Lessons learned from Mn/ROAD (1992 – 2007): Low-Volume Road Concrete Pavement Design and Performance

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Abstract

This paper examines the design and general performance of the five original MnROAD low-volume road (LVR) concrete pavement test sections, which were constructed in 1993 and have been subjected to more than 300,000 80-kN (18-kip) equivalent single-axle loads (ESALs) by a controlled stream of heavy trucks. The test sections include pavements with varying panel lengths, joint designs, foundation designs and drainage systems. Ride quality histories and current distress summaries are presented, along with maintenance records and deflection data. Performance life projections are made on the basis of IRI records, and these projections are compared with predictions that result from using as-built data in selected common design procedures. The effectiveness of various design and construction parameters is evaluated in the context of the performance measures and predictions. Initial ride quality appears to be one of the most important parameters affecting performance life. The accuracy of various design procedures is evaluated in terms of the test section performances. The new AASHTO Mechanistic-Empirical Pavement Design Guide provided pavement performance estimates that most closely matched observed IRI trends, but even this procedure underpredicted project performance by about 23 percent.

Introduction

This paper examines the design and general performance of the five original MnROAD low-volume road (LVR) concrete pavement test sections, which were constructed in 1993 and have been subjected to more than 300,000 80-kN (18-kip) equivalent single-axle loads (ESALs) by a controlled stream of heavy trucks. The test sections include pavements with varying panel lengths, joint designs, foundation designs and drainage systems. Ride quality histories and current distress summaries are presented, along with maintenance records and deflection data. Performance life projections are made on the basis of IRI records, and these projections are compared with predictions that result from using as-built data in selected common design procedures. The effectiveness of various design and construction parameters is evaluated in the context of the performance measures and predictions.

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Research Significance
This study has broad implications for the design and construction of concrete pavements in lower-volume road applications. The results show that commonly accepted thickness design procedures significantly underpredicted the performance of the considered test sections, suggesting that they require calibration for local conditions (at least). The data also show the relative impacts of various design features on pavement performances on the MnROAD low-volume test road; these findings should be considered in the development of low-volume concrete pavement designs at other locations.

The MnROAD Project – A Brief Overview
The Minnesota Road Research Project (MnROAD), a full-scale pavement test facility located about 48 km [30 miles] northwest of Minneapolis, is one of the most sophisticated, independently operated pavement test facilities of its type in the world. The facility includes two separate, heavily instrumented road segments that are located adjacent and parallel to the westbound lanes of Interstate 94: a 5.6-km [3.5-mile] mainline interstate roadway carrying traffic diverted from I-94 (averaging 23,500 westbound vehicles per day with 12% trucks in 2004), and a 4.0-km [2.5-mile] closed-loop low-volume roadway carrying a facility-controlled 5-axle tractor-semi-trailer (Worel 2006, Burnham 2005). When originally constructed (1991 – 1994) and opened to traffic (August 1994), it featured 40 test sections or "cells", including 14 constructed using jointed concrete pavement, 22 with asphalt surfacing, and 4 with aggregate surfacing. Each original test section is about 150 m [500 ft] long and contains numerous instruments for measuring pavement responses to applied loads and environmental effects.

Several more concrete test sections have been added to the MnROAD facility since 1994, including several sections of whitetopping on the mainline pavement, and a section of thin (125-mm [5-in]) concrete and a section with alternative dowel materials on the low-volume test loop. Some of these sections are discussed in an overall project report by Snyder (2008).

Data are collected from the test sections in many ways, from automated and triggered sensor records (e.g., for layer strain and temperature data) to manually collected data (e.g., pavement distress and friction data). The MnROAD Data Base Guide (Worel 2006) provides details concerning data collection protocols.

Detailed descriptions of the concept, design, construction, instrumentation and performance of MnROAD can be found in many of the references listed at the end of this article, as well as at the official Minnesota Road Research website, http://www.mrr.dot.state.mn.us/research/Mnresearch.asp

Design of MnROAD Low-Volume Road Concrete Pavements

The layout of the test cells on the MnROAD low-volume road test loop are shown in figure 1. The thicknesses of the original LVR concrete pavement test sections (cells 36 – 40) were selected after considering the results of the then-current MnDOT pavement design procedure (based on the 1981 AASHTO Interim Design Guide) and 3 years of the planned traffic loads (100,000 80-kN [18-kip] equivalent single axle loads (ESALs)). The resulting design thickness was 110 mm [4.2 inches], which was increased to MnDOT’s minimum concrete pavement thickness of 150 mm [6 inches], except for cell 40, which incorporated a thickened edge design (Burnham and Pirkl 1997).

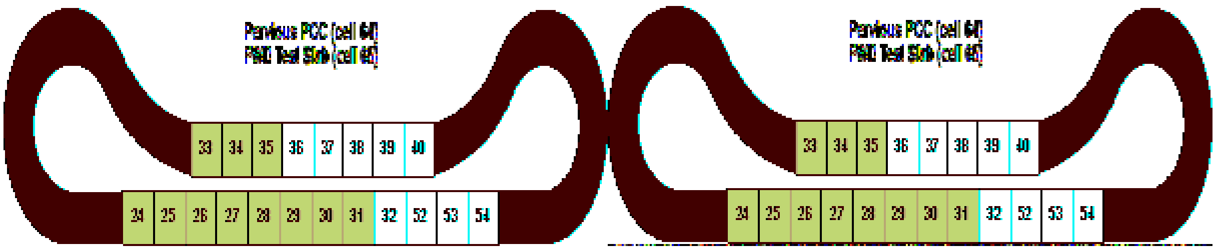

Figure 1. General layout of test cells on the MnROAD low-volume road test loop.

Cell 32 was constructed in 2000 to explore the performance potential of 125-mm [5-in] jointed plain concrete pavement subjected to heavy traffic loads. This pavement has performed well for 7 years and is described in the full study report by Snyder (2008).

Cells 52 and 53 were also constructed in 2000 as near-replicates of mainline test cell 6, except that various types of dowels were installed in lieu of standard epoxy-coated steel. Cell 54 was constructed in 2004 using a structural design similar to that of mainline test cell 6, but using taconite tailings (an iron mining waste product) as coarse aggregate in the concrete mix. These test cells are relatively young and their performances to date are not discussed in this paper or in the project report by Snyder (2008).

A summary of the principal design and construction features of the five original Mn/ROAD low-volume road concrete pavement test cells is presented in Table 1, which shows the variety of structural design and construction variables that are represented in the test sections. The gradation of the granular base used is described in Table 2. All sections were constructed over a silty-clay subgrade of relatively uniform consistency and low strength (R = 12, M_R ~ 4000 psi [28 MPa]).

Table 1. Summary of Low-Volume Road Concrete Test Cell Design Features at Mn/ROAD (after Glasgow 2001, Burnham 2005)

Cell	Nominal Slab Thickness (mm)	As-Built Avg. Slab Thickness (mm, 353-kN/455-kN)	Joint Spacing (m)	Lane Widths, Inside/Outside (m)	Dowel Diameter (mm)	Subbase Type and Thickness	Edge Drains
36	150	165/166	4.6	3.7/3.7	25	125 mm cl5sp over 2.1 m sand	Yes
37	150	167/162	3.7	3.7/3.7	N/A	300 mm cl5sp over 2.1 m sand	Yes
38	150	163/164	4.6	3.7/3.7	25	125 mm cl5sp	No
39	150	168/165	6.1	3.7/3.7	25	125 mm cl5sp	No
40	178/140/178	170/180	4.6	3.7/3.7	N/A	125 mm cl5sp	No

Notes: cl5sp is a granular base materials with gradation as shown in table 2. All transverse joints are skewed at a 2 ft/12 ft angle. 1 inch = 25.4 mm, 1 foot = 0.3049 m, 1kip = 4.889 kN.

Table 2. Aggregate Gradations (% Passing) for Mn/ROAD Class 5 (Special) Base Material (after Glasgow 2001).

Sieve Size	% passing
25 mm [1 in]	100
19 mm [¾ in]	90-100
9.5 mm [3/8 in]	70-85
4.75 mm [#4]	55-70
2.36 mm [#8]	35-55
[600 □m] [#30]	15-30
75 □m [#200]	3-8

"Special" requirement: 10-15% crushed/fractured particles.

The concrete mix used in the original LVR test cells (36-40) was proportioned as follows (Janssen and Snyder 1994):

Coarse Aggregate (19-mm-plus [3/4-in-plus], SSD: 548 kg/m^3 [922 lb/yd^3]
Coarse Aggregate (19-mm-minus [3/4-in-minus], SSD: 540 kg/m^3 [908 lb/yd^3]
Sand, SSD: 720 kg/m^3 [1211 lb/yd^3]
Type I Cement: 304 kg/m^3 [511 lb/yd^3]
Class C Fly Ash: 51 kg/m^3 [86 lb/yd^3]
Water: 163 kg/m^3 [274 lb/yd^3] – w/c = 0.54, w/(c+p) = 0.46
Air-entraining admixture

The coarse aggregate was obtained from a local gravel source containing less than 5 percent carbonate material; the siliceous sand was obtained from the same source (Janssen and Snyder 1994).

Additional information concerning the design and construction of the Mn/ROAD test cells can be found at: http://www.mrr.dot.state.mn.us/research/Mnresearch.asp

Environmental Conditions

MnROAD is located in an area that experiences a wide range of environmental conditions. Temperatures as warm as 39C [102F] and as cold as -42C [-43F] have been observed in the area. Precipitation averages 69.9 cm [27.5 in] per year (including snowfall that averages 113 cm [44.5 in] per year) over 109 days per year. (Source: www.weatherbase.com)

Traffic Loadings

All traffic loadings on the Mn/ROAD low-volume road section are accomplished by passes of standard 5-axle tractor-trailer trucks that are loaded to 355 kN [80,000 lbs] in the inner lane and 453 kN [102,000 lb] in the outer lane. The axle loads for these two configurations are:

355 kN [80-kip] configuration: 53-kN [12-kip] single axle, 151-kN [34-kip] dual-tandem axle, 151-kN [34-kip] dual-tandem axle
453-kN [102-kip] configuration: 55-kN [12.5-kip] single axle, 199-kN [44.75-kip] dual-tandem axle, 199-kN [44.75-kip] dual-tandem axle

The 355-kN [80-kip] lane is generally trafficked 4 days each week and had been subjected to approximately 89,000 vehicle passes and 330,000 ESALs since the construction of the original test cells and through 2006. The 453-kN [102-kip] lane is generally trafficked 1 day each week and had been subjected to approximately 26,000 vehicle passes and 310,000 ESALs since the construction of the original test cells and through 2006.

Performance Observations

After more than 12 years of service in Minnesota's somewhat harsh climate, the five original low-volume road concrete test cells at MnROAD remain in very good condition. They all still provide good ride quality, exhibit very little distress, and have no significant maintenance.

Ride Quality

Pavement ride quality measurements have been obtained in the outer wheel path of each lane at least three times per year since 1994. From 1994 – 1997, pavement profile measurements were obtained using a van equipped with ultrasonic sensors, which were used to measure pavement profile at 150-mm [6-in] intervals. From 1997 to the present, profile measurements were obtained using a laser-based system that obtains 6 measurements per cm [16 per inch] and processes that data using moving averages to produce a profile at 7.5-cm [3-in] intervals. Conversion equations were developed to equate measurements obtained using the two different systems.

The pavement profile data are used to compute an International Roughness Index (IRI) value for each lane of each test section at each point in time. The IRI is calculated as the ratio of the accumulated vertical motion of a standard ¼-car suspension model to the distance traveled over the measured profile at a speed of 80 kph [50 mph]. IRI is typically expressed in units of inches (of suspension movement or "roughness") per mile (meters/kilometer) and is strongly correlated (inversely) with Present Serviceability Rating, or PSR, the ride quality and performance measure used as the basis for all AASHTO pavement design guides since the early 1960s. Details concerning the IRI can be found in Miller and Bellinger (2003).

Figures 2 and 3 show IRI histories for the original MnROAD low-volume road concrete test cells in the 355-kN [80-kip] and 453-kN [102-kip] test lanes, respectively. Linear or bi-linear estimated trendlines have been inserted for cells 37 and 40 in each figure to bracket the lowest and highest ride quality trends, respectively, that have been observed.

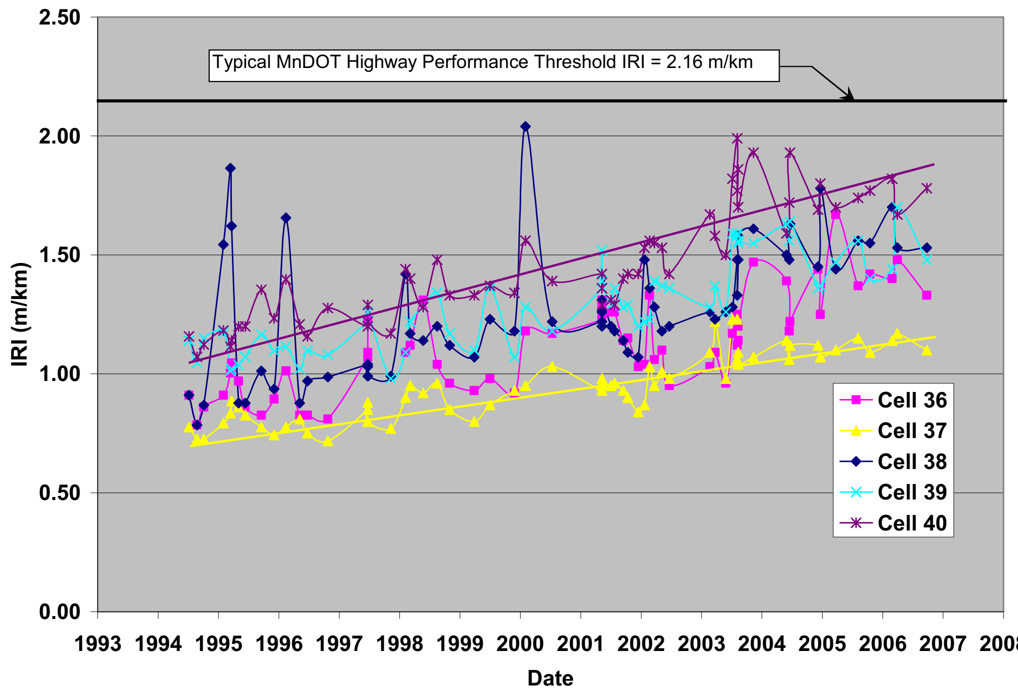

Figure 2. IRI Data (computed from profile data) for MnROAD Low-Volume Road Concrete Test Cells – 355-kN [80-kip] test lane only.

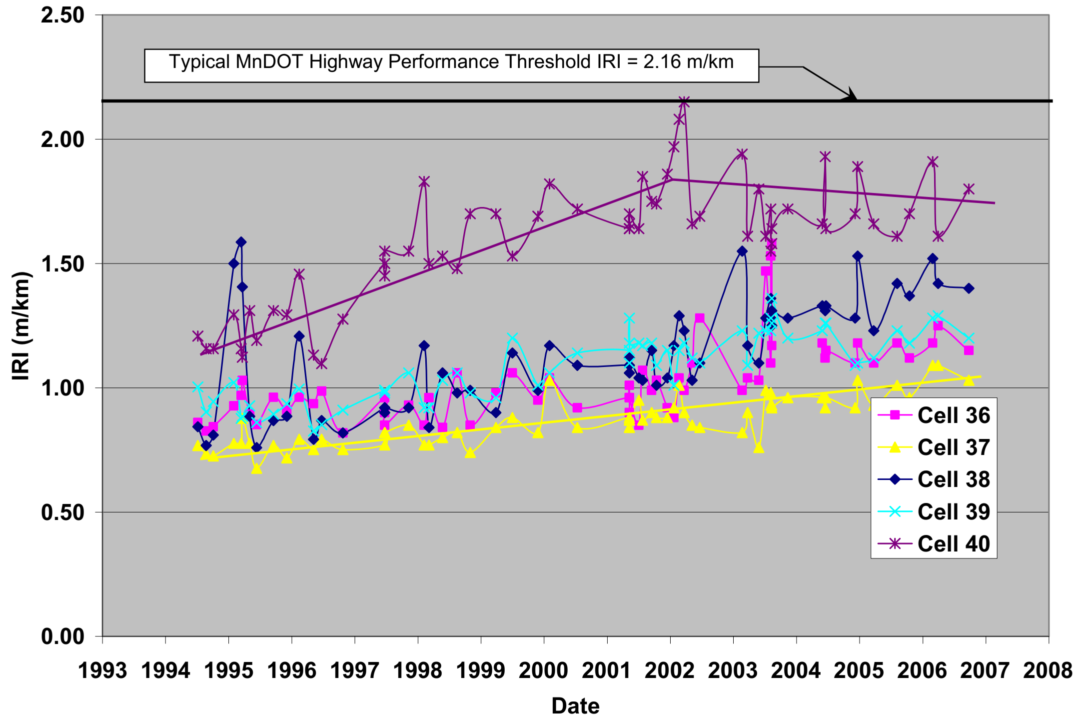

Figure 3. IRI Data (computed from profile data) for MnROAD Low-Volume Road Concrete Test Cells – 453-kN [102-kip] test lane only.

The most obvious conclusion that can be drawn from the these test cell ride quality data is that, after 12 years and 300,000+ ESALs of service, these pavement sections have greatly exceeded their intended design lives of 100,000 ESALs in 3 years. However, since these sections were all built with much greater thicknesses than the computed design thickness of 110 mm [4.2 in], the extended service life is not surprising. Furthermore, even the 110 mm [4.2-in] design thickness was computed using a procedure that provided a built-in reliability of approximately 90 percent (i.e., approximately nine 110-mm [4.2-in] pavements in ten would be expected to endure more than 3 years/100,000 ESALs to reach the terminal IRI value of 2.16 m/km [138 in/mile]). A 150-mm [6-in] concrete pavement would be expected to have a substantially higher reliability or longer design life, as is discussed later in this article.

The IRI trendlines suggest that the current rate of roughness increase for the MnROAD low-volume road concrete test cells varies between about 0.024 to 0.068 m/km/year [1.5 and 4.3 inches/mile/year], depending on the design features and the traffic lane. If this trend continues, test cell 40 will be the first to reach terminal serviceability after providing about 17 years of service and carrying nearly 500,000 ESALs, while cell 37 will be the last to reach terminal serviceability after providing about 41 to 62 years of service and carrying 1.1 to 1.6 million ESALs consisting entirely of 355-kN [80-kip] and 453-kN [102-kip] trucks, respectively.

The overall ride quality trends described above suggest that the as-built low-volume road test cells sections are extremely overdesigned for the target traffic levels of 100,000 ESALs, even when those ESALs are being accumulated solely by heavy trucks. It is likely that significantly thinner sections (e.g., 100 – 125 mm [4 to 5 inches] of concrete with the same foundation and load transfer systems) would have provided the desired levels of service for a lower initial cost.

The IRI data presented in figures 2 and 3 for each of the low-volume road concrete test cells also show a range of ride deterioration *rates* for these test cells, even when the initial IRI values are similar (e.g., for cells 36 – 38). Cell 40 (thickened edge design with no dowels, no added subbase and no drainage) had the highest initial IRI in both lanes and also had the highest rate of IRI change, especially during the first 6 years of service. Cell 37 (undoweled with a thick subbase and edge drains) had the lowest initial IRI and the lowest rate of IRI change in both lanes. Cells 36 (doweled with a thick subbase and edge drains) and 38 (doweled with standard subbase and no edge drains) also had relatively low rates of IRI change. This suggests that the other design parameters that were varied on these test cells (i.e., load transfer, drainage, foundation preparation, etc.) have at least a modest influence on their rates of serviceability loss. This was not found to be true for the mainline pavement sections, where the effects of drainage, panel length and subbase thickness on pavement performance appear to be negligible. The influence of these design parameters appears to be more significant for thinner concrete pavements.

The figures also suggest that *initial ride quality has a significant influence on long-term pavement service life (i.e., initially smooth concrete pavements will have longer service lives than those that are built less smooth).* The slopes of the IRI curves are relatively constant for most of the test cells considered here, even though they vary somewhat from cell to cell. If the slope remains constant for any given set of design parameters, the pavement service life will be extended if the initial IRI is reduced. If this is true, the service life of these sections could also be extended greatly by using diamond grinding techniques to remove most of the built-in and long-term pavement roughness.

Load Transfer Efficiency and Deflection Measurements

Load transfer efficiency (LTE) is a measure of how effectively a concrete pavement joint shares applied loads with the adjacent slab. It is typically determined by applying a load to one side of a transverse joint (usually in the outer wheel path or near the lane-shoulder joint) and measuring the resulting slab deflections on each side of the joint. LTE is typically computed as the ratio (in percent) of the deflection of the unloaded side to the deflection of the loaded side. LTE values of 70% or greater are usually considered to be acceptable; values of 60% or less with peak deflections greater than 0.63 mm [0.025 in] (or differential deflections greater than 0.25 mm [0.01 in]) are often considered to require rehabilitation (FHWA 1997).

Table 3 presents recently measured average FWD test results for the low-volume road concrete pavement test cells (40-kN [9000-lb] nominal load applied in the wheel path of the driving lane). These measurements were all obtained when air temperatures were below 27°C [80°F] to avoid slab expansion effects on load transfer measurements.

Table 3. Recent deflection test data for original MnROAD low volume road concrete pavement test cells (40-kN [9000-lb] nominal FWD load).

Test Cell	Testing Date	Average Loaded Joint Deflection, mm	Average Transverse Joint LTE, %	Average Differential Deflection, mm
36 (drained, doweled)	4/18/2007	0.17/0.17	89/86	0.018/0.023
37 (drained, undoweled)	3/29/2007	0.30/0.31	42/42	0.17/0.18
38 (undrained, doweled)	3/19/2007	0.36/0.37	85/87	0.054/0.048
39 (undrained, doweled)	3/27/2007	0.32/0.34	92/89	0.026/0.038
40 (undrained, undoweled)	3/29/2007	0.42/0.29	53/83	0.20/0.049

Notes: 1) Alternate values shown are for the 80-kip and 102-kip lanes, respectively.
2) 1 inch = 25.4 mm

Figures 4 and 5 present deflection test histories for the doweled and undoweled low-volume road concrete test cells, respectively. These figures include only data from the 355-kN [80-kip] truck lanes; data from the 453-kN [102-kip] truck lanes look very similar.

Table 3 and figures 4 and 5 show the clear benefits of dowel load transfer systems on deflections and load transfer efficiency, even for relatively thin slabs. All of the doweled sections have LTE histories that are very good (LTE generally greater than 70 percent and, more importantly, differential deflections far less than 0.25 mm [0.01 in]) and have been stable over more than 12 years of service to date. Figures 4 and 5 show that there is some variability in test results, presumably due to daily and seasonal environmental effects (especially for the undoweled sections), as well as inherent variability in the test operations and measurements.

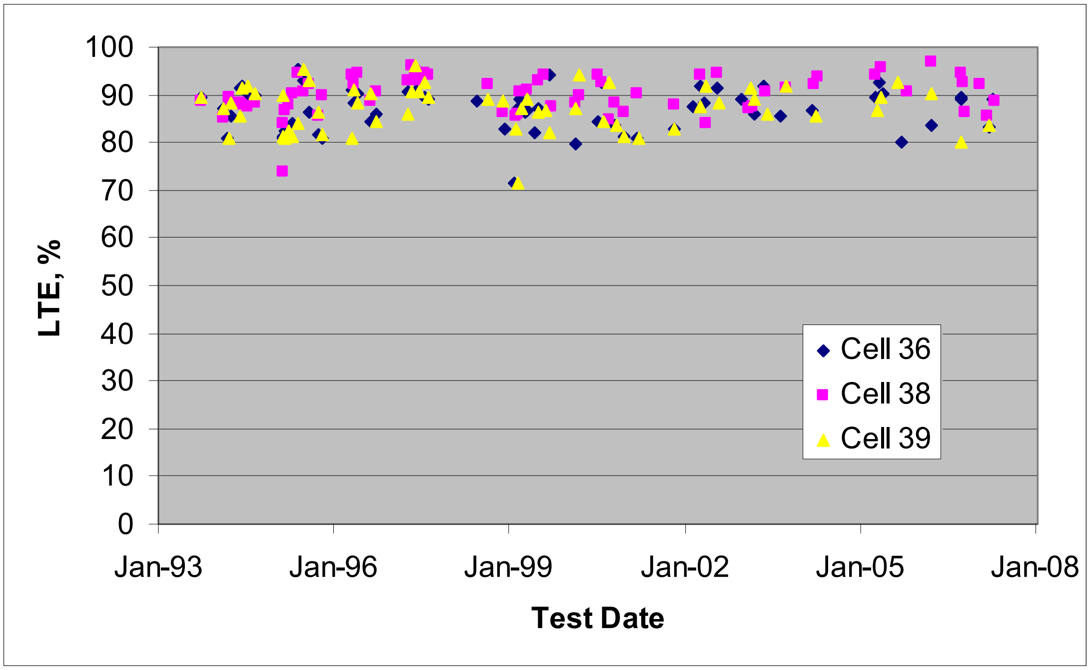

Figure 4. LTE histories for MnROAD low-volume road doweled concrete pavement test cells (353-kN [80-kip] lanes only).

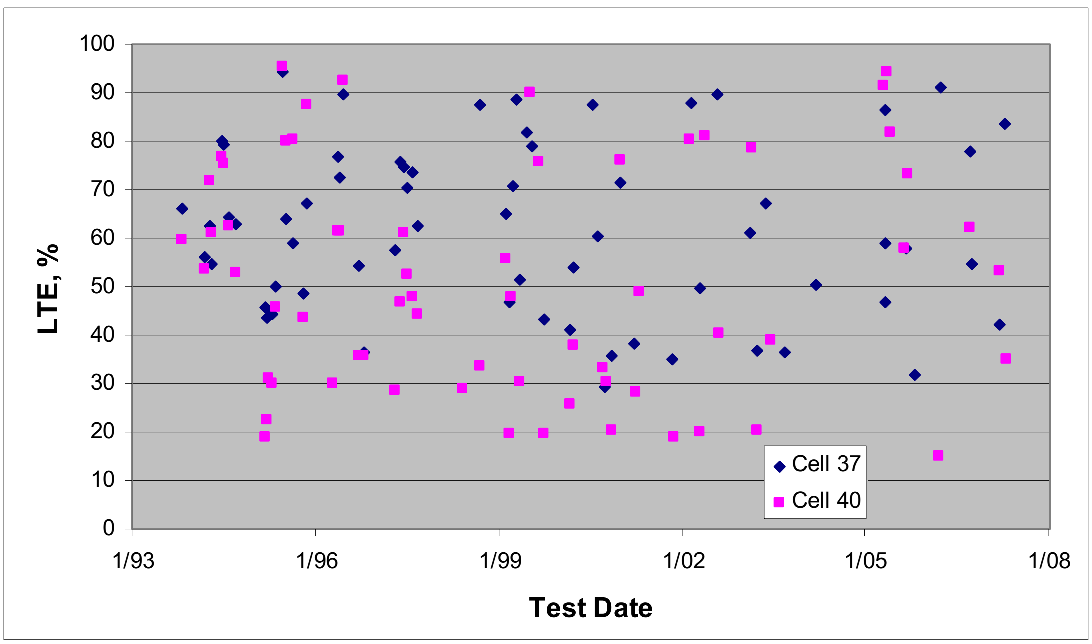

Figure 5. LTE histories for MnROAD low-volume road undoweled concrete pavement test cells (353-kN [80-kip] lanes only).

There is no significant difference in deflection test results and histories for any of the doweled sections, regardless of other design features present. For the undoweled sections, Cell 37 (drained, 13-cm [5-in] granular base over 210-cm [84-in] sand subbase) generally exhibits lower deflections and higher LTE values than does Cell 40 (undrained, no sand subbase). Cell 37 has developed no significant distress to date, while Cell 40 has developed one high-severity transverse crack and one high-severity corner break. It should be noted that Cell 40 has 4.6-m [15-ft] panels, resulting in a ratio of panel length to nominal thickness of 30, while cell 37 has 3.7-m [12-ft] panels, resulting in a ratio of panel length to nominal thickness of 24. ACPA and the 1993 AASHTO Guide recommend a maximum value of 18-24 for this ratio to minimize cracking and other distress.

The positive impact of dowels is apparent in this data. It also appears that thinner pavements subjected to heavy truck traffic loads may benefit from the use of edge drains and improved foundation support, although the cost-effectiveness of these features must be considered. The effects of drainage and foundation design on pavement performance are discussed in the project report (Snyder 2008).

Pavement Distresses

The ride quality (IRI) histories described previously are related to initial construction smoothness, roughness due to long-term environmental effects, and the development of load-related distresses. The contribution of load-related distresses appears to have been minimal so far.

Pavement condition (distress) surveys have typically been performed 3 – 4 times per year using distress measures and definitions described in the FHWA's LTPP Distress Manual (Miller and Bellinger 2003). Summaries of those surveys are presented in Tables 4 and 5 and are discussed below.

Slab Cracking

As of June 2006, Cells 36 and 37 had developed no significant panel cracking after more than 300,000 ESAL applications. Both of these cells have thick (210 cm [84-in] sand subbase layers and edge drains.

Cells 39 (doweled, long panels) and 40 (undoweled, thickened edge) each contained 1 medium- or high-severity transverse crack in each lane. Cell 38 (doweled, 4.6-m [15-ft] panels) had developed 3-4 transverse cracks in each lane, along with about 9.1 m [30 ft] of longitudinal cracking in each lane. Cell 40 had also developed one high-severity corner break.

Table 4. Summary of low-volume road concrete test cell pavement distress (as of June 2006).

Cell:	**36**		**38**		**39**	
Thickness:	150 mm concrete over 300 mm granular + 2.1 m sand		150 mm concrete over 125 mm granular		150 mm concrete over 125 mm granular	
Panel Length:	4.6 m		4.6 m		6.1 m	
Dowels:	25 mm		25 mm		25 mm	
Drains:	Drained		Undrained		Undrained	
	353-kN Lane	**455-kN Lane**	**353-kN Lane**	**455-kN Lane**	**353-kN Lane**	**455-kN Lane**
Trans. Cracking (% Panels):	0	0	3% med, 6% high	3% lo, 3% med, 6% hi	4% hi	4% med
Long. Cracking (ft):	0	0	18 low, 12 hi	8 low, 6 med, 12 hi	0	0
Other Distress:	Jt Seal Damage: 9% med-hi	Jt Seal Damage: 6% med-hi	Jt Seal Damage: 8% med-hi	Jt Seal Damage: 5% med-hi	Jt Seal Damage: 8% med-hi	Jt Seal Damage: None
Maintenance:	None	None	None	None	None	None

Cell:	**37**		**40**	
Thickness:	150 mm concrete over 125 mm granular + 2.1 m sand		178 - 140 -178 mm concrete over 125 mm granular	
Panel Length:	3.7 m		4.6 m	
Dowels:	None		None	
Drains:	Drained		Undrained	
	353-kN Lane	**455-kN Lane**	**353-kN Lane**	**455-kN Lane**
Trans. Cracking (% Panels):	0	0	3% high	3% high
Long. Cracking (ft):	0	0	0	0
Other Distress:	Jt Seal Damage: 7% med-hi	Jt Seal Damage: 7% med-hi	Corner Brk: 1 hi; Jt Seal Damage: 47% med-hi	Jt Seal Damage: 12% med-hi
Maintenance:	None	None	None	None

Table 5. Transverse joint faulting for MnROAD low-volume road concrete pavement test cells, measured 31 cm [12 in] from "fog line" in November 2006.

Test Cell	Average Joint Faulting (mm)	Maximum Joint Faulting (mm)	Std. Dev. Joint Faulting (mm)
Low-Volume Road Concrete Test Cells			
36	0.43/0.46	1.1/1.6	0.58/0.32
37	0.61/0.33	1.5/0.89	0.61/0.38
38	0.15/0.48	1.2/1.2	0.61/0.46
39	0.41/0.30	2.1/1.2	0.76/0.58
40	2.64/1.50	5.0/4.3	1.1/1.3

Notes: 1) Alternate values shown are for the 355-kN [80-kip] and 453-kN [102-kip] lanes, respectively.
2) 1 inch = 25.4 mm

The observed transverse cracking in Cells 38-40 has been attributed to localized settlements because the crack locations coincide with utility trench locations (Burnham 2005). The development of these cracks may have been accelerated by the relatively long panels (L/t = 24, 30 and 24 for cells 38, 39 and 40, respectively) which results in increased fatigue due to combined load and curl/warp stresses.

Joint Faulting

A common failure criterion for faulting of jointed concrete pavements with panel lengths as short as 3.6 m [15 ft] is 6 mm [1/4 in], with somewhat higher values being acceptable for longer panels. Table 5 summarizes recent joint faulting measurements for the low-volume road concrete test sections (average, maximum and standard deviation of 11 or more joints in each test cell). All five of the low-volume road concrete test cells have average faulting measurements of 2.5 mm [0.1 in] or less, and the largest fault measured is approximately 5mm [0.2 in]. Cells 36 – 39 all have average faulting values of less than 0.75 mm [0.03 in]. These low levels of faulting are consistent with the good ride quality (IRI) of these cells.

As expected, the doweled sections generally have much less faulting than the undoweled sections. In addition, the test cells with drainage and thick sand subbase layers have lower faulting rates than cells without these features. If faulting continues to develop at the current average rates, most of these test cells will not develop average faulting levels that approach the 6mm [¼-in] failure criterion until they are more than 100 years old. Cell 40, which has the highest current faulting levels, would be almost 50 years old before reaching the 6mm [¼-in] failure criterion. None of these cells will meet typical failure criteria for faulting until they have carried many times their target design ESALs.

Other Distresses

After 12 years of service, no blowups, corner breaks, D-cracking, map cracking, scaling, popouts, pumping or significant joint spalling have been observed in any of the low-volume road concrete pavement test cells.

Joint Sealant Damage
The silicone transverse joint seals are still generally in good condition in most of the test cells after 12 years of service, with 90 - 100 percent of the joints exhibiting little or no joint sealant damage. Only cell 40 exhibited more sealant damage (up to 47 percent medium- to high-severity). Cell 40 is an end section that may be subject to some movement of the panels, similar to the mechanism that was documented by Burnham (2005) for cell 5, which would result in higher levels of sealant damage.

Maintenance Log
No maintenance activities have been performed on of the original MnROAD low volume road concrete pavement test cells. All other original cells on the low-volume road test loop have been required significant maintenance or reconstruction (some more than once).

Performance Predictions
One of the initial objectives of MnROAD was to validate the pavement design methods then in use by Mn/DOT and published by AASHTO. A study of the concrete pavement test sections was performed by Burnham and Pirkl (1997), who used the as-built physical characteristics of the MnROAD concrete test cells as input parameters for the then-current Mn/DOT design method (a modified version of the 1981 AASHTO method), the 1993 AASHTO method, and the 1984 PCA (Portland Cement Association) method. For each method, the expected test cell service life to reach terminal serviceability (IRI = 2.16 m/km [138 in/mi] or PSR = 2.5) was determined (Burnham and Pirkl, 1997). For the purposes of this document, each test cell was also evaluated using as-built data and the latest version of the Mechanistic-Empirical Pavement Design Guide (MEPDG v. 1.000). In addition, the current average rates of IRI gain/year (generally based on 2000 – 2006 measurements) and projected total life to IRI failure (2.16 m/km [138 in/mi]) were determined. The results of all of these design/analysis procedures are presented in Table 6.

Consideration of the data presented in table 6 lead to the following observations:

- Projections of IRI data to date suggest that the addition of an average of approximately 58 mm [2.3 inches] of concrete thickness to the nominal design developed to last for 3 years/100,000 ESALs will result in design life increases of 14 to 38 years (470 to 1270 percent).
- The design/analysis method that most accurately predicts (on average) the projected performance life is the 1993 AASHTO Method at 75 percent reliability (average error of -2 percent). The range of errors (predicted minus projected) for the data shown in table 6 for this method is -48 to +75 percent, and the standard deviation of the errors is 47 percent. It should be noted, however, that the performance life projections are averages (i.e., 50 percent reliability). While using the 1993 AASHTO Method at 75 percent reliability most closely predicted

these values, a truly accurate model and procedure would predict these values at 50 percent reliability, rather that at 75 percent reliability.

Table 6. Serviceability lives* (years) predicted for MnROAD mainline concrete pavement test cells using various pavement design/analysis procedures (modified from Burnham and Pirkl, 1997).

Test Cell	Current Avg. IRI Change (355-kN [80-k] lane, m/km/year)/ Projected Total Life (yrs)	Mn/DOT Design Method	AASHTO 1993 Method (50% and 75% Reliability)	MEPDG v 1.000 (50% and 75% Reliability)	1984 PCA Method **
36	0.047/28	43.5	43.4/23.7	25/17	125.8
37	0.034/41	37.5	39.3/21.4	19/12	41.7
38	0.063/21	33.5	40.9/22.3	25/17	101.9
39	0.067/20	24.5	27.0/14.8	13/8	97.1
40	0.061/17	50.0	54.6/29.8	11/4	65.7

*Service life estimates based on 7,000 353-kN [80-kip] passes/year, terminal PSR = 2.5, 15% slab cracking.
**Service life is for cracking criterion only, not for erosion criterion.

- The design/analysis method that most precisely predicts (on average) the projected performance life is the MEPDG v1.000 at 50 percent reliability (standard deviation of the errors is only 28 percent). The range of errors for the data shown in table 6 for this method is -54 to +19 percent, and the average error is -23 percent. Since the performance projections considered are average values and the MEPDG v1.000 analysis at 50 percent reliability predicted the projected values with relatively good precision and accuracy, one could conclude that the MEPDG v1.000 IRI performance prediction model is more accurate than the other models considered here, at least for this data set.
- The 1993 AASHTO method at 50 percent reliability generally predicted somewhat longer performance lives than did the MnDOT procedure. This is probably due, at least in part, to the higher “built-in” reliability level (approximately 90 percent) in the MnDOT procedure.
- The PCA procedure generally predicts much longer lives for the low-volume road concrete pavement test sections than is projected. This method considers erosion (faulting) and cracking failure criteria, but cannot directly predict pavement ride quality. This probably accounts for the differences in predicted service life.

In almost all of the low volume road concrete test cells, IRI values have generally increased at reasonably constant (but sometimes different) rates over their entire performance lives. Therefore, the data from this study suggest that the time required to reach terminal IRI value will vary inversely with initial ride quality (i.e., pavement sections with lower initial IRI values have longer service lives). The MnROAD low-volume road concrete pavement test cells currently exhibit IRI increase rates ranging from approximately 0.024 to 0.068 m/km [1.5 to 4.3 in/mile per year]; initial IRI values (1994) varied from approximately 0.76 to 1.21 m/km/year [48 to 77 in/mi], a range of nearly 0.47 m/km/year [30 in/mile]. Improving the initial ride quality by just 0.16 m/km [10 in/mile] could reasonably be assumed to provide between 2 (10/4.3) and 7 (10/1.5) years of additional service before failing according to pavement ride (IRI) criteria.

Effects of Design and Construction Variables
The MnROAD low-volume road concrete pavement test cells differ with respect to many design and geometric variables, including: panel length, the use of dowel load transfer devices, foundation support (base thickness and presence of thick sand subbase), the use of edge drains, and the use of a thickened edge structural section. Unfortunately, none of these variables can be evaluated directly because all five test cells differ from each other in more than one design or construction variable. Therefore, observed differences in performance may be the result of changes in two or more variables. In addition, there are no replicate test cells on the low-volume road section of MnROAD, so care must be taken in drawing conclusions from such small samples.

Panel geometry is extremely important in the development of pavement cracking. No cracking was observed in Cell 37, which has the shortest panels (3.7 m [12 ft]). Some transverse cracking was observed in cells with 4.6-m [15-ft] and 6.1-m [20-ft] panels, although the greatest amount of cracking was not in the cell with the longest panels. The observed cracking overlies and is generally attributed to utility trenches beneath the pavement.

The use of *dowels* is highly effective in reducing deflections and improving load transfer efficiency, even for relatively thin slabs. All of the doweled sections have LTE histories that are very good (LTE generally greater than 70 percent and, more importantly, differential deflections far less than 0.25 mm [0.01 in]) and have been stable over more than 12 years of service to date. The undoweled sections exhibit much higher joint deflections and much more seasonal variability in deflections.

The *thickened edge section* used in Cell 40 has not resulted in significantly better performance to date. In fact, cell 40 has developed relatively high increases in IRI and has the worst LTE records (e.g., lower, more variable LTE values than other test cells) of the low-volume road concrete pavement test cells. Some of this poor performance may be a result of the test cell location, which is adjacent to an asphalt pavement section that provides no longitudinal resistance to slab movement.

The effects of *subbase type and thickness*, and *edge drains* are discussed in the project report (Snyder 2008) and are not described in detail here other than to summarize the conclusions that both of these parameters may have some influence on the performance of low volume roads but may not be cost-effective.

Summary – What Have We Learned?

The following "lessons" are suggested by the general performance to date of the MnROAD low-volume road concrete pavement test cells:

- After 12 years and 300,000+ ESALs of service, the low-volume road concrete pavement sections have greatly exceeded their intended design lives of 100,000 ESALs in 3 years while requiring absolutely no maintenance to date. This extended service life is to be expected, however, since these sections were all built with nominal 150-mm [6-in] pavement thicknesses (and as-built thicknesses of approximately 165 mm [6.5 inches]) rather than the computed design thickness of 110 mm [4.2 in]. It is likely that thinner concrete sections would have provided the desired service life for a lower initial cost.
- IRI trendlines suggest that the IRI values for the MnROAD low-volume road concrete test cells are increasing at rates that vary between 0.090 to 0.170 m/km/year [1.5 and 4.3 inches/mile/year], depending on the design features and the traffic lane. If these trends continue, cell 40 will be the first to reach terminal serviceability after providing about 17 years of service and carrying nearly 400,000 ESALs, while cell 37 will be the last to reach terminal serviceability after providing about 41 years of service and carrying about 1.3 million ESALs consisting entirely of 355-kN [80-kip] and 453-kN [102-kip] trucks.
- The low-volume road concrete test cells show a range of ride deterioration *rates* which suggests that the other design parameters (i.e., load transfer, drainage, foundation preparation, etc.) that were varied on these test cells have at least a modest influence on their rates of serviceability loss. This was not found to be true for the mainline pavement sections, where the effects of drainage, panel length and subbase thickness on pavement performance appear to be negligible. The influence of these design parameters appears to be more significant for the thinner concrete pavements.
- Initial IRI of concrete pavements has a tremendous impact on how long it takes for the pavement to "fail" according to ride quality. Concrete pavement performance life may be extended by many years simply by building it smoother to begin with.
- Dowel load transfer systems are highly effective in reducing joint deflections and maintaining high LTE values, even for relatively thin, low-volume pavement designs.
- The use of a very thick subbase material with edge drains was effective in reducing joint deflections and improving LTE values for both doweled and undoweled concrete pavements. The cost-effectivness of these design features is discussed in the project report (Snyder 2008).

- The thickened edge design (without dowels, edge drains or thick subbase layer) was not effective in reducing joint deflections and improving pavement performance.
- Panel cracking was attributed mainly to localized loss of support over utility trenches. Changes in panel length were not strongly linked to changes in panel cracking.
- The use of dowels, drains and/or thick subbase layers appears to effectively reduce joint faulting, although none of the test cells evaluated is projected to develop significant faulting in less than 50 years of service.
- The MEPDG v1.000 provided the estimates of pavement performance that most closely match projected IRI trends when using 50 percent reliability performance curves. This analysis procedure generally underpredicted project performance by about 23 percent.

Implications for Pavement Design and Construction

- Concrete pavements with thicknesses of less than 150 mm [6 inches] can be expected to provide acceptable levels of service in low-volume road applications, even when significant volumes of heavy truck traffic are expected. This implication is supported by the performance of a 125-mm [5-inch] concrete pavement section constructed in 2000 on the MnROAD low-volume test facility, which is described in Snyder (2008).
- The use of incentives should be considered to achieve extended pavement life through improved initial ride quality (reduced initial IRI).
- Studies of the cost-effectiveness of dowel load transfer systems in low-volume road applications should be performed. While dowels clearly reduce joint deflections and the development of faulting, they present construction difficulties in very thin pavements and may not produce significant improvements in long-term performance. Nonuniform dowel spacing (e.g., dowels clustered near the wheel paths) should be evaluated as a possible cost-effective approach, but construction issues (e.g., sensitivity of dowel alignment and thickness of concrete cover on long-term performance) must be considered and addressed as well.
- Recommendations concerning pavement subbase type/thickness and pavement drainage are presented in other articles in this series.
- Steps should be taken to avoid built-in curl/warp during construction. This may include preferred paving during the night and/or in the fall when built-in temperature gradients are generally reduced, and/or improved curing conditions to further reduce temperature gradients and loss of moisture.
- Designers should be aware that some concrete pavement design procedures considered in this study were conservative and underpredicted concrete pavement performance, while others greatly overpredicted concrete pavement performance. Of the procedures evaluated in this article, the MEPDG v1.000 offered the best combination of relative accuracy and precision in predicting projected pavement performance lives when using as-built inputs with 50 percent reliability.

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