine the layer properties of the pavement test cell. Again, similar dates in both spring and summer seasons were compared for the year 2009 and 2013. The analysis returned inconsistent results for the spring season comparison, suggesting that the base conditions may have been different between years with respect to thaw progress. However, the results for the summer did show a slight decrease in calculated Moduli values for the base, sub-base and subgrade layers, for both the inside and outside lane. This slight decrease over the period of five years could be expected, and should not necessarily be interpreted as failure in the base layers.

A comparison of the strains in the 60 year design cell to the cells of lesser thickness indicated a difference in strain levels based on a 95% confidence level. This validates original hypothesis that the strains are different, thus accentuating one of the advantages of the 60 year design cell. As an extension of the t-test, a z-statistic was used to examine the probability of exceeding the critical strain, but with the established difference it was evident that a z-statistic indicated a lower probability of fatigue failure in the 60 year design cell than the non-60 year design cell with which the comparison was performed.

The valuable data collected during the first five years of service of Cell 53 presented in this report can be used to assess MnDOT's current standards for 60 year design concrete pavement. This data, along with the data collected from the sensors instrumented within the cell, can be used to develop a complete life prediction model for similar types of pavement designs.

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