Long Term Performance of Phase 1 Jointed Concrete Pavement Test Sections at the MnROAD Facility

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Abstract

Since 1994, the MnROAD pavement test facility has conducted comprehensive measurements of the performance and response of a variety of jointed concrete pavement designs. The primary objective of each MnROAD test section is to provide data toward validation or improvement of pavement performance prediction models. This paper examines the long-term trends of several critical performance parameters, for each of the fourteen original jointed concrete pavement sections constructed during Phase 1 (1994-2007) of MnROAD. These parameters include slab cracking, transverse joint deflection and load transfer efficiency, and ride quality. Through continual monitoring of the long-term performance of MnROAD jointed concrete pavement sections, there now exists a useful database of information related to concrete pavement behavior, particularly in colder climates. Analysis of MnROAD Phase 1 data reaffirms that AASHTO-based design methods are conservative in their prediction of performance.

Introduction

MnROAD Facility. The Minnesota Road Research facility, commonly known as MnROAD, was constructed in the early 1990's to serve the purpose of validating pavement design methods of that time period, particularly for pavements constructed in cold regions. Most pavement design methods at that time were based at least in part on pavement performance models developed from the AASHO Road Test, conducted approximately 30 years earlier (Highway Research Board 1962). Many pavement designers were concerned about the continued use of those design methods, given the significant changes in traffic loadings, materials, and construction processes that had occurred over time.

The MnROAD test facility was designed to be a full-scale test track, subject to real-time environment and traffic. Divided into two main segments, the MnROAD facility has one set of test sections or "cells" placed end-to-end that receive live traffic loading diverted from a parallel section of Interstate 94 near Albertville, Minnesota. Another portion of the facility contains a set of test sections arranged in a closed loop, similar to those used in the AASHO Road Test. Comprehensive information and photographs of the MnROAD facility can be found on the MnROAD web page (Mn/DOT, 2011).

The MnROAD facility was originally constructed with forty test sections, each approximately 150m (500 ft) in length. Twenty-three of those sections comprised the interstate traffic portion, consisting of nine concrete and thirteen asphalt pavement test cells. The closed loop portion, also known as the "Low Volume Road" or "LVR," consisted of five concrete, eight asphalt, and four aggregate-surfaced test cells.

The experiments conducted during the first phase of MnROAD, now known as "Phase 1", occurred from 1994 to 2007. In 2008, a large number of test sections on the interstate portion of the facility were reconstructed with sections designed to study more current research topics. Three of the original sections removed were concrete test sections (Cells 5, 6, and 13). Additional test cells were removed or altered in

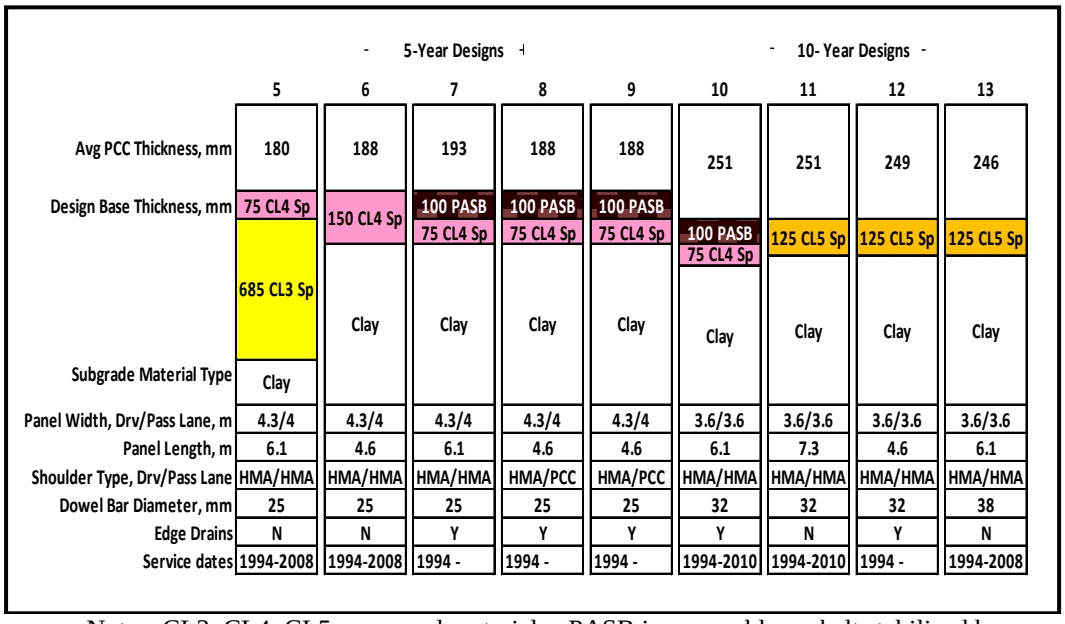
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subsequent years. By the end of 2010, only four of the Phase 1 interstate concrete test cells remained in service.

Given the current need for reliable pavement performance data to calibrate new mechanistic-empirical pavement design procedures, the time seemed right to compile the long history of data available from the MnROAD Phase 1 test cells. This paper provides the performance history of the fourteen original concrete test cells at MnROAD over the time period of 1994-2010. The long term trends of several critical pavement performance parameters are plotted and discussed. This information can be used by pavement researchers or practitioners as they validate or improve recently developed jointed concrete pavement performance prediction models and design methods.

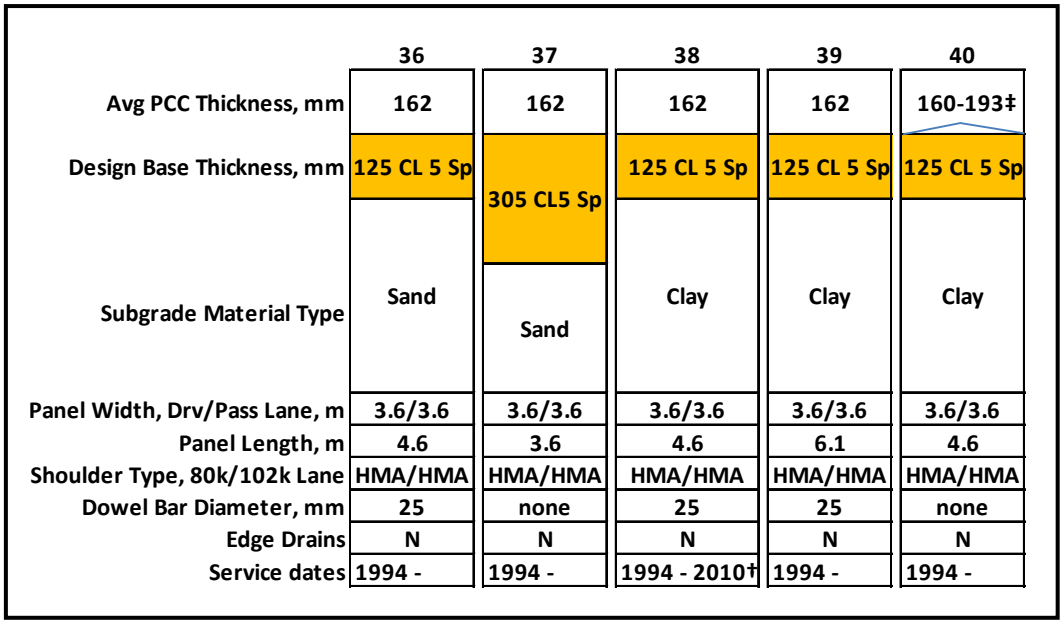
Test Section Design. The original concrete test cells on the interstate portion of MnROAD were divided into two groups. One group, with a design concrete layer thickness of 190 mm (7.5 inches), was designed using the Minnesota Department of Transportation (Mn/DOT) design procedure (Minnesota Department of Transportation 2010) to perform with an AASHTO (American Association of State Highway and Transportation Officials)-based terminal serviceability index above 2.5 for at least 5 years. The second group, with a design concrete layer thickness of 240 mm (9.5 inches), was designed to perform 10 years under the same criteria. Figure 1 provides comprehensive design details for each of the original concrete test cells.

Concrete test cells on the Low-Volume Road portion of MnROAD were designed according to minimum thickness practices, rather than terminal serviceability criteria. Individual cross-section details are shown in Figure 2.



Notes: CL3, CL4, CL5 are gravel materials. PASB is permeable asphalt stabilized base.
Unit Conversions: 1 inch = 25.4 mm, 1 foot = 0.3049 m.

Figure1. MnROAD Phase 1 interstate concrete test cells. PCC thickness shown is the average as-built thickness.



Notes: CL 5 is a gravel material. ‡Cell 40 is a thickened edge PCC design.
Unit Conversions: 1 inch = 25.4 mm, 1 foot = 0.3049 m.

Figure 2. MnROAD Low-Volume Road concrete test cells. PCC thickness shown is the average as-built thickness.

Each of the LVR test cells, except cell 40, had a 152 mm (6 inch) thick design concrete layer. Cell 40 was designed with a "tapered" or "thickened-edge" cross section of 140 mm (5.5 in.) at the centerline, and 178 (7 in.) near the shoulder.

All of the original concrete pavement sections at MnROAD were jointed, with 0.6 m (2 ft.) in 3.6 m (12 ft.) skewed transverse contraction joints. Dowel bar diameter varied in each section, with the exception of Cells 37 and 40, which were undoweled. Dowel bar length was 380 mm (15 in.) and they were spaced 305 mm (12 in.) on center.

Test Cell Alterations. As mentioned previously, several test cells have been altered in recent years. Table 1 summarizes the changes. Of special note are the changes made to Cell 12 in 2006. Several areas near transverse joints in the driving lane of Cell 12 were manually undermined to study their tendency toward corner cracking.

Table 1. Alterations to Phase 1 concrete test cells

Cell(s)	Month/Year	Alterations
12	Jul/2006	Voids created under slab near joint/shoulder to study tendency toward for corner cracking
7-8	Oct/2007	Diamond grind surface as part of surface characteristics study
9	Oct/2008	Diamond grind surface as part of surface characteristics study
39	Oct/2008	Pervious concrete overlay applied
38	Oct/2010	Full-depth joints replacements with innovative load transfer devices

Traffic Loads. Traffic on the interstate portion of MnROAD consists predominantly of 24-hour live traffic diverted off of an adjacent interstate highway. Exceptions include periods when traffic is redirected to safely conduct specific vehicle load tests,

routine pavement performance measurements, or maintenance and reconstruction activities. Figure 3 summarizes the history of live traffic in terms of cumulative CESALs (Concrete [pavement] Equivalent Single Axle Loads) for the test cells located on the interstate portion of MnROAD. Interstate traffic loading began in August 1994.

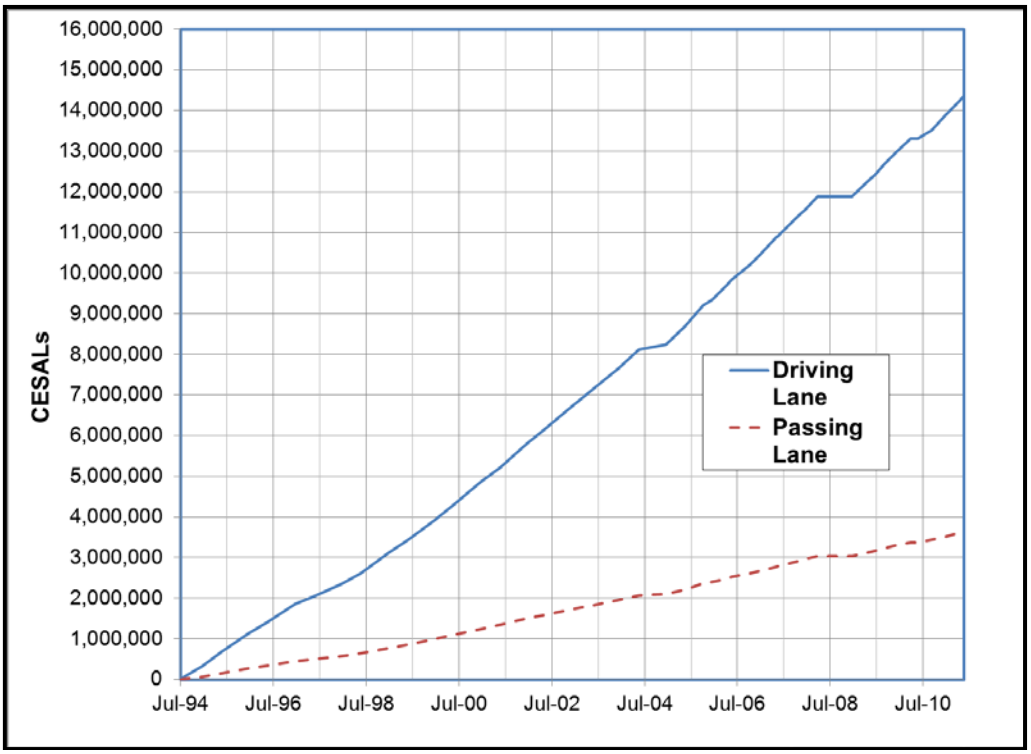


Figure 3. History of traffic loads, in terms of cumulative CESALs, on interstate portion of MnROAD

Traffic on the Low-Volume Road portion of MnROAD is applied predominantly during daytime hours by one semi-tractor trailer combination. For the time period of 1994 to 2007, the truck traveled four days each week, on the inside lane of the loop road loaded to a total weight of 355 kN (80,000 lbs.). During the same period, the truck traveled one day each week on the outside lane of the loop road, loaded to a total weight of 454 kN (102,000 lbs). Since 2008, the truck now travels five days per week only on the inside loop (loaded to 355 kN [80,000 lbs]). The outside lane now receives no traffic, in order to study only the environmental effects on Phase 2 and newer test sections. Figure 4 summarizes the history of Low-Volume Road traffic. Flat sections in the traffic load plots indicate periods of minimal loadings due to test cell maintenance or reconstruction.

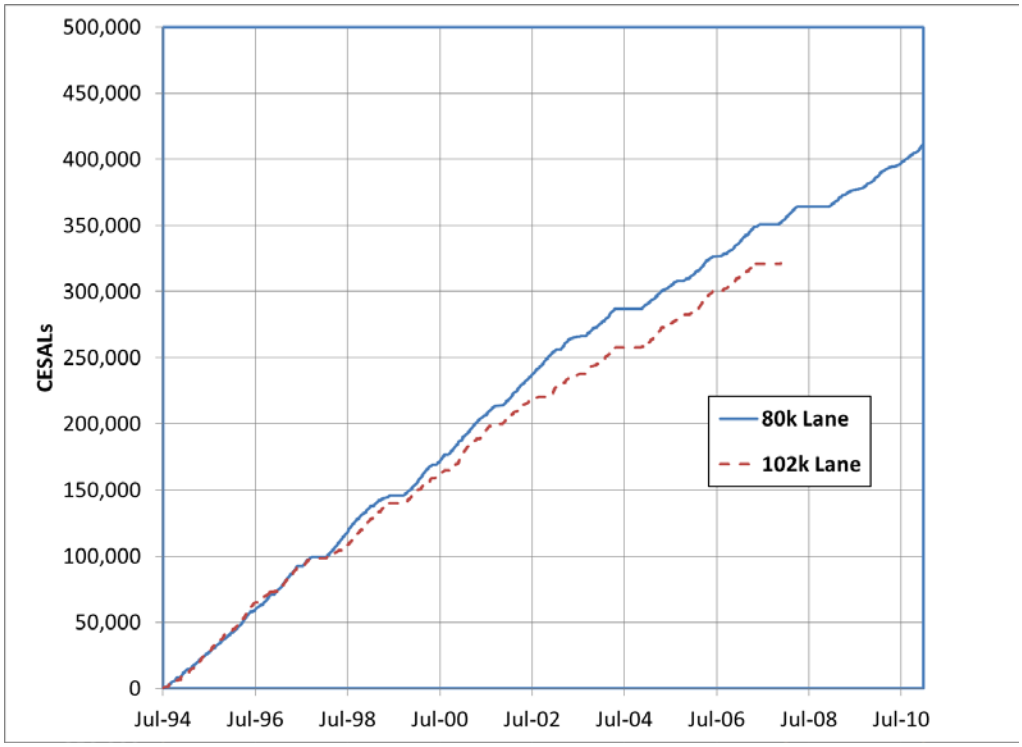


Figure 4. History of traffic loads, in terms of cumulative CESALs, on Low- Volume Road of MnROAD

Table 2 shows the range of traffic loads predicted by the AASHTO-based Mn/DOT concrete pavement design procedure to achieve a terminal serviceability index (P_t) of 2.5 for each design group (Burnham and Pirkl 1997). Also shown is the approximate dates when those traffic loads had actually accumulated in the driving lane. In general, it took longer to achieve the predicted loads than originally planned.

Climate. The climate at MnROAD can be classified as extreme. Recorded concrete pavement temperatures have ranged from -35 to 56ºC (-32 to 133ºF) (Johnson and Worel 2009). Average annual precipitation is 73.7 cm (29 inches) (Burnham and Rohne 2011). The long periods of frozen base and subgrade in winter, following by relatively rapid thawing in the spring, have dramatic impacts on pavement response at MnROAD. It is therefore critical to account for seasonal effects when analyzing MnROAD pavement performance data.

Table 2. Predicted traffic loads to terminal serviceability, and when they were achieved in the driving lane

Design Group	Range of Traffic Loads to P_t =2.5 (CESALs)	Approx. dates to achieve loadings
5-year cells	2.5 to 6.2 million	4/1998 - 9/2002
10-year cells	13.8 to 15.2 million	9/2010 - 7/2011 (est)
LVR cells	1 to 2.4 million*	Not applicable*

*Mn/DOT minimum PCC thickness of 152 mm (6 in.) controlled design.

Test Cell Performance

Critical Parameters. There are only a few critical concrete pavement performance parameters that can be easily measured over long periods of time. These include: slab cracking, joint performance, and ride quality. Previous studies (Burnham 1998, 2005, 2009; Worel and Clyne 2007) have documented the early history of several of these parameters for the MnROAD Phase 1 concrete test cells.

In 2008, several of the original concrete pavement-related studies at MnROAD ended, and their associated test cells were removed. The remaining test cells are now approaching 17 years old, and have endured both heavy traffic loads and exposure to the extreme climate of Minnesota. Many of the cells have carried substantially more traffic loads than they were predicted to carry before reaching AASHTO-defined terminal serviceability. It is appropriate and timely, therefore, to document the long term history of the original cells in terms of the critical performance parameters listed above.

Slab Cracking. Traffic was first applied to the original MnROAD cells in August 1994. Visual distress surveys were conducted periodically since that time. Interestingly, only one of the Phase 1 concrete test cells on the interstate portion of MnROAD developed panel cracking. The driving lane of Cell 5 first developed three corner-cracked areas in 1997. Figure 5A shows one of the "C" shaped cracks that formed in adjacent panel corners. Figure 5B shows the other area, which grew into a meandering longitudinal crack over 4 panels, eventually reaching the centerline. All of the cracks were repaired with slot stitching in August 2006 to keep the cell open to live traffic through 2007.

The most probable cause for the cracking in Cell 5 was loss of support near the edge of the slab and transverse joints. This cell had a history of wide transverse joint openings caused by panels sliding down the grade in the direction of traffic. The wide joint openings caused breaches in the silicone sealant, which led to increased amounts of water and deicing materials entering the joints (Rohne and Burnham 2010). This was also the only cell in the 5 and 10-Year design groups that had a deep 760 mm (30 in.) subbase. The relatively thin slabs, with inherently higher deflections under interstate traffic loadings, may have caused increased compaction and consolidation in the deep base layer. As with all of the other Phase 1 concrete cells at MnROAD, no fatigue type cracking was observed in other panels within Cell 5.

As just mentioned, none of the Phase 1 concrete test cells on the interstate or LVR had observable transverse fatigue cracking as of the winter of 2010. Several LVR cells, the first being Cell 38, did experience transverse cracking within a few years following construction. These cracks were caused by settlement of the backfill in underlying utility trenches. During most winters, these cracks allow frost to heave the pavement slightly, with the slabs returning to near level each summer.

The undermined areas created in Cell 12 in 2006, had not resulted in visible cracking as of the winter of 2010.

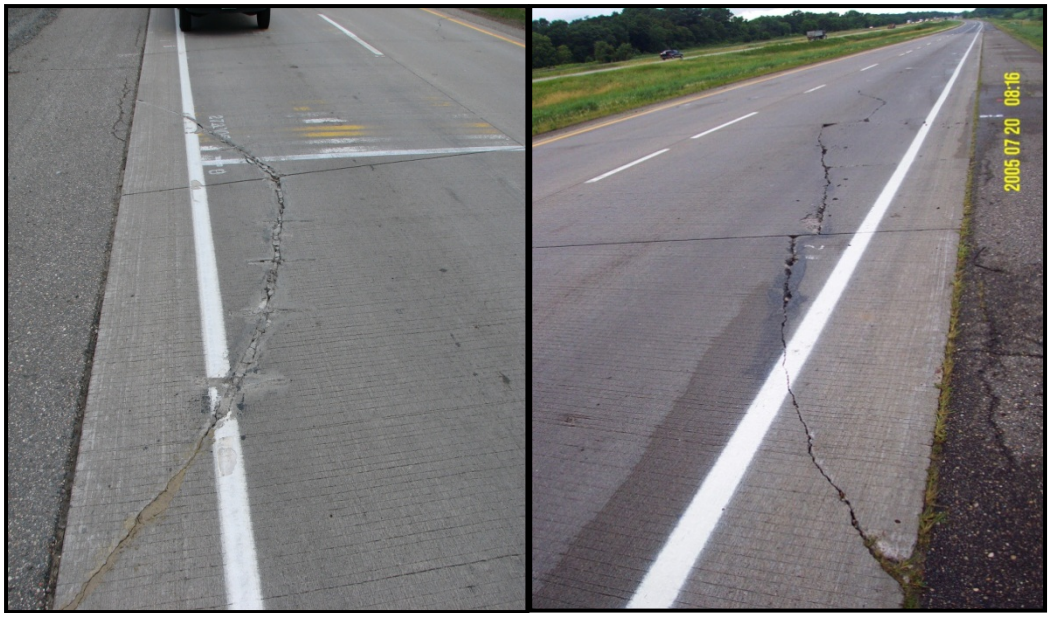


Figure 5. Loss of support cracking in MnROAD Cell 5.
A) Adjacent panel corners. B) Longitudinal crack.

Joint Faulting. Periodic measurements of joint faulting have been done on all of the MnROAD Phase 1 cells since they first received traffic loading in 1994. It should be noted again that all of the original Phase 1 concrete test cells were constructed with skewed joints, a common practice at the time of their construction (U.S. DOT, FHWA 1997). All MnROAD concrete test cells constructed after 1999 adopted the modern practice of non-skewed joints.

Interestingly, virtually no joint faulting occurred in the original Phase 1 interstate test cells with doweled joints. Even after 16 years and nearly 14 million CESALs, the 5-year design 190 mm (7.5 in.) thick slabs only had faulting measurements in the range of the depth of the surface texture (< 1.0 mm). The larger 38 mm (1.5 inch) diameter dowel bars in Cell 13, did show significantly less development of joint faulting than other interstate cells.

Figure 6 shows the joint faulting history for the LVR test cells. Trends for the cells with doweled joints (Cells 36, 38, 39) are similar to the interstate cells. The undoweled cells however, show different trends. Cell 37 has a deep sand subgrade, which seems to significantly slow the development of joint faulting. Cell 40, constructed over a silty-clay subgrade, continues to develop faulting with traffic and time. This is despite the fact it has skewed transverse joints.

As indicated by the arrow in Figure 6, modifications were made to the faultmeter and testing procedure in 2002. Prior to 2002, there appeared to be a gradual increase in joint faulting for all of the cells. It was discovered that due to the design of the Georgia faultmeter, as well as the imprecision with which the measurements were being taken, these were false trends (Burnham 2003).
Following modifications, the measurements began to more closely represent the true trends in joint faulting.

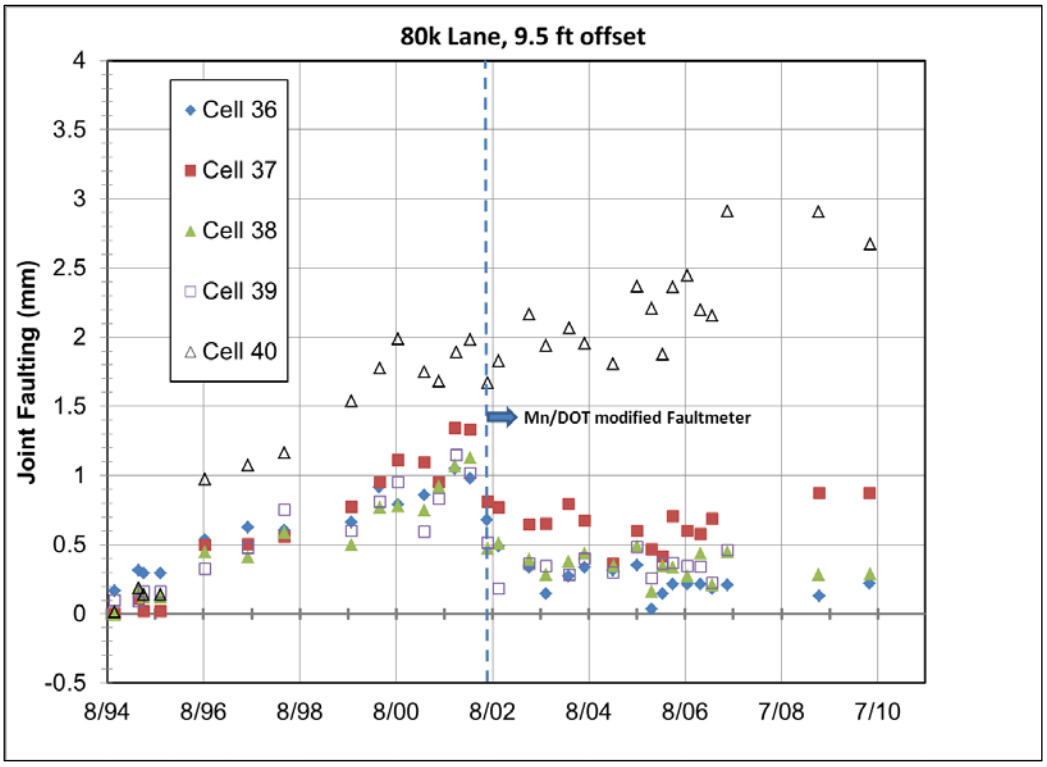


Figure 6. Joint faulting history for MnROAD Phase 1 LVR test cells

Load Transfer Efficiency and Joint Deflection. The load transfer efficiency (LTE) history of transverse joints is an important indicator of their remaining service life. LTE values in this study were calculated using the method outlined in section 3.5.4 of the *AASHTO Guide for Design of Pavement Structures(1993) (AASHTO 1993)*:

$$LTE\ (\%) = d_{je} = d_u/d_l \times 100$$

Where d_{je} is the load transfer efficiency in percent, d_u is the deflection at the joint of the unloaded slab, and d_l is the deflection of the loaded slab. In addition to LTE, it is important to examine the total deflection at the joint. High values of LTE will not always indicate joints with excessive deflection, which can mask the potential for pumping of subsurface material.

Deflection measurements at MnROAD are accomplished using a Falling Weight Deflectometer (FWD). FWD testing is done on a seasonal basis for all cells at MnROAD. To avoid artificially high LTE values (joints closed due to temperature expansion), transverse joints are only tested when pavement temperatures are below 25°C (77°F). For concrete test sections, the load levels applied were 26.7, 40, and 53.4 kN (6000, 9000, and 12000 lbs.). For brevity, only values for the 40kN (9000 lbs.) load level are reported in this paper.

LTE testing of the joints at MnROAD take place in the outer wheelpath of each lane. For each MnROAD Phase 1 concrete test cell, five randomly chosen joints in each lane were selected and periodically measured, beginning shortly after the traffic was first applied in August 1994. Since the driving lane of the interstate test cells at MnROAD receive four times more live traffic than the passing lane, only data collected from the driving lane are reported in this paper.

Figures 7 and 8 show the history of average LTE and joint deflection in the driving lane of each cell for the 5 and 10-Year design cells, respectively. Due to the

wide variability in the measurements, caused by seasonal effects on the panels and base layers, trend lines were not applied to the plots.

In Figure 7A, it is clear that Cells 7-9 all started with lower levels of LTE. The common design variable in these cells was the PASB base layer. Cells 5 and 6 began to show a decline in LTE before they were removed in 2008. This behavior seems reasonable, given the significant deterioration found within the joints of Cell 5 and 6 during a 2008 forensic investigation (Rohne and Burnham 2010). Otherwise, the remaining 5-Year design cells still exhibit good LTE (>70%) after 16 years of interstate traffic loads.

Figure 7B shows that Cells 5 and 6, which were constructed over standard granular bases, had higher joint deflections then the cells over stabilized bases. In all cases, there appeared to be an initial jump in joint deflections when the cells were new. This was likely a result of several factors, including settlement of the base layers, increased upward slab curling due to shrinkage, or consolidation of the base layers under heavy traffic loads.

Figure 8A reveals that, before its removal in 2010, Cell 10 was starting to demonstrate a downward trend in LTE. Like Cells 7-9, this cell had a PASB base layer. It has not been determined yet whether this was the primary cause for the decline. Cell 11 exhibited the lowest overall LTE throughout its life. It also demonstrated the highest joint deflections in Figure 8B. This seems reasonable, given that Cell 11 has the longest panel length in this group. In general, there appears to be a reduction in joint deflection of approximately 50 microns between the 5 and 10-Year design cells. An analysis of whether this difference is related more to slab thickness or base type, will be investigated in future studies.

Figure 9 shows the history of average LTE and joint deflection in the 80k lane of the LVR cells. As expected, the undoweled joints in Cells 37 and 40 demonstrate low LTE and high seasonal variability. The other LVR cells still exhibit very good LTE after 16 years. Figure 9B shows that Cell 36 experiences the lowest joint deflections of the group. Contributing factors are likely the incorporation of doweled joints and a deep sand subgrade. The extremely low deflection values in the plot indicate measurements that were conducted over a frozen base. The overall range in deflections of the LVR cells was on average twice those of the interstate cells. This resulted in the common observation of pumping of the slabs when the underlying layers were saturated.

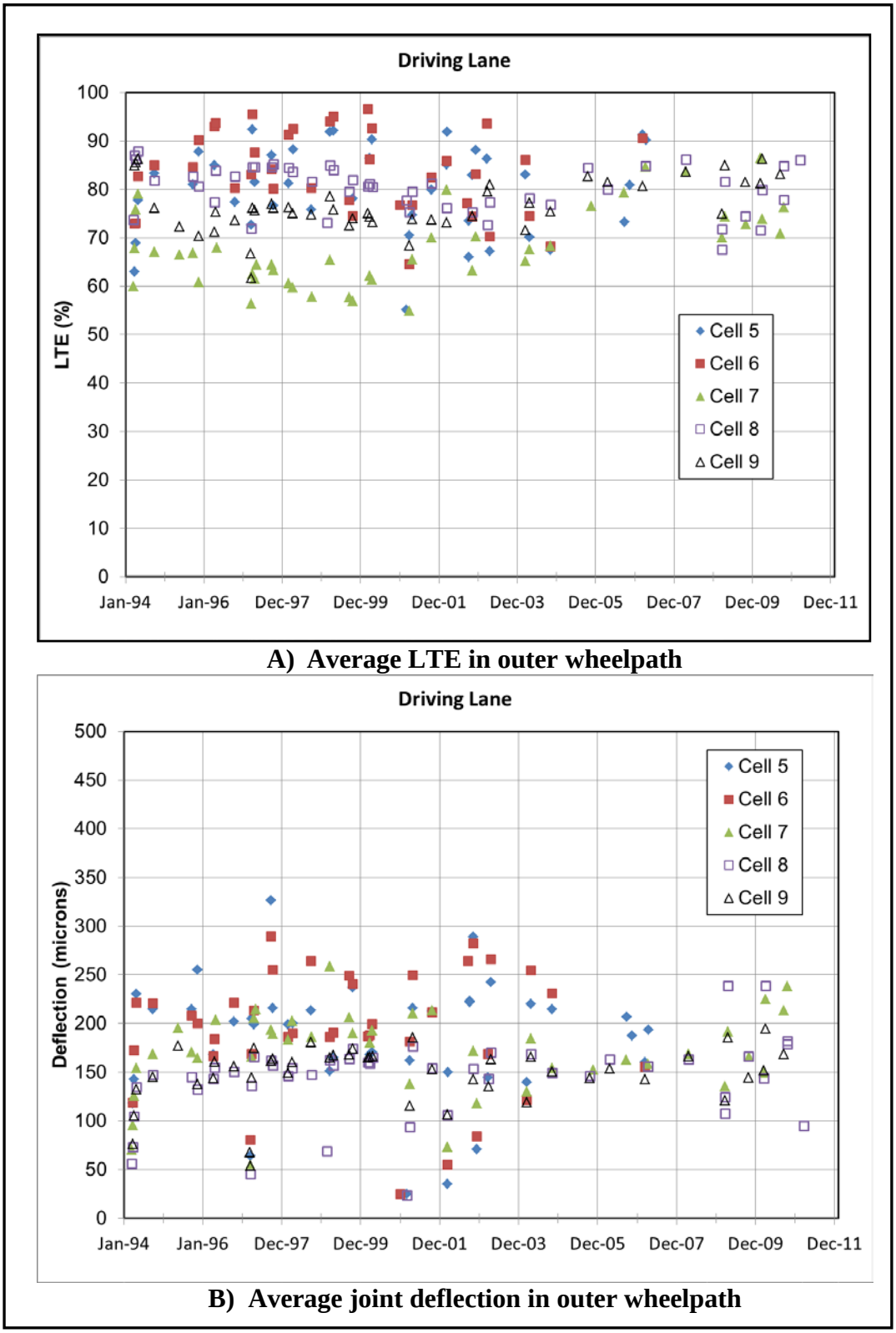
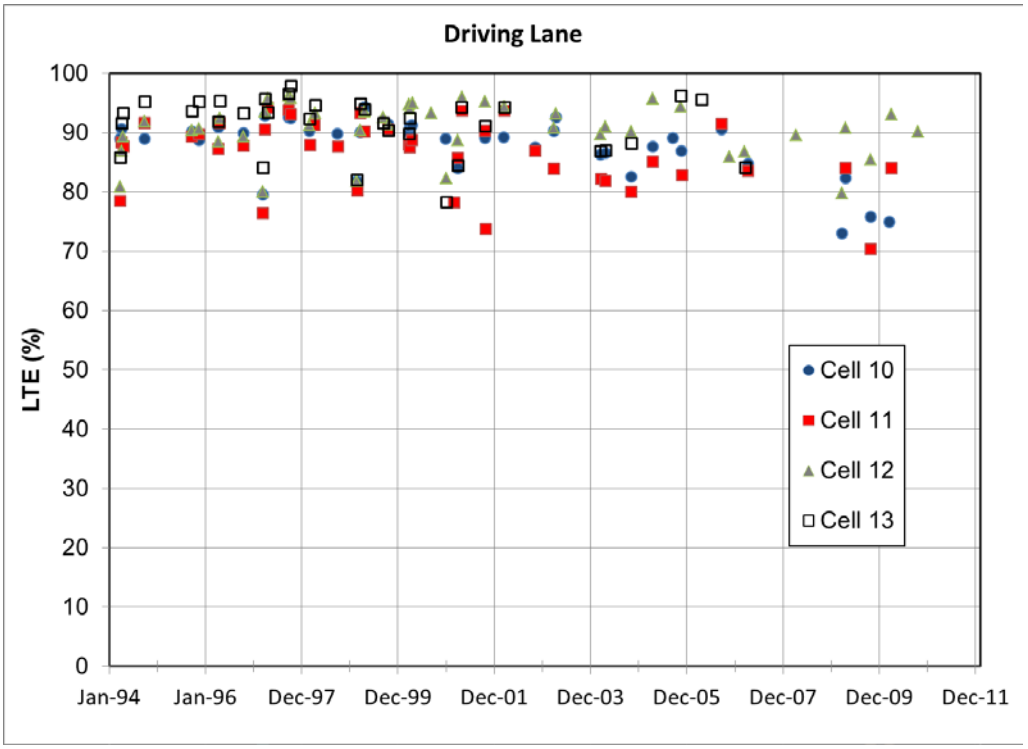
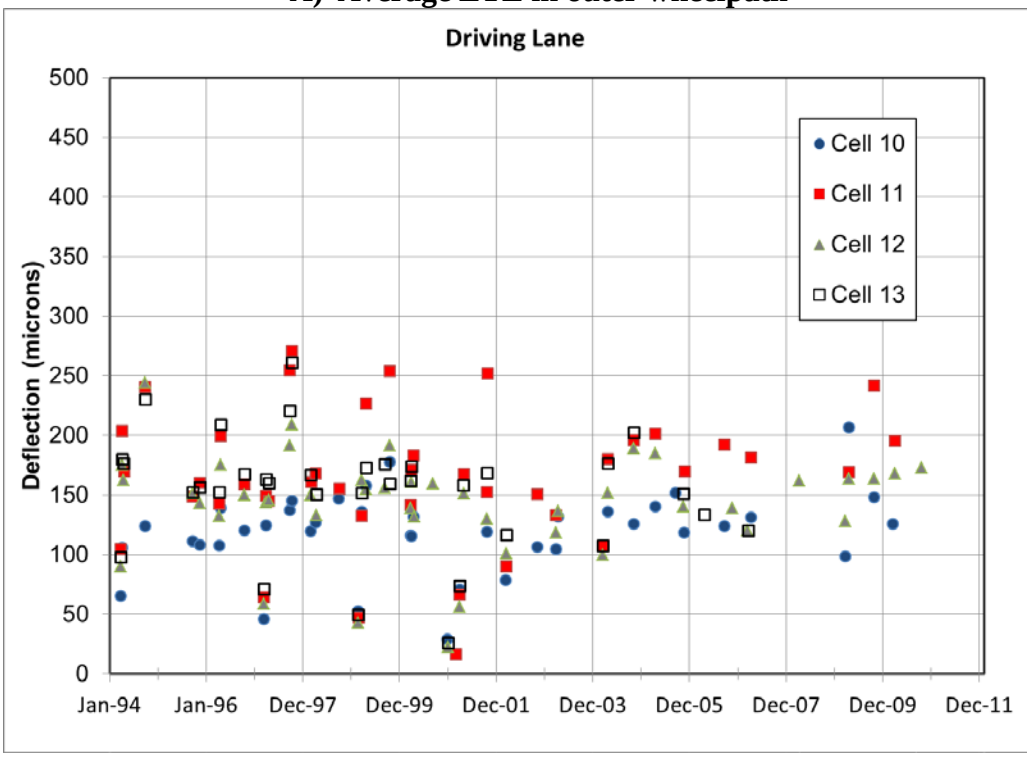


Figure 7. Joint performance for MnROAD 5-Year design test cells

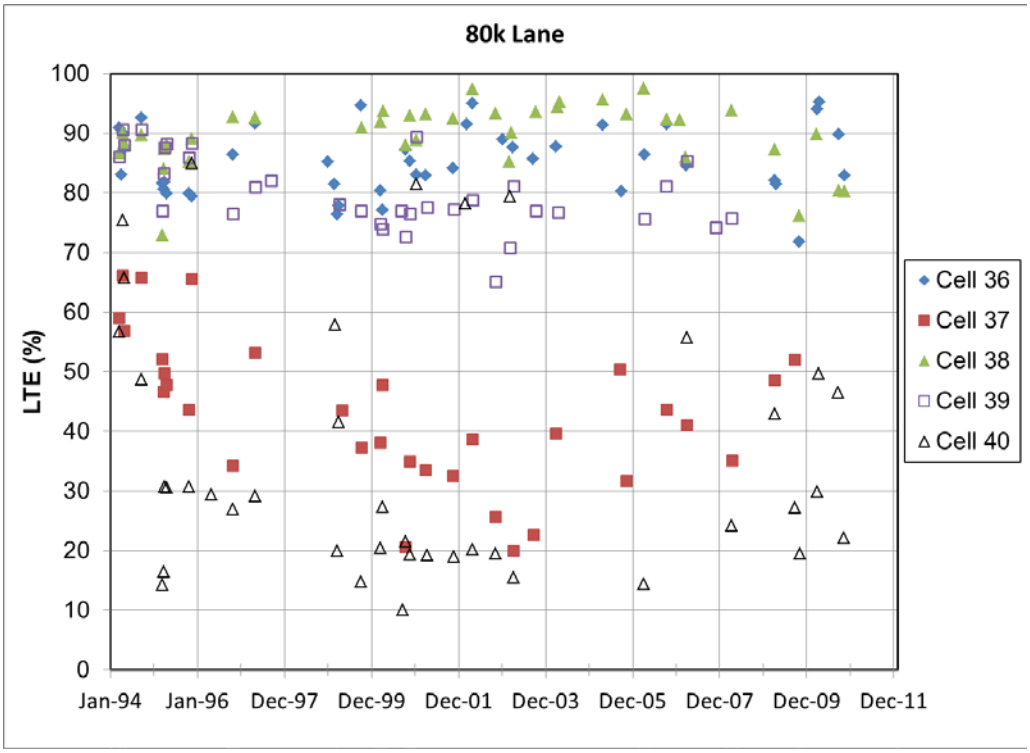


A) Average LTE in outer wheelpath

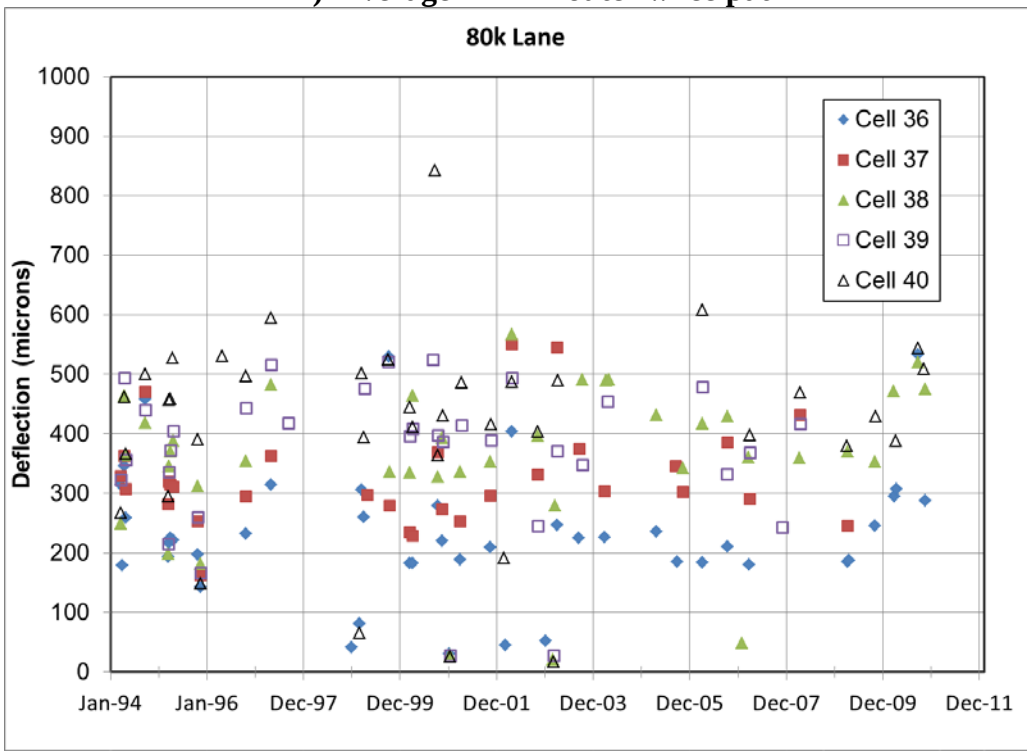


B) Average joint deflection in outer wheelpath

Figure 8. Joint performance for MnROAD 10-Year design test cells.



A) Average LTE in outer wheelpath



B) Average joint deflection in outer wheelpath

Figure 9. Joint performance for MnROAD LVR test cells.

Ride Quality. Ride quality at MnROAD has been measured over the life of each test cell using a variety of methods Pavement surface profile measurements were conducted twice yearly using a pavement management van (Mn/DOT 2012). More recently, newer surface profiling technologies were used. Data from each of these

methods were combined into one set of International Roughness Index (IRI) values for each cell.

Figure 10 shows the history of IRI for the 5-Year design cells. The trend of Cell 7 confirms findings from other concrete pavement performance studies; that smoothly constructed pavements remain smoother longer (Smith et al 1997). Before its removal in 2008, Cell 6 stood out to be likely the first to approach the Mn/DOT terminal serviceability IRI of 2.16 m/km, though it had not reached it after 14 years of interstate traffic. As indicated by the arrow in Figure 11, the drop in IRI after October 2007 was due to diamond grinding in Cells 7-9. Overall IRI trends in the passing lane do not differ greatly from the driving lane, despite experiencing much less traffic loading. This suggests that the environmental response of concrete pavements (faulting, curling, warping) may have a stronger influence on ride quality than roughness induced by traffic loadings. This of course would change, as the sections develop significant panel cracking.

Figure 11A shows that the driving lane of Cell 11 (removed in 2010) was to be the first of the 10-year designs to approach terminal serviceability. Some potential causes for the more rapid increase in IRI have been examined (Khazanovich et al 2008), but results so far have been inconclusive. Laser based IRI measurements can be affected by simple things, like increased depth measurements caused by transverse joints with missing sealant. Cell 11 did not exhibit any panel cracking, and the joints had not started to noticeably fault.

Figure 12 shows that, not counting seasonal spikes, Cell 40 will likely be the first to reach terminal serviceability on the LVR. This is not surprising, given the significant amount of joint faulting that has developed. What is noticeable is the much higher and earlier increase in IRI in the less traveled 102k lane. The initial premise was that, based on AASHTO guide load equivalency factors, one pass of the 102k loaded vehicle would cause equal damage as four passes of the 80k loaded vehicle. Further investigation will be needed to determine whether the difference in IRI is due strictly to the unique design parameters of Cell 40, or other contributing factors. Cell 37 continues to maintain the lowest IRI readings. This is remarkable for undoweled joints, but can be attributed to shorter slabs and the more uniform support provided by the deep sand subgrade.

In Figure 12, the large jump in IRI in cell 39 is due to a pervious concrete overlay applied in the fall of 2008. The method of construction (forms and screed) produced a rough initial ride profile. It is also possible the laser-based IRI measurements are affected by the large pores in the pervious concrete surface (Izevbekhai and Lukanen 2012).

Conclusions

The MnROAD Phase 1 concrete pavement test cells have provided, and will continue to provide, invaluable data toward improvement of mechanistic-empirical design methods. This paper examined the overall performance of the concrete test cells for the period of 1994 to 2010.

An assessment of the live traffic loadings applied to the interstate test cells since 1994, revealed that accumulation of CESALs took longer than the planned 5 or 10 year design periods. The as-built slab thicknesses also had significant effects on the predicted time to terminal serviceability. Nevertheless, all of the MnROAD Phase 1 concrete test cells carried more traffic, and at higher levels of serviceability, than predicted.

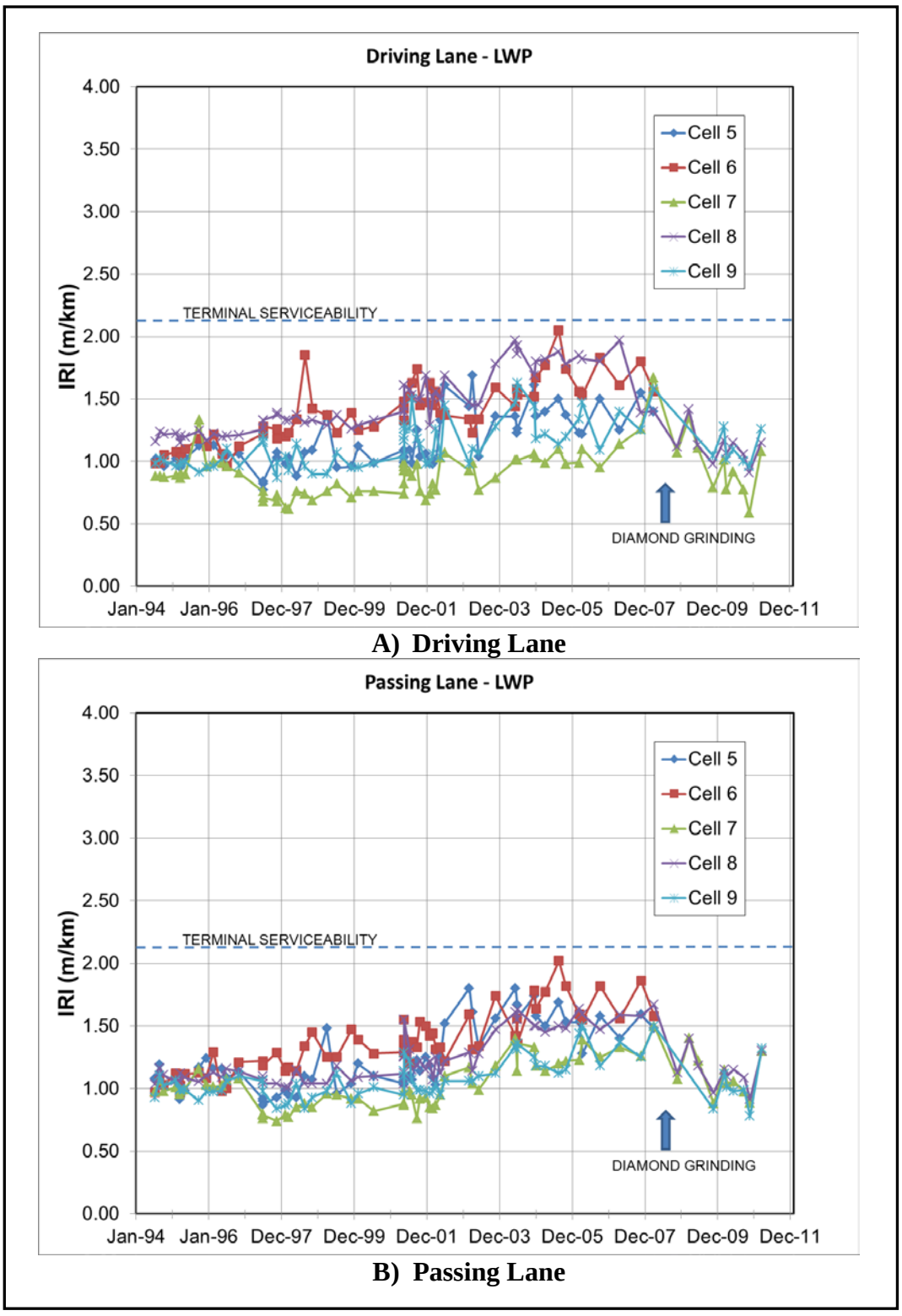


Figure 10. IRI history for 5-Year design cells

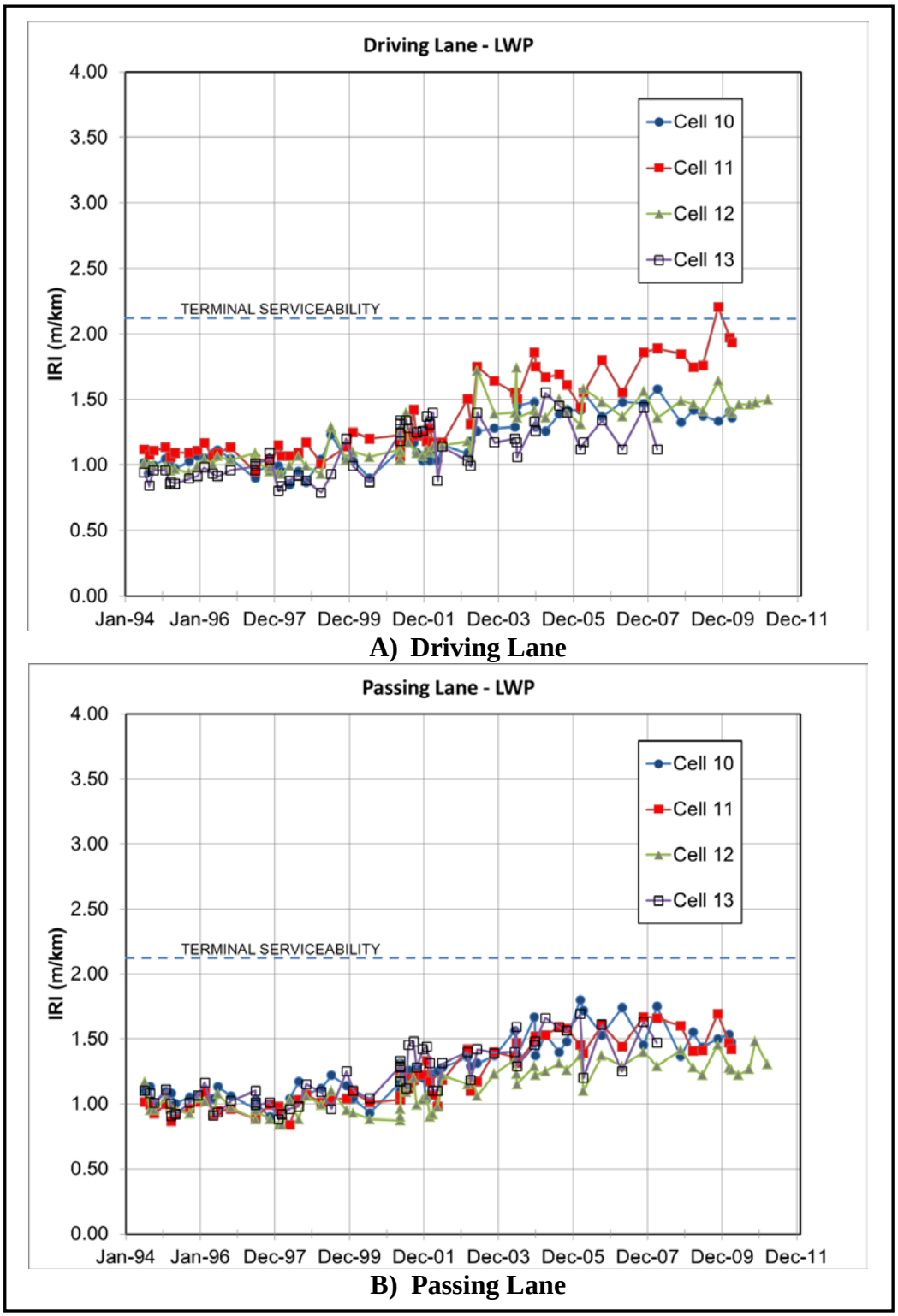


Figure 11. IRI history for 10-Year design cells

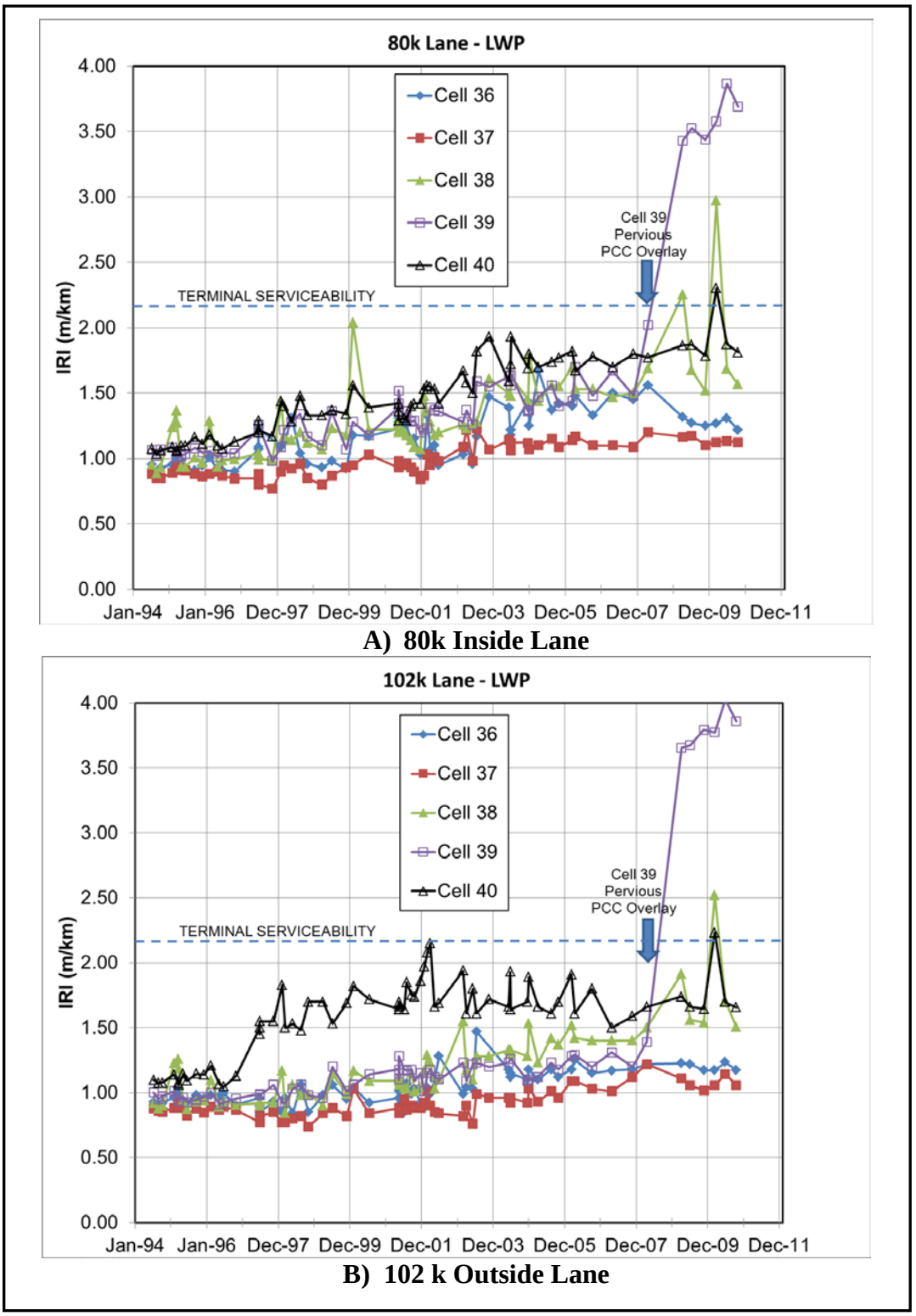


Figure 12. IRI history for LVR cells

Improved equipment and measurement procedures showed that joint faulting, for all but the undoweled cells, never developed beyond the range of surface texture depth after 16 years of traffic. The undoweled Cell 37, with shorter panels and a deep sand subgrade, substantially outperformed Cell 40, which rested on a silty-clay subgrade.

Joint load transfer efficiency remained high in most of the Phase 1 cells, only falling off in later years due to increasing joint deterioration. The overall range of transverse joint deflections for LVR cells was twice those of the interstate cells. The higher deflections of the LVR sections often resulted in significant slab pumping for sections over the silty-clay subgrade.

Ride quality measurements of the cells, based on IRI, confirmed that the smoothest constructed sections remained the smoothest over time. Cell 11, with its long panels and deteriorating joints, would have been the first interstate test cell to reach terminal serviceability. Cell 40, with its undoweled joints and silty-clay subgrade, will be the first cell to reach terminal serviceability on the MnROAD low volume road.

Through continual monitoring of the long-term performance of MnROAD jointed concrete pavement sections, there now exists a useful database of information related to concrete pavement behavior, particularly in colder climates. Analysis of MnROAD Phase 1 data reaffirms that AASHTO-based design methods are conservative in their prediction of performance.

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